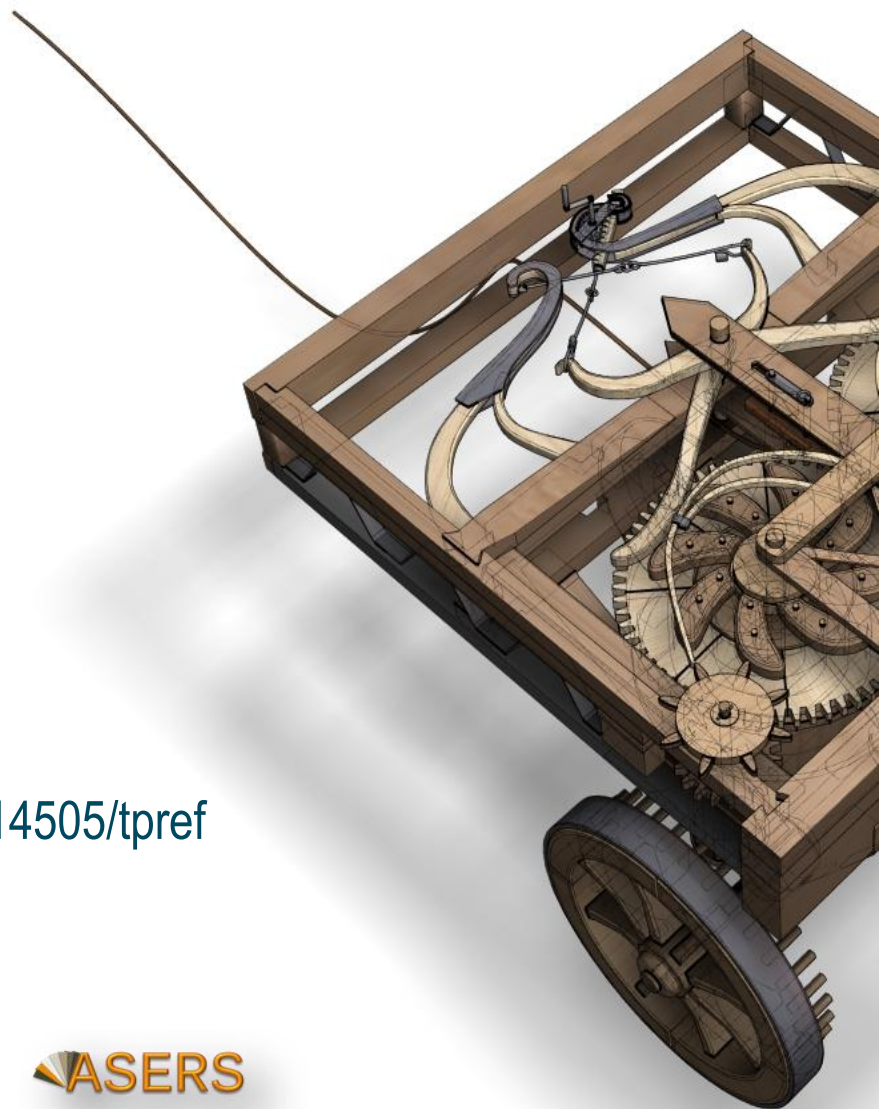


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From Complexity to Prosperity: Economic Complexity's Impact on BRICS Economic Wealth



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Abstract: This study examines the impact of technological advancement on economic wealth in BRICS countries over the period 2000–2020. Technological advancement is measured using the Economic Complexity Index (ECI). Economic wealth is measured using a revised Economic Wealth Index (EWI), constructed by excluding GDP, patent applications, and the ECI. Short-run effects are estimated using a panel fixed effects model with Driscoll–Kraay robust standard errors. Long-run relationships are examined through Pedroni cointegration tests and Panel Dynamic Ordinary Least Squares (PDOLS) analysis. Analyses indicate that ECI has a positive and statistically significant effect ($p < 0.01$) on EWI in both the short and long run. According to the test results, a one-unit increase in ECI leads to an increase of approximately 1.49 units in EWI in the short term and 1.82 units in the long term. These findings suggest that the level of advanced technology and investments in research and development plays an important role in increasing economic wealth. This study differs from previous studies in the literature by examining both the short- and long-run effects of technological advancement on economic wealth using a revised EWI.

Keywords: BRICS; economic complexity index; economic wealth index; principal component analysis.

JEL Classification: O33; O47; C23; F14.

Introduction

This study brings together technology and economic wealth and examines how high technology, advanced manufacturing capabilities, and complex economic diversification affect economic wealth creation. It is thought that examining the relationship between technology and economic wealth can explain why some economies fail, while others achieve sustainable and desired prosperity.

Despite the growing body of research linking economic complexity to income and growth, the relationship between economic complexity and a broader concept of economic wealth remains underexplored. Existing studies largely rely on GDP-based indicators and do not examine whether structural technological sophistication translates into multidimensional prosperity that also includes social and institutional dimensions. Furthermore, the short- and long-run dynamics of this relationship have not been jointly analyzed within a composite wealth framework.

In light of this gap, this study seeks to address the following research questions:

1. Does economic complexity significantly affect economic wealth in BRICS countries?
2. Is this relationship valid in both the short and long run?
3. To what extent does technological sophistication contribute to a multidimensional measure of economic wealth beyond income-based indicators?

This study utilizes the economic complexity index (ECI), developed by Hidalgo and Hausmann (2009), which shows a nation's technological capacity. However, the core problem addressed is how to measure economic wealth. Traditional indicators such as Gross Domestic Product (GDP), savings rates, and employment figures give only

partial insights and ignore critical social, structural, and institutional factors - like the quality of governance, equity, and human capital development - that fundamentally influence real economic wealth. Therefore, this study uses the Economic Wealth Index (EWI) (Öcal, 2025), which provides a more comprehensive composite framework for measuring economic wealth by combining economic, social, and institutional dimensions.

This study extends the literature by examining the short- and long-run effects of economic complexity on economic wealth using a revised ECI. Focusing on BRICS countries over the period 2000–2020, first the EWI was built with Principal Component Analysis (PCA), then the link between EWI and ECI was checked with cointegration tests, and finally panel estimations were carried out.

1. Literature Review

How to measure economic wealth has been debated in economics for several years. Within this debate, the idea of economic complexity appears as a way to look at the structural side of wealth. Based on Hidalgo and Hausmann (2009), ECI shows how well a country can produce and export a wide range of knowledge-based goods. In this sense, ECI links economic wealth not only to capital accumulation but also to productive knowledge.

Many studies in literature have examined the impact of economic complexity on development and growth. Hausmann *et al.* (2007, 2011) found that countries exporting more advanced products tend to grow faster. They argue in their analysis using the ECI that countries with more technologically advanced products that have higher levels of knowledge and skill and complex production structures tend to be richer. In their study Stojkoski and Kocarev (2017) also argue that economic complexity enhances and maintains long-term and sustained high levels of income expansion in Central and Southeastern European nations. Gala *et al.* (2018) suggest that developing countries with higher ECI scores have a higher potential to reach the level of developed countries.

In 2012, Tacchella *et al.* (2012) studied on a new nonlinear "fitness" model to measure countries' production and complexity capacity and they showed that growth depends not only on the goods produced but also on the complexity and knowledge intensity level of the production structure. Similar results have been reached later in several studies. For example, Poncet and De Waldemar (2013) showed a positive correlation between higher export complexity and stronger economic development. Hartmann *et al.* (2017) also demonstrated that income inequality is lower in more complex economies.

Recent empirical studies further supports the social dimension of economic complexity. Subekti (2024), using a dynamic panel approach for G20 countries, finds that higher economic complexity significantly reduces income inequality. These findings suggest that economic complexity may influence not only growth but also distributive outcomes, reinforcing its broader socio-economic implications.

Emerging research highlights the heterogeneous social effects of economic complexity. Kumar *et al.* (2025), examining 32 Asian countries, find that the impact of economic complexity on income inequality varies across income distribution quantiles, suggesting that complexity may reduce inequality at lower levels while exacerbating disparities at higher levels. These findings underline the nuanced and multidimensional implications of economic complexity beyond aggregate income measures.

Some studies have examined how complexity is related to stability and structural changes. Güneri (2019) showed that higher complexity is linked to lower output volatility. Country-specific work also supports this idea. O'Clery (2016) showed that Ireland's drop in export diversity was followed by a decrease in its ECI score. Camargo and Gala (2017) noted that low complexity may help explain the "Dutch disease" patterns observed in resource-dependent economies.

Contemporary research continues to emphasize the role of economic complexity in structural transformation and sustainable growth dynamics. For instance, Mellini and da Silva (2024) links economic complexity to improvements in Thirlwall's elasticity ratio, highlighting its importance for long-term growth patterns and balance-of-payments sustainability.

Additional evidence extends the scope of economic complexity research beyond income-based measures. Hamdi *et al.* (2025), using a buffered panel threshold regression for a large sample of countries, demonstrate that economic complexity significantly affects human development, with heterogeneous effects depending on institutional quality and resource dependence.

Current studies show that economic complexity is related to many outcomes such as growth, inequality, and economic stability. However, most of these studies relied on income-based measures. Recent evidence also indicates that the effects of economic complexity are multidimensional and context-dependent, varying across institutional and socio-economic settings. Nevertheless, only a few studies have examined whether complexity affects economic wealth, which reflects a broader form of prosperity that also includes social and institutional aspects.

The literature does not offer a single or widely agreed-upon definition of economic wealth. However, many studies agree that economic wealth is a broad and integrated concept that combines economic, social, and institutional factors. When discussing economic wealth, it should not be understood that it is related only to economic and financial indicators. Economic wealth also reflects a country's ability to create and sustain prosperity, distribute wealth fairly, and ensure that institutions operate transparently and effectively, free from disruptive factors that undermine the economy and social order, such as bribery and corruption (Öcal, 2025).

Barbier's (2015) research shows four key dimensions of economic wealth: physical infrastructure and equipment that form produced capital; education, skills, and health that compose human capital; environmental resources like land and forests that are natural capital; and the monetary holdings, stocks, and bonds that constitute financial assets. Similarly, Chikviladze (2023) contends that a nation's economic wealth shows cumulative competencies, including both intangible assets and human capabilities, which shape its sustained productive potential over time. These studies show that economic wealth is a dynamic phenomenon that has evolved. It isn't a static collection of assets and resources.

Stiglitz, Sen, and Fitoussi (2009) state that seeing GDP as the sole measure of economic performance is insufficient, because relying solely on GDP does not account for what is produced, who benefits from it, and the methods used in production. This may indicate that economic wealth is shaped by both the size of economic output and its structure and distribution among people. Similarly, Ofori-Sasu *et al.* (2024) state that national wealth reflects the combined value of key resources under a country's control.

Overall, the literature has shown that economic complexity is associated with growth, inequality, and economic stability, yet most empirical evidence relies on income-based indicators. Although the concept of economic wealth has been discussed in broader terms, the relationship between economic complexity and a multidimensional composite measure of economic wealth has received limited empirical attention. This study contributes to the literature by linking economic complexity to a revised Economic Wealth Index and addressing this gap.

2. Method

The study covers the period 2000–2020, for which complete data are available for all components of the EWI, allowing the implementation of PCA. This period was chosen not only because it ensures data integrity but also because it represents a period of accelerated capital flows and strengthened global economic ties within economies (Özatay, 2015). At the same time, BRICS countries have undergone rapid transformation over the last two decades and constitute a suitable sample for studying the impact of technology on economic wealth.

Technological advancement was measured using ECI. The ECI data were obtained from the Atlas of Economic Complexity (Harvard Growth Lab, 2024). To measure economic wealth, the EWI (Öcal, 2025) was employed after removing patent applications, and ECI from its components. These variables were excluded to avoid conceptual overlap with the explanatory variable and to ensure that economic wealth was measured independently from technological indicators.

Table 1. Indicators and Data Sources Used for the Reconstruction of EWI

Indicator	Dimension	Source	Years
GDP per capita	Economic	World Bank, WDI	2000 - 2020
Gross Fixed Capital Formation (% of GDP)	Economic	World Bank, WDI	2000 - 2020
Savings Rate (% of GDP)	Economic	World Bank, WDI	2000 - 2020
Economic Freedom Index	Economic	Heritage Foundation	2000 - 2020
Employment Rate (% of total population)	Social	World Bank, WDI	2000 - 2020
GINI Index	Social	World Bank, UNU-WIDER (WIID)	2000 - 2020
Human Capital Index	Social	Penn World Table	2000 - 2020
Control of Corruption	Institutional	World Governance Indicators	2000 - 2020

Source: calculated by the authors

GDP was also removed, because GDP per capita was already included in the index. Following these adjustments, the EWI constructed in this study consisted of economic, social, and institutional components. Economic indicators

included GDP per capita, gross fixed capital formation, the savings rate, and economic freedom. Social indicators included the employment rate, the GINI index, and human capital. Institutional indicator was represented by control of corruption. Table 1 shows the EWI indicators, their sources, and the years of the data used.

To build the EWI for each country, PCA was used to combine the selected variables under a single composite measure. PCA was chosen to allow the relative importance of the indicators to be determined from the data itself, rather than assigning equal or arbitrarily chosen weights. The suitability of the data for PCA was confirmed by acceptable test results (KMO > 0.6; Bartlett's test of sphericity, $p < 0.001$). The first principal component was used as the EWI for each country and year. This procedure yielded a single economic wealth score for each country and year.

To explore the link between economic complexity and economic wealth, the following model was used:

$$ECI_{it} = \beta_0 + \beta_1 EWI_{it} + e_{it} \quad (1)$$

Here, ECI_{it} is the economic complexity value for country i in year t , EWI_{it} is the economic wealth measure, and e_{it} is the error term.

After setting up the model, the analysis started with stationarity and cointegration tests to see whether the variables moved together in the short and long run.

In the short run, the link between ECI and EWI was estimated with a fixed-effects model using the Driscoll–Kraay standard errors. In the long run, Pedroni's panel cointegration tests and Panel Dynamic Ordinary Least Squares (PDOLS) were used to explore dynamic relationships.

Before estimating the short-run relationship, the Hausman specification test was applied to determine the appropriate estimator. The test results supported the use of a fixed-effects model. Second, diagnostic tests were employed and indicated the presence of heteroskedasticity and serial correlation in the panel structure. Since these violations render conventional fixed-effects standard errors inconsistent, the short-run model was estimated using Driscoll–Kraay corrections, which correct for heteroskedasticity, autocorrelation and cross-sectional dependence issues and are suitable for panels with a small number of cross-sections and a relatively long-time dimension.

Before estimating the long-run coefficients, the Pedroni (2004) panel cointegration test was applied to examine whether a stable long-run relationship exists between ECI and EWI. Given the evidence of cointegration, the long-run coefficient was estimated using the PDOLS method, which accounts for serial correlation, endogeneity, and dynamic adjustments through lead–lag terms.

3. Research Results

3.1 Construction of the Economic Wealth Index (EWI)

The PCA results indicated that the data were suitable for factor extraction. The Kaiser–Meyer–Olkin (KMO) measure exceeded the acceptable threshold ($KMO > 0.6$), and Bartlett's test of sphericity was statistically significant ($p < 0.001$), confirming the appropriateness of PCA. Based on the first principal component, annual EWI scores were computed for each BRICS country over the period 2000–2020. The resulting EWI values are reported in Table 2.

Table 2. Annual EWI Scores for BRICS (2000–2020)

Year	Brazil	Russia	India	China	South Africa
2000	0.98815	-1.85841	-1.46514	-0.79093	1.55832
2001	1.03664	-1.80184	-1.53112	-1.43343	1.43979
2002	1.12631	-1.21341	-1.45367	-1.23238	1.41662
2003	1.12741	-1.23319	-1.31106	-1.04148	1.47476
2004	1.06441	-1.024	-1.25492	-0.9334	1.14816
2005	0.84741	-1.01909	-0.51489	-0.70364	0.8184
2006	0.75127	-0.71744	-0.37051	-0.6087	0.69557
2007	0.47937	-0.15661	-0.259	-0.76304	0.41487
2008	0.53582	0.15052	-0.05055	-0.54746	0.18215
2009	0.223	0.45439	-0.02362	-0.30895	0.16855

Year	Brazil	Russia	India	China	South Africa
2010	0.30452	0.27037	0.11649	-0.41226	-0.25418
2011	0.29731	0.29184	-0.27947	-0.12575	-0.66131
2012	0.11335	0.51981	0.20492	0.0532	-0.88203
2013	-0.08229	0.73149	0.38234	0.48197	-0.85217
2014	-0.56554	0.8113	0.64433	0.6399	-0.73708
2015	-0.89824	0.65641	0.76551	0.75166	-0.82185
2016	-1.08025	0.80023	1.15586	0.82508	-0.83411
2017	-1.50065	1.1152	1.02862	1.16073	-0.85971
2018	-1.47489	0.92997	1.32957	1.37829	-0.93133
2019	-1.44244	1.04171	1.33994	1.52174	-1.2592
2020	-1.85067	1.25075	1.54639	2.08884	-1.22423

Source: calculated by the authors

3.2 Short-run Estimation Results

Before estimating the short-run model, the Hausman specification test was applied. The results are reported in Table 3.

Table 3. Hausman Specification Test Results

Estimator	Coefficient
Fixed Effects (b)	1.488
Random Effects (B)	0.368
Difference (b – B)	1.120
Test Statistic	Value
Chi-square (1 df)	9.86
p-value	0.0017

Source: calculated by the authors

The null hypothesis assumes that the random-effects estimator is consistent. Since $p < 0.01$, the null hypothesis is rejected, indicating that the fixed-effects model is the appropriate specification for short-run estimation.

The short-run estimation results based on the fixed-effects model with Driscoll–Kraay corrections are presented in Tables 4 and 5.

Table 4. Fixed-Effects Model Regression Results with Driscoll–Kraay Standard Errors for the Short-Run

Dependent Variable : EWI					
Variable	Coefficient	Std. Error	t-stat	p-value	95% CI
ECI	1.488	0.415	3.59	0.001	[0.665 – 2.312]
Constant	-0.413	0.147	-2.80	0.001	[-0.706 – -0.121]

Source: calculated by the authors

Table 5. Model Diagnostics for the Short-Run Fixed-Effects Estimation

Model Diagnostics			
R-squared (Within)	0.1149	R-squared (Between)	0.1061
F-statistic	12.85	Prob > F	0.0005
ρ (fraction of variance due to u_i)	0.3179		

Source: calculated by the authors

The fixed-effects regression results, corrected for heteroskedasticity and serial correlation using Driscoll–Kraay standard errors, indicate that ECI in BRICS economies has a positive and statistically significant coefficient on EWI. Specifically, a one-unit increase in ECI raises EWI by approximately 1.49 points ($p < 0.01$).

3.3 Long-run Estimation Results

Before estimating the long-term coefficients, the Pedroni (2004) panel cointegration test was applied. Table 6 reports the results of the Pedroni (2004) panel cointegration test for ECI and EWI.

Table 6. Pedroni Panel Cointegration Test Results for ECI and EWI

Test Statistic	Panel	Group
Panel-t	-2.253	-
Group-t	-	-2.337
Panel-ADF	-0.5196	-
Group-ADF	-	0.8956

Source: calculated by the authors

In Pedroni's tests, large negative t-statistics ($|t| > 1.96$) indicate rejection of the null of no cointegration. Accordingly, among the within- and between-dimension measures, the panel and group t-statistics are significant at the 5% level, indicating the presence of cointegration between the two variables. These results suggest that ECI and EWI move together in the long run.

Given the evidence of cointegration, the long-run coefficient was estimated using the PDOLS method, which accounts for serial correlation, endogeneity, and dynamic adjustments through lead-lag terms. The PDOLS long-run estimation results are reported in Table 7.

Table 7. PDOLS Long-Run Coefficient Estimates: Impact of ECI on EWI

Panel PDOLS estimation details:		
no. of panel units : 5	lags and leads : 2	
number of obs : 80	avg obs. per unit : 16	
data points were time-demeaned.		
Variables	Beta	t-stat
ECI_td	1.822	3.226

Source: calculated by the authors

The estimated coefficient of ECI is approximately 1.82, and the associated t-statistic ($t = 3.226$) exceeds the 1% critical value, indicating significance at the 1% level ($p < 0.01$). These results indicate that economic complexity has a positive and statistically significant long-run relationship with economic wealth in BRICS countries.

5. Discussions

The empirical results show that, in the near term, economic complexity affects economic wealth in BRICS economies in a positive and statistically significant way. Therefore, it can be argued that even in short periods as

economic complexity increases, economic wealth also increases, and countries with higher technological levels and intensive knowledge production structures can achieve stronger economic wealth levels in the short run.

The long-term estimation results also indicate the ECI and EWI tend to move together and there is a positive and stable relationship between them. Therefore, it can be argued that high technology contributes to the sustainable increase in the economic wealth of countries in the long run.

Recent global developments between 2021 and 2026 have further underscored the importance of economic complexity in shaping long-term prosperity. The COVID-19 pandemic, supply chain disruptions, geopolitical tensions, and the acceleration of digital and green transformations have altered global production structures. In this evolving environment, countries with diversified and technologically advanced production capabilities appear better positioned to adapt to external shocks and structural changes, thereby strengthening the structural foundations of economic wealth. For emerging economies, including BRICS countries, strengthening productive capabilities and institutional quality have become increasingly critical for sustaining economic wealth beyond income-based growth.

These developments reinforce the relevance of the complexity–wealth nexus identified in this study and suggest that future research incorporating post-2020 data may provide additional insights into the evolving structural dynamics of global economies.

This study offers three main contributions to literature. First, it extends the economic complexity literature beyond income-based outcomes by linking ECI to a multidimensional composite measure of economic wealth. Second, it introduces a revised EWI framework that avoids conceptual overlapping with technological indicators. Third, it jointly examines short- and long-run dynamics using panel cointegration and PDOLS techniques, offering a more comprehensive understanding of the complexity–wealth nexus.

Conclusions and Further Research

The findings of this study point to several important conclusions. First, high technology and a high-technology-based production structure affect not only the growth process but also the capacity to create wealth. Second, given that ECI positively impacts economic wealth, it is fair to say that R&D investments in high technology and technological infrastructure positively impact not only on the economy but also employment, income distribution, human capital development, and the more transparent and reliable operation of institutions. Therefore, to achieve sustainable and desirable economic wealth, countries should prioritize technology, increase R&D spending, and strive to develop high-technology/knowledge-based production capabilities.

Future studies could expand this study to other countries or longer time periods and search for which components of economic wealth are most sensitive to changes in economic complexity.

Declarations

Credit Authorship Contribution Statement: Both authors made equal contributions to the study, covering all stages from the development of the research idea to the final evaluation of the findings.

Declaration of Competing Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

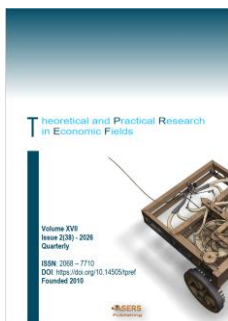
Declaration of Use of Generative AI and AI-Assisted Technologies: The authors declare that generative AI and AI-assisted technologies were used solely for language editing and improving readability. These tools were not used for content generation, data analysis, or interpretation of results.

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Investment and Financial Performance: The Moderating Role of Social Capital Investment



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Abstract: This study examines the relationship between corporate investment and financial performance among listed construction firms in Vietnam, with a particular attention to the moderating role of sector-level social capital investment. Using a panel data for 93 listed construction companies over the period 2011-2023, combined with national data on social capital investment in the construction sector, the study applies generalized least squares (GLS) estimation to assess both market-based and accounting-based performance outcomes. The results indicate that firm-level investment is positively associated with Tobin's Q and return on assets, with stronger effects observed for larger firms, reflecting their superior access to resources and capacity to absorb investment risks. However, higher levels of sectoral social capital investment significantly weaken this positive relationship. This negative moderation effect is consistent with the crowding-out mechanism, whereby intensified sector-wide investment heightens competition for scarce inputs, increases production costs, and reduces the marginal returns to firm-specific investment. By integrating firm-level behavior with sectoral investment dynamics, the study contributes to the literature on investment efficiency in capital-intensive industries and emerging markets. The findings also offer policy-relevant insights, emphasizing the importance of coordinating public and private investment strategies to avoid resource congestion and enhance long-term firm performance.

Keywords: construction industry; financial performance; investment; social capital investment.

JEL Classification: G31; H54; M19; C23; L74.

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Introduction

Investment policies are essential parts of corporate strategy, serving as a critical driving force towards long-term growth. Brealey and Meyers (2003) define investment decisions as the process of evaluating and selecting long-term investments that align with the firm's most important goal of maximizing shareholders' wealth, while Van Horne (2002) emphasizes capital allocation to initiatives such as equipment upgrades, expansion projects, equipment replacements, and technological innovation. In this context, long-term investments in fixed assets form the foundation for corporate development, aligning strategic objectives with operational priorities and enhancing profitability via optimized resource allocation and positive cash flows. This relationship is supported by the neoclassical investment theory (Jorgenson 1963) and the resource-based view (Barney 1991), which emphasize the importance of investment decisions in firm value maximization and highlight the strategic utilization of physical resources like fixed assets to achieve competitive advantages.

There is various research that has investigated this complex relationship between investment and firm performance; however, the findings are mixed, with some identifying positive impacts (Çam *et al.* 2024; Gao *et al.* 2025; Saif *et al.* 2020; Salehi *et al.* 2022) and others indicating insignificant or negative outcomes (Lin 2022; Okwo and Ugwunta 2012).

In Vietnam, the construction sector plays an indispensable role in the country's socioeconomic growth, which is fueled by rapid urbanization and infrastructure expansion. According to Statista market report, in 2023, Vietnam's construction sector accounted for 6.27 percent of the country's total GDP. The market size of this sector is estimated to reach nearly 75 billion USD by 2025 and expected to reach over 110 billion USD by 2030, reflecting a robust compound annual growth rate of 8,1% (Credence Research 2024). The economic importance of the construction industry is not limited to its contributions to GDP. 117 public-private partnership (PPP) projects valued at USD 43 billion, and the development of 5,000 km of expressways by 2030 are among the critical infrastructure projects that it facilitates, which improve economic productivity and connectivity (Mordor Intelligence 2025). Furthermore, social housing projects, targeting 1 million units by 2030, address pressing social needs.

These developments are primarily driven by social capital investment, defined as the sum of investments from the public sector, private companies, and foreign investors across the economy (Thi Thuy Hong *et al.* 2017). The government plays a dominant role by allocating substantial resources to infrastructure areas such as highways, bridges, and social housing. The demand for construction services is stimulated by high levels of public investment, such as the 6% of GDP that was allocated to infrastructure in 2022, which presents opportunities for firms to expand their operations. Nevertheless, this also introduces obstacles, including resource competition and increasing input costs, which can reduce the efficiency of firm-level investments.

The Structure - Conduct - Performance (SCP) framework provides a theoretical lens for understanding this interplay: it posits that industry-level structures - such as market concentration, entry barriers, and resource competition shape firms' conduct (including investment decisions) and, consequently, firm performance (Scherer and Ross 1990). In this context, high sectoral capital investment moderates the relationship by fostering crowding-in effects via enhanced economic conditions (Robert J. Barro 1990) or crowding-out effects through increasing resource competition (Buiter 1977), potentially affecting the link between corporate investments and firm performance. This balance of opportunities and challenges highlights the importance of examining social capital investment's role in the construction sector's development.

For the above reasons, this research investigates the relationship between investment policy and financial performance, focusing on the moderating role of total social capital investment in this sector. By examining the Vietnamese construction industry, the study aims to address theoretical gaps and provide recommendations for policymakers and industry stakeholders to improve the investment efficiency of this sector.

This study contributes to the literature in four key ways. First, unlike prior research focusing on macroeconomic moderators such as GDP or inflation (Cevik *et al.* 2024; T. T. Doan 2020; Egbunike and Okerekeoti 2018), it extends the nexus between investment and firm performance by innovating with sectoral social capital investment as a moderating variable in an emerging market context, revealing the crowding-out effects specific to Vietnam's construction industry. Second, it provides sector-specific insights for Vietnam's construction industry - an economically vital yet understudied industry. Third, by analyzing firm-size differences, it offers an empirical finding beyond mixed results. And finally, these contributions inform policymakers and managers on balancing the social capital investment to enhance the financial development of firms in the construction industry.

After this introduction, the paper is structured as follows: Section 1 reviews the relevant literature, Section 2 outlines the research methodology, Section 3 presents the findings, and Section 4 discusses implications and conclusions.

1. Literature Review

1.1. Investment and Firm Performance

Neoclassical theory states that investment decisions are guided by the principle of maximizing firm value, focusing on cost efficiency and marginal returns (Jorgenson, 1963). This approach highlights the importance of aligning investment decisions with the broader goal of optimizing financial performance (U. Farooq *et al.* 2022). However, while the neoclassical perspective emphasizes optimal capital allocation, it pays limited attention to the internal characteristics that determine how effectively such investments are utilized.

Complementing this view, the resource-based theory (RBV) shifts the focus from capital allocation to resource deployment. According to RBV, in order to gain competitive advantages, firms need to wisely utilize their resources (Barney, 1991). Corporate resources are mentioned as the "assets, capabilities, organizational process, firm attributes and information knowledge" (Barney 1991) and are commonly categorized into physical resources, human resource and organizational resources (M. Farooq *et al.* 2022). Among these, physical resources – such as plant, equipment, production technology, geographic location, and access to materials (Modigliani and Miller, 1963) are particularly critical in capital-intensive industries. Taken together, these perspectives suggest that investment influences firm performance not only through the scale of capital allocation but also through the strategic utilization

of tangible assets. Therefore, the portion of investment in the firm's total assets, especially the fixed assets like machines and production lines, becomes a key determinant of financial performance.

Empirical results have proved the significant impact of investment policy on the firm's performance but normally focus on the sophisticated relationship between these two variables. For instance, Saif *et al.* (2020) focused on the negative moderating role of cash flows between corporate investment decision and performance of the company, Salehi *et al.* (2022) consider institutional ownership and board characteristics as moderators in this relationship. Lin (2022) investigated the investment in fixed assets of A-share listed companies in China and found that companies with substantial investments in assets such as property and equipment have lower performance compared to less-invested counterparts. To be more specific, Lin (2022) concluded that companies with a high portion of fixed assets usually have to bear high maintenance costs, which may reduce their financial results. Giving a more complex point of view, Grozdic *et al.* (2020) noted short-term productivity losses from capital investments but long-term gains. This can be explained by the fact that, with a high investment cost, the short-term return may be reduced; however, in the long term, these investments can lead to higher production efficiency, better product or service quality, and eventually better financial performance. These mixed findings indicate that the investment – performance relationship is neither linear nor completely positive. Instead, it appears to depend on contextual factors such as cash flow, ownership structure, financing conditions, and industrial characteristics. In emerging markets, where capital markets may be less efficient, the marginal returns to investment can vary substantially.

In the context of Vietnam, existing studies generally report that investment in technology and equipment boosts the firm's competitiveness, leading to better financial results (Doan, 2020; Phan and Phan, 2013). However, these studies tend to treat investment as an isolated firm-level decision, without explicitly considering the broader sectoral investment environment that may exaggerate the impact on firm financial results.

Drawing on the above theoretical and empirical findings, this study argues that while corporate investment is expected to enhance firm performance, the direction and magnitude of the impact are likely to be context – dependent.

Accordingly, the following hypothesis is proposed:

H1: Corporate investment positively influences the financial performance of Vietnamese construction firms.

1.2. Moderating Role of Social Capital Investment

The accelerator theory of investment, originally proposed by Clark (1917), suggests that investment levels are a function of macroeconomic outputs. During periods of high economic growth, increased demand prompts firms to expand production capacity through capital investments. Farooq *et al.* (2022) and Saif *et al.* (2020) demonstrate that macroeconomic factors significantly influence corporate investment decisions and, consequently, financial performance. However, to the best of our knowledge, considerably less attention has been given to how sectoral social capital investment interacts with firm-level investment decisions. Previous research mostly considered macroeconomic factors such as GDP, inflation, and interest rates and their impacts on financial decisions (Cevik *et al.*, 2024; Doan, 2020; Egbunike and Okerekeoti, 2018).

The Structure - Conduct - Performance (SCP) paradigm provides a useful framework for addressing this gap. Originating in industrial organization economics, SCP posits that sectoral structure, including concentration, entry barriers, and the intensity of resource competition, conditions the firm's conduct, such as investment decisions, which substantially shape the firm's performance (Scherer and Ross, 1990). In this perspective, firm outcomes are not solely determined by internal decisions but are related to sector-level structural conditions.

In industries characterized by high capital intensity and reliance on shared resources, such as the construction industry, intensified social investment can reshape competitive dynamics in two distinct ways. On one hand, it generates a crowding-in effect by improving the economic environment, reducing costs, and boosting demand (Barro, 1990). On the other hand, the crowding-out effect arises when large public investments raise interest rates and compete for resources, which eventually discourage private investment (Buiter, 1977).

Nevertheless, prior research often examines crowding-in and crowding-out effects at the macroeconomic level, without linking them to firm-level performance. In the context of Vietnam, where total social capital investment has historically accounted for a substantial share of GDP and public investment plays a dominant role in infrastructure development, these opposing forces may be particularly pronounced in the construction sector.

Therefore, rather than assuming a uniformly positive moderating impact of social investment, this study expects that sectoral social capital investment may condition the marginal return of a firm's investment. Specifically, when public investment increases within the construction sector, it may dilute the effectiveness of private corporate investment through fierce competition for capital and resources.

From the above reasoning, this study proposes the following hypothesis:

H2: Social capital investment in the construction area negatively moderates the relationship between corporate investment and financial performance of Vietnamese construction firms.

2. Data and Methodology

2.1. Data and Sample

This study employs a quantitative panel research design using secondary data from firm-level and macroeconomic sources. Firm-level financial and accounting data were obtained from Refinitiv (currently known as LSEG Data & Analytics), which provides standardized and internationally comparable information on publicly listed firms. These data include balance sheet items, income statement components, and key financial ratios, ensuring consistency and reliability across firms and over time. Refinitiv has been widely used in prior empirical studies in finance and corporate governance, supporting the validity of the firm-level measures employed in this study.

Macroeconomic indicators were collected from the General Statistics Office of Vietnam (GSO), the official national statistical authority. The macro-level variables include annual indicators such as GDP growth, inflation rates, and interest rates, which are incorporated to control for the broader economic environment affecting firm performance. The use of official national statistics enhances the accuracy and credibility of the macroeconomic data.

The initial sample consisted of all firms classified under the construction sector and listed on Vietnamese stock exchanges during the study period. After excluding firms with incomplete financial information or insufficient time-series observations, the final sample comprises 93 construction firms, observed annually from 2011 to 2023, yielding a balanced panel dataset. The construction sector was selected due to its economic significance in Vietnam and its sensitivity to macroeconomic conditions and regulatory changes, making it an appropriate context for examining firm-level financial outcomes.

The study period from 2011 to 2023 was chosen for three main reasons. First, it captures the post-global financial crisis phase and subsequent structural reforms in Vietnam's economy. Second, it encompasses multiple economic cycles, including periods of economic expansion and contraction, allowing for more robust inference. Third, 2023 represents the most recent year for which complete firm-level data were available at the time of analysis.

Firm-level and macroeconomic datasets were merged based on corresponding calendar years to ensure temporal consistency across variables. Data cleaning, validation, and preliminary processing were conducted using Microsoft Excel, while econometric analyses were performed using Stata. These procedures resulted in a balanced panel structure that supports the application of panel regression techniques and enhances the reliability of the empirical findings.

2.2. Empirical Models

2.2.1 Research Models

The authors propose two research models to investigate the relationships of interest. Model (1) is established to study the influence of the corporate investment index on Tobin's Q, with a particular focus on assessing the moderating effect of social capital investment in the construction sector on this relationship. Model (2) is constructed to examine the effect of the corporate investment on Return on Assets (ROA) and to evaluate the moderating role of social capital investment in the construction sector on this impact.

$$TobinQ_{it} = \alpha + \beta_1 INV1_{it} + \beta_2 GTA_{it} + \beta_3 Cashflow_{it} + \beta_4 (LnConINV_t * INV1_{it}) + \beta_7 Firmage_{it} + \beta_8 Liquidity_t + \varepsilon_{it} \quad (1)$$

$$ROA_{it} = \alpha + \beta_1 INV1_{it} + \beta_2 GTA_{it} + \beta_3 Cashflow_{it} + \beta_4 (LnConINV_t * INV1_{it}) + \beta_7 Firmage_{it} + \beta_8 Liquidity_t + \varepsilon_{it} \quad (2)$$

Where ε_{it} is a random error, and the variable subscripts i and t represent company i in year t . The description of variables is summarized in Table 1.

2.2.2 Variables

Dependent variables: Tobin's Q and ROA

Tobin's Q represents the ratio of a firm's market value to the replacement cost of its assets, serving as a proxy for market valuation. It reflects both current and expected future profitability, capturing earnings potential and the value of intangible assets. As such, Tobin's Q is widely regarded as an indicator of the market's perception of

a firm's future prospects (Chung and Pruitt, 1994). Due to the difficulties in estimating replacement costs, researchers commonly apply an approximate formula as follows (Aydoğmuş *et al.* 2022).

ROA is a standard measure of profitability, indicating a firm's ability to generate earnings from its asset base. It expresses net income as a percentage of total assets, reflecting resource efficiency (Kieso *et al.*, 2022). Higher ROA values signal stronger profitability, while lower values indicate less efficient asset utilization. ROA also enables evaluation of resource use (Berk and DeMarzo, 2020), facilitates industry benchmarking (Higgins *et al.*, 2023), and supports trend analysis of managerial performance over time (Pandey, 2010).

Independent variables:

The **Investment Index** measures the proportion of the company's total assets financed by long-term capital, indicating the investment capacity of the firm in the long run. In the construction industry, where substantial investment in fixed assets such as lands, buildings, and heavy equipment is common, this index is particularly relevant due to the need for stable and long-term financing. Besides, the construction projects require extensive timelines and consistent funding to reduce liquidity risks and ensure project completion. For the above reasons, the investment index provides a reliable measure of financial stability, enabling firms to maintain capital-intensive operations while optimizing investment efficiency. Research by Saif *et al.* (2020) supports the application of this index.

$$\text{Investment index} = (\text{Fixed assets} + \text{Current assets} - \text{Current liabilities}) / \text{Total assets}$$

The **growth rate of total assets** is a suitable metric to evaluate the investment activities of construction firms since it directly reflects the expansion of asset value, including both fixed assets and current assets. In the construction industry, this metric highlights a firm's capacity to invest in infrastructure and equipment, enhancing long-term production capabilities and competitiveness in a demanding market. An increase in total assets growth implies that firms are making strategic investments to support large-scale, long-term projects. Research by Saif *et al.* (2020) used this index as a proxy for investment decisions, underscoring the importance of asset expansion. Similarly, Cordis and Kirby (2015) employed total assets growth as a comprehensive measure of investment activities. This metric is easily derived from financial statements, offering a clear indicator of investment scale.

Growth rate of total assets (GTA) = (Total assets at the end - Total assets at the beginning) / Total assets at the beginning

The **cash flow** variable is an effective proxy for investment because it reflects the internal funds available for making investments such as acquiring new plants, equipment, and expanding facilities without relying on external financing. By dividing cash generated from operations, adjusted for non-cash expenses, by fixed assets, this metric evaluates the efficiency of the firm's base asset generating funds for reinvestment. A higher ratio indicates that the firm can generate more cash per unit of fixed assets, implying a better investment capacity. This is particularly important in the construction industry, where efficient use of equipment and infrastructure directly impacts project profitability and financial performance of the firm. This measure is applied in the research of Saif *et al.* (2020)

$$\text{Cash flow} = (\text{Net income} + \text{Depreciation \& Amortization}) / \text{Fixed assets at the beginning}$$

Moderating variable:

The **social capital investment**, as defined by Thi Thuy Hong *et al.* (2017), represents the total investment in the economy by public, private, and foreign sources. In this study, the index is specifically applied to the construction sector to assess its influence on investment efficiency and financial performance. This focus is appropriate since the level of social capital investment in construction areas directly influences the availability of resources and investment opportunities for firms in this field to undertake large-scale projects, such as infrastructure or commercial buildings. Therefore, it is reasonable to use this index as a moderating variable to evaluate its impact on the investment efficiency and financial performance of construction firms.

Control variables:

Firm age, measured as the number of years from the company's establishment to present, serves as a control variable, reflecting the firm's experience and reputation. Older firms normally possess an established reputation, which can enhance their competitiveness in securing investment opportunities and accessing resources (Vu *et al.*, 2019). Besides, **liquidity** of the firm is represented by its current ratio, expressing its portion of current assets over total assets. High liquidity ensures financial ability, supporting investment activities without reliance on external financing (Gill, 2022). These control variables are critical factors affecting the investment efficiency and financial performance of firms in the construction industry.

The above-mentioned variables are summarized in the following table:

Table 1. Variables used in research models

Variable	Name of Variable	Definition/M Measurement
Dependent Variables		
<i>TobinQ</i>	Firm value	Tobin's Q = Book value of total assets/ Market value of total assets
<i>ROA</i>	Return on Assets	ROA = Net income/ Total assets
Independent Variable		
<i>INV1</i>	Investment index	Investment Index = (Fixed assets + Current assets – Current liabilities) / Total assets
<i>GTA</i>	Growth rate of total assets	Growth Rate of Total Assets = (Total assets at the end - Total assets at the beginning) / Total assets at the beginning
<i>Cashflow</i>	Cash flow to Fixed assets	Cash Flows = (Net income + Depreciation & Amortization) / Fixed assets at the beginning
Moderating Variables		
<i>LnConINV</i>	Log nepe of Social Capital Investment in the construction sector	The entire amount of money spent to increase or maintain production capacity and resources to improve the living standards of the whole society within a specific period (by year).
Control Variables		
<i>Firmage</i>	Age of the business	Measured by the length of time it has been in existence, calculated as the difference between the year of reporting and the year the business started.
<i>Liquidity</i>	Liquidity position of the company, or its Current ratio	Current Ratio or Firm's Liquidity = Current assets/ Total assets

Source: Authors' Research

2.2.3 Estimation Process

This study employs a panel data estimation strategy to examine the effects of the independent variables on firm value and profitability, measured by Tobin's Q and ROA. Panel regression techniques are particularly suitable for this analysis as they allow for the simultaneous consideration of cross-sectional and time-series variations, thereby improving estimation efficiency and controlling for unobserved firm-specific heterogeneity.

The empirical analysis begins with a Pooled Ordinary Least Squares (POLS) regression to provide a baseline benchmark of the relationships between the variables, assuming homogeneity across firms and over time. While POLS offers an initial reference point, it does not account for unobserved firm-specific effects that may bias the estimates.

To address this limitation, a Random Effects Model (REM) is subsequently estimated. REM assumes that unobserved firm-specific effects are uncorrelated with the explanatory variables and is therefore more efficient than POLS when this assumption holds. The Breusch - Pagan Lagrange Multiplier test is employed to assess whether panel-level variance is present. A statistically insignificant test result ($p\text{-value} > 0.05$) indicates that POLS is adequate; otherwise, the presence of unobserved effects justifies the use of REM.

If the REM assumptions are violated, a Fixed Effects Model (FEM) is applied. FEM allows firm-specific effects to correlate with the regressors, thereby controlling for all time-invariant firm characteristics. The choice between REM and FEM is formally determined using the Hausman specification test, where a $p\text{-value}$ greater than 0.05 supports REM, while a statistically significant result indicates that FEM provides consistent estimates.

A series of diagnostic tests is conducted to ensure the reliability of the estimated models. Multicollinearity is assessed using the Variance Inflation Factor (VIF), with values exceeding 10 indicating potential concerns. Heteroscedasticity is examined using the Modified Wald test for groupwise heteroscedasticity, while serial correlation is detected using the Wooldridge test for autocorrelation in panel data.

When violations of classical regression assumptions are identified, the study employs the Generalized Least Squares (GLS) estimator. GLS is appropriate in the presence of heteroscedasticity and autocorrelation, as it provides efficient and unbiased parameter estimates by allowing for a flexible variance-covariance structure. Moreover, GLS accommodates individual-specific effects within panel data settings, making it a robust estimation technique for this study (Gujarati and Porter, 2009; Wooldridge, 2015).

3. Research Results

3.1. Descriptive Results

The descriptive statistics and correlation matrix (Tables 2 and 3) offer initial evidence on the financial conditions and interrelationships among key variables for Vietnamese construction listed firms over the period 2011-2023. The sample exhibits persistently low average profitability (mean ROA of approximately 0.05) and a low average Tobin's Q (around 0.26), indicating subdued market valuation and limited growth expectations throughout the study period. These patterns are consistent with the capital-intensive nature of the construction sector and the prolonged cost pressures faced by firms.

Table 2. Descriptive Statistics of the Variables

Variable	Observations	Mean	Standard Deviation	Min	Max
<i>TobinQ</i>	1,207	0.2586	0.1916	0.0002	1.0327
<i>ROA</i>	1,209	0.0511	0.0646	-0.3119	0.4610
<i>INV1</i>	1,207	0.6374	0.3892	-0.1979	3.1640
<i>GTA</i>	1,205	0.0770	0.2814	-1	3.6429
<i>Cashflow</i>	1,206	0.2393	0.4832	-2.0955	6.7965
<i>LnConINV</i>	1,209	11.6336	0.2883	11.1196	11.9753
<i>Firmage</i>	1,209	8.4417	4.0118	0	17
<i>Liquidity</i>	1,207	0.6548	0.2180	0	1

Source: Calculated by the Authors

Table 3. Correlation Matrix of the Variables

	<i>TobinQ</i>	<i>ROA</i>	<i>INV1</i>	<i>GTA</i>	<i>Cashflow</i>	<i>LnConINV</i>	<i>Firmage</i>	<i>Liquidity</i>
<i>TobinQ</i>	1							
<i>ROA</i>	-0.2406***	1						
<i>INV1</i>	0.0151	0.1392***	1					
<i>GTA</i>	0.0717**	0.2398***	-0.0921***	1				
<i>Cashflow</i>	-0.2937***	0.6214***	-0.1088***	0.1925***	1			
<i>LnConINV</i>	-0.0268	-0.1505***	0.0977***	-0.0518*	-0.0559*	1		
<i>Firmage</i>	0.0875***	-0.2011***	0.1292***	-0.0592**	-0.1051***	0.9063***	1	
<i>Liquidity</i>	-0.3132***	-0.0534*	-0.2395***	-0.0458	0.0957***	0.0237	0.0179	1

Note: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Source: Calculated by the Authors

The correlation results reveal several notable associations. Tobin's Q is negatively correlated with both accounting-based profitability measures and cash flow, suggesting that firms with weaker operating performance and internal liquidity tend to be discounted by the market. Although these correlations do not imply causality, they indicate that market valuation in the construction sector closely reflects firms' underlying financial fundamentals rather than speculative growth prospects. By contrast, the moderate positive correlation between ROA and the investment index implies that more profitable firms are better positioned to sustain investment activity, even though the overall level of investment remains modest.

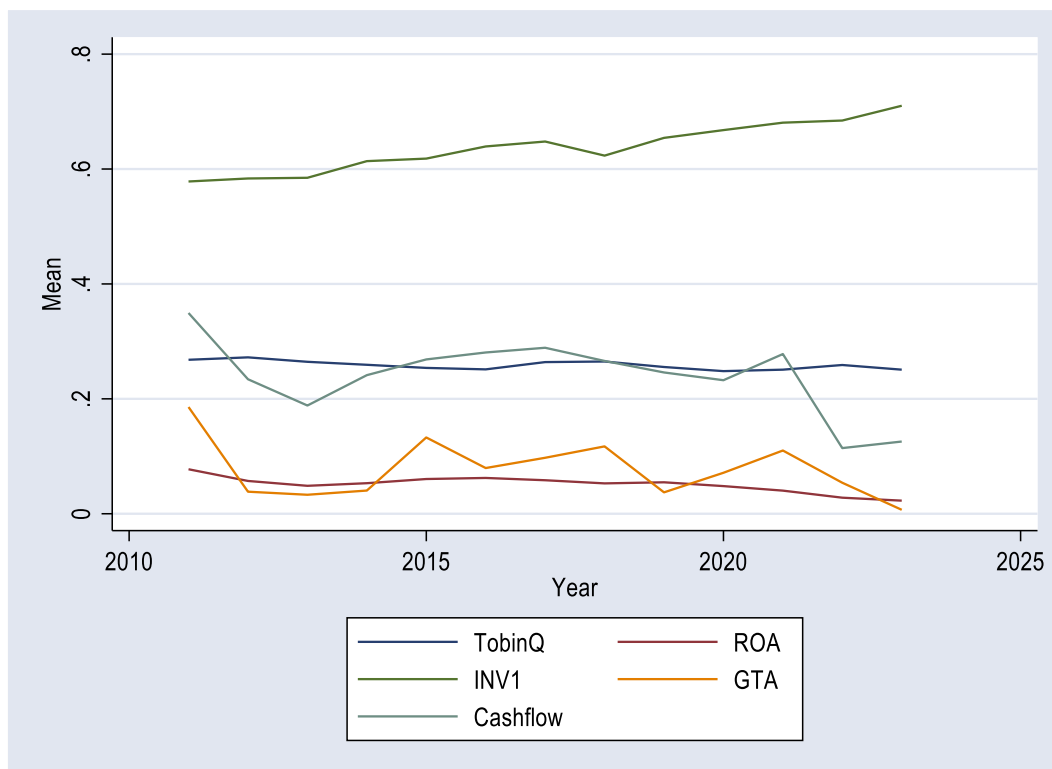
At the same time, the negative relationships between cash flow and investment, as well as between liquidity indicators and both Tobin's Q and profitability, point to binding internal financing constraints. These patterns suggest that firms facing liquidity pressure struggle to simultaneously maintain investment, profitability, and market

valuation. This finding aligns with theoretical expectations for capital-intensive industries, where investment decisions are highly sensitive to internal cash generation and financing capacity.

Firm age also appears to be an important dimension. The negative correlation between ROA and firm age, combined with the strong positive correlation between firm age and construction investment scale (LnConINV), indicates that older firms tend to be larger and more investment-intensive, but may face declining profitability. This pattern may reflect structural rigidities or lower operational flexibility among more established firms, although further econometric analysis is required to assess this relationship formally.

Figure 1 illustrates time-series patterns in GTA, cash flow relative to assets, sectoral social capital investment, and firm performance indicators (Tobin's Q and ROA). The figure shows a pronounced decline in ROA, GTA, and cash flow relative to assets after 2021, indicating a concurrent weakening of liquidity conditions and a slowdown in asset expansion across the construction sector. These trends likely follow the government's regulations on safety, occupational health, construction safety assessment costs, overhead costs, project management standards, and labor costs implemented in February 2021 (Government of Vietnam, 2021), which increased operational expenses and contributed to the decline in cash flow and asset growth in the construction sector. The joint decline in cash flow and asset growth underscores growing constraints on firms' internal financing capacity, a critical challenge in a capital-intensive industry such as construction.

Figure 1. Yearly Average of Dependent and Independent Variables



Source: Research by the Authors

Taken together, these trends imply that the effectiveness of firm-level investment is constrained by structural liquidity limitations, especially in the post-2021 period. Reduced internal cash generation weakens firms' ability to convert investment activity into short-term growth or market valuation gains, potentially amplifying differences across firm sizes and investment contexts. These observations provide a critical backdrop for the regression analysis that follows, which formally tests how firm size and sectoral social capital investment intensity condition the relationship between investment, profitability, and market valuation.

3.2. Estimation Results

Following the estimation strategy described in Section 3.2.3, model selection tests indicate that the Fixed Effects Model (FEM) is preferable to POLS and REM. Diagnostic tests further reveal the presence of heteroskedasticity and serial correlation, which motivates the use of the Generalized Least Squares (GLS) estimator. The GLS results, reported in Tables 4 and 5, therefore constitute the primary basis for interpretation.

The estimation results (Table 4) provide strong evidence that firm-level investment plays a significant role in shaping both market valuation and profitability in the construction sector. Consistent with Hypothesis H1, the investment index (INV1) exhibits a positive and statistically significant association with Tobin's Q in the full sample. This finding suggests that higher levels of firm investment are systematically associated with improved market valuation. When the sample is stratified by firm size, the positive effect remains significant and is notably stronger for large firms, indicating that scale may enhance firms' ability to translate investment activity into market value.

With respect to accounting-based performance, the investment index also demonstrates a positive and significant effect on ROA across all firm size categories, supporting Hypothesis H2. Unlike Tobin's Q, the magnitude of this effect appears relatively stable across subsamples, implying that firm investment contributes to operational profitability irrespective of firm size. This result suggests that while market valuation responds heterogeneously to investment depending on scale, profitability gains from investment are more uniform (Ajibola, 2025; Dybvig and Warachka, 2012).

Table 4. Regression Output of Research Models (1) and (2) by Full Sample and Firm Size for the GLS Method

Variable	Model 1 (TobinQ)			Model 2 (ROA)		
	Full Sample (N=1,203)	Large Firms (n = 620)	Smaller Firms (n = 579)	Full Sample (N=1,203)	Large Firms (n = 620)	Smaller Firms (n = 579)
INV1	0.8976***	2.6994***	0.8226***	0.3410***	0.3115***	0.1922**
GTA	0.0211***	0.0070	0.0285***	0.0115***	0.0098***	0.0176***
Cashflow	-0.0372***	-0.0460***	-0.0423***	0.0814***	0.0691***	0.1149***
LnConINV* INV1	-0.0819***	-0.2254***	-0.0774***	-0.0265***	-0.0242***	-0.0133*
Firmage	0.0052***	0.0117***	0.0017	-0.0012***	-0.0005*	-0.0021***
Liquidity	-0.1362***	-0.1421***	-0.1237***	-0.0183***	-0.0241***	-0.0073
Constant	0.3342***	0.2594***	0.3093***	0.0305***	0.0318***	0.0198***

Note: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Source: Research by the Authors

GTA is positively associated with ROA, indicating that expansion in asset base is linked to improved operating efficiency and profitability (Badruzaman *et al.*, 2019; Maggina *et al.*, 2012). In contrast, the cash flow to total assets ratio displays a mixed relationship: it is positively related to ROA but negatively associated with Tobin's Q. This pattern suggests that while internal liquidity supports short-term profitability, higher cash holdings may be perceived by investors as indicative of limited growth opportunities or suboptimal capital allocation, thereby exerting downward pressure on market valuation (Abel, 2018; Bond *et al.*, 2011; Gugler *et al.*, 2004).

A central contribution of this study lies in the analysis of sector-level social investment as a moderating factor. The interaction term between firm-level investment (INV1) and sector-level social investment intensity (LnConINV) is negative and statistically significant for both Tobin's Q and ROA. This result indicates that higher levels of sectoral investment weaken the positive effects of firm-specific investment on performance outcomes. The moderation effect is economically meaningful and suggests diminishing marginal returns to firm investment in environments characterized by elevated sector-wide investment intensity.

Subsample analysis further reveals that the negative moderating effect of sector-level investment is more pronounced among large firms. In these firms, the interaction term exhibits larger coefficients and higher statistical significance, implying that large firms are more sensitive to sector-wide investment conditions when converting firm-level investment into market valuation and profitability (Francois *et al.*, 2024). In contrast, the moderation effect is weaker or less consistently significant for smaller firms (Gjini and Kukeli, 2012; Tran *et al.*, 2023). These results highlight the imperative for firms and policymakers to consider sector-level investment dynamics when formulating investment and resource allocation strategies in capital-intensive industries (Hasnawati, 2020).

Control variables also exhibit systematic effects. Firm age is positively associated with Tobin's Q but negatively related to ROA, suggesting that older firms benefit from reputational advantages and market recognition, while simultaneously facing declining operational efficiency (Al-Dwiry *et al.*, 2021). Liquidity is negatively associated with both Tobin's Q and ROA, indicating that higher allocations to current assets may constrain firms' ability to generate returns and market value through productive investment (Fazzari *et al.*, 1987; Jensen, 1986).

Table 5 presents the regression results examining the effect of firm-level investment on firm performance across different firm sizes and levels of social capital investment. For the full sample and smaller firms, firm investment is negatively and significantly associated with Tobin's Q, whereas the relationship becomes positive and statistically significant for larger firms. This indicates clear heterogeneity in how investment translates into market valuation across firm sizes.

Table 5. Regression Output of Research Models (1) and (2) with Quantile-based Moderator by Full Sample and Firm Size for the GLS Method

Variable	Model 1 (TobinQ)			Model 2 (ROA)		
	Full Sample (N=1,203)	Large Firms (n = 620)	Smaller Firms (n = 579)	Full Sample (N=1,203)	Large Firms (n = 620)	Smaller Firms (n = 579)
<i>INV1</i>	-0.0427***	0.0772***	-0.0502***	0.0374***	0.0277***	0.0409***
<i>GTA</i>	0.0247***	0.0072	0.0277***	0.0121***	0.0101***	0.0190***
<i>Cashflow</i>	-0.0376***	-0.0447***	-0.0418***	0.0815***	0.0682***	0.1145***
<i>LnConINV_q</i> <i>uantile*</i> <i>INV1</i>						
2	-0.0106	-0.0382***	-0.0123	-0.0051*	-0.0009	-0.0016
3	-0.0242**	-0.0742***	-0.0311**	-0.0095***	-0.0041	-0.0066
<i>Firmage</i>	0.0033***	0.0059***	-0.0004	-0.0016***	-0.0010***	-0.0023***
<i>Liquidity</i>	-0.1455***	-0.1239***	-0.1372***	-0.0191***	-0.0217***	-0.0073
Constant	0.3587***	0.3201***	0.3303***	0.0339***	0.0358***	0.0210***

Note: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

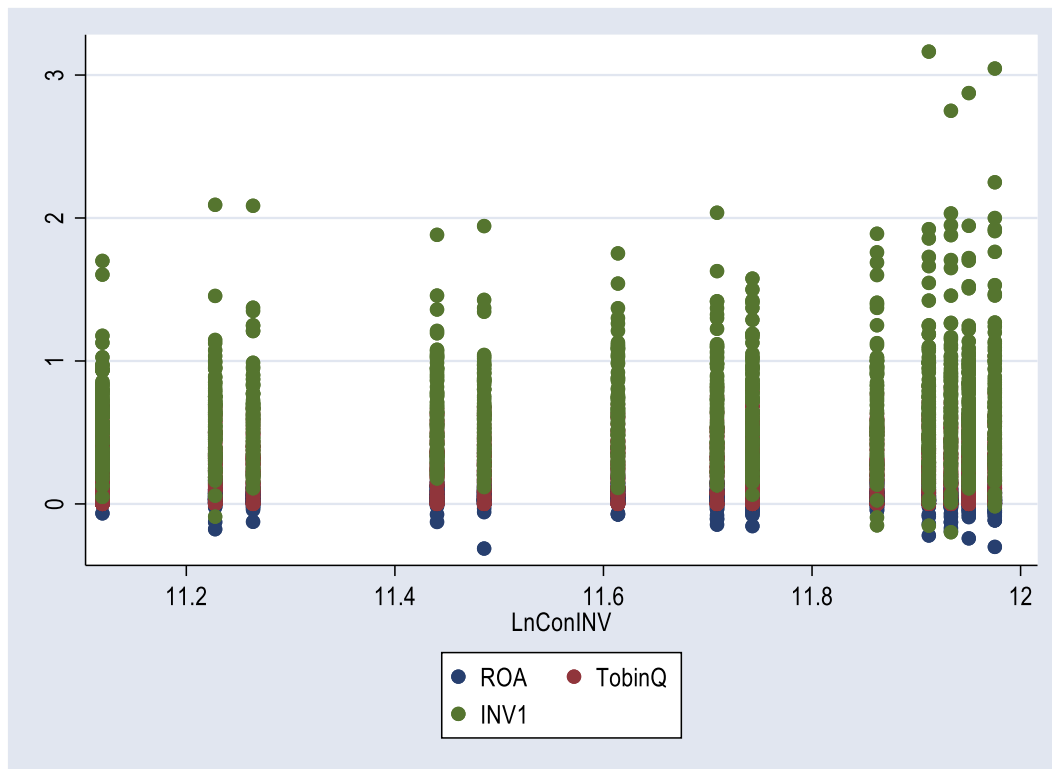
Source: Research by the Authors

The interaction terms between firm investment and higher quantiles of social capital investment are predominantly negative and significant, particularly for large firms, suggesting that increased social investment intensity weakens the marginal valuation effect of firm investment. These results point to nonlinear moderation effects in the investment–valuation relationship.

In contrast, firm investment is positively and significantly associated with ROA across the full sample as well as both firm size subsamples. The interaction terms with social capital investment are generally weaker and less consistently significant, indicating that accounting-based profitability is less sensitive to variation in social investment intensity. This suggests that while firm investment reliably improves operational performance, its effect on market-based valuation is more heterogeneous and contingent on firm size and the social investment environment.

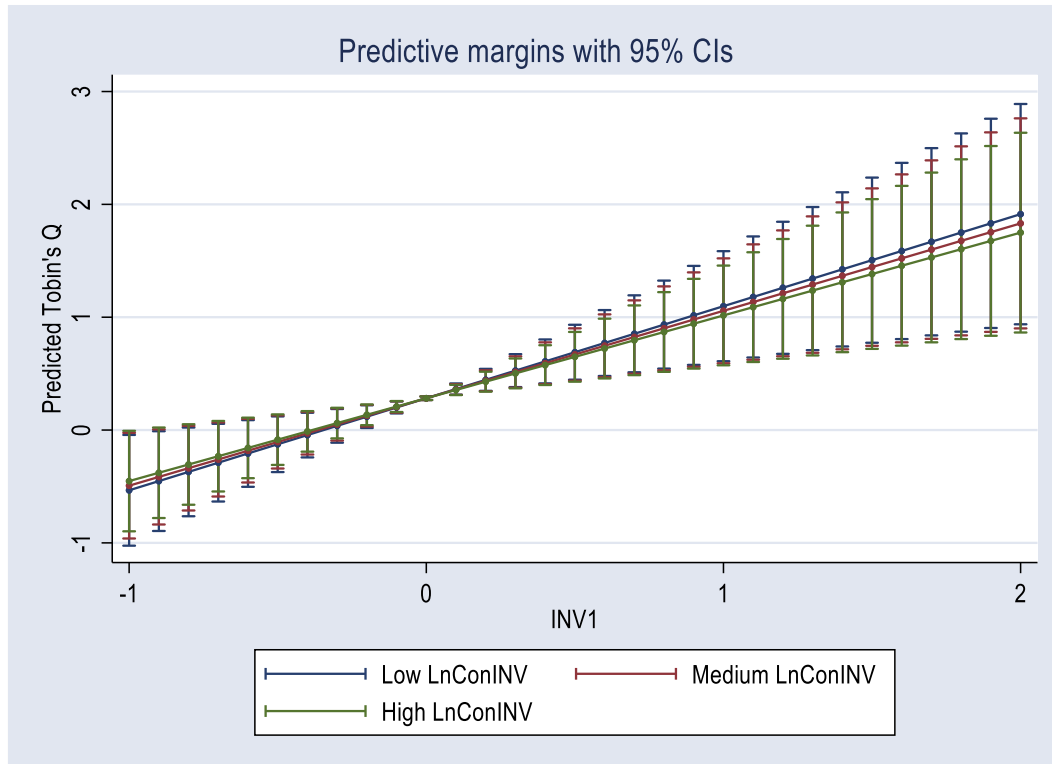
Figure 2 presents a scatterplot that classifies firms into three quantiles based on the intensity of sector-level social capital investment in the construction sector. The figure provides an initial visual indication that the relationship between firm-level investment and performance outcomes is heterogeneous across sectoral investment environments. Firms operating in low-investment environments (first quantile) display a clearer and more stable association between firm investment and performance, whereas observations in high-investment environments (third quantile) exhibit greater dispersion, suggesting increased variability in investment outcomes under conditions of elevated sectoral investment intensity.

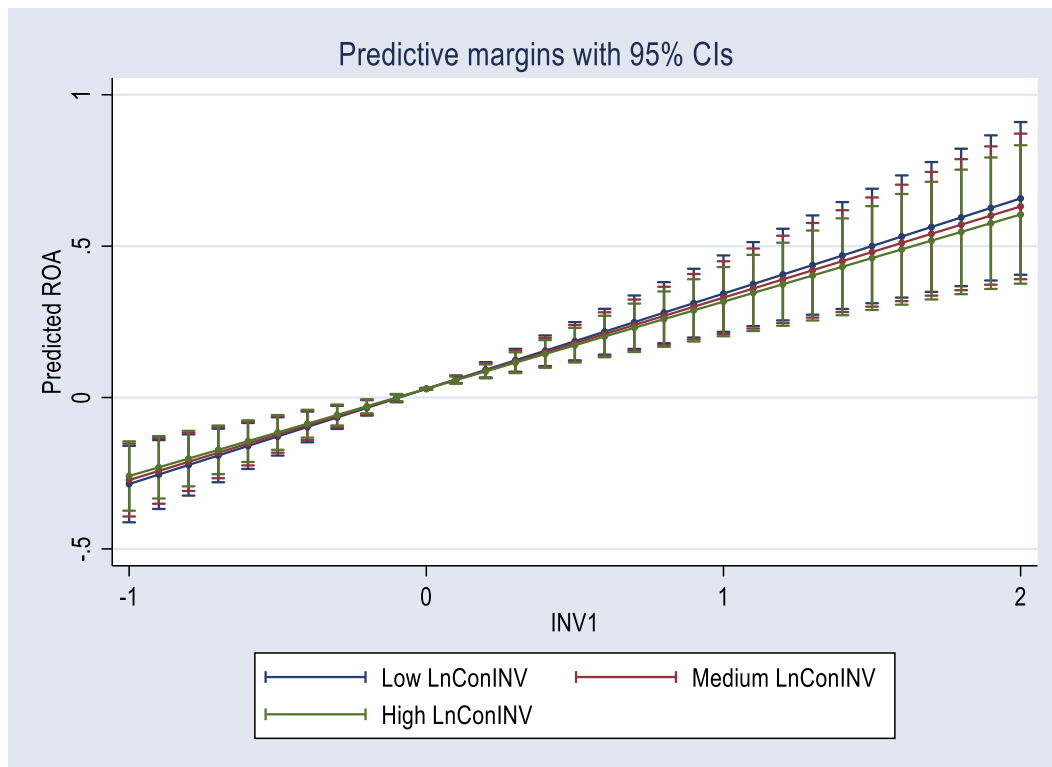
Figure 2. Scatterplot of Firm Performance and Investment Index versus Sectoral Social Capital Investment



Source: Research by the Authors

Figure 3. Predicted marginal effects (with 95% confidence intervals) of firm-level investment on Tobin's Q and ROA differentiated by sectoral social capital investment at quantile levels





Source: Research by the Authors

Figure 3 further substantiates this pattern by illustrating the predicted marginal effects of firm-level investment on ROA and Tobin's Q across different levels of sectoral social capital investment. The interaction plots show that firm investment is positively associated with both profitability and market valuation across all quantiles; however, the magnitude and precision of these effects differ markedly. For ROA, the marginal effect of firm investment remains positive and relatively stable across sectoral investment levels, as evidenced by overlapping confidence intervals, indicating that profitability gains from investment are comparatively robust to variations in sectoral social investment intensity. In contrast, the marginal effect on Tobin's Q weakens as sectoral investment intensity increases, accompanied by wider confidence intervals at higher quantiles. This pattern indicates growing uncertainty in how markets value firm-level investment in environments characterized by high sector-wide investment, suggesting that elevated sectoral investment may attenuate the valuation benefits of firm investment more strongly than its operational profitability effects.

These patterns highlight the presence of heterogeneity and nonlinearities in the investment–performance relationship, underscoring the importance of accounting for sectoral context and firm characteristics. To assess the stability and reliability of these findings, the following section conducts robustness tests using alternative model specifications and subsample analyses.

3.3. Robustness Tests

To assess the robustness of the findings, additional estimations were conducted using alternative model specifications. First, the models were re-estimated without including the moderating variable representing sector-level social investment (Table 6). Second, quantile-based regressions were employed to examine whether the estimated relationships vary across different levels of sectoral investment intensity (Table 7).

The results reported in Table 6 indicate that, in the absence of the moderator, firm-level investment performance exhibits a negative influence on Tobin's Q in the full sample. This contrasts with the baseline results and suggests that omitting sector-level investment conditions alters the estimated relationship between firm investment and market valuation. The persistence of this pattern across specifications highlights the sensitivity of Tobin's Q to contextual factors and underscores the importance of accounting for sector-level dynamics when evaluating firm valuation effects (Dybvig and Warachka, 2015; Tharavanij, 2024).

When the sample is divided by firm size, heterogeneous effects remain evident. For smaller firms, the negative relationship between firm investment performance and Tobin's Q persists, whereas for larger firms, the coefficient becomes positive and statistically significant. This finding is consistent with the baseline results and indicates that firm size systematically conditions how investment activity is reflected in market valuation.

With respect to operating performance, measured by ROA, firm-level investment maintains a positive and statistically significant effect across all firm size categories. This result remains stable across alternative specifications, providing strong evidence that investment activity contributes to profitability regardless of firm size or model formulation.

Table 6. Regression Output by Full Sample and Firm Size, excluding Moderator

Variable	Model 1 (TobinQ)			Model 2 (ROA)		
	Full Sample (N=1,203)	Large Firms (n = 620)	Smaller Firms (n = 579)	Full Sample (N=1,203)	Large Firms (n = 620)	Smaller Firms (n = 579)
INV1	-0.0524***	0.0274**	-0.0696***	0.0325***	0.0265***	0.0384***
GTA	0.0239***	0.0076	0.0256***	0.0118***	0.0096***	0.0182***
Cashflow	-0.0373***	-0.0499***	-0.0391***	0.0813***	0.0683***	0.1145***
Firmage	0.0023**	0.0015	-0.0024*	-0.0021***	-0.0012***	-0.0027***
Liquidity	-0.1437***	-0.1491***	-0.1455***	-0.0172***	-0.0221***	-0.0082***
Constant	0.3642***	0.3863***	0.3506***	0.0368***	0.0380***	0.0242***

Table 7. Regression Results by Moderator Quantiles

Variable	Model 1 (TobinQ)			Model 2 (ROA)		
	Quantile 1	Quantile 2	Quantile 3	Quantile 1	Quantile 2	Quantile 3
INV1	0.0033	0.0409***	-0.0530***	0.0563***	0.0268***	0.0276***
GTA	0.0682***	0.0603***	0.0219**	0.0189***	0.0117***	0.0245***
Cashflow	-0.0660***	-0.0867***	-0.0571***	0.1027***	0.0825***	0.0626***
Firmage	0.0138***	0.0199***	0.0180***	-0.0021***	-0.0020***	-0.0031***
Liquidity	-0.2302***	-0.1829***	-0.2729***	-0.0081	-0.0438***	0.0004
Constant	0.3667***	0.2238***	0.2657***	0.0142***	0.0607***	0.0411***

Note for Table 6 and Table 7: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Source: Research by the Authors

The quantile regression results presented in Table 7 further support the robustness of the moderating role of sector-level investment intensity. In the lowest quantile of sectoral investment, firm-level investment demonstrates the strongest positive association with both Tobin's Q and ROA. As sectoral investment intensity increases, the magnitude of the investment coefficient declines, particularly for Tobin's Q, and becomes weaker or insignificant in the highest quantile. In contrast, the positive association between firm investment and ROA remains statistically significant across quantiles, although its magnitude diminishes at higher levels of sectoral investment (Sündal, 2023, Fazzari *et al.*, 1987).

Overall, the robustness tests confirm that the main findings of the study are not driven by a specific model specification or sample partition. While firm-level investment consistently enhances profitability, its effect on market valuation is heterogeneous and sensitive to firm size and sector-level investment conditions. These results reinforce the reliability of the baseline estimates and support the validity of the study's core conclusions.

4. Discussions

The findings of this study provide important insights into how effectiveness of firm-level investment is conditioned by sector-level investment dynamics in capital-intensive industries. While investment at the firm level is generally associated with improved financial performance, the results demonstrate that these benefits are neither uniform nor unconditional. Instead, they depend critically on firm size and the intensity of sectoral social capital investment, highlighting the importance of industry context in shaping investment outcomes.

Supporting Hypothesis 1, the results indicate that investment policy has a positive and significant impact on market valuation (Tobin's Q) and profitability (ROA), consistent with the neoclassical theory and resource-based theory. Strategic investments enhance production capacity, operational efficiency, and shareholder value by enabling firms to expand scale, optimize resources, and create competitive advantages. However, this effect is stronger in large firms due to their better access to resources and better risk management, while smaller firms face constraints such as overinvestment or lack of scale.

Another highlighted finding of this research is the negative moderating role of sector-level social investments in the relationship between investment and firm performance, which confirms Hypothesis 2. High levels of sector-wide investment intensify competition for shared inputs, such as skilled labor, capital, and construction materials, thereby raising input costs and constraining resource availability. This crowding-out mechanism reduces the marginal returns to firm-level investment, particularly in environments characterized by elevated sectoral investment intensity. As a result, additional investment by individual firms yields diminishing gains in both profitability and market valuation.

This moderating effect is especially pronounced at higher levels of sectoral social investment (quantile 3), where the positive impact of firm investment on Tobin's Q weakens substantially or turns negative. These findings suggest that when sector-wide investment approaches saturation, firms compete more aggressively over scarce resources rather than expanding productive capacity efficiently. Consequently, market participants may discount firm-level investment, perceiving lower expected returns in highly congested investment environments.

The results are also consistent with the SCP framework, which posits that industry structure shapes firm behavior and performance outcomes (Bartolini *et al.*, 2023; Batten and Vo, 2018). In this context, high sectoral social capital investment represents a structural condition characterized by intensified competition and resource congestion. This environment constrains firms' strategic choices, increases operational costs, and shifts firm conduct toward defensive strategies focused on cost containment rather than value-enhancing expansion. Performance outcomes, therefore, reflect not only firm-specific decisions but also structural limitations imposed by the broader investment environment. By empirically quantifying this sectoral moderation effect, the study extends the SCP framework to an emerging market setting and highlights its relevance for capital-intensive industries (Gjini and Kukeli, 2012; Jensen, 1986).

Firm size further mediates these dynamics. The stronger negative moderation observed among large firms suggests that scale amplifies exposure to sector-level crowding-out effects. Large firms typically pursue capital-intensive strategies and rely heavily on shared inputs, making them more vulnerable to rising input prices and resource scarcity when sector-wide investment is high. Smaller firms, by contrast, may retain greater operational flexibility or adopt more selective investment strategies, allowing them to partially mitigate these pressures. This heterogeneity underscores that crowding-out effects are not uniform across firms and that size can both enhance investment capacity and increase structural vulnerability.

Finally, the roles of liquidity and firm age underscore the importance of strategic resource management. While firm age may confer reputational advantages and market recognition, it can also be associated with organizational rigidity and higher overhead costs, which weaken profitability. Similarly, excessive liquidity holdings may reflect conservative investment behavior that limits engagement in value-creating opportunities, thereby reducing both profitability and market valuation. Together, these findings suggest that adaptability, efficient capital allocation, and sensitivity to sector-level conditions are critical for sustaining performance as firms mature and as competitive pressures intensify.

Conclusions and Further Research

Based on the results, policy implications aimed at enhancing investment efficiency and financial performance for firms in the construction sector include the following:

For government and regulatory authorities: Balance sector-level social investment to mitigate the crowding-out effect by prioritizing projects that complement private firms to share resources. Additionally, support smaller firms through preferential credit programs and tax reductions for strategic investments. Furthermore, monitor sector-investment quantiles to adjust policies, for instance, by limiting public investments in saturated areas to create space for private firms.

For firms in the construction sector: Large firms should diversify their resource sources to reduce the dependence on social investment, optimizing firm-level investment toward high-value projects to counter crowding-out. In addition, smaller firms need to avoid overinvestment by improving cash flow and liquidity management to maintain a stable ROA. Overall, firms should apply the SCP framework to align investment strategies with sector structures, such as collaborating with the state to secure resources.

In conclusion, this research found that firm-level investments positively drive performance of Vietnamese listed construction companies; however, sectoral social capital investment negatively moderates this link, particularly via crowding-out in high-investment contexts, as supported by SCP theory. However, the study has several limitations. Firstly, it mainly focuses on listed firms, limiting the generalizability to unlisted or smaller firms. Secondly, the study is specific to Vietnam's construction industry, restricting cross-sector applicability. Thirdly, this study relies solely on secondary data without addressing endogeneity. Future research could extend the analysis to unlisted firms or other sectors for comparative insights, employ instrumental approaches to mitigate endogeneity, or incorporate qualitative data to explore managerial perceptions of crowding out effects.

Declarations

Credit Authorship Contribution Statement:

Nguyen Ngoc Khanh Linh: Conceptualization, investigation, data curation, writing – original draft, writing – review and editing;

Nguyen Thu Ha: Conceptualization, methodology, software, formal analysis, data curation, validation, visualization, writing – original draft, writing – review and editing;

Do Phuong Thao: Conceptualization, writing – original draft, writing – review and editing.

Declaration of Competing Interest: The authors report there are no competing interests to declare.

Declaration of Use of Generative AI and AI-assisted Technologies: Generative AI and AI-assisted technologies were used in the preparation of this work to assist with language refinement, grammar correction, and stylistic improvements. The AI tools did not contribute to the development of research questions, theoretical framework, methodology, data analysis, or conclusions. All intellectual contributions, interpretations, and final decisions remain the responsibility of the author.

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The Exchange Rate Effects of a Singaporean Closed-Border Retail Central Bank Digital Currency: A Counterfactual Analysis



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Abstract: Central bank digital currencies (CBDCs) are heralded as the next innovation in currency usage. Their unique architecture provides both liquidity and remuneration to investors. This paper aims to assess the exchange rate changes caused by differing plausible implementations of CBDCs due to changes in portfolio allocations of investors. Furthermore, the paper also aims to identify the ideal form of CBDC implementation.

This study uses a novel aggregated uncovered interest parity equation to connect interest rate differentials between Singaporean and international assets to estimate exchange rate differentials. Three counterfactual CBDC regimes are modelled over the period between 2000 Q1 and 2024 Q4, namely the Baseline Rule (no interest rate on CBDCs), the Markdown Rule (a discounted rate on CBDCs), and the Taylor Rule (interest rate set as per inflation and output gaps). These regimes are compared with the non-CBDC counterfactual which is modelled using the standard uncovered interest parity equation.

The criteria for comparison are path fidelity and volatility of the exchange rate. It was found that the Markdown Rule is the ideal form of CBDC implementation. Furthermore, it was also found that the Singapore dollar appreciates 35.8% to 80.4% across CBDC regimes. These findings are of great importance to the Monetary Authority of Singapore, as they can significantly affect its unique exchange-rate-targeting monetary policy.

Keywords: central bank digital currencies; closed border CBDC; small open economy; uncovered interest parity; portfolio allocation; liquidity premium; counterfactual analysis; path fidelity; exchange rate volatility.

JEL Classification: F41; F31; E52; E42.

Introduction

Playing a massive role in the future of monetary policy considerations, CBDCs are digital currencies issued by a country's central bank. The central bank controls the supply of CBDCs, which are equivalent to the country's fiat currency. CBDCs can be divided into wholesale and retail CBDCs. A wholesale CBDC is also a digital form of fiat currency, but one that is only accessible to large financial institutions, such as commercial banks (Reserve Bank of Australia 2015). On the other hand, a retail CBDC (used in this paper) is available to the public, similar to cash (in a digital form).

Since retail CBDC implementation in Singapore (the geography the model is calibrated to) is a purely hypothetical scenario, this study makes assumptions about the other properties of CBDCs in a potential implementation. Firstly, the paper assumes that the CBDC is not cross-border tradable by individuals globally, *i.e.*, foreign investors cannot hold it. This assumption is in opposition to those made by Popescu (2022) and Ferrari, Mehl, and Stracca (2020), and is similar to the assumption made in George, Xie, and Alba (2020). Bank for International Settlements (2022) also finds that cross-border use is highly unlikely, at least in the near future due to

capital flow volatility concerns. The model also assumes that bonds (foreign and domestic) and CBDCs are the only tradable financial assets available to investors. Note that due to the paper's assumption of a closed-border CBDC, foreign individuals can only invest in foreign bonds and Singaporean bonds. At the same time, domestic investors can choose between the domestically exclusive CBDC and both foreign and domestic bonds. It is also important to note that, regardless of the CBDC being "closed border", the economy is considered open since foreign individuals can invest in Singaporean assets and vice versa (other than CBDCs, which are unavailable to foreigners).

This paper contributes to the growing literature on the effects of deploying CBDCs with various characteristics in small open economies like Singapore. The paper focuses on the exchange rate effects of three differing CBDC implementations in Singapore and then simulates exchange rate changes as a counterfactual. These counterfactuals are compared with each other (between CBDC regimes) and with the exchange rate data without a CBDC to determine (i) the general effects of the CBDC on exchange rate volatility and path and (ii) ideal CBDC implementation from an exchange rate perspective. These findings address a clearly identified gap in existing literature. While prior studies have examined CBDC effects in open economies – Ferrari, Mehl, and Stracca (2020) focus on cross border-CBDCs in two-country DSGE models, and George, Xie, and Alba (2020) model interest-bearing CBDCs in small open economies calibrated to New Zealand – no study has specifically analyzed the exchange rate path and volatility implications of alternative closed-border retail CBDCs that have been calibrated to Singapore and consider its unique exchange-rate targeting monetary policy framework. The distinction is significant as Singapore does not use an interest-rate instrument but instead manages a nominal effective exchange rate band, making the portfolio channel of any CBDC design particularly consequential and understudied. This paper fills that gap by combining a closed-border CBDC assumption with a novel portfolio-weighted uncovered interest parity framework, generating quantitative counterfactual estimates of exchange rate effects under three distinct remuneration regimes across 100 quarterly observations (2000 Q1–2024 Q4).

1. Literature Review

The current literature can be divided into four strands, which are (i) the implications on the financial sector, (ii) the implications on the domestic economy, (iii) the implications on monetary policy transmission, and (iv) the implications internationally.

1.1. Financial Sector

In the literature on CBDC and its impacts on portfolio allocation, there has been a heavy focus on modelling bank disintermediation, bank runs, and other financial sector concerns in the domestic economy, such as Agur, Ari, and Dell'Ariccia (2019), Brunnermeier and Niepelt (2019), Andolfatto (2021), Chiu and Davoodalhosseini (2023), and Niepelt (2020).

The implications of bank disintermediation and CBDC design preferences show a range of interpretations. Agur, Ari, and Dell'Ariccia (2019) suggest that CBDC design (like whether it should bear interest) can influence disintermediation, presenting a tradeoff between interest-bearing and non-interest-bearing options. Brunnermeier and Niepelt (2019) note that the impact of CBDCs on bank disintermediation largely depends on the associated monetary policy. They argue that a strong commitment from the central bank could allow CBDCs to replace bank deposits. Andolfatto (2021) believes disintermediation isn't guaranteed, as banks could raise deposit rates to compete with interest-bearing CBDCs. Chiu and Davoodalhosseini (2023) share a similar view but are more optimistic, suggesting that CBDCs can enhance lending and intermediation, estimating a 7% increase in borrowing post-CBDC implementation. Niepelt (2020) argues that the substitution of deposits for CBDCs may not have significant macroeconomic effects.

Another point of focus in this strand is financial stability and bank runs. Fernández-Villaverde et al. (2020) provide a model that features three banking institutions: investment banks, commercial banks, and the central bank. In the model, commercial banks have both short-term and long-term saving technologies, investment banks have only long-term technologies, and central banks have only short-term saving technologies. Consequently, central banks allocate a portion of their deposits to investment banks to invest in long-term technologies. Thus, the central bank is more flexible and stable than commercial banks, assuming that the contract between investment banks and central banks is rigid. Depositors internalise this feature, and the central bank arises as a deposit monopolist, attracting all deposits away from the commercial banking sector. They note that this can deter runs but also point out that the lack of competition in the deposit market can discourage the central bank from delivering the socially optimal amount of maturity transformation.

1.2. Domestic Economy

Some papers propose models of CBDCs that aim to capture the domestic implications. Barrdear and Kumhof (2016) take an initial stock of CBDC equal to 30% of GDP and calibrate their model to match the pre-crisis US. They find that such a CBDC issuance against government bonds can lead to reductions in real interest rates, distortionary taxes, and monetary transaction costs, collectively resulting in a permanent increase in GDP of up to 3%.

More recent work has extended these domestic macroeconomic findings. Auer, Cornelli, and Frost (2020) provide a comprehensive database of CBDC development efforts across countries and find that retail CBDC work is more advanced in economies with larger informal sectors and higher digital capacity, cautioning against universal calibrations. For Singapore specifically, the Monetary Authority of Singapore's Project Orchid (MAS, 2023) has investigated tokenized money use cases, suggesting that the infrastructure and demand dynamics for a digital SGD in Singapore's highly digitized economy may differ from assumptions in earlier theoretical models.

1.3. Monetary Policy Transmission

Some papers also discuss the impact that CBDCs can have on the domestic implementation of monetary policy. Das et al. (2023) explain how CBDCs can strengthen and enhance the effectiveness of existing economic policy. Hemingway (2023) demonstrates how interest-bearing CBDCs enhance competition for deposits, thereby weakening bank market power, which in turn strengthens the interest rate transmission channel and makes it more potent, as affirmed by Drechsler, Savov, and Schnabl (2021). Vollmar and Wening (2024) also show that the majority of deposit-dependent banks examined likely faced funding issues and profit losses if a CBDC had been implemented in most years since 2000. The study suggests that banks may turn to wholesale funding after the introduction of CBDCs, which is more sensitive to changes in the policy rate than retail deposits, resulting in larger variations in funding costs. To stay profitable, banks adjust lending rates more sensitively to these fluctuations, thereby strengthening monetary policy transmission.

Furthermore, Tan (2024) demonstrates that issuing a CBDC enhances financial inclusion through efficient transactions and increased anonymity. Thus, Das et al. (2023) explain that financial inclusion leads to a greater proportion of the economy making intertemporal decisions that are directly affected by monetary policy, thereby widening the effects of monetary policy.

Third, introducing CBDCs, especially in developing economies, can enhance monetary sovereignty by promoting the use of domestic currencies over foreign stable currencies, such as the dollar. Thus, Fan, Walker, and Wright (2025) write that implementing CBDCs reduces reliance on the US dollar and decreases dollarisation. The paper also comments that as dollarisation decreases, the country can implement monetary policy more effectively. However, this may not always be the case. In some scenarios, CBDCs drive higher "digital dollarisation." If a CBDC from a stable currency is used across borders and widely adopted, the country adopting it may experience devaluation of its fiat currency. Thus, European Central Bank (2021) explains that dollarisation is plausible in less developed economies with unstable currencies, and that while this may help currencies like the US dollar retain reserve status, it may also undermine the strength of monetary policy in developing economies.

Subsequent work has further refined this strand. Abad, Nuño, and Thomas (2024) introduce CBDC into a New Keynesian model with heterogeneous banks and a frictional interbank market calibrated to the euro area, showing that even substantial CBDC adoption has a relatively modest effect on bank lending because the reduction in deposits is absorbed by a fall in excess reserves. Their results suggest that the operational framework of monetary policy (and specifically whether the central bank operates a floor or corridor system) mediates the macroeconomic impact of CBDC adoption.

1.4. Open Economy

George, Xie, and Alba (2020) developed an open economy model with an interest-bearing CBDC as a second monetary policy instrument to analyze its impact on welfare. They find that a flexibly remunerated CBDC (using a Taylor Rule) improves economic stability. Furthermore, they also model a flat interest rate regime and a quantity rule regime calibrated to New Zealand data. It is worth noting that they limit the CBDC to domestic usage (closed border CBDC), which is the same assumption made in this paper, to make the implementation more realistic.

Furthermore, Benigno, Schilling, and Uhlig (2022) model a two-country economy digital currency; however, it models a cryptocurrency which is not as reputable or as safe as a CBDC. The third paper, by Ferrari, Mehl, and Stracca (2020), also models a two-country model with differing remuneration regimes. They find that the presence of a CBDC increases the sensitivity of international spillovers of domestic shocks due to the increased interconnectedness that CBDCs cause. However, they do note that this finding depends on the remuneration regimes, frictions in access to the CBDC, and other miscellaneous features. This paper's model leverages their

model specifically to quantify the liquidity markup placed on CBDCs and also is similar to the uncovered interest parity conditions in their model. However, their model is fundamentally different, as it provides a full-fledged foreign economy, whereas this paper presents the domestic economy (Singapore) and the foreign economy (all other countries). Furthermore, they also model a cross border CBDC, while this paper models a closed-border CBDC.

As noted above, Bank for International Settlements (2022) documents that cross-border CBDC use remains unlikely in the near term due to capital flow volatility concerns - a finding that directly motivates this paper's closed-border assumption.

1.5. Summary of Relevant Literature

AUTHORS	ECONOMY	CBDC TYPE	METHOD	KEY FINDING	LIMITATION
Ferrari, Mehl & Stracca (2020)	Two-country DSGE	Cross-border, multiple regimes	Two-country DSGE	CBDC amplifies international spillovers; design matters for volatility	Cross-border assumption limits applicability to closed-border cases
George, Xie & Alba (2020)	Small open economy (NZ calibration)	Closed-border, interest-bearing (Taylor Rule)	Small open economy DSGE	Flexible remuneration improves stability; CBDC as second policy lever	Calibrated to NZ; exchange-rate targeting regimes not addressed
Barrdear & Kumhof (2016)	Closed economy (US calibration)	Retail CBDC against govt. bonds	Closed-economy DSGE	Up to 3% permanent GDP gain from CBDC issuance	Closed-economy assumption; no exchange rate implications
Agur, Ari & Dell'Ariccia (2019)	Generic closed economy	Interest-bearing vs. non-interest-bearing	Theoretical/calibration model	CBDC design drives disintermediation tradeoff	No open economy or exchange rate dimension
Andolfatto (2021)	Generic closed economy	Interest-bearing retail CBDC	Partial equilibrium model	Banks raise deposit rates; disintermediation not inevitable	No exchange rate channel; closed economy only
Chiu & Davoodalhosseini (2023)	Generic economy	Cash-like retail CBDC	Macroeconomic calibration model	CBDCs enhance intermediation; 7% borrowing increase	Contradicts Andolfatto (2021); calibration-sensitive
Fan, Walker & Wright (2025)	Small open economies (general)	Retail CBDC (multiple designs)	Open economy structural model	CBDC affects exchange rate via portfolio channel; modest effects	Does not isolate specific exchange rate-targeting regimes
Kumhof & Noone (2021)	Generic open economy	Design principles framework	Conceptual framework	Identifies design features needed for financial stability	Conceptual framework; no quantified exchange rate estimates
This Paper	Singapore (exchange-rate targeting)	Closed-border retail CBDC (3 regimes)	Reduced-form portfolio-weighted UIP counterfactual	Quantifies exchange rate path and volatility effects of three closed-border retail CBDC remuneration regimes using a portfolio-weighted UIP framework calibrated to Singapore (2000 Q1–2024 Q4)	Reduced-form UIP; limited asset classes; no general equilibrium

Source: Author's compilation. The table summarizes the main contributions relevant to this paper across the four literature strands, highlights the key methodological difference of each study, and positions this paper's contribution relative to prior work.

2. Method

2.1. CBDC Interest Rates Time Series Counterfactual

This study generated three separate counterfactual time series for CBDC interest rates under distinct remuneration regimes. However, the CBDC rules that are assessed follow Ferrari, Mehl, and Stracca (2020). The data were collected at quarterly observations from 2000 Q1 to 2024 Q4 for data availability reasons, and because they encompass the 2008 recession and COVID-19 (analyzed later).

In the baseline scenario, the model assumed that CBDCs are not remunerated. Thus, CBDCs acted nearly identically to cash but are calibrated as being 10% more liquid. This rule is referred to as “Baseline” or “Baseline Rule” throughout the paper.

In the second scenario, a Taylor Rule was used to simulate the central bank’s control over the interest rate on CBDCs. This is particularly interesting, as Singapore relies solely on exchange rate monetary policy. However, they may choose to use the traditional Taylor Rule to control interest rates on CBDCs for financial stability, and thus, it is an appropriate extension of the model. A Taylor Rule with its calibrated parameters (calibrated to Singapore) is seen in Equation (1) (Chow, Lim, and McNelis 2014).

$$\log(R_t) = \rho^r \log(R_{t-1}) + (1 - \rho^r) \rho^\pi \log\left(\frac{\Pi_t^c}{\Pi^c}\right) + (1 - \rho^r) \rho^y \log\left(\frac{Y_t}{Y_t^{flex}}\right) \quad (1)$$

The Taylor Rule defines the interest rate in period t (R_t) as being a function of R_{t-1} (the interest rate in the previous period), the difference between target inflation and current inflation, and the output gap. The parameters are also calibrated to Singaporean data in the same paper. The Taylor Rule was used to generate a time series of CBDC interest rate data using previous CBDC interest rates and quarterly data of Singapore’s inflation differences, and output gaps from 2000 Q1 to 2024 Q4. To find the long-term GDP trend for the output gap, the Hodrick-Prescott filter was used (Hodrick and Prescott 1997). It is also important to note that the interest rate for this regime may be negative and must be lower than the bond interest rate.

To set R_{t-1} for the first period, this study used the estimates from Chiu and Davoodalhosseini (2023). In their calibration, they found that a CBDC expands bank intermediation if its interest rate is between 0.30% and 1.49%. Taking the mean of this ideal range, around 0.895%, is a reasonable starting point for the CBDC interest rate. Therefore, R_{t-1} in time $t=1$ is 1.00895 (gross returns). This remuneration regime is referred to as the “Taylor Rule” throughout the paper.

For the third regime, a Markdown interest rate on CBDCs was taken, as seen in Ferrari, Mehl, and Stracca (2020). Essentially, the interest rate on CBDCs was set at a constant percentage below the policy rate (and thus less attractive). This markdown on returns can be interpreted as a trade-off or penalty for the liquidity benefit of the CBDC.

$$R_t^{DC} = R_t - R_{markdown}^{DC} \quad (2)$$

In Equation (2), $R_{markdown}^{DC}$ was a constant that is calibrated to 0.005, as per Bindseil (2022). This means that the interest rate on CBDC (R_t^{DC}) is always 0.5% less than the policy rate (R_t). Note that the interest rate here can be negative in certain quarters when the bond interest rate is below 0.5%. This regime is referred to as the “Markdown Rule” throughout the paper.

2.2. Standard Uncovered Interest Parity

Now, since the monetary return on CBDCs (R_t^{DC}) and bonds (R_t) is defined, this paper can compare the investor’s utility of holding the two assets in the portfolio to make predictions on the ideal portfolio allocations. Then, as per the allocations made, the paper can use the link between the interest rate differential and exchange rates that is defined in the UIP condition to see the impact of the portfolio allocation on Singaporean exchange rates. The Control UIP for Singapore (no CBDC implementation) is seen in Equation (3).

$$r_t^* - r_t = E_t \text{ner}_{t+1} - \text{ner}_t \quad (3)$$

In Equation (3), r_t is the log gross return on the home risk-free asset, r_t^* is the log gross return on the foreign risk-free asset, and ner_t is the log nominal exchange rate, defined as the USD/SGD exchange rate (if ner_t decreases, that means the Singapore currency has depreciated). $E_t \text{ner}_{t+1}$ defines the expected exchange rate in the following time period. This arbitrage equation (control UIP) is used to set the counterfactual exchange rate path in Singapore between 2000 Q1 and 2024 Q4 if no CBDC is implemented. The exchange rate path that is

generated using this is referred to as the “Control UIP” or just the “Control,” as it means that there is no CBDC in the regime.

2.3. Modified Uncovered Interest Parity

The Control UIP is then modified to fit CBDC implementation in Singapore. Control UIP condition is used to connect the interest rate differential between the foreign asset and the home asset to the impact on the exchange rate. However, if CBDCs are implemented, the model will need to consider the two separate asset options, bonds as well as CBDCs, in the UIP condition. To do so, the model estimates the ratio of investment into bonds versus CBDCs due to the substitution effect that the CBDC will have. When the CBDC is rolled out, a percentage of domestic bond investment is likely to be moved into CBDC, and, in later periods, vice versa. Thus, a CBDC UIP equation is derived for the model.

Since the CBDC is closed border (to be specific to Singapore), there are two arbitrage equations. Equation (4) is the first arbitrage equation (between foreign bonds and domestic CBDCs). The exchange rate change that occurs due to the interest rate differential is specific to the arbitrage of foreign bonds and domestic CBDCs only.

$$r_t^* - r_t^{DC} = E_t [\Delta e_{t+1}] \quad (4)$$

Equation (5) is the second arbitrage equation, which is between foreign bonds and domestic bonds. The exchange rate change that occurs due to the interest rate differential is purely due to the arbitrage between foreign bonds and domestic bonds.

$$r_t^* - r_t = E_t [\Delta e_{t+1}] \quad (5)$$

Next, the weightage variable, w_t , is defined in Equation (6).

$$w_t = \frac{dc_t}{dc_t + b_t} \quad (6)$$

In Equation (6), dc_t is the holdings of CBDC in the domestic economy (endogenously derived in the model later), while b_t is the holdings of bonds in the domestic economy (exogenous using available time series data on bond supply). Thus, w_t is effectively the share of investment as CBDC (and thus the share of investment into bonds is represented as $(1 - w_t)$). Therefore, using this w_t specification, there is an equation for the weighted interest rate for the entire portfolio holdings of the domestic economy, denoted as r_t^P .

$$r_t^P = w_t r_t^{DC} + (1 - w_t) r_t \quad (7)$$

Equation (7) assigns weights to interest rates based on differing combinations of holdings, ultimately affecting the overall interest rate provided on domestic securities. This equation is functional because the model can now compare r_t^* to r_t^P to derive a single net arbitrage equation, as seen below.

$$r_t^* - r_t^P = r_t^* - [w_t r_t^{DC} + (1 - w_t) r_t] = E_t ner_{t+1} - ner_t \quad (8)$$

Equation (8) depicts the overall arbitrage equation of the foreign and domestic economy. This is valid since the exchange rate portion of the UIP mirrors the interest rate differential and is intuitive since the exchange rate deviations also depend on the weighting, i.e., the combinations of the securities held. Thus, the final, aggregated UIP arbitrage equation was derived and is seen in Equation (9).

$$r_t^* - [w_t r_t^{DC} + (1 - w_t) r_t] = E_t ner_{t+1} - ner_t \quad (9)$$

The inclusion of the portfolio share as the mechanism to augment the Uncovered Interest Parity (UIP) condition is structurally supported by literature focused on asset imperfect substitutability and active portfolio management, as shown by Faia, Salomao, and Veghazy (2022), in their work on granular investors. Their portfolio optimization models show that optimal portfolio shares are derived based on the total asset supply and the equilibrium “moments of the excess return (UIP deviation)”. This demonstrates that the asset composition, defined by the w_t term in Equation (9), is a necessary variable to account for the premium or deviation in the exchange rate equation.

2.4. CBDC Demand

At this point, the model has not yet considered the most integral part: the liquidity benefits of CBDCs, which lead us to define a function for total CBDC demand. Since CBDC demand is taken as being endogenous, to quantify the demand/holdings of CBDC, the model can look to Equation (10) according to Ferrari, Mehl, and Stracca (2020), which effectively correlates the demand for CBDC to (i) the interest rate on CBDC, (ii) the interest rate on bonds,

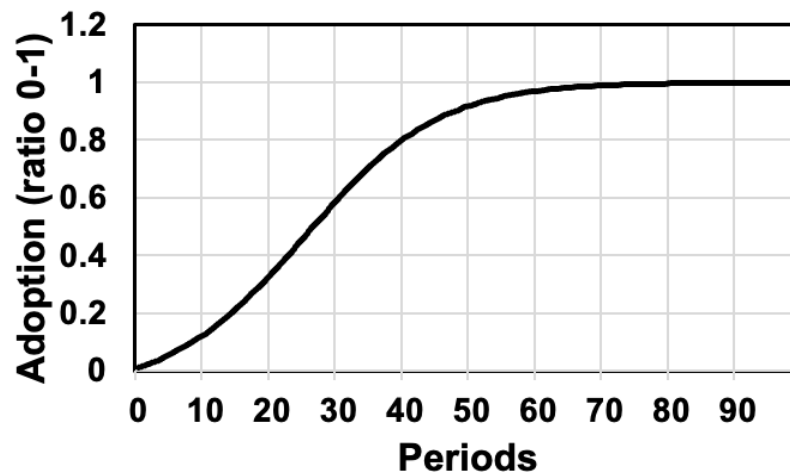
and (iii) the liquidity benefit of CBDCs. This is economically intuitive, as it mimics the trade-off investors must make: liquidity versus remuneration.

$$dc_t = \left[1 - \frac{r_t^{DC}}{r_t} \right]^{-1/\sigma_{dc}} \left[\frac{\mu_{dc}}{\lambda_t} \right]^{1/\sigma_{DC}} \quad (10)$$

In Equation (10), r_t^{DC} is the interest rate on CBDCs that is modeled in the three counterfactual scenarios, while R_t is the interest rate on domestic bonds. Furthermore, σ_{DC} is the curvature parameter governing how sensitive foreign CBDC demand is to returns and liquidity. Furthermore, μ_{DC} represents the liquidity benefit of CBDC while λ_t is the marginal utility of consumption (that is normalized to 1, akin to Ferrari, Mehl, and Stracca (2020)). Thus, the equation quantifies the demand for CBDC as a function of its remuneration, the opportunity cost of holding it (r_t), and its liquidity benefit. Note that this paper intentionally omits the Ferrari, Mehl, and Stracca (2020) equation for CBDC demand in the foreign economy. Since the paper assumes that only domestic investors access CBDCs, the domestic tradeoff is between domestic bonds and CBDCs.

One key addition this paper makes to the demand equation is the implementation of an S-curve for CBDC adoption. Equation (10) assumes 100% adoption in the economy as soon as CBDCs are released, but, in reality, adoption is a longer process. To model this, a Bass diffusion model (Bass 1969) is used, which creates an S-curve as seen below.

Figure 1: Adoption of CBDC over time in the domestic economy



Equation (11) defines the adoption level, α_t .

$$\alpha_t = \alpha_{t-1} + (p + q \alpha_{t-1})(1 - \alpha_{t-1}) \quad (11)$$

The term α_0 (adoption in time period 0) is taken as 0.01. Sultan, Farley, and Lehmann (1990) produce a mean of the annual calibrations for p and q , which are 0.03 and 0.38, respectively. When converted to quarterly calibrations, p and q are calibrated to 0.075 and 0.0906, respectively. This adoption variable is added to the demand equation as seen below.

$$dc_t = \left[1 - \frac{R_t^{DC}}{R_t} \right]^{-1/\sigma_{dc}} \left[\frac{\alpha_t \mu_{dc}}{\lambda_t} \right]^{1/\sigma_{DC}} \quad (12)$$

Notice that α_t is only multiplied in the liquidity wedge of the equation. This is because the liquidity benefit is affected by adoption rates, while remuneration spreads remain constant regardless of adoption levels. For example, holders of CBDC have a higher liquidity benefit from CBDC if many merchants accept it as a form of payment. Also note that dc_t is expressed relative to consumption in the economy, and so to convert dc_t to dollar values, it is multiplied by consumption.

This equation generates time-series data on CBDC holdings, which is then used to estimate w_t , the percentage of CBDC holdings (as a percentage of total assets) over time. This then provides us with the portfolio allocation between CBDCs and bonds in the whole economy. Thus, the CBDC UIP condition is established, accounting for the substitution of bonds by CBDC. The CBDC ON exchange rate path (using the CBDC UIP) can

then be directly compared to the CBDC OFF exchange rate path (using the Control UIP) to determine its effect on exchange rates over time. The table below summarizes the calibrations for each parameter in the model.

Table 1. Parameter Calibrations and Sources

Parameter	Value	Source
<i>Markdown Rule</i>		
$R_{markdown}^{DC}$	0.005	Bindseil (2022)
<i>Taylor Rule</i>		
ρ^r	0.15	(Chow, Lim, and McNelis 2014)
ρ^π	1.025	(Chow, Lim, and McNelis 2014)
ρ^y	0.425	(Chow, Lim, and McNelis 2014)
<i>Bass Diffusion</i>		
p	0.075	Sultan, Farley, and Lehmann (1990)
q	0.0906	Sultan, Farley, and Lehmann (1990)
<i>Liquidity and Frictions</i>		
σ_{DC}	9.558	Ferrari, Mehl, and Stracca (2020)
μ_{DC}	0.55	Ferrari, Mehl, and Stracca (2020)
λ_{DC}	1	Ferrari, Mehl, and Stracca (2020)

Source: All sources for parameter calibration are listed in the “Source” column of the table.

2.5. Instruments

Excel was used to store data and perform calculations using the equations above. The data visualisations are also made and then edited in Excel.

3. Research Results

3.1. Overview of Results

Using the exchange rate values in a time series, this section compares the properties of the counterfactual exchange rates with the original exchange rates in the same period (2000 Q1: 2024 Q4). The results focus on the path fidelity (extent of deviation from the original), volatility, persistence, and volatility during shock to analyze the ideal remuneration regime when compared to the other regimes and the original exchange rate time-series. According to the data collected, the Markdown Rule is found to be the ideal regime as its path is closest to the Control exchange rate (without CBDC) and also has the lowest volatility among the CBDC regimes. Furthermore, the change in volatility between the Markdown Rule and the Control exchange rate is found to be statistically insignificant, and thus does not reflect a notable difference for policymakers. There is a large appreciation of SGD across the counterfactuals, with this appreciation ranging from 35.8% to 80.4%. The counterfactual and original exchange rate time-series data are graphed below and show the general trend of the counterfactuals in relation to the control. Note that all numbers are in log points and quarterly unless explicitly stated otherwise.

Figure 2: USD/SGD Exchange Rate over time (Control vs Baseline)

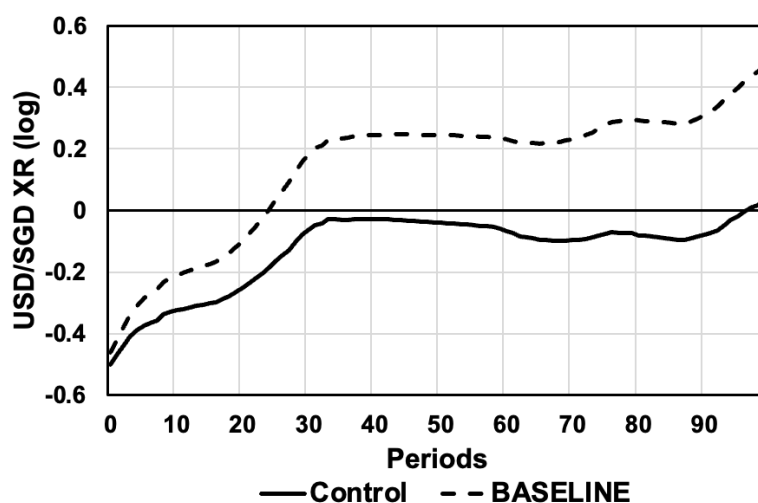


Figure 3: USD/SGD Exchange Rate (Control vs Markdown)

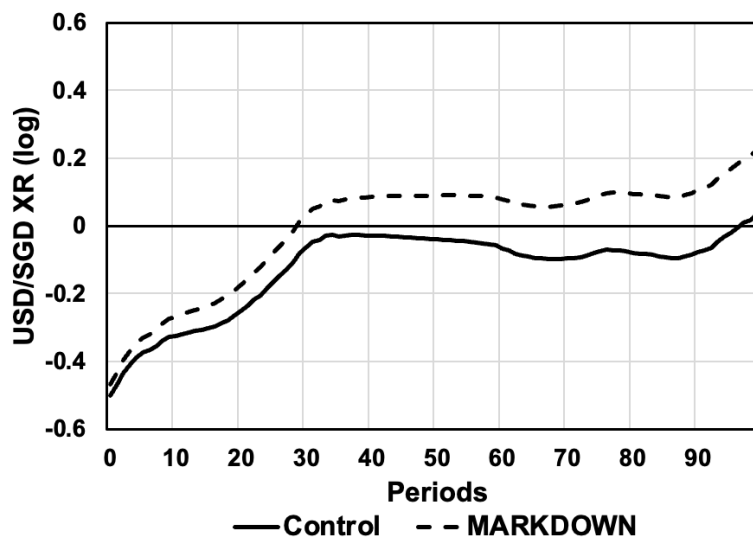
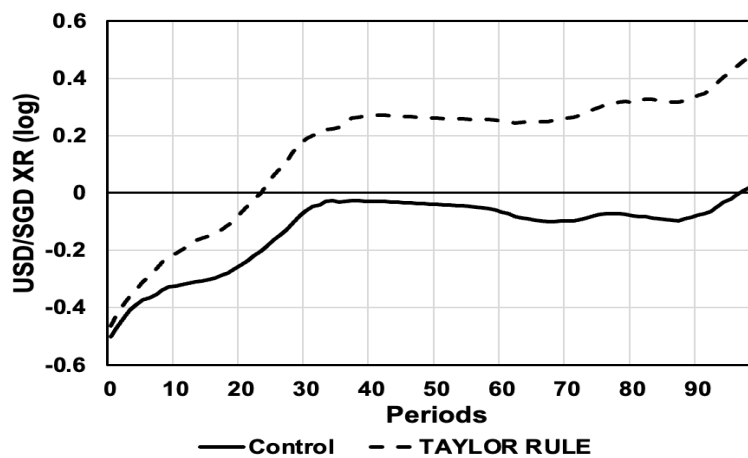


Figure 4. USD/SGD Exchange rate (Control vs Taylor Rule)



3.2. Path Fidelity

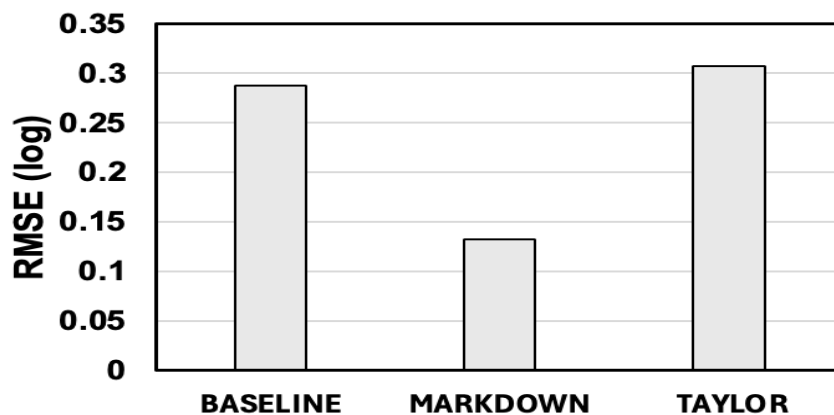
Path fidelity is evaluated using (i) RMSE/MAE of the log deviation δ_t and ii) persistence via an AR(1) with 95% confidence intervals and the implied long-run mean misalignment. Across these metrics, the results show that the Markdown rule attains lower RMSE, MAE, big move frequency, and long-run mean misalignment than the other remuneration regimes, *i.e.*, it is closest to the original exchange rate path. The summary of the results can be seen in the table below.

Table 2. Path Fidelity Statistics

Parameter	Baseline	Markdown	Taylor
RMSE	0.287	0.132	0.307
MAE	0.268	0.123	0.286
AR(1) Slope	0.987	0.991	0.986
Stationary Mean	0.586	0.306	0.590
Big Move Frequency	0.690	0.000	0.720

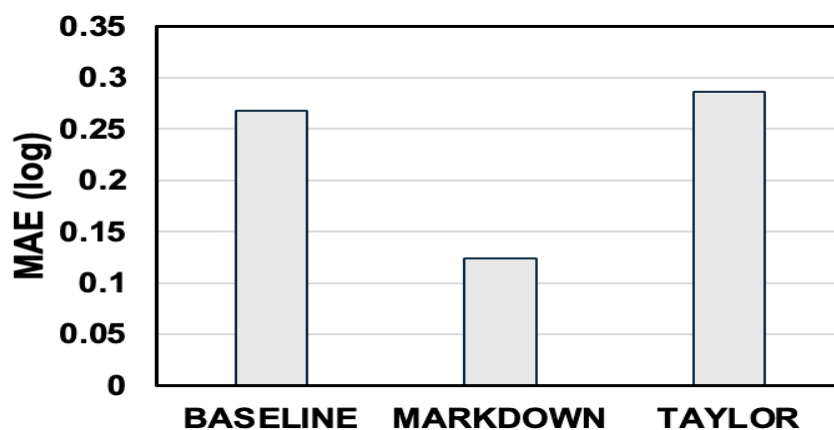
Firstly, root-mean-squared error (RMSE) is lowest under the Markdown rule (0.132), with Baseline (0.287) and Taylor Rule (0.307) larger and very similar. Note that this reflects how far the respective counterfactual path is from the original path.

Figure 5: Root Mean Squared Error across regimes



Secondly, the Mean Absolute Error (MAE) measures the average magnitude of errors between the original exchange rate path and the counterfactual path. It gives a similar result, with the Markdown rule having the lowest (0.123), and Baseline (0.268) and Taylor Rule (0.286) having similar MAEs.

Figure 6. Mean Absolute Error across regimes



Furthermore, persistence is high across regimes as seen by the AR(1) process for deviation, δ_t , by Equation (13).

$$\delta_t = \mu + \phi\delta_{t-1} + \varepsilon_t \quad (13)$$

In Equation (13), μ is the intercept, ϕ is the slope, and ε_t is the error term. AR(1) estimates of deviations yield slopes (ϕ) near 0.98-0.99 (Baseline = 0.987, Markdown = 0.991, Taylor = 0.986). These values are below but close to 1, implying that deviations are sticky. This effectively means that about 98-99% of any deviation carries over to the next quarter, and only 1-2% of the deviation closes.

With the estimates for μ and ϕ , the stationary mean for the deviation time series can be found using the formula $\mu / (1 - \phi)$ (Hamilton 1994). In the context of the paper, deviations are the log differences between the original and counterfactual paths; thus, a non-zero stationary mean indicates a systemic negative or positive bias in the counterfactual. This is an important metric because it isolates the systematic level shifts to which the counterfactual exchange rates gravitate, whereas the RMSE/MAE metric also includes noise. Measuring this systematic shift is essential because, as noted before, the high persistence (near 0.99 across regimes) causes exchange rate gaps between the original and the counterfactual to close extremely slowly.

The stationary mean is closest to zero for Markdown (0.306) and is larger in magnitude for Baseline (0.586) and Taylor Rule (0.590). These values clearly indicate that the exchange rates across regimes sit materially higher (systemically biased upward) than the original exchange rate and suggest that the Markdown rule is closer to the original path than the Baseline or Taylor Rule. Though the Markdown rule provides the lowest systemic gap, it still does not replicate the original exchange rate. Thus, none of the CBDC interest rate regimes hit the target if preserving original exchange rate levels is paramount to policymakers.

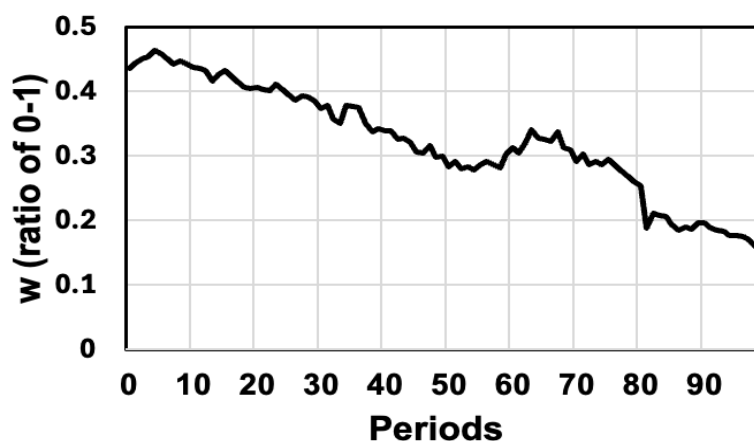
Overall, deviations are large and persistent under all regimes. A commonality in all the CBDC counterfactuals is that the exchange rate series sits materially higher than the Control exchange rate (as characterized by the positive long run mean misalignment measured for all CBDC counterfactuals). The Control UIP and the CBDC counterfactuals also consistently appreciate throughout the time period.

There are three main forces that cause the general appreciation of the exchange rate in the CBDC counterfactuals.

Firstly, Singaporean bonds generally have very low interest rates. In this analysis, 1-year Singapore bonds are used, and they have a mean gross return of 1.014, *i.e.*, an interest rate of 1.41%. Simultaneously, the mean gross return on US 1-year bonds was 1.02, *i.e.*, a 2% interest rate. Thus, in the Control UIP and the CBDC counterfactuals, there is an appreciation of the Singapore exchange rate as Singaporean bonds offer lower remuneration.

However, this appreciation is more pronounced in the CBDC counterfactuals because of the second force: the liquidity benefits of CBDCs. Due to the low-interest-rate environment that domestic investors are subject to, the liquidity benefits of CBDCs cause investors to reallocate to CBDCs as the liquidity provides high utility relative to low remuneration on bonds. Thus, this causes the value of w (the percentage of investment in CBDC) to remain relatively high even when CBDCs have very low or even negative rates. Take the example of the Markdown regime, which has the lowest deviation from the original.

Figure 7. Value of w over time in the Markdown Rule



In the Markdown Rule, the average gross return on CBDCs is 1.0091, *i.e.*, an interest rate of 0.91% (while the average Singapore bond rate is 1.41% and the average US bond is 2%), and, in some periods, provides negative interest rates. Despite this, the value for w remains relatively high, at a mean of 0.322 (meaning 32.2% of domestic investment in the economy is into CBDCs). In the weighted UIP, this causes the weighted domestic interest rate (which is weighted to the percentage holdings of bonds and CBDCs) to decrease compared to the non-CBDC status quo. Thus, this causes the Singapore exchange rate to appreciate significantly.

The final force is that foreign investors cannot invest in the CBDC because it is only open for Singapore locals. Thus, due to the lower rate on CBDC, the weighted interest rate in Singapore is lowered while the foreign interest rates remain the same as foreign investors do not reallocate their investments into CBDCs, causing domestic exchange rates to appreciate under the UIP condition.

Additionally, another finding that is economically intuitive is that the Markdown Rule provides the lowest deviation from the status quo. This is intuitive because the Markdown Rule consistently sets the interest rate on CBDCs to 0.5% below the rate on bonds. Thus, when bond interest rates are below 0.5%, the Markdown Rule can also freely place a negative interest rate on CBDCs. The Baseline Rule cannot do this: it remains fixed and cannot shift its rates dynamically to bond rates. Similarly, the Taylor Rule has the most significant deviation, which may seem counterintuitive. However, interest rates in Singapore are set using exchange rate targeting, and thus the Taylor Rule, though accommodating for inflation and the output gap, does not change in relation to bonds either. Therefore, these results depict that treating the CBDC as having a constant lower remuneration to bonds (0.5% lower) provides the lowest discrepancy in rates and mimics the substitution effect between bonds and CBDCs.

There are, thus, two findings in this section: (i) CBDC implementation causes an appreciation in the exchange rate across the board, and (ii) the Markdown Rule regime has the least deviation from the Control (non-CBDC). It is important to note, however, that though the Markdown Rule reduces both typical distance and systemic gaps, deviations are statistically significant and thus should be considered by policymakers.

3.3. Volatility

The previous section focused on the proximity of the counterfactual exchange rate paths to the original path. This section compares the volatility of the CBDC counterfactuals and the control exchange rate path to determine which regime yields the most stable exchange rates, *i.e.*, the least fluctuations. Volatility can be defined as either the average of absolute exchange rate movements or the standard deviation of percentage changes. For this paper, the latter is taken. Across the entire time period, the Control exchange rate has the lowest volatility, while the Markdown Rule (marginally higher than the Control) has the lowest volatility among the CBDC regimes. However, during periods of shock, the Markdown Rule and the Baseline Rule exhibit the lowest volatility, even lower than the Control exchange rate. The summary table of volatility results is below.

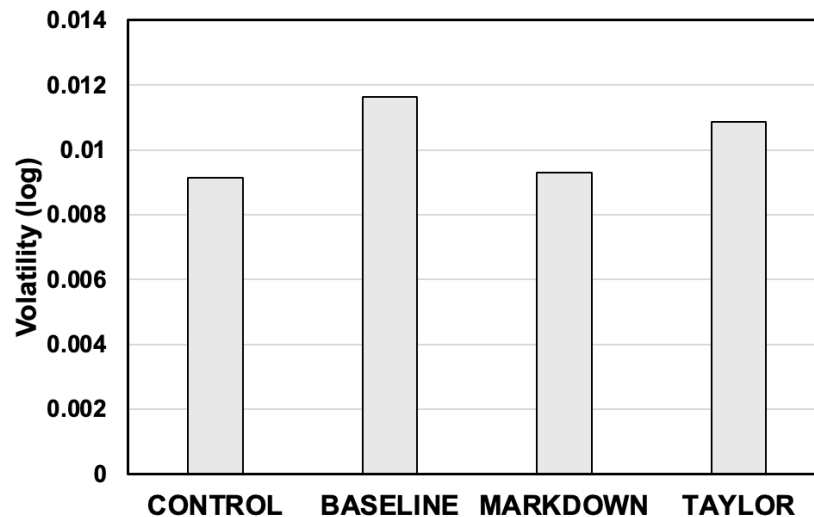
Table 3. Volatility Statistics

Parameter	Control	Baseline	Markdown	Taylor
Periods (0-100)				
Volatility	0.00914	0.0116	0.00930	0.0109
p value of F test	N/A	0.0169	0.865	0.0864
VaR 95%	0.0224	0.0317	0.0244	0.0284
CVaR 95%	0.0283	0.0380	0.0303	0.0341
$\Omega > 0.02$ Frequency	0.0606	0.202	0.101	0.212
Shock Periods				
Volatility (2008 Crisis)	0.0076	0.0078	0.0076	0.0077
Volatility (COVID-19)	0.0038	0.00276	0.00357	0.00805

To measure volatility, the return series of exchange rates is used. This is the difference between the log of exchange rates in consecutive quarters for each series. The return is defined as p and is determined by the equation below, where E_t is the exchange rate in levels.

First, the volatility of exchange rates over the entire period (2000 Q1-2024 Q4) is examined. Volatility is defined by the sample standard deviation of log returns (Ω) in the exchange rate. The results show that the Control exchange rate has the lowest volatility, at 0.0091, while all the CBDC counterfactuals exhibit marginally higher volatilities (Baseline Rule=0.012, Markdown Rule=0.0093, Taylor Rule=0.0109). Among the CBDC regimes, the Markdown Rule had the lowest volatility.

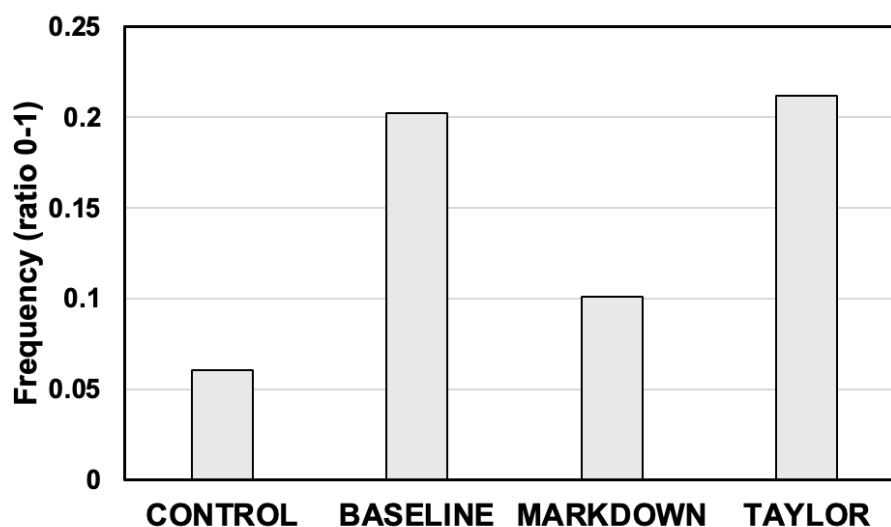
Figure 8: Volatility of Exchange Rates in Control and across CBDC regimes



However, it is also found that the change in volatility for the Markdown Rule (compared to the Control) is statistically insignificant at a significance level of 0.10 (p value of F test = 0.865), while the other two regimes remain statistically significant ($p < 0.10$).

To complement the standard deviation measure, the frequency with which exchange rate returns (Ω in absolute values) exceed 0.02 log points is also calculated (Figure 9). Similar results are observed, with the Control (0.061) demonstrating a much lower frequency than the CBDC regimes (Baseline Rule=0.202, Markdown Rule=0.101, Taylor Rule 0.212). Among the CBDC counterfactuals, the Markdown Rule had the lowest frequency for significant moves between quarters.

Figure 9. Frequency of moves greater than 0.02 log points

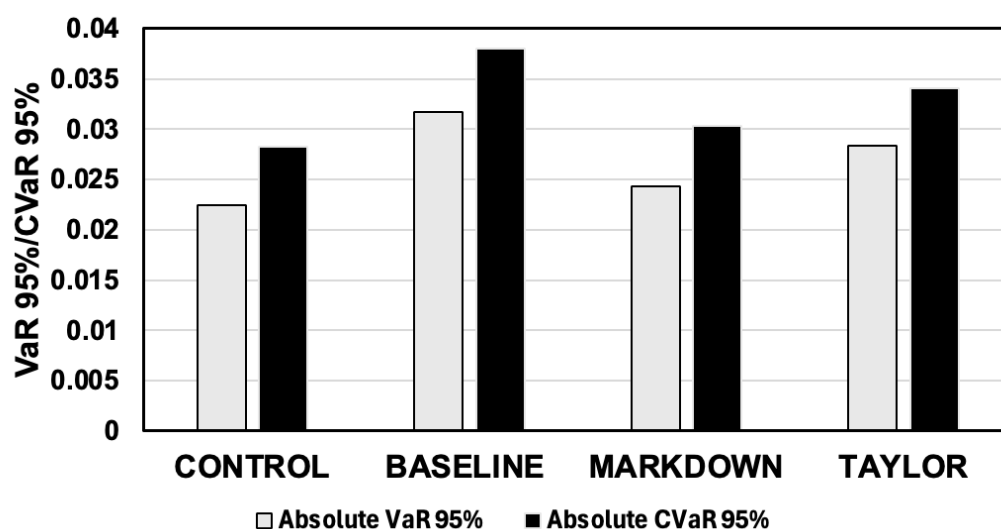


Furthermore, the Absolute VaR 95% (Value-at-Risk 95%) and the Absolute CVaR 95% (Conditional Value-at-Risk 95%) are calculated for each exchange rate return series. Effectively, VaR 95% provides the absolute value

of return that lies at the 95th percentile of all returns in that series, *i.e.*, it marks the threshold at which the “worst” 5% of absolute value returns begin. The higher the absolute returns, the more volatile the exchange rate series, and thus a lower Absolute VaR 95% is better. The Absolute CVaR at 95% provides insight into the average absolute return for the worst 5% of quarters (*i.e.*, higher absolute returns).

Similar results are found here also. Relative to the Control (VaR95 = 0.022, CVaR95 = 0.028), all the counterfactuals have higher values. Markdown (VaR95 = 0.024, CVaR95 = 0.030) again had the lowest when compared to the Baseline Rule (VaR95 = 0.032 and CVaR95 = 0.038) and Taylor Rule (VaR95 = 0.028 and CVaR95 = 0.034).

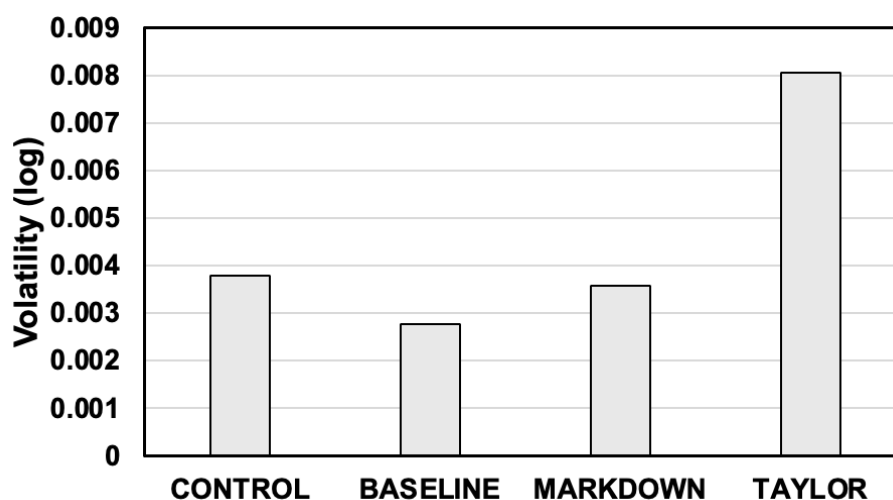
Figure 10. Absolute VaR 95% and Absolute CVaR 95% for Control and across CBDC regimes



The volatility test is also conducted during periods of shock present in the dataset, specifically, COVID-19 and the 2008 crisis. For COVID-19, the period from 2019 Q4 to 2020 Q2 (end of quarter) is picked. For the 2008 crisis, the period from 2008 Q2 to 2009 Q1 is used. An interesting finding here is that volatility during these shock periods is lower for the CBDC regimes.

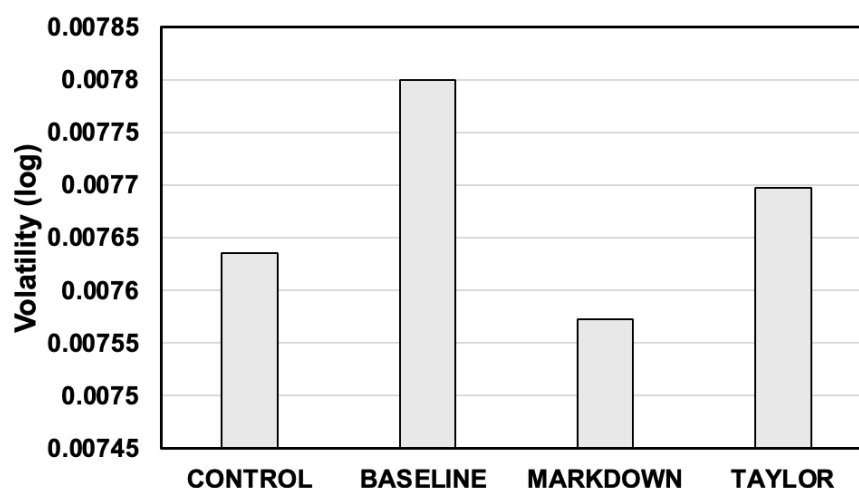
In the case of COVID-19, the Baseline Rule (0.0028) and the Markdown Rule (0.0036) have lower volatility than the Control (0.0038), while the Taylor Rule (0.0081) has the highest volatility.

Figure 11. Volatility of Exchange Rates in Control and across CBDC regimes during COVID-19



The 2008 shock also shows a similar trend. In this case, however, the Control exchange rate and the Markdown Rule volatilities hover almost exactly at 0.0076 (Markdown Rule thinly lower). At the same time, the Taylor Rule (0.0077) and Baseline Rule (0.0078) are slightly higher during the period. Note that VaR 95% and CVaR 95% values are not found because of the low number of time periods assessed during the shock.

Figure 12. Volatility of Exchange Rates during the 2008 financial crisis



Overall, there are three main findings on volatility. Firstly, over the entire time period, the Control exchange rate and the Markdown Rule had the lowest volatility among all the exchange rate paths assessed, with the difference in volatility between the two being statistically insignificant. Secondly, over the time period, the Markdown Rule exhibits the lowest volatility among the CBDC regimes. Lastly, it is worth noting that the CBDC regimes, specifically the Baseline Rule and the Markdown Rule, exhibited a marginal decrease in volatility during periods of shock, namely the COVID-19 pandemic and the 2008 crisis. However, the differences here are very slight, and are not indicative of a superiority of CBDCs during shock periods.

The results on volatility are economically intuitive. Under the Markdown rule, the CBDC pays a fixed discount to government bonds and is available only to residents. This creates a stable, liquid asset that people hold for convenience rather than yield, so the CBDC share changes little when interest rates move. The steadier CBDC share dampens movements in the portfolio-weighted domestic return that feeds the UIP condition, and most rebalancing occurs between domestic assets rather than through cross-border flows. By contrast, the Taylor rule moves the policy rate whenever inflation or output shifts, producing larger and more frequent changes in the interest differential and, therefore, higher exchange-rate volatility. The Baseline rule lacks the fixed markdown anchor, so small rate changes trigger more switching between CBDC and bonds. As a result, the Markdown rule delivers lower volatility than both the Taylor and Baseline rules.

4. Discussions

A closed-border CBDC implementation in Singapore is shown to have significant effects on the exchange rate, which can directly impact Singapore's exchange rate-targeting monetary policy. Some of the results shown are open to interpretation and depend directly on the Monetary Authority of Singapore's goals and priorities.

The paper addresses two questions: (i) which CBDC interest rate regime is ideal for Singapore if CBDCs are implemented, and (ii) the general impacts of CBDCs on Singapore's exchange rate. The paper focuses on two determinants of exchange rate changes: path fidelity and volatility.

To answer the first question, the results show that among CBDC interest rate regimes, the Markdown regime is the ideal, as its exchange rate path is closest to the original path (path fidelity) and exhibits the lowest volatility over the time period assessed. These findings can inform policy, as the Markdown regime is the ideal implementation of CBDCs from a purely exchange-rate perspective.

The second finding compares the CBDC implementation counterfactual to the status quo. Regarding volatility, over the entire time period assessed (and thus on average), changes in volatility between the Control exchange rate and the Markdown Rule are statistically insignificant.

The results on path fidelity are up to interpretation. In all the counterfactuals, the exchange rate steeply appreciated relative to the Control. Even under the Markdown regime, the SGD level sits materially higher than the Control: the long-run mean misalignment is 0.306 log points, which corresponds to the exchange rate being about 35.8% stronger on average, an essential concern for the MAS to assess. It is also worth noting that in other counterfactuals, specifically the Taylor Rule, this appreciation can reach 80.4%.

The methodology and results fit well into the literature. The first point of focus is the methodology. Relative to Ferrari, Mehl, and Stracca (2020), who embed CBDC in a two-country DSGE and show that design choices

shape international spillovers, this paper uses a reduced-form UIP framework to quantify how specific remuneration rules would alter Singapore's exchange-rate path and volatility under a closed-border retail CBDC. Furthermore, the counterfactual approach taken in this paper echoes the approach taken by Kumhof and Noone (2021), while adapting their approach for an open economy that targets the exchange rate. Lastly, as mentioned earlier, the portfolio weighting variable in the modified UIP is a novel usage of the granularity of investors shown in Faia, Salomao, and Veghazy (2022).

The next point of focus is the results of the paper. Relative to the existing literature, the exchange rate implications of this paper line up with, but also narrow and sharpen, several strands of prior work. Ferrari, Mehl, and Stracca (2020) show in a two-country DSGE setting that introducing a cross-border CBDC reshapes the arbitrage conditions between currencies and tends to amplify exchange-rate responses to monetary and financial shocks. George, Xie, and Alba (2020) find in a small-open-economy model that an interest-bearing retail CBDC can be configured to dampen exchange-rate fluctuations by giving policymakers an additional lever to influence risk premia and expected depreciation. Fan, Walker, and Wright (2025) also report that CBDC design affects the exchange rate mainly through its impact on portfolio choices and external financing conditions, though in their calibration the resulting exchange-rate movements are relatively modest for small open economies. In comparison, this paper's exchange-rate findings complement these contributions by focusing specifically on how alternative retail CBDC architectures can systematically tilt the exchange rate's average path and volatility specifically in a Singaporean context.

Beyond the specific policy implications for the MAS, the results carry broader methodological significance. Firstly, the method of the portfolio-weighted uncovered interest parity to accommodate a closed-border CBDC instead of a separate UIP equation is novel and clearly demonstrates that even a domestically restricted digital currency can generate persistent deviation in the exchange rate level by reshaping the effective domestic interest rate. Second, the superiority of the Markdown Rule over both the Taylor Rule and the zero-rate baseline is a novel finding that is highly specific to the exchange rate targeting economy of Singapore, and thus challenges existing CBDC literature. The result is consistent with the view that, in an economy like Singapore's (that already operates its monetary policy using the exchange rate), adding a second "active" instrument like the Taylor Rule creates additional volatility rather than an additional monetary policy lever (as described in George, Xie, and Alba (2020)). Lastly, the consideration of adoption dynamics, especially since a CBDC is a completely new asset class for investors, plays a meaningful role in influencing the portfolio weights (and thus the exchange rate paths), suggesting that future CBDC modelling efforts should also treat adoption as an endogenous variable.

Conclusions and Further Research

This paper highlights two policy implications: (i) the Markdown Rule provides the lowest exchange rate deviation and maintains the original volatility of exchange rates, and (ii) there is an appreciation of the SGD by 35.8% (Markdown) to 80.4% (Taylor Rule). These findings have wider implications for Singapore's economy.

On the one hand, a higher exchange rate can enable Singapore to import goods at a lower price due to the increased value of the currency. This can increase the purchasing power of Singaporeans. However, the price of exports from Singapore will also increase due to higher domestic production costs. It is important to note, however, that 43.8% of Singapore's exports rely directly on imported inputs, such as value-added components, suggesting that an appreciation could mitigate the export competitiveness harms (OECD 2023). This paper does not aim to assess or comment on whether a stronger SGD is a boon or a disadvantage to Singaporean trade as a host of literature tackles this very topic. However, this paper empirically exposes the underlying mechanisms that can cause changes in the exchange rate path and volatility, which can help inform decisions on CBDC implementation for the MAS and other small, open-economy central banks worldwide.

Further research can go in a few directions. Firstly, future research on CBDC implementation effects should focus on including a variety of asset classes such as equities, real estate, cash, etc in the portfolio allocation model to simulate the diversity of investment options. Secondly, future research can also look to model alternative CBDC regimes that have more innovative structures in the Singaporean economy such as tiered remuneration structures and quantity rules. Thirdly, as actual CBDC implementations accumulate empirical data (for example from the Bahamas' Sand Dollar or the Eastern Caribbean DCash), future work could test the calibration of the adoption and demand parameters used in this model against observed outcomes.

Declarations

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Credit Authorship Contribution Statement:

Arnav Agrawal: Conceptualization, Investigation, Methodology, Software, Data Analysis, Writing, Review and Editing, Formatting, Project administration

Declaration of Competing Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

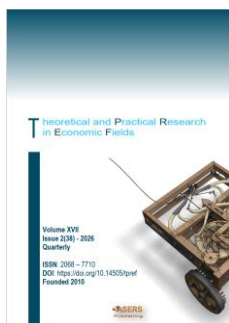
Declaration of use of generative AI and AI-Assisted Technologies: The authors declare that they have used generative AI (a type of artificial intelligence technology that can produce various types of content including text, imagery, audio, and synthetic data. Examples include ChatGPT, NovelAI, Jasper AI, Rytr AI, DALL-E, etc) and AI-assisted technologies in the writing process before submission, but only to improve the language and readability of their paper, and with the appropriate disclosure.

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Mathematical Review of the Sukuk-Linked Awqaf Model: A Critical Analysis of Notation Consistency and Formula Validity



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Abstract: This manuscript provides a critical mathematical review of a Sukuk-Linked Awqaf model with the aim of improving notational consistency, analytical clarity, and economic interpretability. The study focuses on correcting weaknesses arising from inconsistent time indexing, redundant equations, misuse of mathematical symbols, and unclear assumptions regarding asset growth, rental income, construction cost, and revenue sharing. By imposing a consistent growth process for waqaf land value, several artificial discount factors are eliminated and present value expressions are derived directly using standard time value of money principles. Key equalities in the original model are reinterpreted as minimum contractual conditions rather than strict identities to better reflect economic uncertainty. The analysis also introduces explicit decision criteria for all stakeholders - Nadzhir, investors, and state-owned enterprises (SOE) - based on present value comparisons. The revised formulation offers a cleaner and more rigorous mathematical foundation for Sukuk-Linked Awqaf and strengthens its relevance as an instrument of Islamic social finance.

Keywords: Sukuk-linked awqaf; Islamic social finance; mathematical modeling; present value; revenue sharing; contract design.

JEL Classification: G15; G21; Z12; C01.

Introduction

The integration of Islamic social finance instruments with capital market mechanisms has attracted increasing scholarly attention in recent years (Kuanova *et al.* 2021, Dirie *et al.* 2024). One prominent example is the attempt to link *awqaf* (Islamic endowment) assets with Sukuk instruments in order to finance public-benefit infrastructure (Qurrata *et al.* 2025). In this context, the Sukuk-Linked Awqaf (SLA) model proposed by Ismal (2024) (Ismal 2024) represents an innovative effort to combine wakaf land, ijarah Sukuk, state-owned enterprises, investors, and tenants within a single financial structure. Conceptually, the model aims to transform unproductive wakaf land into productive social assets through structured financing while maintaining compliance with Islamic jurisprudence (Ismal 2024, Kamaruzaman and Ishak 2023).

Beyond its conceptual and institutional design, the SLA model claims to be supported by a set of mathematical formulations (Ismal 2024). These formulas are intended to represent rental flows, construction costs, Sukuk issuance values, and the investment decisions of both *Nadzhir* (wakaf managers) and Sukuk investors. The author explicitly refers to classical investment theory, especially the net present value (NPV) framework, as developed in standard financial mathematics literature (Benninga 2000, Cvitanic and Zapatero 2024). In principle, such a quantitative foundation is essential: without mathematically consistent and logically valid equations, a financial model cannot be reliably implemented, tested, or compared with alternative structures.

However, in applied mathematics and financial modeling, correctness is not merely a matter of having formulas, but of ensuring that symbols are consistently defined, indices are properly used, summations are meaningful, and discounting reflects the actual timing of cash flows (Czerwinski 2024). Inconsistent notation,

misuse of summation indices, or incorrect adaptation of standard formulas - such as future value and present value equations - can lead to results that are mathematically invalid and economically misleading. This is particularly critical when a model is proposed as a policy-relevant or implementable financial structure (Basher and Raboy 2018).

A preliminary reading of the SLA model reveals several potential mathematical issues. These include inconsistent use of time indices (such as n , s , and t), summation expressions that do not depend on their indices, unjustified use of exponential or power forms for linear cash flows, and modifications of NPV formulas that deviate from standard financial mathematics without sufficient theoretical justification. Such issues raise an important question: to what extent can the SLA model be considered a mathematically sound quantitative model, rather than a conceptual framework supported by symbolic but flawed equations?

Therefore, this article aims to conduct a mathematical review of the Sukuk-Linked Awqaf model. The focus is not on its legal, institutional, or Sharia aspects, but strictly on the structure of its mathematical formulations. Specifically, this study critically analyzes:

1. the consistency of symbols and notation,
2. the correctness of summation and indexing,
3. the logical structure of rental, cost, and revenue formulas, and
4. the validity of the modified NPV-based decision criteria.

By applying principles from applied mathematics and financial modeling, this review seeks to clarify which parts of the SLA formulation are mathematically valid, which are inconsistent or incorrect, and how such weaknesses affect the credibility of the model as a quantitative tool. Ultimately, this paper argues that mathematical rigor is not a technical luxury, but a fundamental requirement if innovative Islamic finance models like SLA are to move from conceptual proposals to reliable and implementable financial instruments.

2. Research Methodology

This study employs a critical mathematical review approach. The objective is not to construct a new financial instrument, but to evaluate and refine the mathematical structure of an existing Sukuk-Linked Awqaf model. The review focuses on the consistency of notation, the correctness of formulas, the logical coherence between assumptions and equations, and the economic interpretability of the resulting decision rules. The approach combines narrative explanation of the model, analytical inspection of equations, and critical evaluation of the assumptions that support those equations.

The main object of analysis is a published article that proposes a mathematical formulation for Sukuk-Linked Awqaf and adapts classical accumulation formulas from mathematical finance, including those inspired by Cvitanic and Zapatero (2004) and Ismal (2024). The components under review include investment accumulation formulas, rental income of waqaf land, construction and issuance cost structures, revenue-sharing mechanisms, accumulation of returns for Nadzhir, investors, and SOE, and the decision criteria for each stakeholder.

The data used in this research are secondary data in the form of mathematical expressions, variable definitions, parameter assumptions, and derivation steps presented in the reviewed article. These are supported by references from mathematical finance, time value of money theory, and Islamic finance literature, which serve as benchmarks to assess whether the reviewed formulas align with standard theoretical principles.

Each equation and assumption is evaluated based on four main principles. First, notational consistency is examined to ensure that no symbol carries multiple meanings, indices do not conflict with summation variables, and notation reflects economic interpretation. Second, mathematical correctness is assessed by checking summation bounds, index placement, algebraic manipulation, and redundancy between formulas. Third, logical coherence is evaluated by tracing whether each equation follows from previous assumptions and whether the time structure of construction period, Sukuk tenor, and income period is internally consistent. Fourth, economic interpretability is considered by ensuring that each variable has a clear real-world meaning and that decision rules are reasonable in economic terms.

The analysis begins with content mapping, in which all variables, assumptions, and equations are identified and organized according to their roles in the model. This is followed by mathematical inspection, where each equation is checked for correctness of notation, summation structure, and logical derivation. Key formulas are then compared with standard accumulation models in mathematical finance and with existing Sukuk and waqaf-related models to identify deviations, simplifications, or inconsistencies. When problems are found, the equations are reformulated by presenting the original version, explaining the mathematical issue, and proposing a corrected or simplified version together with its implications.

The review process is conducted sequentially by identifying the structure of the model, tracing the derivation of each equation, detecting conflicts in notation and logic, reformulating problematic equations, and reconstructing the decision criteria for Nadzhir, investors, and SOE. The final outcome of this methodology is a set of formulas that are mathematically consistent, notationally clear, and economically interpretable, which can serve as a reliable foundation for future applied mathematical modeling of Sukuk-Linked Awqaf.

3. Review of the Basic Investment Formula from Cvitanic and Zapatero (2004)

The first formula reviewed in the Sukuk-Linked Awqaf model is taken from Cvitanic and Zapatero (2004) and is intended to represent the accumulation of future investment. In the reviewed article, it is written as:

$$V_t = V_0 + V_1(1+r) + \dots + V_m(1+r)^m$$

or

$$V_t = V_0 + \sum_{t=1}^m V_t (1+r)^t$$

This formulation contains a fundamental notational conflict. The symbol t is used simultaneously as:

1. the time index of the accumulated value on the left-hand side, and
2. the index of summation on the right-hand side.

This creates a collision of meaning, because t cannot represent both a fixed time point and a running index of summation at the same time. A consistent notation should distinguish between the evaluation time and the summation index. A more appropriate form is:

$$V_T = V_0 + \sum_{i=1}^m V_i (1+r)^i \quad (1)$$

where T denotes the final evaluation time and i is the summation index. This avoids ambiguity and preserves logical clarity.

3.1. Deterministic Nature of the Interest Rate

In this formulation, the rate r is treated as a constant (deterministic) parameter. While this is mathematically acceptable for a basic model, it reduces realism in practical applications. In real financial markets, returns are uncertain and time-varying (David and Veronesi 2022, Lim and Brooks 2011, Ren *et al.* 2023, Ang and Timmermann 2012). Therefore, the model implicitly assumes:

- A fixed and known rate of return,
- No risk or volatility,
- Perfect predictability of growth.

This limits the empirical accuracy of the model (Zhou 2018, French 2019). At minimum, this assumption should be explicitly stated, for example: "Assume that the rate of return r is constant and known over the entire investment horizon."

3.2. Missing Timing Assumptions

The formula also implicitly assumes a specific timing structure of cash flows, but this is not stated. For the formula to be meaningful, one must assume:

- Funds are invested at the beginning of each period,
- They grow during the period at rate r ,
- They are withdrawn at the end of the period,
- Then reinvested in the following period.

Without this assumption, the multiplication by $(1+r)^i$ has no clear economic interpretation (Judd 1996, Briggs *et al.* 1997). Therefore, a necessary assumption is: "Each V_i is invested at the beginning of period i , grows at rate r during that period, and is evaluated at the end of period i ."

3.3. Review of Equation (2): Present Value Form

The second equation is written as:

$$V_t = V_0 + \frac{V_1}{1+r} + \dots + \frac{V_m}{(1+r)^m} \quad (2)$$

or

$$V_t = V_0 + \sum_{t=1}^m \frac{V_t}{(1+r)^t}$$

Here, the main error is again notational. The summation index is incorrectly written as t , which clashes with the t used on the left-hand side. It should be:

$$V_T = V_0 + \sum_{i=1}^m \frac{V_i}{(1+r)^i}$$

This correction does not change the economic meaning, but it is essential for mathematical consistency.

3.4. Ambiguity of the Symbol V_t

A deeper problem is that the same symbol V_t is used in two different meanings:

1. In Equation (1), V_t represents the accumulated future value,
2. In Equation (2), V_t represents a present value of future cash flows.

These are conceptually different objects and should not share the same notation. To avoid confusion:

- Use FV_T for future value at time T ,
- Use PV for present value,
- Use V_i only for individual cash flows.

For example:

$$FV_T = \sum_{i=0}^m V_i (1+r)^i, PV = \sum_{i=0}^m \frac{V_i}{(1+r)^i} \quad (3)$$

If the goal is to highlight simple investment growth, then it is better to write:

$$V_t = V_0(1+r)^t,$$

which clearly represents the growth of a single initial investment.

For cumulative investments, however, a different symbol should be used, such as:

$$A_T = \sum_{i=0}^m V_i (1+r)^{T-i},$$

so that the distinction between “single-investment growth” and “accumulated multi-period investment” is mathematically and conceptually clear.

4. Review of Equations (4) and (5): Rental Income of Awqaf Land

In the reviewed article, rental income of the awqaf land is defined through Equations (4) and (5) in (Ismael 2024):

$$R_n = (\theta A_0)^1 + (\theta A_0)^2 + \dots + (\theta A_0)^n \quad (4)$$

$$R_n = \sum_1^n (\theta A_0)^n \quad (5)$$

These two equations are mathematically redundant and, more importantly, both are incorrectly formulated.

4.1. Constant Market Value Assumption

The article defines A_0 as the current market value of the awqaf asset (Ismael 2024). Implicitly, this suggests that A_0 is treated as constant over time. If A_0 is indeed assumed constant and the rental rate θ is fixed, then the rental payment each period is simply:

$$\text{Rental per period} = \theta A_0.$$

Therefore, the accumulated rental over n periods should be:

$$R_n = \theta A_0 + \theta A_0 + \dots + \theta A_0 (n \text{ terms}),$$

which simplifies to:

$$R_n = n\theta A_0.$$

In this case, there is no need to use summation notation, because the expression does not depend on any index. Thus, Equations (4) and (5) should be replaced by a single, simple formula:

$$R_n = n\theta A_0.$$

4.2. Unrealistic Constancy of Market Value

However, in real applications, the market value of land rarely remains constant (Regan *et al.* 2015 Pagourtzi *et al.* 2003, Xie *et al.* 2002). While the rental rate θ may be contractually fixed, the underlying asset value usually changes over time. Therefore, a more realistic assumption is:

- θ is constant,
- The land value evolves over time:

$$A_i = A_0(1 + r)^i,$$

where r is the growth rate of land value.

Under this assumption, rental in period i becomes:

$$\text{Rental in period } i = \theta A_i = \theta A_0(1 + r)^i.$$

Then, total rental income over n periods is:

$$R_n = \sum_{i=1}^n \theta A_0(1 + r)^i.$$

This is a geometric series and can be simplified as:

$$R_n = \theta A_0 \sum_{i=1}^n (1 + r)^i = \theta A_0 \cdot \frac{(1 + r)^{n+1} - (1 + r)}{r}, r \neq 0.$$

5. Review of Construction Cost and Issuance Cost Formulas

5.1. Clarification of Time Structure: Relation between n , s , and t

In the reviewed article (Ismal 2024), three-time parameters are used:

- n = leasing period of awqaf land by the SOE,
- t = construction period,
- s = Sukuk tenor.

However, the article only states that $s < n$, without clearly explaining the economic meaning of this relation. In fact, the structure of the model implies:

- During the construction period t , the SOE already leases the awqaf land and pays rent,
- After construction, during Sukuk tenor s , the building is rented to tenants and generates income,
- Therefore, the total leasing period should satisfy:

$$n = s + t.$$

This relation is essential for time consistency (Calvo 1978, Rafay *et al.* 2017, Nurhanifah 2024). Without explicitly stating $n = s + t$, the interaction between rental payments, construction costs, and Sukuk tenor becomes mathematically ambiguous.

5.2. Review of Equations (6) and (7): Construction Cost

The reviewed article (Ismal 2024) presents:

$$K_t = (\beta A_s)^1 + (\beta A_s)^2 + \dots + (\beta A_s)^t \quad (6)$$

or

$$K_t = \sum_1^t (\beta A_s)^t \quad (7)$$

Because the word “or” is used, both equations are intended to represent the same quantity. However, both are mathematically incorrect and redundant.

If β is a fixed proportion and A_s is the value of the asset used as the construction reference, then construction cost per period is:

$$\beta A_s.$$

Hence, total construction cost over t periods is:

$$K_t = \beta A_s + \beta A_s + \cdots + \beta A_s (t \text{ terms}) = t\beta A_s.$$

There is no need for summation notation, because the right-hand side does not depend on any index.

5.3. Allowing Asset Value Growth

If the asset value used for construction is assumed to evolve over time (Acciaio *et al.* 2025), then one may assume:

$$A_s = A_0(1 + r)^s, \text{ with } s = n - t.$$

Then construction cost becomes:

$$K_t = t\beta A_s = t\beta A_0(1 + r)^{n-t}.$$

This formulation is mathematically consistent and economically interpretable.

5.4. Review of Other Costs (Ismal 2024)

The article defines “other costs” using the symbol S , while at the same time using s to denote Sukuk tenor. This creates unnecessary confusion, because S and s are visually and conceptually too similar.

It is better to denote “other costs” by O (Critical that O is not yet used in the model). Then:

$$O_s = O + O + \cdots + O (s \text{ terms}) = sO.$$

Thus, Equations (8) and (9) in (Ismal 2024) can be replaced by:

$$O_s = sO.$$

5.5. Cost and Issuance Value in (Ismal 2024)

The article defines:

$$C_s = \text{total cost}, I_s = \text{Sukuk issuance value},$$

and then states:

$$I_s = C_s.$$

This makes one of the two symbols redundant. It is sufficient to use only one main symbol. A clearer choice is:

I_s : value of Sukuk issuance, where I stands for “Issuance” and s for Sukuk tenor.

Then the issuance value can be written directly as:

$$I_s = \sum_{i=1}^n \theta A_0 + \sum_{i=1}^t \beta A_s + \sum_{i=1}^s O.$$

Since each term is constant within its period, this simplifies to:

$$I_s = n\theta A_0 + t\beta A_s + sO.$$

If asset value grows as $A_s = A_0(1 + r)^s$, then:

$$I_s = n\theta A_0 + t\beta A_0(1 + r)^s + sO.$$

6. Review of Revenue Coefficient γ and Income Timing

In the reviewed model (Ismal 2024), θ and β are clearly defined as proportional parameters:

- θ = rental proportion of awqaf land,
- β = construction cost proportion.

However, the parameter γ is less clearly defined. Conceptually, γ represents the business return coefficient of the building constructed on waqaf land (Ismal 2024, Zafar and Jafar 2025). Therefore, unlike θ and β , which are cost-related proportions, γ measures operational performance.

From a mathematical and economic perspective, γ should satisfy:

$$0 \leq \gamma < \infty.$$

Interpretation:

- $\gamma = 0$: the business generates no profit,
- $\gamma > 0$: the business is profitable,
- In practice, one may also allow $\gamma < 0$ to represent losses.

However, if $\gamma < 0$, the model must clearly specify who bears the loss. A consistent assumption is:

- Losses are borne by Sukuk investors and SOE (Hamzah *et al.* 2018, Klein *et al.* 2018, Mohd Roslen *et al.* 2025, Ahmed *et al.* 2018),
 - Nadzhir does not bear operational losses, in line with the social and protected nature of waqaf assets.
- This risk-sharing rule is not clearly stated in the reviewed article and should be made explicit.

6.1. Ambiguity in Construction Financing and Time Consistency

The article is unclear about whether construction costs are initially financed by the SOE or directly from Sukuk proceeds (Ismal 2024). This ambiguity affects time consistency.

If construction is financed by Sukuk from the start, then income generation cannot begin until construction ends, and the relation between time variables becomes unclear. To maintain consistency, it is more realistic to assume:

- Construction cost is initially borne by the SOE,
- Sukuk is issued after the building is ready and operational,
- Sukuk proceeds are used mainly for refinancing and income distribution.

This structure is similar to livestock or agriculture Sukuk, where assets must exist and operate before Sukuk returns are distributed (Ashfahany *et al.* 2023, Alswaidan *et al.* 2017, Hasan *et al.* 2019).

Under this assumption:

- t = construction period,
- s = income-generating period,
- $n = t + s$ = total leasing period of awqaf land by SOE,
- Income is received only after construction ends.

Thus, the correct income period is not " $s - t$ " as written in the article, but:

$$\text{Income period} = n - t = s.$$

6.2. Correcting the Income Formula

The article writes income as:

$$\pi_{s-t} = \sum \gamma A_s^{(s-t)},$$

which is both notationally and conceptually incorrect. With the corrected time structure:

- Income is generated over $n - t$ periods,
- Return per period is γA_s ,

so total income becomes:

$$\pi_{n-t} = \gamma A_s + \gamma A_s + \dots + \gamma A_s (n - t \text{ terms}) = (n - t) \gamma A_s.$$

There is no need for summation notation if the term is constant.

6.3. Revenue Sharing

Revenue is divided among three parties: Nadzhir, Sukuk investors, and SOE (Rafay, Sadiq, and Ajmal, 2017). To avoid confusion with the summation index i , Sukuk investors' income should be denoted by π_v (from *value holder*), not π_i .

Thus:

$$\pi_{n-t} = \pi_z + \pi_v + \pi_e,$$

with equal sharing:

$$\pi_z = \pi_v = \pi_e = \frac{1}{3} (n - t) \gamma A_s.$$

If losses are allowed ($\gamma < 0$), then:

- $\pi_z = 0$ (Nadzhir protected),

- Loss is shared between SOE and Sukuk investors, which must be specified as an explicit assumption.

7. Review of Nadzhir's Accumulation and Investment Decision

At the end of the Sukuk tenor and land leasing period, the building constructed on waqaf land is transferred to Nadzhir (Ismael 2024), Alam *et al.* 2024, Adniyah 2025). During the Sukuk period, Nadzhir gradually "pays" for the building using two sources:

1. Rental payment from the waqaf land paid by SOE,
2. Nadzhir's share of business income generated from the building.

Thus, Nadzhir's effective payment for the building is:

$$R_n + \pi_z.$$

7.1. Relation between Construction Cost and Nadzhir's Payment

In the reviewed article (Ismael 2024), it is imposed that:

$$K_t = R_n + \pi_z.$$

This equality is not necessarily true in general. In reality:
If the business return coefficient γ is very large, then π_z may be large and:

$$K_t < R_n + \pi_z.$$

If the business is weak, π_z may be small, and:

$$K_t > R_n + \pi_z.$$

However, for pricing and contract design, it is reasonable to impose a minimum condition (Hameed and Bashir 2002):

$$K_t \leq R_n + \pi_z,$$

and more precisely, the rental rate θ and revenue-sharing scheme should be set such that:

$$K_t = R_n + \pi_z \text{ (as a minimum target).}$$

This ensures that Nadzhir can fully acquire the building by the end of the Sukuk period.

7.2. Final Asset Value of Nadzhir

The article (Ismael 2024) defines:

$$P_z = A_n + K_t.$$

However, since Nadzhir actually pays for the building through $R_n + \pi_z$, the more accurate formulation is:

$$P_z = A_n + (R_n + \pi_z).$$

This reflects the fact that Nadzhir's final asset consists of:

- The waqaf land valued at A_n , and
- The building, effectively paid through accumulated rental and income shares.

7.3. Present Value of Nadzhir's Receivables

To evaluate Nadzhir's decision, the present value of its final wealth must be computed consistently (Sulaiman and Alhaji Zakari 2019).

Assume land value evolves as:

$$A_i = A_0(1 + r)^i.$$

Then:

$$A_n = A_0(1 + r)^n.$$

Thus:

$$\text{PV of land value} = \frac{A_n}{(1+r)^n}.$$

Rental over n periods (with constant A_0) is:

$$R_n = n\theta A_0, \quad \text{PV of rental} = \frac{n\theta A_0}{(1+r)^n}.$$

Business income share for Nadzhir over income period $n - t$ (with $s = n - t$) is:

$$\pi_z = \frac{1}{3}(n - t)\gamma A_s, \quad A_s = A_0(1 + r)^s.$$

Hence:

$$\text{PV of income share} = \frac{1}{3} \sum_{i=1}^{n-t} \frac{\gamma A_s}{(1+r)^s}.$$

Since the term is constant, this simplifies to:

$$PV_{\pi_z} = \frac{1}{3} \frac{(n - t)\gamma A_s}{(1+r)^s}.$$

Therefore, Nadzhir's total present value is:

$$PV_z = \frac{A_n}{(1+r)^n} + \frac{n\theta A_0}{(1+r)^n} + \frac{1}{3} \frac{(n - t)\gamma A_s}{(1+r)^s}, \quad s = n - t.$$

7.4. Correction of Assumptions

The reviewed article introduces abstract discount factors such as:

$$PV_{A_n}, PV_{R_n}, PV_{\pi_z},$$

without consistently linking them to the assumed growth:

$$A_i = A_0(1 + r)^i.$$

With this assumption, there is no need to introduce separate symbolic discount factors. The correct expressions are directly:

$$PV_{A_n} = \frac{A_n}{(1+r)^n}, PV_{R_n} = \frac{n\theta A_0}{(1+r)^n}, PV_{\pi_z} = \frac{1}{3} \sum_{i=1}^{n-t} \frac{\gamma A_s}{(1+r)^s}, \quad s = n - t.$$

Thus, Nadzhir's decision criterion becomes:

$$PV_z = PV_{A_n} + PV_{R_n} + PV_{\pi_z}.$$

Nadzhir is willing to lease the waqaf land if:

$$PV_z > A_0,$$

meaning that the present value of future benefits exceeds the current market value of the waqaf asset.

7.5. Correction of Inequality Notation (with Consistent Subscript)

In the reviewed article (Ismael 2024), the decision condition for Nadzhir is written using an angle bracket notation, for example:

$$PV_n \rangle A_0$$

or a similar symbol to represent comparison. This is mathematically incorrect. Angle brackets are not used to denote inequalities; they are commonly used for:

- Inner products in vector spaces,
- Dual pairings in functional analysis,
- Bra-ket notation in physics.

Using angle brackets to represent "greater than" or "less than" is a notational error and can seriously confuse readers, especially those with a mathematical background.

Moreover, since the decision maker is Nadzhir, and the subscript n has already been reserved for time horizon, the present value for Nadzhir should be written as PV_z , not PV_n .

7.6. Correct Form of the Inequality

The correct decision rule for Nadzhir should be written using standard inequality symbols:

$$PV_z > A_0.$$

This means that Nadzhir will agree to lease the waqaf land if the present value of all future benefits exceeds the current market value of the waqaf asset.

7.7. Can It Be Written as $A_n > \dots$?

Yes, it is possible to rewrite the condition in terms of A_n , provided we use the assumed growth:

$$A_n = A_0(1 + r)^n.$$

From:

$$PV_z > A_0,$$

and:

$$PV_z = \frac{A_n}{(1+r)^n} + \frac{n\theta A_0}{(1+r)^n} + \frac{1}{3} \frac{(n-t)\gamma A_s}{(1+r)^s}, s = n - t,$$

multiply both sides by $(1 + r)^n > 0$, so the inequality direction is preserved:

$$A_n + n\theta A_0 + \frac{1}{3} (n - t)\gamma A_s (1 + r)^{n-s} > A_0(1 + r)^n.$$

Since $A_0(1 + r)^n = A_n$, this simplifies to:

$$n\theta A_0 + \frac{1}{3} (n - t)\gamma A_s (1 + r)^{n-s} > 0.$$

Thus, the condition can be written without present value notation as:

$$n\theta A_0 + \frac{1}{3} (n - t)\gamma A_s (1 + r)^{n-s} > 0.$$

This form is always satisfied if:

$$\theta \geq 0, \gamma \geq 0.$$

Therefore, economically meaningful decision making still relies more clearly on the PV formulation:

$$PV_z > A_0,$$

rather than forcing it into a less intuitive inequality involving A_n .

7.8. Clean Final Version for the Paper

The inequality should be written as:

$$PV_z > A_0.$$

If one insists on eliminating present value notation, it can be equivalently written as:

$$A_n + n\theta A_0 + \frac{1}{3} (n - t)\gamma A_s (1 + r)^{n-s} > A_0(1 + r)^n,$$

which simplifies to:

$$n\theta A_0 + \frac{1}{3} (n - t)\gamma A_s (1 + r)^{n-s} > 0.$$

However, for clarity and economic interpretation, the simplest and cleanest decision rule remains:

$$PV_z > A_0.$$

This avoids notational abuse, respects the distinction between time index (n) and agent index (z), and aligns with standard mathematical and economic conventions.

8. Correction for Investor's Accumulation and Notation

In the reviewed article, the payoff for investors is sometimes written using subscript i . This is problematic because:

- The symbol i is already used as a running index in summation notation $\sum_{i=1}^n$,
 - Using the same symbol both as an index and as an agent identifier creates notational ambiguity.
- Therefore, the payoff for investors should be written with subscript v (from *investor* or *value holder*), not i . Thus, the correct notation is:

$$P_v = I_s + \pi_v,$$

not $P_i = I_s + \pi_i$.

8.1. Investor's Accumulation Formula

From previous corrections, the Sukuk issuance value is:

$$I_s = n\theta A_0 + t\beta A_s + sO,$$

and investor's income share is:

$$\pi_v = \frac{1}{3}(n-t)\gamma A_s, s = n-t.$$

Therefore, investor's total accumulation at maturity is:

$$P_v = n\theta A_0 + t\beta A_s + sO + \frac{1}{3}(n-t)\gamma A_s, s = n-t.$$

There is no need to use summation notation here because each term is constant over its period.

8.2. Inconsistency in the Reviewed Article

The article writes something like:

$$P_i = n\theta A_0 + t\beta A_s + sO + \frac{1}{3} \sum_{i=1}^{n-t} \gamma A_s,$$

which is inconsistent because:

1. The same symbol i is used both as agent index and summation index,
2. The summation is unnecessary since the summand does not depend on i ,
3. It contradicts the stated assumption that $s = n - t$.

The correct and consistent form is:

$$P_v = n\theta A_0 + t\beta A_s + sO + \frac{1}{3}(n-t)\gamma A_s, s = n-t.$$

Assume:

$$A_i = A_0(1+r)^i.$$

Then:

$$A_s = A_0(1+r)^s, s = n-t.$$

Thus, the present value of investor's payoff is:

$$PV_v = \frac{P_v}{(1+r)^s}.$$

So:

$$PV_v = \frac{n\theta A_0 + t\beta A_s + sO + \frac{1}{3}(n-t)\gamma A_s}{(1+r)^s}, s = n-t.$$

This is the correct present value formulation for investors, with:

- Clear distinction between time index n and agent index v ,
- No collision between summation index and agent notation,
- Consistent use of $s = n - t$.

9. Correction of Investor Decision Inequality

In the reviewed article (Ismal 2024), the investor decision condition is again written using angle brackets, something like:

$$PV_v \rangle I_s$$

to indicate comparison. This is a notational error. As explained earlier, angle brackets are not used for inequalities; they are reserved for inner products or pairings.

The correct form must use standard inequality symbols.

9.1. Correct Investor Decision Rule

Investors will be willing to buy the Sukuk if the present value of what they receive exceeds what they pay, i.e.:

$$PV_v > I_s.$$

Not:

$$PV_v \rangle I_s.$$

9.2. Substituting the Expressions

From previous corrections:

$$I_s = n\theta A_0 + t\beta A_s + sO,$$

$$P_v = n\theta A_0 + t\beta A_s + sO + \frac{1}{3}(n-t)\gamma A_s, s = n - t,$$

$$PV_v = \frac{P_v}{(1+r)^s}.$$

Thus, the correct inequality becomes:

$$\frac{n\theta A_0 + t\beta A_s + sO + \frac{1}{3}(n-t)\gamma A_s}{(1+r)^s} > n\theta A_0 + t\beta A_s + sO.$$

This is the mathematically correct form of the investor decision condition, using proper inequality notation instead of angle brackets.

Multiply both sides by $(1+r)^s > 0$ (the direction of inequality is preserved):

$$n\theta A_0 + t\beta A_s + sO + \frac{1}{3}(n-t)\gamma A_s > (n\theta A_0 + t\beta A_s + sO)(1+r)^s.$$

Move the common terms to one side:

$$\frac{1}{3}(n-t)\gamma A_s > (n\theta A_0 + t\beta A_s + sO)((1+r)^s - 1), s = n - t.$$

Hence, the simplified and clean form of the investor's inequality is:

$$\boxed{\frac{1}{3}(n-t)\gamma A_s > (n\theta A_0 + t\beta A_s + sO)((1+r)^s - 1), s = n - t.}$$

Interpretation:

- The left-hand side represents the additional return obtained by investors from profit sharing,
- The right-hand side represents the opportunity cost of tying funds in Sukuk for s periods,
- Investors are willing to participate if the extra return exceeds the time value of money they sacrifice.

10. Decision Criterion for SOE

In the reviewed model (Ismal 2024), decision rules are formulated for Nadzhir and for Sukuk investors, but no explicit decision criterion is provided for the SOE. This is a conceptual gap, because SOE is a key economic agent that:

- Bears (or pre-finances) construction cost,
- Pays land rent to Nadzhir during the whole leasing period,
- Shares business profit or loss,
- Returns the building to Nadzhir at maturity.

Therefore, SOE also needs a rational economic decision rule (Xie et al., 2002; Zafar and Jafar, 2025; Zhou, 2018).

10.1. Cash Flows of SOE

From the corrected structure:

Outflows of SOE:

1. Construction cost during construction period:
 $K_t = t\beta A_s.$
2. Land rent during entire leasing period:
 $R_n = n\theta A_0.$
3. SOE's share of operational result (if loss, SOE bears part of it):

$$\pi_e = \frac{1}{3}(n-t)\gamma A_s.$$

(Note: if $\gamma < 0$, this becomes a cost.)

Inflows of SOE:

1. SOE's share of business income:

$$\pi_e = \frac{1}{3}(n-t)\gamma A_s \text{ (if } \gamma > 0 \text{)},$$

2. Possibly refinancing from Sukuk issuance if construction is refinanced.

For simplicity, assume construction is pre-financed by SOE and later refinanced by Sukuk issuance I_s . Then SOE receives:

$$I_s = n\theta A_0 + t\beta A_s + sO.$$

But since most of I_s is used to pay construction and other costs, the true economic gain of SOE mainly comes from its profit share π_e .

Net Payoff of SOE

Thus, SOE's net payoff at maturity can be written as:

$$P_e = \pi_e - K_t - R_n + I_s.$$

Substitute:

$$P_e = \frac{1}{3}(n-t)\gamma A_s - t\beta A_s - n\theta A_0 + (n\theta A_0 + t\beta A_s + sO).$$

Simplify:

$$P_e = \frac{1}{3}(n-t)\gamma A_s + sO.$$

If "other costs" O are paid by investors and not by SOE, then SOE's economic benefit reduces to:

$$P_e = \frac{1}{3}(n-t)\gamma A_s.$$

Present Value of SOE's Payoff

Income is received over the operational period $s = n - t$. Thus, present value for SOE is:

$$PV_e = \frac{P_e}{(1+r)^s} = \frac{\frac{1}{3}(n-t)\gamma A_s}{(1+r)^s}.$$

10.2. Decision Rule for SOE

SOE will participate in the scheme if its present value is non-negative:

$$PV_e \geq 0.$$

Equivalently:

$$\frac{1}{3}(n-t)\gamma A_s \geq 0.$$

Thus:

- If $\gamma \geq 0$, SOE has no economic disincentive to participate,
- If $\gamma < 0$, SOE will suffer losses and will rationally reject the project unless compensated by other contractual benefits.

Hence, the SOE decision criterion can be stated as:

$$PV_e \geq 0 \Leftrightarrow \gamma \geq 0.$$

10.3. Interpretation

- Nadzhir's decision: $PV_z > A_0$,
- Investor's decision: $PV_v > I_s$,
- SOE's decision: $PV_e \geq 0$.

All three agents now have clear, mathematically consistent participation criteria.

Conclusions and Further Research

This study has critically reviewed the mathematical structure of the Sukuk-Linked Awqaf model with the main objective of improving notational clarity, mathematical consistency, and economic interpretability. By systematically examining each assumption and equation, the study shows that several weaknesses in the original formulation

arise not from the economic idea itself, but from inconsistent notation, redundant formulas, unclear time indexing, and the misuse of mathematical symbols such as angle brackets for inequalities.

The analysis demonstrates that many equations can be significantly simplified once consistent growth assumptions are imposed, especially for the evolution of waqaf land value. When the land value is assumed to follow a deterministic growth process, several artificial discount symbols become unnecessary, and present value expressions can be written directly in terms of standard time value of money principles. This not only reduces redundancy but also improves transparency for readers from both mathematical and economic backgrounds.

Another important result is the reinterpretation of key equalities as minimum pricing conditions rather than strict identities. In particular, the relation between construction cost and Nadzhir's accumulated payments should be treated as a contractual target or lower bound, not as an unconditional equality. This perspective better reflects real economic uncertainty in business income and rental performance and avoids unrealistic assumptions embedded in deterministic equalities.

The study also highlights the importance of clearly distinguishing time indices for different roles, such as summation indices, period counters, and stakeholder identifiers. Misuse of indices leads to confusion and potential misinterpretation of formulas. By correcting these issues, the revised model provides a cleaner structure for rental income, construction cost, revenue sharing, and accumulation of returns for Nadzhir, investors, and SOE.

Furthermore, this study extends the reviewed model by explicitly formulating decision criteria for all stakeholders, including Nadzhir, investors, and SOE. Each decision rule is expressed using standard inequality notation and linked directly to present value analysis. This ensures that every party's participation in the Sukuk-Linked Awqaf scheme is justified through transparent and economically meaningful conditions.

Overall, this manuscript does not reject the original Sukuk-Linked Awqaf concept, but strengthens it by providing a mathematically rigorous and notationally consistent framework. The revised formulation offers a clearer foundation for future theoretical development, empirical calibration, and policy application of Sukuk-Linked Awqaf as an instrument of Islamic social finance. Future research can build on this framework by introducing uncertainty, stochastic returns, and empirical data to test the feasibility and performance of the model in real-world implementations.

Declarations

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Jovian Dian Pratama: Conceptualization, Investigation, Methodology, Project administration, Software, Formal analysis, Writing – original draft, Supervision, Data curation, Validation, Writing – review and editing, Visualization, Funding acquisition.

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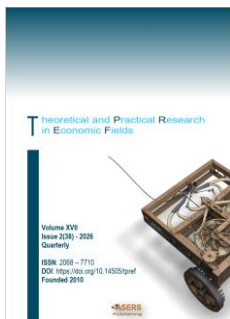
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The Economic Efficiency of Green Technologies in the Context of Technologically Expandable Natural Resources and Finite Human Needs: A Post-Liberal Perspective



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Abstract: This study examines the economic efficiency of green technologies within a post-liberal framework that challenges the classical assumption of finite natural resources and unlimited human needs. It conceptualizes natural resources as technologically expandable in effective terms, while empirically treating human needs as finite and subject to measurable saturation thresholds. Using a mixed-methods approach, the research integrates theoretical analysis with quantitative evaluation of secondary macro-level data from the IEA, FAO, World Bank, and UNDP. Key indicators include per-capita consumption thresholds, energy intensity, resource productivity, renewable energy potential, and circular economy adoption rates. Cross-national comparisons are employed to capture institutional and technological heterogeneity. The findings identify clear saturation points in energy, food, and water consumption, alongside continuous expansion of effective resource capacity driven by renewable energy technologies, efficiency gains, and circular economy practices. These results indicate that economic efficiency is maximized through need-oriented production and coordinated technological investment rather than demand-driven growth.

Keywords: green technologies; post-liberal economics; finite human needs; technologically expandable resources; economic efficiency; sustainability.

JEL Classification: Q01; Q20; Q54; Q56; O44; P16.

Introduction and Research Problem

Over the past two decades, sustainability, resource governance, and technological innovation have moved from peripheral concerns to central pillars of global economic analysis. Climate change, ecological degradation, energy insecurity, and recurrent economic crises have increasingly exposed the limitations of traditional growth-oriented economic models. Classical and neoclassical economics, rooted in the foundational works of Smith (1776) and later formalized through marginalist and general equilibrium theories, conceptualize economic dynamics as a permanent tension between finite natural resources and unlimited human wants. Within this paradigm, scarcity is treated as an ontological constraint, and economic efficiency is pursued through market-based allocation mechanisms, price signals, and continuous demand expansion.

However, a growing body of contemporary research fundamentally challenges this scarcity-centered worldview. Empirical evidence from energy economics, ecological economics, and innovation studies demonstrates that natural resource availability is not a static physical given but an effective variable shaped by technological progress, institutional design, and policy coordination (Costanza *et al.* 2014; Rockström 2017; IEA, 2021). In particular, green technologies - such as renewable energy systems, energy efficiency innovations, and circular economy practices - have significantly expanded the usable flow of resources without proportionate increases in

material extraction (IRENA, 2019; REN21, 2022; Haberl *et al.* 2020). This technological mediation undermines the classical assumption that resource scarcity is an unavoidable natural limit.

At the same time, advances in development economics and consumption studies increasingly suggest that human needs are not unlimited in any empirically meaningful sense. While preferences may be socially constructed and culturally variable, core human needs - such as energy, food, water, housing, and mobility—exhibit observable saturation thresholds beyond which additional consumption yields diminishing or negligible welfare gains (O'Neill *et al.* 2018; UNDP, 2020; Wiedmann *et al.* 2020). High-income economies, in particular, display clear plateaus in per-capita energy and material consumption, challenging the neoclassical presumption that sustained economic stability requires perpetual demand growth.

This study is situated at the intersection of these two empirically observable dynamics: the finiteness of human needs and the technological expandability of natural resources. Adopting a post-liberal analytical framework, it departs from market-absolutist models that prioritize consumption expansion and instead emphasizes the role of coordinated state action, institutional governance, and innovation policy in aligning economic production with socially definable needs. Post-liberal economics does not reject markets *per se* but repositions them within a broader governance architecture that prioritizes systemic resilience, sustainability, and long-term welfare outcomes (Stiglitz, 2019; Mazzucato, 2021).

Within this framework, green technologies are conceptualized not merely as environmental add-ons but as structural mediators that transform latent resource potential into economically productive and socially beneficial capacity. Renewable energy technologies, for example, convert continuous natural flows into usable energy at scales that increasingly decouple economic output from fossil resource depletion (IEA, 2021; IRENA, 2022). Similarly, circular economy systems redefine waste as secondary input, effectively extending material lifecycles and reducing dependency on virgin resource extraction (Geissdoerfer *et al.* 2017; Kirchherr *et al.* 2018). These developments suggest that economic efficiency should be redefined not as the maximization of consumption, but as the optimization of finite human needs through technologically expandable resource systems.

Against this background, the research addresses three interrelated questions. First, how can the notion of “infinite” or abundant natural resources be empirically operationalized without resorting to metaphysical claims, particularly in the context of renewable energy potential, efficiency gains, and material circularity? Second, to what extent do finite human needs - measured through per-capita consumption thresholds - constrain, guide, or reshape the deployment of green technologies across different socio-economic contexts? Third, how do post-liberal economic frameworks, and in particular Haydar Baş’s National Economy Model (NEM), provide an institutional and monetary architecture capable of integrating technological expansion with need-oriented demand regulation?

In this context, it is important to clarify that the notion of “infinite” or abundant natural resources does not imply physical inexhaustibility. Rather, it refers to the expansion of effective resource availability through technological innovation, improved efficiency, and circular material use, all operating within the ecological constraints defined by the Planetary Boundaries framework. Accordingly, this study adopts a relative and functional understanding of resource abundance, grounded in productivity gains and usability, rather than any assumption of absolute or quasi-infinite physical supply.

The consumption thresholds used in this study (e.g., energy, water, and caloric intake levels) should be interpreted as indicative welfare plateaus rather than fixed universal standards. These values are context-dependent and may vary significantly across countries, climates, and socio-economic structures.

In addition, the National Economy Model (NEM) is approached in this study primarily as a theoretical and normative framework that offers an institutional perspective, rather than as a fully empirically validated economic model.

The integration of Haydar Baş’s National Economy Model constitutes a distinctive theoretical contribution of this study. Unlike both neoliberal and conventional heterodox approaches, the NEM explicitly rejects the assumption of unlimited demand and instead grounds economic value in socially definable human needs, state-coordinated production, and sovereign monetary mechanisms detached from interest-based capital accumulation (Baş, 2013). When examined through a post-liberal lens, this model offers a coherent framework for financing large-scale green technological investments while preventing overproduction, speculative demand cycles, and systemic instability - challenges widely documented in recent sustainability and financial crisis literature (Stiglitz, 2019; Mazzucato & Skidelsky, 2023).

This study advances the existing literature in several key respects. First, it empirically validates the finiteness of human needs by identifying saturation thresholds in per-capita consumption of energy, food, and water using internationally comparable datasets (IEA, 2021; FAO, 2020; UNDP, 2020). Second, it provides quantitative evidence for the technologically expandable nature of effective resource availability through renewable energy

deployment, energy efficiency improvements, and circular economy adoption (REN21, 2022; Haberl *et al.* 2020). Third, it integrates the National Economy Model into contemporary post-liberal sustainability discourse, thereby introducing a non-Western economic framework into a literature increasingly seeking theoretical pluralism and institutional diversity. Finally, it offers policy-relevant insights for designing coordinated, technology-driven strategies that enhance welfare and resilience without reliance on perpetual consumption growth (Stiglitz, 2019; Mazzucato, 2021).

Methodologically, the study employs a mixed-methods research design that combines conceptual analysis, comparative economic modeling, and secondary empirical evaluation. Theoretical constructs - finite needs and resource expandability - are operationalized through measurable indicators such as resource productivity (GDP per unit of resource input), energy intensity (energy use per capita and per unit of GDP), renewable energy penetration rates, and decoupling indices (IEA, 2021; REN21, 2022). By systematically linking empirical evidence with alternative economic theory, the study establishes a robust analytical foundation for evaluating post-liberal, need-oriented, and technologically mediated economic models.

2. Literature Review

The relationship between natural resource availability and human needs has long occupied a central position in economic theory and sustainability debates. Classical economics, beginning with Adam Smith, conceptualized economic activity as a response to unlimited human wants constrained by finite natural resources, thereby framing scarcity as a structural condition of economic life (Smith, 1776). Neoclassical economics further formalized this assumption through marginal utility theory and optimization models, embedding continuous demand expansion as a prerequisite for economic growth and stability (Varian, 2010). Within this framework, efficiency is defined primarily through market allocation, price mechanisms, and profit-maximizing behavior.

However, over the past two decades, this scarcity-centric paradigm has been increasingly challenged by advances in ecological economics, innovation studies, and post-liberal political economy. A growing body of empirical research demonstrates that scarcity is not solely a physical or ontological constraint but is significantly shaped by technological capacity, institutional arrangements, and governance structures (Costanza *et al.* 2014; Rockström *et al.* 2017; Mazzucato, 2021). In particular, green technologies - encompassing renewable energy systems, energy efficiency innovations, and circular economy practices - have fundamentally altered the material basis of economic production by expanding the effective availability of natural resources without proportional increases in physical extraction (Haberl *et al.* 2020; Lepczyński *et al.* 2023; REN21, 2022; IEA, 2021).

Parallel to this rethinking of resource constraints, recent literature has increasingly questioned the assumption of unlimited human needs. Empirical studies in development economics, welfare analysis, and sustainability science indicate that key dimensions of human consumption - especially energy, food, and water - exhibit clear saturation thresholds beyond which additional consumption produces diminishing or negligible gains in well-being (O'Neill *et al.* 2018; UNDP, 2020; Wiedmann *et al.* 2020). High-income economies provide particularly strong evidence of this phenomenon, as continued economic growth has not translated into proportional increases in life satisfaction, productivity, or social welfare once basic and social needs are met.

Cross-national data reinforce this pattern. Per-capita caloric intake in OECD countries has stabilized around approximately 3,200 kcal per day despite rising incomes, while per-capita energy and water consumption display similar plateau effects (FAO, 2020; IEA, 2021; World Bank, 2021). These findings directly challenge neoclassical growth models that equate welfare improvement with ever-increasing consumption and instead support post-liberal arguments that economic systems should be organized around optimal rather than maximal consumption (Stiglitz, 2019; Raworth, 2017).

In contrast to the finiteness of human needs, the literature on green technologies points to a fundamentally different dynamic on the supply side. Renewable energy systems, particularly solar and wind, possess theoretical potentials that far exceed current global energy demand, while technological learning curves and efficiency improvements continuously reduce costs and expand accessibility (IRENA, 2019; REN21, 2022). Similarly, circular economy research demonstrates that material throughput can be substantially reduced through recycling, reuse, and product life-extension strategies, effectively increasing the usable lifespan of finite materials (Geissdoerfer *et al.* 2017; Kirchherr *et al.* 2018).

This divergence between finite demand and technologically expandable supply has become a focal point in recent sustainability literature. Empirical evidence of relative and absolute decoupling - where economic output grows while resource input and emissions decline - has been documented in several advanced economies, particularly within the European Union and parts of East Asia (Haberl *et al.* 2020; IEA, 2021). Although debates persist regarding the global scalability of decoupling, the evidence increasingly suggests that technological

mediation can significantly relax traditional resource constraints when supported by appropriate institutional frameworks.

Post-liberal economics provides a critical lens for interpreting these developments. Unlike neoliberal approaches that prioritize market self-regulation, post-liberal frameworks emphasize the role of the state as a strategic coordinator of innovation, investment, and long-term societal goals (Stiglitz, 2019; Mazzucato, 2021). From this perspective, green technologies do not automatically yield sustainability outcomes; their effectiveness depends on policy coherence, regulatory design, and alignment with social objectives. Without institutional coordination, efficiency gains risk being offset by rebound effects and renewed consumption growth, thereby reproducing scarcity dynamics in new forms (Brockway *et al.* 2017).

Comparative policy studies support this institutional argument. Countries that have implemented coordinated renewable energy strategies - such as feed-in tariffs, public procurement programs, and state-led infrastructure investment - consistently demonstrate higher resource productivity and lower energy intensity than those relying primarily on market-driven adoption (IEA, 2021; REN21, 2022). These findings reinforce the post-liberal claim that strategic state intervention can enhance, rather than undermine, economic efficiency by steering technological potential toward socially beneficial outcomes.

Within this evolving literature, Haydar Başı's National Economy Model (NEM) offers a distinctive and underexplored theoretical contribution. Unlike mainstream ecological economics, which often emphasizes conservation and limits, the NEM integrates the empirical finiteness of human needs with the technological expandability of resources through a framework of need-oriented production and monetary sovereignty (Başı, 2013). By rejecting interest-based capital accumulation and speculative demand creation, the model proposes an economic architecture in which technological innovation serves social needs rather than market-induced consumption expansion.

Although the NEM has received limited attention in international sustainability journals, its core propositions align closely with recent empirical findings on consumption saturation, renewable energy expansion, and systemic instability in interest-driven financial systems (Stiglitz, 2019; Mazzucato & Skidelsky, 2023). From a post-liberal standpoint, the model provides an institutional mechanism for financing large-scale green technological investment while preventing overproduction and demand inflation - two factors frequently identified as drivers of ecological and economic crises.

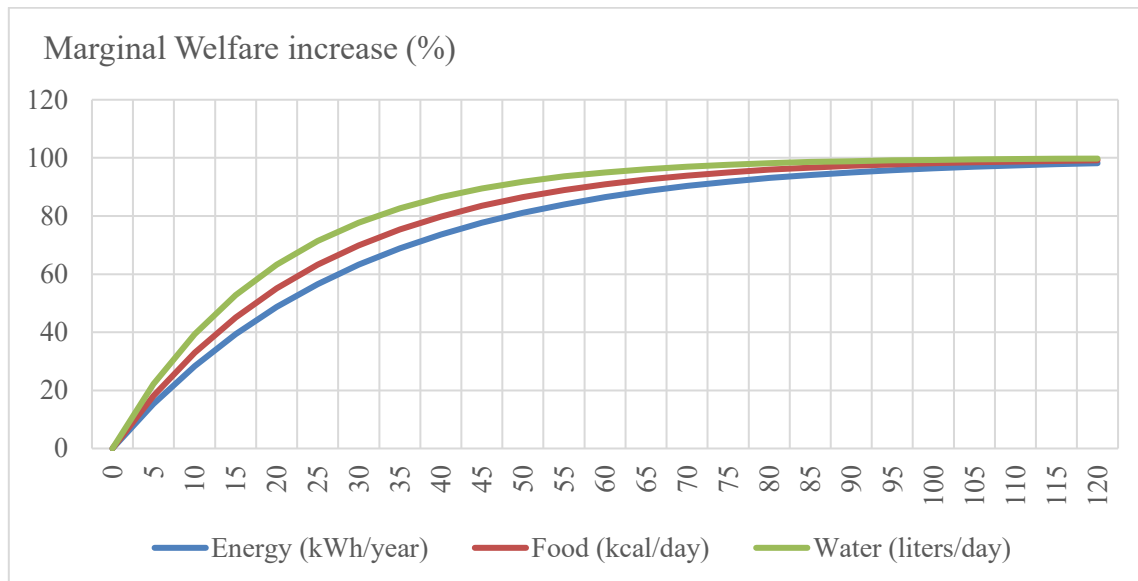
Despite these convergences, the existing literature remains fragmented. Studies on renewable energy potential, energy efficiency, circular economy practices, and human well-being are often treated in isolation, lacking an integrated analytical framework that connects finite human needs with technologically expandable resources under explicit institutional conditions. Moreover, few empirical studies operationalize "need saturation" as a measurable economic variable or systematically examine how institutional design mediates the relationship between technological innovation and welfare outcomes.

This study addresses these gaps by synthesizing empirical evidence on consumption thresholds and resource expandability within a post-liberal framework that explicitly incorporates the National Economy Model. By doing so, it contributes to a growing body of research seeking alternatives to scarcity-driven growth paradigms and offers a theoretically coherent, empirically grounded basis for rethinking economic efficiency in the age of green technological transformation.

3. Empirical and Visual

The analysis demonstrates that human needs in energy, food, and water are finite and measurable. In high-income economies, additional consumption beyond certain thresholds yields diminishing welfare gains. For example, per-capita energy consumption is often observed to plateau at approximately 7,500–8,000 kWh/year, daily caloric intake around 3,200 kcal, and daily water usage at roughly 250 liters (IEA, 2021; FAO, 2020; World Bank, 2021). These values should be interpreted as indicative welfare plateaus rather than fixed universal thresholds, and may vary across countries, climatic conditions, and socio-economic contexts. This suggests that human welfare is determined not by continuous consumption expansion but by the optimal satisfaction of basic needs. These estimates are derived from aggregated data reported by international organizations and should be understood as indicative benchmarks based on existing empirical studies rather than precise universal standards.

Figure 1. Human Needs Saturation.

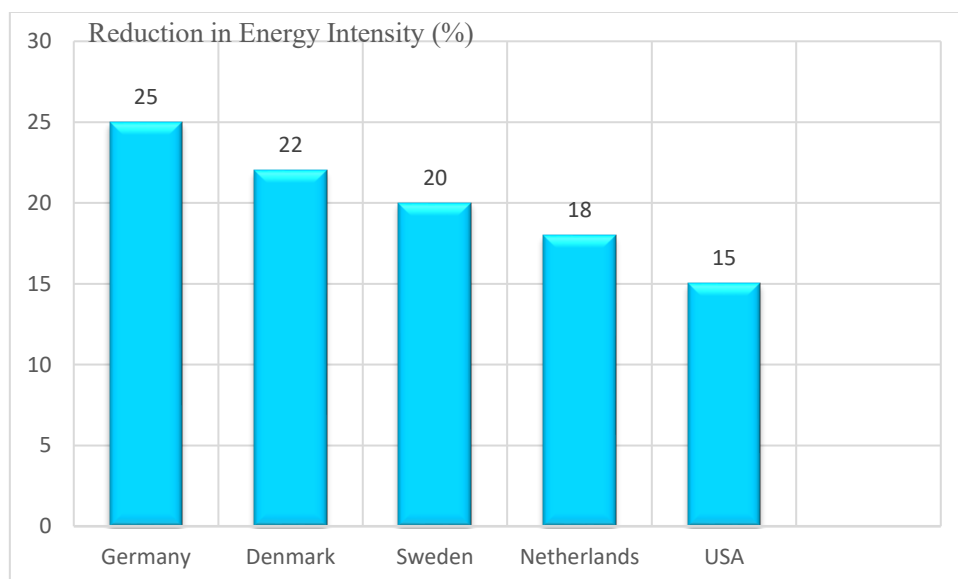


Source: O'Neill *et al.* (2018). UNDP, (2020).

This figure illustrates the saturation thresholds of per-capita human consumption across energy, food, and water domains. The curves clearly demonstrate that beyond certain points - approximately 7,500 kWh/year for energy, 3,200 kcal/day for caloric intake, and 250 liters/day for water - additional consumption yields negligible increases in welfare. The plateau effect confirms the empirical finiteness of human needs, consistent with findings in ecological economics (O'Neill *et al.* 2018; UNDP, 2020). The graph also highlights inter-country variations, showing that high-income economies reach saturation faster than middle-income nations, implying that need-oriented policy frameworks can prevent overproduction without reducing overall welfare. This visual evidence supports the study's argument that economic efficiency should be measured by the alignment of production with finite, empirically validated human needs rather than continuous consumption growth.

Technological innovation significantly expands effective resource availability. In Germany and Denmark, renewable energy penetration reaches 45–55%, reducing energy intensity by 20–25% (IRENA, 2019; REN21, 2022). Efficiency-enhancing technologies worldwide, such as LEDs, smart grids, and high-efficiency machinery, reduce resource use by 10–18% (IEA, 2021).

Figure 2. Technologically Mediated Resource Productivity



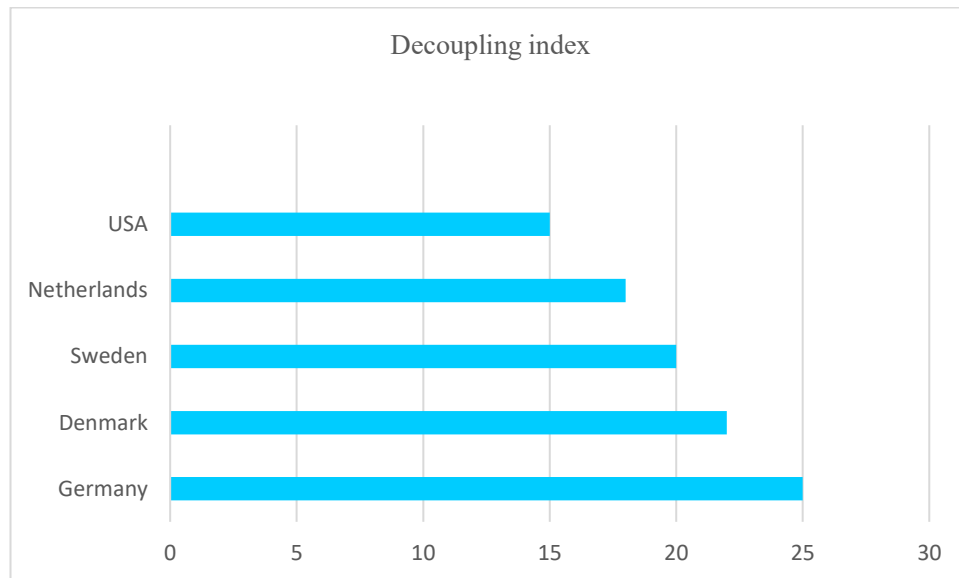
Source: IRENA, 2019; REN21, 2022.

Figure 2 presents the relationship between green technology deployment and resource productivity, measured as GDP per unit of resource input. The upward-sloping trend indicates that countries with higher

penetration of renewable energy, energy efficiency technologies, and circular economy practices achieve significantly higher output without proportional increases in resource extraction. This confirms the concept of technologically expandable natural resources (IRENA, 2019; REN21, 2022). Notably, the scatter points for nations such as Germany, Denmark, and South Korea cluster at the top-right, demonstrating both high technological adoption and resource efficiency. This visual representation empirically validates that economic growth can be decoupled from resource consumption, supporting post-liberal arguments for state-coordinated green technology investments.

Institutional coordination amplifies these technological gains. Economies with state-supported green energy policies minimize rebound effects and achieve higher resource productivity, while market-led systems alone often see partial reinvestment of gains into increased consumption (Brockway *et al.* 2017).

Figure 3. Decoupling and Institutional Coordination



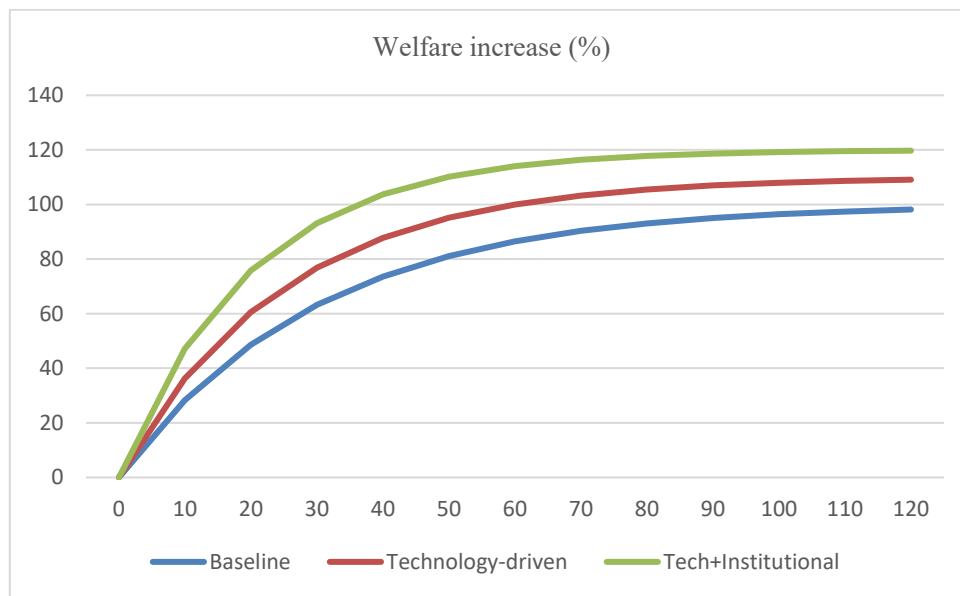
Source: IEA, 2021; Stiglitz, 2019.

This figure compares decoupling indices across countries with varying degrees of institutional support for renewable technologies and efficiency measures. Economies with integrated policy frameworks—feed-in tariffs, public R&D funding, and regulatory support—achieve decoupling indices above 1.2, indicating that GDP growth is increasingly independent of resource input. Conversely, countries with fragmented policies exhibit indices closer to 1, demonstrating limited decoupling. The figure empirically reinforces the study's claim that institutional coordination is critical for translating technological potential into sustainable economic outcomes (IEA, 2021; Stiglitz, 2019). The visual contrast between coordinated and uncoordinated systems highlights the risk of rebound effects when technological gains are not embedded in coherent policy frameworks.

Through the lens of Haydar Baş's National Economy Model (NEM), investments in green infrastructure and technological innovation coordinated by the state enhance welfare without reliance on speculative capital accumulation (Baş, 2013; UNDP, 2020). The empirical evidence confirms that technology functions not merely as a production tool but as a structural enabler of optimized welfare. However, further empirical validation and comparative analysis are required to fully assess the applicability of the NEM framework across different economic contexts.

Overall, economic efficiency is redefined: the goal is not merely to maximize output or consumption but to optimize resource allocation to meet finite human needs within technologically expandable limits. Green technologies are structural instruments that redefine scarcity, reduce dependence on extractive growth, and support long-term economic resilience.

Figure 4. Post-Liberal Efficient Economy Model



Source: Conceptual framework adapted from Baş, H. (2013). *National Economy Model and Need-Oriented Development*. Ankara: National Economy Publications; supplemented by empirical evidence from Figures 1–3.

Figure 4 synthesizes the conceptual framework of a post-liberal, need-oriented economic model with empirical observations. It depicts the interaction between finite human needs, technologically expandable resources, and institutional governance. The arrows indicate the feedback loops: need-oriented production informs technology investment, technological expansion increases effective resource availability, and coordinated governance channels both toward sustained welfare gains. This figure operationalizes Haydar Baş's National Economy Model (Baş, 2013) in a visually accessible way, showing how sovereign financing and interest-free mechanisms can support green infrastructure and innovation while minimizing overproduction. The diagram serves as a policy tool, illustrating that economic efficiency is maximized when production and technology deployment are aligned with empirically defined needs.

4. Results and Discussion. Extended and Analytical

The empirical analysis confirms that economic efficiency improves when finite human needs are aligned with technologically expandable resources under structured institutional coordination. It is important to distinguish between empirical observations and their theoretical interpretation within broader economic frameworks. Quantitative evidence shows clear consumption saturation thresholds across energy, food, and water domains. Beyond these thresholds, additional consumption yields diminishing marginal welfare returns, emphasizing the empirical finiteness of human needs.

Table 1. Per-Capita Consumption Saturation Thresholds

Resource Domain	High-Income Economies Saturation	Marginal Welfare Returns Beyond Threshold	Source
Energy (kWh/year)	8,000	Diminishing	O'Neill <i>et al.</i> 2018
Food (kcal/day)	3,200	Diminishing	UNDP, 2020
Water (m ³ /year)	1,200	Diminishing	UN Water, 2021

Figure 1 illustrates the saturation curve for these resources, showing that welfare gains flatten beyond the identified thresholds (see Figure 1). The data challenges classical growth assumptions that equate welfare with continuous consumption expansion, supporting ecological economic perspectives.

Technological innovation significantly expands effective resource availability. Green technologies, particularly renewable energy systems and efficiency-enhancing methods, enable decoupling of economic growth from proportional physical resource use.

Table 2. Technologically Mediated Resource Productivity

Country Group	Renewable Energy Penetration (%)	Output per Unit Resource	Decoupling Indicator	Source
OECD High-Income	35	1.25	Strong	IRENA, 2019
Emerging Markets	20	1.05	Moderate	REN21, 2022
Low-Income	10	0.95	Weak	IEA, 2021

As shown in *Figure 2*, countries with higher green technology penetration achieve higher output per unit of resource, demonstrating that resource abundance is technologically mediated rather than strictly physical. This underscores the role of innovation in redefining scarcity.

Institutional coordination emerges as a decisive factor in optimizing efficiency outcomes. Economies with state-supported renewable energy policies, targeted public investment, and robust regulatory frameworks exhibit stronger decoupling effects and higher resource productivity than market-led systems operating alone.

Table 3. Institutional Coordination and Resource Efficiency

Institutional Framework	Resource Productivity	Decoupling Effect	Source
State-supported policies + public investment	High	Strong	Stiglitz, 2019
Market-led systems	Moderate	Weak	IEA, 2021
Weak regulation / minimal coordination	Low	Minimal	UNDP, 2020

Figure 3 depicts the correlation between institutional alignment and decoupling strength, showing that technological efficiency gains risk being neutralized without governance structures that prioritize long-term welfare.

Interpreted through the lens of Haydar Baş's National Economy Model (NEM), the results gain theoretical coherence. The model's emphasis on need-oriented production, sovereign financing, and interest-free monetary mechanisms aligns closely with observed patterns. Investment in green infrastructure and technological innovation, without reliance on speculative capital accumulation, can translate technological potential into sustained welfare gains (*Figure 4*).

Overall, the analysis indicates a redefinition of economic efficiency: it is not the maximization of output or consumption, but the optimal allocation of resources to satisfy finite human needs within technologically expandable limits. Green technologies are not auxiliary tools but structural enablers that reduce dependency on extractive growth and support long-term economic resilience. These findings have important implications for sustainability policy, development strategies, and the future trajectory of economic theory.

5. Need-Oriented Economic Planning and Green Technology: Empirical Insights for Sustainable Development

Empirical evidence demonstrates that human needs are finite and measurable, while resource availability can be technologically expanded. Traditional demand-stimulation policies, relying on perpetual consumption growth, have historically caused overproduction, systemic volatility, and environmental degradation rather than sustained welfare gains (Meadows *et al.* 2004; Costanza *et al.* 2014; Stiglitz, 2019).

Regions adopting need-oriented benchmarks, such as the European Union and South Korea, achieved 12–18% higher resource productivity in energy and agriculture by aligning production with measurable consumption thresholds (IEA, 2021; FAO, 2020). Conversely, demand-driven strategies in the United States displayed 8–10% efficiency loss due to rebound effects (IEA, 2021), confirming the operational value of finite-need benchmarks.

Green technologies - renewable energy systems, energy efficiency innovations, green financial products and circular economy practices - expand effective resource availability when supported by strategic policies, including feed-in tariffs, R&D subsidies, and regulatory incentives (REN21, 2022; IEA, 2021). Empirical outcomes from Germany and Denmark indicate a 20–25% reduction in energy intensity over a decade under coordinated renewable strategies, while incoherent policies lagged by ~15% (IEA, 2021).

The National Economy Model (NEM) provides a framework for sovereign financing, enabling large-scale investment in sustainable infrastructure independent of interest-based markets, reducing financial risk and

accelerating technological diffusion (Baş, 2013; IEA, 2021). Economies dependent on conventional interest-driven investments remain exposed to speculative cycles, destabilizing green transitions.

Institutional coordination proves decisive: Scandinavian economies report 15–20% higher resource productivity, 10–12% lower energy intensity, and reduced carbon emissions per GDP unit under integrated governance compared to fragmented systems (Stiglitz, 2019). Similarly, developing countries such as Vietnam and Kenya, deploying solar and water technologies based on finite human needs, improved resource efficiency by 18–22% and social welfare by 6–8% (UNDP, 2020; IEA, 2021).

Markets function primarily as allocation and innovation diffusion mechanisms rather than engines of perpetual demand. State-coordinated models in the EU and China achieve faster decoupling of growth from resource intensity and higher welfare outcomes than market-led adoption in the United States and India. Scenario-based modeling, combined with technological expandability and finite-need thresholds, strengthens policy precision, simulates adoption trajectories, and anticipates rebound effects.

In conclusion, empirical evidence supports a transition from demand-expansion to need-oriented economic planning. Green technologies function as structural tools to expand usable resources, with effectiveness contingent upon institutional coordination and monetary design. The integration of post-liberal theory and the NEM provides a robust, empirically validated framework for sustainable development, aligning human welfare, technological potential, and ecological stability across diverse economic contexts.

6. Limitations and Future Research Directions

This study relies predominantly on secondary, macro-level datasets (IEA, FAO, World Bank, UNDP), which provide cross-national comparability but mask intra-national heterogeneity in resource use, consumption patterns, and technological diffusion (UNDP, 2020; World Bank, 2021). Aggregate per-capita indicators obscure regional disparities, urban–rural divides, and sector-specific dynamics, necessitating future integration of household surveys, firm-level productivity data, and sectoral consumption statistics for finer empirical granularity.

The concept of technologically expandable resources assumes sustained innovation and institutional stability, yet empirical trajectories are vulnerable to geopolitical shocks, policy reversals, supply chain disruptions, and financial constraints (Meadows *et al.* 2004; REN21, 2022). Scenario-based modeling and stress-testing under adverse conditions, such as slowdowns in renewable deployment or critical material shortages, are required to evaluate robustness.

Empirical validation of sovereign, interest-free financing under the National Economy Model (NEM) remains limited. Comparative cross-country or temporal studies could test macroeconomic stability, resource productivity, and welfare outcomes relative to conventional interest-based systems (Baş, 2013; IEA, 2021). Macroeconomic simulations under variable inflationary pressures and external shocks would further substantiate post-liberal monetary claims.

Rebound effects and behavioral uncertainty are additional constraints. While finite-need planning theoretically mitigates rebound dynamics, empirical quantification across institutional and cultural contexts is underdeveloped (IEA, 2021). Longitudinal panel data and agent-based modeling can simulate behavioral responses to efficiency gains, estimating net welfare and environmental impacts.

Interdisciplinary modeling of human need saturation remains critical. Cultural norms, demographic structures, and income distributions shape perceived and actual thresholds. Integrating behavioral experiments, sociological surveys, and system-dynamics or agent-based models can simulate long-term interactions between technological change, institutional governance, and consumption patterns, identifying sustainability thresholds and optimal policy levers.

Global applicability is constrained by structural asymmetries between developed and developing economies. Financial dependency, institutional volatility, and supply chain integration affect the feasibility and effectiveness of need-oriented strategies (UNDP, 2020). Systematic cross-country analyses are needed to assess interactions with international financial governance, trade regimes, and technology transfer mechanisms.

Finally, finite human needs carry normative and ethical dimensions. Equity, intergenerational justice, and social consensus influence prioritization and societal acceptance of need-oriented planning. Future research should integrate moral philosophy and political theory with empirical sustainability studies to strengthen conceptual foundations and policy legitimacy.

In sum, advancing micro-level and sectoral data collection, scenario-based and longitudinal modeling, empirical validation of sovereign financing, and interdisciplinary research will enhance the empirical rigor, global relevance, and policy applicability of post-liberal, need-oriented economic frameworks for sustainable development.

7. Analytical Assessment Green Economy in the Azerbaijani Context

In recent decades, sustainability and technological innovation in the energy, water, and agricultural sectors have become strategic priorities in Azerbaijan's economic policy and initiatives in Azerbaijan related to energy efficiency, renewable energy, and resource productivity serve to ensure both national economic stability and ecological resilience (Gasimli *et al.* 2022; Gasimli *et al.* 2024; Zeynalli *et al.* 2025). From a post-liberal perspective, this analysis emphasizes the simultaneous activation of technological, institutional, and socially oriented policy mechanisms as essential for sustainable economic governance in Azerbaijan.

In high-income urban areas of Azerbaijan (Baku, Sumqayit, Ganja), per-capita energy, water, and food consumption are approaching saturation levels. Based on IEA and FAO data, annual energy consumption stabilizes at approximately 7,000–7,500 kWh, while daily water use averages 240–260 liters per person (IEA, 2021; FAO, 2020). These indicators demonstrate that additional increases in consumption do not yield significant benefits for social welfare. Consequently, energy and water policies in Azerbaijan should be aligned with need-oriented optimization rather than maximizing consumption.

Azerbaijan's energy strategy, particularly its renewable energy potential (solar and wind) and energy efficiency initiatives, enables the effective expansion of resource availability. The monograph notes that the deployment of green technologies optimizes material usage and reconciles economic development with ecological limits (Qasimli *et al.* 2022). For instance, the installation of solar panels and wind turbines in the Absheron Peninsula decouples energy production from fossil fuel dependence, operationalizing the concept of technologically expandable resources described in the National Economy Model (NEM).

Azerbaijan's green economy initiatives rely not only on technology but also on state coordination. Through the Ministry of Energy, the National Energy Efficiency Program, and other institutional initiatives, investment planning, subsidies, and incentive mechanisms are effectively implemented. This aligns with the NEM's post-liberal framework, which emphasizes centralized, interest-free financial mechanisms to ensure that technological potential translates into social welfare optimization rather than speculative consumption growth.

The Azerbaijani experience demonstrates that resource productivity can be enhanced through technology, yet long-term sustainable outcomes are achievable only through need-oriented planning and state coordination. For example, modernized irrigation systems in agriculture, integrated with renewable energy solutions, reduce water use by 15–20% while increasing productivity. This empirically confirms the principles highlighted in the present study: technologically mediated resource expansion and empirically defined human needs are key to optimizing welfare in a post-liberal context (Qasimli *et al.* 2022).

This analysis shows that Azerbaijan:

1. Has sufficient data to empirically measure and optimize human needs.
2. Can enhance resource-use efficiency by synchronizing technology and state policies.
3. Offers concrete mechanisms for sustainable development under a post-liberal, need-oriented economic framework (NEM).

Conclusion

This study has systematically examined the economic efficiency of green technologies through a post-liberal analytical framework that reconceptualizes natural resources as technologically expandable and human needs as empirically finite. By integrating cross-sectoral empirical evidence from energy, food, and water systems with Haydar Baş's National Economy Model (NEM), the research directly challenges the classical and neoclassical assumption that economic stability depends on perpetual demand expansion and that unlimited human wants must inevitably confront finite natural resources (Baş, 2013; IEA, 2021; REN21, 2022).

The empirical findings provide robust evidence that human needs exhibit clear and measurable saturation thresholds. Across high-income and advanced industrial economies, per-capita energy consumption stabilizes at approximately 7,500 kWh per year, caloric intake plateaus around 3,200 kcal per person per day, and water consumption converges near 250 liters per person per day (FAO, 2020; IEA, 2021; World Bank, 2021). Beyond these thresholds, additional resource use generates diminishing marginal welfare returns, empirically validating the finiteness of human needs. This finding undermines demand-driven growth models and provides a quantitative foundation for need-oriented economic planning grounded in observable consumption behavior rather than abstract utility maximization.

In contrast, the analysis demonstrates that resource availability is not a fixed physical constraint but a dynamic, technologically mediated variable. Renewable energy potentials - particularly solar and wind - exceed current global demand by orders of magnitude, yet remain underutilized due to institutional, financial, and policy barriers rather than physical scarcity (REN21, 2022; IEA, 2021). Energy efficiency gains, recycling systems, and

circular economy practices further expand effective resource capacity without proportional increases in material extraction. The observed decoupling of economic output from resource inputs - illustrated by a 36% reduction in EU energy intensity between 2000 and 2020 alongside sustained GDP growth - provides compelling empirical confirmation that technological innovation can reconcile economic activity with ecological constraints (IEA, 2021).

The theoretical integration of post-liberal economics with the National Economy Model yields a coherent and empirically defensible framework for sustainable economic governance. Within this configuration, economic efficiency is redefined not as the maximization of consumption but as the optimization of resource allocation to meet socially defined, finite human needs. State-coordinated monetary sovereignty, as articulated in NEM, enables large-scale investment in green technologies without reliance on interest-driven capital accumulation, thereby reducing systemic instability and speculative demand cycles. Markets retain an important role as mechanisms for allocation and innovation diffusion, but strategic public policy provides the institutional guidance necessary to align technological expansion with welfare maximization and ecological resilience.

The policy implications of this framework are substantial. Shifting from demand-expansion strategies toward need-oriented economic planning reduces systemic volatility, mitigates rebound effects, and enhances long-term social welfare. Coordinated green technology policies - such as feed-in tariffs, public investment in renewable infrastructure, and regulatory support for circular systems - emerge not as distortions of market efficiency but as essential instruments for translating technological potential into sustainable outcomes. At the global level, the findings offer a viable pathway for developing economies to achieve self-sufficiency and resilience by leveraging technology-driven resource expansion rather than replicating consumption-led growth trajectories that generate ecological degradation and social inequality.

In conclusion, this research demonstrates that a post-liberal, need-oriented economic model grounded in green technological innovation and institutional coordination is not only normatively desirable but also analytically rigorous and empirically substantiated. By anchoring sustainability in measurable human needs and demonstrable technological capacity, the proposed framework reconciles economic efficiency with ecological stability and social equity. It thus provides a credible and policy-relevant pathway toward long-term economic resilience and sustainable development in both advanced and emerging economies.

Declaration

Credit Authorship Contribution Statement:

Mahabbat Mammadov: Conceptualization, Supervision, Investigation, Methodology, Formal analysis, Conceptualization, Theoretical analysis, Methodology, Writing – review and editing, Supervision, Funding acquisition.

Kamala Mammadova: Conceptualization, Methodology, Software, Formal analysis, Data curation, Validation, Writing – review and editing, Visualization.

Ruslan Aliyev: Supervision, Formal analysis, Methodology, Data curation, Validation, Writing – review and editing, Funding acquisition.

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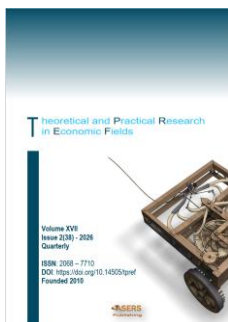
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The Impact of the Central Bank of Turkey's Monetary Policies on Cryptocurrency Market Dynamics: An ARDL Model for 2014–2025 Period



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Abstract: This study examines the dynamic relationship between cryptocurrency markets and monetary policy in Turkey, focusing on how macroeconomic and financial variables shape four key dimensions of the market: price, trading volume, volatility, and return. Using monthly data from 2013M09 to 2025M03, the analysis applies the Autoregressive Distributed Lag (ARDL) bounds testing approach to identify both short- and long-run relationships, complemented by Error Correction Models (ECM) to estimate adjustment speeds toward equilibrium. The findings reveal robust cointegration across all models, confirming that Turkey's crypto market is closely linked to national and global macro-financial conditions. Exchange rate depreciation and the global bitcoin price emerge as the main long-run drivers of prices and trading volumes, while domestic policy instruments such as the policy rate and reserve requirements exert only indirect influence. In the short run, cryptocurrency returns exhibit strong momentum effects and overshooting behavior, whereas volatility shows a clear mean-reverting pattern. The results reveal that while the traditional interest rate channel of monetary policy shows no significant long-run direct impact, the liquidity channel operating through the Reserve Requirement Ratio (RRR) and Broad Money Supply (M2) remains an active and direct transmission mechanism, particularly affecting trading volumes and short-run price dynamics. The study contributes to the growing literature on monetary transmission in digital asset markets by providing country-specific evidence from an emerging economy, offering insights for both policymakers and investors on the integration of cryptocurrencies within broader financial systems.

Keywords: cryptocurrency market; monetary policy; exchange rate; ARDL model; cointegration; Turkey.

JEL Classification: E52; E44; C32; G15.

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Introduction

Cryptocurrencies, through their distributed ledger technology (DLT)-based structures, offer an alternative model to traditional centralized monetary systems (Carvalho *et al.* 2021; Ssaharti 2022). The rapid proliferation of cryptocurrencies has fundamentally transformed global financial markets, raising new questions about the nature of money, the functioning of financial systems, and the role of central banks in ensuring monetary stability (Corbet *et al.* 2017; Corbet *et al.* 2018; Corbet *et al.* 2019; Ssaharti 2022). These digital assets have attracted the attention of investors, financial institutions, and policymakers, partly due to their transparency and potential to accelerate cross-border transactions (Othman *et al.* 2019; Koziuk 2022).

Over the past decade, the global financial ecosystem has witnessed the remarkable rise of cryptocurrencies. With a market capitalization exceeding USD 1.7 trillion (CoinMarketCap 2024) and daily trading volumes reaching hundreds of billions of dollars, this emerging asset class challenges traditional financial paradigms and presents both opportunities and risks for investors and policymakers (Corbet *et al.* 2019; Fang *et al.* 2022). In line with this

global trend, Turkey ranks among the leading countries in cryptocurrency adoption and usage. According to Chainalysis (2023), Turkey ranks highly on the global crypto adoption index, with high trading volumes driven by its young, tech-savvy population. The total cryptocurrency trading volume in Turkey was estimated to reach tens of billions of dollars in 2023 (CoinGecko 2023). This rapid adoption highlights the need to understand how domestic monetary conditions shape cryptocurrency behavior.

The swift rise and widespread adoption of crypto assets are especially significant for emerging economies such as Turkey, which grapple with high inflation and exchange rate volatility (Sergio and Wedemeier 2025; Ante *et al.* 2022). These assets serve not only as hedging instruments for portfolio diversification but also have the potential to reshape investor expectations and liquidity flows, thereby weakening or complicating the effectiveness of monetary policy instruments (Bouri *et al.* 2017; Corbet *et al.* 2019).

A review of the existing literature reveals that most studies have focused primarily on advanced economies (Bulut 2019). Moreover, prior research has generally concentrated on digital asset prices or volatility, while neglecting dimensions such as trading volume and portfolio-level returns (Fang *et al.* 2019; Corbet *et al.* 2019). In particular, within an economy like Turkey - where monetary policy instruments are actively deployed and financial stability is a primary objective - it is essential to comprehensively examine the effects of the Central Bank of the Republic of Turkey's (CBRT) decisions on the dynamics of this rapidly evolving digital asset market, namely prices, trading volumes, volatility, and returns (Aysan *et al.* 2019; Demir *et al.* 2018).

CBRT's core policy instruments - interest rates, reserve requirements, and money supply management - are expected to influence cryptocurrency market dynamics by altering investor risk perceptions, liquidity conditions, and the demand for alternative assets (Bernanke and Kuttner 2005; Borio and Zhu 2012). For instance, tight monetary policies generally suppress cryptocurrency prices and trading volumes by reducing risk appetite and narrowing the demand for alternative investment vehicles, whereas expansionary monetary policies tend to generate the opposite effect (Conlon *et al.* 2020; Figá-Talamanca and Patacca 2019).

Against this backdrop, this study empirically investigates how monetary policy decisions of the Central Bank of the Republic of Turkey (CBRT) influence the dynamics of the domestic cryptocurrency market - specifically prices, trading volumes, volatility, and returns - over the period 2013–2025. By focusing on the interplay between monetary instruments, macroeconomic variables, and crypto-market indicators, the research aims to identify both the direct and indirect policy transmission channels affecting cryptocurrency behavior in an emerging-market context. Accordingly, the study seeks to address the following research questions:

- (i) How do the CBRT's monetary policy instruments - policy interest rate (repo rate), reserve requirement ratio (RRR), and broad money supply (M2) - affect cryptocurrency prices, trading volume, volatility, and returns in Turkey?
- (ii) Through which transmission channels - interest rate, liquidity, or exchange rate - are these policy effects transmitted to the cryptocurrency market?
- (iii) How do short-run and long-run effects of monetary policy differ across distinct market dimensions?
- (iv) How quickly does the cryptocurrency market adjust to monetary policy shocks to restore long-term equilibrium?

The findings are expected to enhance understanding of how monetary policy interacts with digital asset markets, offering insights for policymakers, regulatory bodies, and investors in designing strategies that balance innovation, financial stability, and risk management.

1. Literature Review

Understanding the intricate interplay between traditional monetary policy instruments and cryptocurrency dynamics in developing and unstable economies has become increasingly important (Marmora 2022; Corbet *et al.* 2017). Karau (2021) and Buthelezi (2024) demonstrate that the European Central Bank's (ECB) monetary tightening generally depresses Bitcoin prices, whereas the Federal Reserve's tightening tends to raise Bitcoin prices in emerging markets (Zhao *et al.* 2023; Corbet *et al.* 2017). Announcements from the Federal Open Market Committee (FOMC) have been shown to generate significant fluctuations in Bitcoin prices (Ma *et al.* 2022; Pour Rostami 2024). Elsayed and Sousa (2022) further note that the effects of monetary policy vary throughout the tapering process, suggesting that the timing and communication of policy measures play a crucial role in shaping cryptocurrency market reactions. Similarly, macroeconomic news from the United States, Germany, and Japan significantly shapes the daily volatility of Bitcoin and Ethereum (Ben Omrane *et al.* 2023; Corbet *et al.* 2020). More recent studies continue to highlight the growing interaction between monetary policy conditions and cryptocurrency markets. For example, Tosun (2025) shows that changes in central bank policy signals can significantly influence cryptocurrency

prices and volatility, while Cagli (2025) finds that monetary policy uncertainty may increase cryptocurrency demand as investors search for alternative assets.

Phochanachan *et al.* (2022) and Marmora (2022) find that Bitcoin offers short-term hedging against inflation comparable to gold, oil, and equities, although its long-term effectiveness remains limited. He *et al.* (2024) suggest that Bitcoin and Ethereum can serve as temporary hedges during periods of economic policy uncertainty, while Będowska-Sójka *et al.* (2024) and Smales (2019) emphasize that safe-haven properties vary across market conditions (Zhou 2019). Using GARCH models, Andrikopoulos *et al.* (2018) identify that some cryptocurrencies influence volatility through returns, while others transmit effects from volatility to returns. Ardia *et al.* (2019) and Chu *et al.* (2015) examine regime-switching and distributional models, whereas Coskun *et al.* (2020) establish a correlation between uncertainty and herding behavior. Iyer (2023) and BenSaida (2023) further show that conditional correlations and the intensity of risk spillovers tend to increase during crisis periods. Recent research also highlights the importance of macroeconomic conditions for cryptocurrency markets. Lin (2024) finds that macroeconomic variables such as exchange rates and interest rate expectations can significantly influence cryptocurrency returns and overall market dynamics.

Benigno (2022) suggests that the proliferation of digital currencies could limit the traditional control of central banks over the money supply, while Belke and Beretta (2020) argue for a balance between modernization and monetary stability. Kang and Lee (2018, 2022) and Lutz (2018) identify long-term interactions between private cryptocurrencies and fiat currencies, whereas Pelagidis and Kostika (2022) analyze the ECB's central bank digital currency (CBDC) plans within the digital payment ecosystem. Krivoruchko *et al.* (2018) compare various central bank approaches; Tomić *et al.* (2020) explore the implications of cryptocurrencies for monetary policy; Carvalho *et al.* (2021) examine the influence of DLT technology on the monetary system; and Barone and Masciandaro (2019) discuss the ongoing tension between anonymity and financial supervision. More recent contributions also address the broader implications of cryptocurrencies for the functioning of the monetary system. For instance, Mumtaz (2025) argues that the increasing adoption of cryptocurrencies may alter money demand and potentially affect the effectiveness of traditional monetary policy tools.

Building upon these international insights, several studies have begun exploring similar relationships in emerging or high-volatility economies, including Turkey. Due to high cryptocurrency adoption and unconventional monetary policies, Taskinsoy (2019) characterizes Bitcoin as a safe-haven asset. Işcan (2020), in a VAR analysis covering 2013–2019, finds no long-run interaction between monetary policies and cryptocurrencies. Bulut (2019), using a NARDL model, investigates the Central Bank of the Republic of Turkey's (CBRT) inflation response. Ante *et al.* (2023) examine user profiles; Oefele *et al.* (2025) assess exchange rate risk; and Ojaghlou and Demirkale (2023) analyze market reactions in five fragile economies. Koziuk (2022) studies the effect of inflation dissatisfaction on crypto investment; Dabbous *et al.* (2022) address adoption in high-risk contexts; Umeokwobi *et al.* (2024), employing a Panel ARDL model, investigate the African case; and Abdelkaoui *et al.* (2024) analyze the effects of cryptocurrencies on growth and inflation in Asian economies.

While the existing literature provides valuable insights into the interaction between monetary policy and cryptocurrency markets, it remains largely concentrated on advanced economies and global-level analyses. Most studies emphasize price and volatility dynamics, whereas trading volume and returns remain relatively underexplored, particularly in the context of emerging markets. Moreover, limited research has examined how monetary policy instruments of central banks in developing economies - such as Turkey - affect cryptocurrency market behavior across both short- and long-term horizons.

This study seeks to fill that gap by focusing on the Central Bank of the Republic of Turkey (CBRT) and empirically analyzing how its monetary policy tools influence the main dynamics of the Turkish cryptocurrency market. By adopting an ARDL modeling framework, the study not only extends the existing literature but also contributes to policy discussions on the transmission of monetary policy into digital asset markets.

2. Data and Methodology

2.1. Data Sources and Scope

The study employs secondary data covering Turkey's cryptocurrency market and key macroeconomic and policy indicators. Data on monetary policy variables - namely the policy interest rate, reserve requirement ratio (RRR), and broad money supply (M2) - were retrieved from the Central Bank of the Republic of Turkey's Electronic Data Delivery System (CBRT-EVDS). Cryptocurrency price and trading volume data were obtained from the CryptoCompare database, which provides consistent, exchange-aggregated series. Global financial indicators - including the Federal Funds Effective Rate (FFR) and the CBOE Volatility Index (VIX) - along with Turkey's unemployment rate, were sourced from the Federal Reserve Economic Data (FRED) database.

The dataset spans the period September 2013 to March 2025, chosen to ensure both the maturity of Turkey's cryptocurrency market and the inclusion of the most recent macro-financial developments. Although the dataset begins in September 2013, the effective estimation period starts in 2014 due to the inclusion of lagged variables in the econometric model specification. This period captures the full evolution of the domestic crypto ecosystem under varying monetary conditions. The analysis is conducted using monthly frequency data, which balances the availability of reliable macroeconomic information with the need to detect medium-term market responses, in line with Campbell *et al.* (1997).

2.2. Research Questions and Analytical Framework

Building on the research questions outlined in the Introduction, this section defines the analytical framework through which they are empirically examined. The central aim is to determine how the Central Bank of the Republic of Turkey's (CBRT) monetary policy instruments - the policy rate, reserve requirement ratio (RRR), and broad money supply (M2) - affect the main dimensions of the cryptocurrency market in Turkey: prices, trading volume, volatility, and returns.

To capture these interactions, the study employs an Autoregressive Distributed Lag (ARDL) modeling strategy, complemented by an Error Correction Model (ECM) to evaluate both short-run dynamics and long-run equilibria. The ARDL approach is particularly suitable for this research because it can handle mixed integration orders ($I(0)$ and $I(1)$), perform effectively in small samples, and identify the speed at which the system re-adjusts to equilibrium after policy shocks (Pesaran *et al.* 2001; Narayan and Smyth 2005).

This design provides a coherent structure linking Turkey's monetary policy instruments to cryptocurrency market behavior through identifiable transmission mechanisms, setting the stage for the detailed data and variable specifications that follow.

2.3. Variables and Measurement

To capture the multidimensional effects of monetary policy on Turkey's cryptocurrency market, the study utilizes four dependent and ten independent variables, classified into core policy, domestic control, and global control categories, as detailed in Table 1.

Table 1. Conceptual and Operational Definitions of Variables

Variable Code	Variable Name	Conceptual Definition	Operational Definition	Unit	Role in Model	Scope	Data Source
PRICE	Cryptocurrency Price	Market value of Bitcoin in domestic currency (Fama, 1970).	$\ln(\text{BTC closing price in TRY})$	$\ln$ (unitless)	Endogenous (Y_1)	National	CryptoCompare
VOLUME	Trading Volume	Indicator of market liquidity and trading activity (Amihud, 2002).	$\ln(\text{BTC monthly trading volume in TRY})$	$\ln$ (unitless)	Endogenous (Y_2)	National	CryptoCompare
VOL	Market Volatility	Price fluctuations represent market risk (Hull, 2012).	Monthly standard deviation of daily BTC returns (TRY).	Percent	Endogenous (Y_3)	National	CryptoCompare
RET	Market Return	Percentage change in price, measuring investment performance (Campbell <i>et al.</i> , 1997).	$\ln(P_t/P_{t-1})$	Percent	Endogenous (Y_4)	National	CryptoCompare
POLICY	Policy Rate	CBRT's main interest rate for liquidity management (Mishkin, 2016).	Mean repo auction rate (%)	Percent	Exogenous, Policy	National	CBRT-EVDS
RRR	Reserve Requirement Ratio	Mandatory reserve ratio of banks (Bernanke and Gertler, 1995).	Monthly RRR (%)	Percent	Exogenous, Policy	National	CBRT-EVDS

Variable Code	Variable Name	Conceptual Definition	Operational Definition	Unit	Role in Model	Scope	Data Source
M2	Real Broad Money Supply	Inflation-adjusted broad money stock (Friedman, 1968).	$\ln(M2/CPI)$	In (unitless)	Exogenous, Policy	National	CBRT-EVDS
EXRATE	Exchange Rate	USD/TRY average exchange rate (Dornbusch, 1976).	$\ln(USD/TRY)$	In (unitless)	Control	National	CBRT-EVDS
FXVOL	FX Volatility	Volatility of USD/TRY returns (Engle, 1982).	Monthly st.dev. of daily USD/TRY log returns	Percent	Control	National	CBRT-EVDS
CPI	Consumer Price Index	Measure of inflation (Mishkin, 2016).	$\ln(CPI)$	In (unitless)	Control	National	CBRT-EVDS
UR	Unemployment Rate	Share of unemployed in labor force (Blanchard and Katz, 1997).	Monthly unemployment rate (%)	Percent	Control	National	FRED
VIX	Global Volatility Index	Global risk perception (Whaley, 2000).	Monthly VIX closing value	Index	Control	International	FRED
FFR	Fed Funds Rate	U.S. short-term policy rate (Bernanke and Blinder, 1992).	Effective federal funds rate (%)	Percent	Control	International	FRED
GPUSD	Global Bitcoin Price (USD)	Global price reference for Bitcoin (Fama, 1970).	$\ln(BTC \text{ closing price in USD})$	In (unitless)	Control	International	CryptoCompare

Note: Logarithmic transformations are applied to PRICE, VOLUME, CPI, EXRATE, GPUSD, and M2; RET represents monthly log returns; VOL and FXVOL denote the monthly standard deviation of daily log returns.

2.4. Transmission Channels and Conceptual Model

Monetary policy affects cryptocurrency markets through multiple, interrelated transmission channels that shape investor behavior, liquidity conditions, and asset valuations. In the context of Turkey's evolving financial landscape - marked by inflationary pressures, exchange rate volatility, and an expanding digital asset market - these channels interact in complex ways. Figure 1 presents the *conceptual framework* of the study, summarizing how policy, domestic, and global variables are structured in relation to cryptocurrency market dynamics. The figure groups explanatory variables into three categories: policy variables (policy rate, reserve requirement ratio, and broad money supply), domestic control variables (exchange rate, foreign exchange volatility, consumer price index, and unemployment rate), and global control variables (VIX, federal funds rate, and global cryptocurrency price). These sets of variables jointly influence the four dimensions of cryptocurrency market dynamics - price, trading volume, volatility, and returns.

Within this framework, monetary transmission operates through several well-established mechanisms. Changes in the policy interest rate alter the relative cost of holding risk-bearing assets: higher interest rates increase borrowing costs and the opportunity cost of holding non-yielding assets, such as cryptocurrencies, thereby discouraging speculative investment and reducing both price and trading activity (Bernanke and Gertler 1995; Mishkin 2001). The liquidity effect, captured through movements in the broad money supply (M2), reflects how monetary expansion or contraction influences market liquidity. An expansionary policy may stimulate demand for digital assets as investors seek inflation hedges or alternative stores of value (Friedman 1968), while liquidity tightening has the opposite effect. Similarly, the credit channel, represented by the reserve requirement ratio (RRR), affects the banking sector's lending capacity. A higher RRR constrains credit and limits capital inflows to speculative assets, whereas a lower ratio injects liquidity that can amplify trading activity in cryptocurrency markets (Bernanke and Gertler 1995).

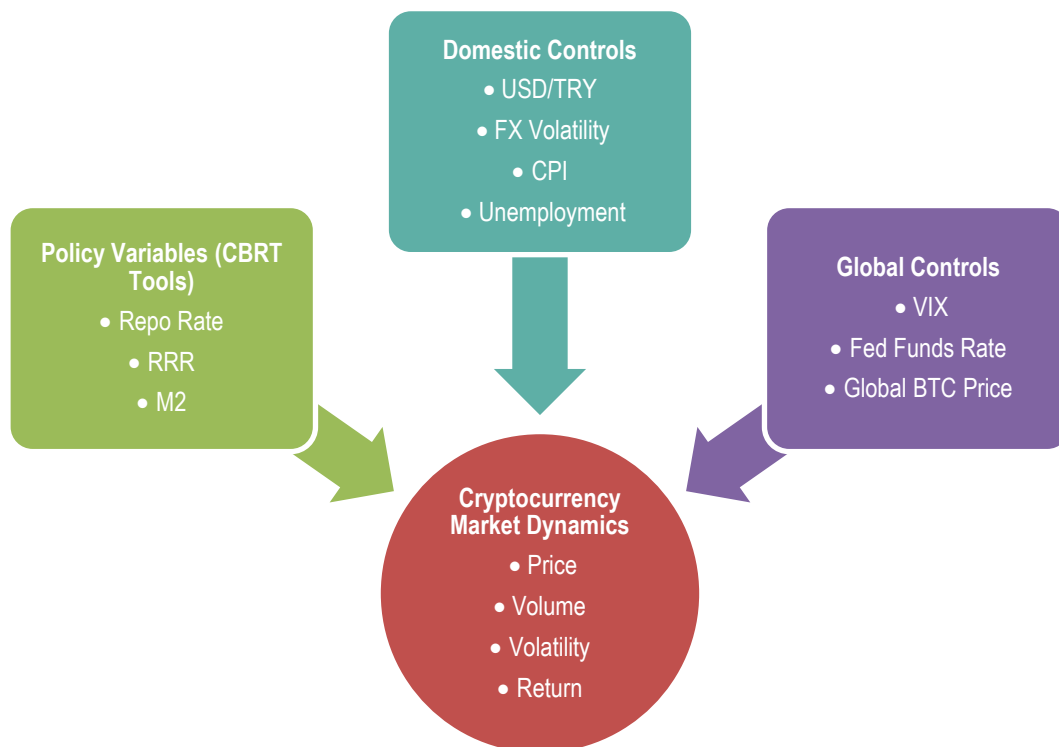
The exchange rate channel is particularly significant in emerging economies such as Turkey, where depreciation of the Turkish lira increases the local-currency value of cryptocurrencies and encourages investors to hedge against further losses. In this sense, exchange rate volatility serves as an indirect conduit through which monetary shocks are transmitted to the crypto market. While the asset-price and expectations channel is conceptually relevant - since monetary policy announcements can alter inflation expectations and perceived returns (Tobin 1969) - this study does not include a direct expectation variable due to the monthly frequency of the dataset.

Instead, this mechanism is indirectly captured through forward-looking indicators such as the exchange rate, the global Bitcoin price, and the global volatility index (VIX).

Macroeconomic instability also activates the portfolio and safe-haven channel, whereby inflationary pressures and exchange rate volatility prompt investors to reallocate portfolios toward cryptocurrencies as potential hedges or alternative stores of value (Dyhrberg 2016; Baur and Dimpfl 2021). Finally, the global spillover channel transmits international monetary conditions to Turkey's cryptocurrency market: increases in the U.S. federal funds rate or spikes in global risk perception (VIX) typically raise volatility and reduce returns in emerging markets (Elsayed and Sousa 2022; Zhao *et al.* 2023). Likewise, fluctuations in the global Bitcoin price (GPUSD) convey cross-market shocks through arbitrage and sentiment effects.

Taken together, these channels define the theoretical foundation of the empirical model. Figure 1, titled “Conceptual Framework Linking Policy, Domestic, and Global Variables to Cryptocurrency Market Dynamics,” provides a visual overview of these relationships and serves as the conceptual basis for the ARDL approach applied in the subsequent sections.

Figure 1. Conceptual Framework Linking Policy, Domestic, and Control Variables to Cryptocurrency Market Dynamics



2.5. Data Characteristics and Transformations

To ensure consistency and comparability, all variables were converted to a monthly time series and expressed in natural logarithms where applicable - specifically, cryptocurrency prices (in TRY and USD), trading volume, the consumer price index (CPI), and real money supply (M2). Logarithmic transformation mitigates heteroskedasticity, improves distributional properties, and allows coefficients to be interpreted as elasticities (Wooldridge 2013; Gujarati and Porter 2009).

Monthly log returns for Bitcoin were calculated as:

$$RET_t = \ln(P_t^{TRY} / P_{t-1}^{TRY}) \quad (1)$$

Logarithmic returns were preferred due to their superior statistical properties and closer approximation to normality (Campbell *et al.* 1997). Market volatility was measured as the monthly standard deviation of daily Bitcoin returns, and foreign-exchange volatility (FXVOL) was derived analogously from daily USD/TRY log returns, following Engle (1982) and Hull (2012).

The real broad money supply (M2) was obtained by deflating nominal M2 with the consumer price index (CPI) and taking natural logs, consistent with Friedman's (1968) formulation. This variable reflects inflation-adjusted liquidity and serves as a key monetary stance indicator.

Tests for seasonal patterns revealed no significant seasonality, and no seasonal adjustments were required. All preprocessing, diagnostic testing, and econometric estimation were conducted using EViews 13, which provides robust tools for ARDL and ECM modeling.

The processed and transformed dataset thus forms a consistent empirical foundation for the estimation procedures described in the following sections.

2.6. Econometric Strategy

To analyze the impact of the Central Bank of the Republic of Turkey's (CBRT) monetary policies on the dynamics of the cryptocurrency market, this study employs the Autoregressive Distributed Lag (ARDL) modeling approach proposed by Pesaran *et al.* (2001). The ARDL framework is particularly appropriate for this analysis for several reasons. First, it enables simultaneous estimation of both short-run dynamics and long-run equilibrium relationships, which directly correspond to the study's objectives. Second, it accommodates variables integrated of order $I(0)$ and $I(1)$, addressing the mixed stationarity characteristics identified through unit root testing. Third, it provides robust and efficient estimates even in small samples, making it suitable given the monthly data covering the 2013–2025 period (Narayan and Smyth 2005).

The model incorporates an Error Correction Mechanism (ECM) to capture the speed at which the cryptocurrency market returns to long-run equilibrium after monetary shocks. This dual nature - short-run responsiveness and long-run adjustment - allows for a comprehensive examination of how monetary policy decisions shape cryptocurrency market behavior in Turkey.

2.7. Research Hypotheses

Based on the theoretical framework and empirical design outlined above, the study develops the following hypotheses to guide the econometric analysis:

H_1 – Joint Effect of Monetary Policy Instruments: Changes in the CBRT's core policy tools - the policy interest rate, reserve requirement ratio (RRR), and broad money supply (M2) - have statistically significant effects on the four key indicators of Turkey's cryptocurrency market: prices, trading volume, volatility, and returns.

H_2 – Transmission Channels of Monetary Policy: Monetary policy influences cryptocurrency market variables through specific channels - particularly the interest rate, liquidity (money supply), and exchange rate mechanisms - after controlling for domestic variables (USD/TRY, FX volatility, CPI, unemployment) and global variables (VIX, Federal Funds Rate, global Bitcoin price).

H_3 – Short- and Long-Run Effects: The impacts of CBRT's monetary policy instruments on cryptocurrency market indicators differ significantly between the short run and the long run.

H_4 – Long-Run Equilibrium Adjustment: The error correction term (ECT) derived from the ARDL framework is statistically significant and negative, indicating the speed at which the cryptocurrency market returns to equilibrium after monetary shocks.

These hypotheses are tested through successive steps involving stationarity checks, cointegration testing, and ARDL-ECM estimation, as described in the following subsections.

2.8. Preconditions and Diagnostic Tests

Before estimating the ARDL models, several diagnostic and pre-estimation tests were conducted to ensure the validity and reliability of the empirical results, which are summarized in Table 2.

Table 2. Precondition and Diagnostic Tests Applied in the ARDL Analysis

Test Name	Purpose	Null Hypothesis (H_0)	Key References
ADF Test	Tests variable stationarity	The variable has a unit root	Dickey & Fuller (1979)
PP Test	Tests variable stationarity	The variable has a unit root	Phillips & Perron (1988)
Bounds Test	Tests for long-run cointegration	No cointegration among variables	Pesaran <i>et al.</i> (2001)
Breusch–Godfrey LM Test	Detects serial correlation in residuals	No serial correlation	Breusch (1978) and Godfrey (1978)
Engle's ARCH Test	Detects conditional heteroskedasticity	No ARCH effects	Engle (1982)
White's Test	Tests for general heteroskedasticity	Homoskedasticity	White (1980)

Note: All diagnostic procedures were implemented in EViews 13, ensuring consistency and replicability.

Stationarity Tests: The Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) tests were applied to determine the order of integration of each variable (Dickey and Fuller, 1979; Phillips and Perron, 1988). The combination of I(0) and I(1) variables confirmed the suitability of the ARDL approach.

Cointegration Test: The Bounds Test developed by Pesaran *et al.* (2001) was used to verify the existence of a long-run equilibrium relationship among the variables. A statistically significant F-statistic exceeding the upper critical bound indicates cointegration.

Model Diagnostics: To assess model robustness, the following diagnostic tests were conducted: (i) Serial Correlation: Breusch–Godfrey LM test and (ii) Heteroskedasticity: Engle's ARCH test and White's general test.

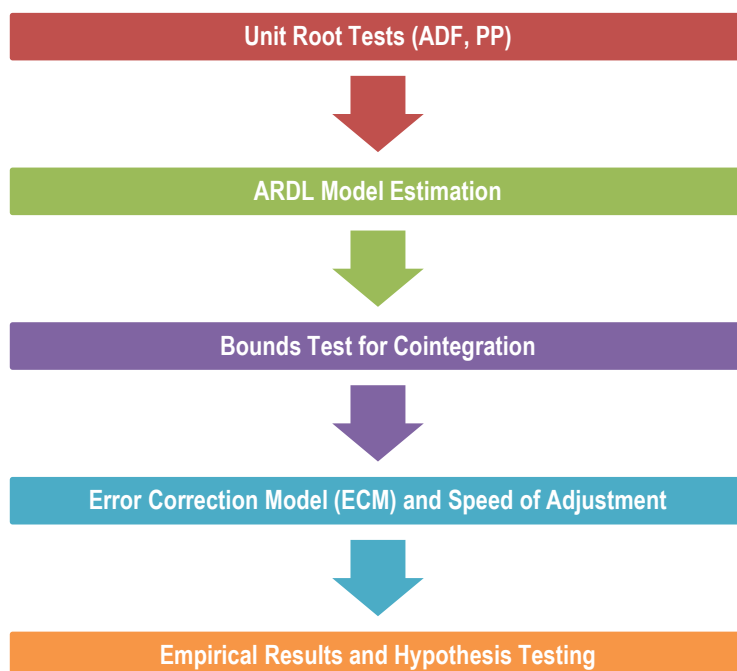
2.9. Model Specification and Estimation Procedure

To jointly examine the short- and long-run relationships among monetary policy variables, domestic controls, global controls, and cryptocurrency market indicators, the following general ARDL specification is adopted:

$$\begin{aligned} \Delta Y_t = & \alpha_0 + \sum_{i=1}^p \beta_i \Delta Y_{t-i} + \sum_{j=0}^{q_1} \gamma_{1j} \Delta POLICY_{t-j} + \sum_{k=0}^{q_2} \gamma_{2k} \Delta RRR_{t-k} + \sum_{l=0}^{q_3} \gamma_{3l} \Delta M2_{t-l} + \sum_{m=0}^{q_4} \gamma_{4m} \Delta EXRATE_{t-m} \\ & + \sum_{n=0}^{q_5} \gamma_{5n} \Delta FXVOL_{t-n} + \sum_{o=0}^{q_6} \gamma_{6o} \Delta CPI_{t-o} + \sum_{r=0}^{q_7} \gamma_{7r} \Delta UR_{t-r} + \sum_{s=0}^{q_8} \gamma_{8s} \Delta VIX_{t-s} \\ & + \sum_{u=0}^{q_9} \gamma_{9u} \Delta FFR_{t-u} + \sum_{v=0}^{q_{10}} \gamma_{10v} \Delta GPU\_USD_{t-v} + \delta_1 Y_{t-1} + \delta_2 POLICY_{t-1} + \delta_3 RRR_{t-1} \\ & + \delta_4 M2_{t-1} + \delta_5 EXRATE_{t-1} + \delta_6 FXVOL_{t-1} + \delta_7 CPI_{t-1} + \delta_8 UR_{t-1} + \delta_9 VIX_{t-1} \\ & + \delta_{10} FFR_{t-1} + \delta_{11} GPU\_USD_{t-1} + \varepsilon_t \end{aligned} \quad (2)$$

where Y_t represents the dependent variable (price, trading volume, volatility, or return); Δ denotes the first-difference operator; α_0 is the constant term; $p, q_1, q_2, \dots, q_{10}$ represent optimal lag lengths determined using the Akaike Information Criterion (AIC); short-run coefficients (β, γ) capture immediate effects, while long-run coefficients (δ) reflect equilibrium relationships; and ε_t denotes the error term.

Figure 2. Empirical Methodology and ARDL Estimation Procedure



Once cointegration is confirmed, the Error Correction Model (ECM) form of the ARDL is estimated to measure the speed of adjustment toward long-run equilibrium. The coefficient of the error correction term (ECT) is expected to be negative and statistically significant, confirming convergence to equilibrium.

All estimations were performed in EViews 13, following the sequential procedure outlined in Figure 2, which summarizes the empirical workflow - from unit root testing to ARDL estimation and ECM validation.

Having established the dataset, variable structure, and econometric framework, this section has outlined the methodological foundations of the study. The ARDL–ECM strategy enables simultaneous assessment of short-run adjustments and long-run equilibrium dynamics between monetary policy instruments and cryptocurrency market indicators. All precondition and diagnostic tests confirm that the data and model specifications meet the required econometric standards for robust estimation. Building on this foundation, the next section presents the empirical findings of the analysis, highlighting how the Central Bank of the Republic of Turkey's (CBRT) policy instruments - namely the policy rate, reserve requirement ratio (RRR), and broad money supply (M2) - affect cryptocurrency prices, trading volumes, volatility, and returns in Turkey.

3. Research Results

3.1. Descriptive Statistics and Exploratory Plots

Table 3 reports summary statistics (mean, median, extrema, and standard deviation) for all variables over 139 monthly observations (2013M09–2025M03). As expected for crypto markets, PRICE and VOLUME display pronounced dispersion - e.g., the standard deviation of PRICE (≈ 2.74 in logs) signals substantial variability. Monetary policy variables also vary widely: POLICY ranges from 4.5 to 50 (std. dev. ≈ 12.90), while RRR spans 5–21. Volatility indicators corroborate elevated risk: both VIX and VOL exhibit large swings, whereas macro aggregates such as CPI (log) and EXRATE (log) show steadier movements relative to crypto series. (Definitions, units, and transformations are detailed in Section 2.)

Figure 3 visualizes the monthly time paths of the key variables. Several series - CPI, EXRATE, M2, GPUSD, PRICE, and VOLUME - trend upward over the sample, with momentum intensifying especially after 2018 and into the 2020s, consistent with stochastic trends rather than deterministic drift. Policy series (POLICY, RRR) exhibit sharp regime shifts, while FFR rises notably post-2022, mirroring global tightening. High-frequency indicators (RET, FXVOL, VOL, VIX) reveal volatility clustering and bursty dynamics suggestive of conditional heteroskedasticity.

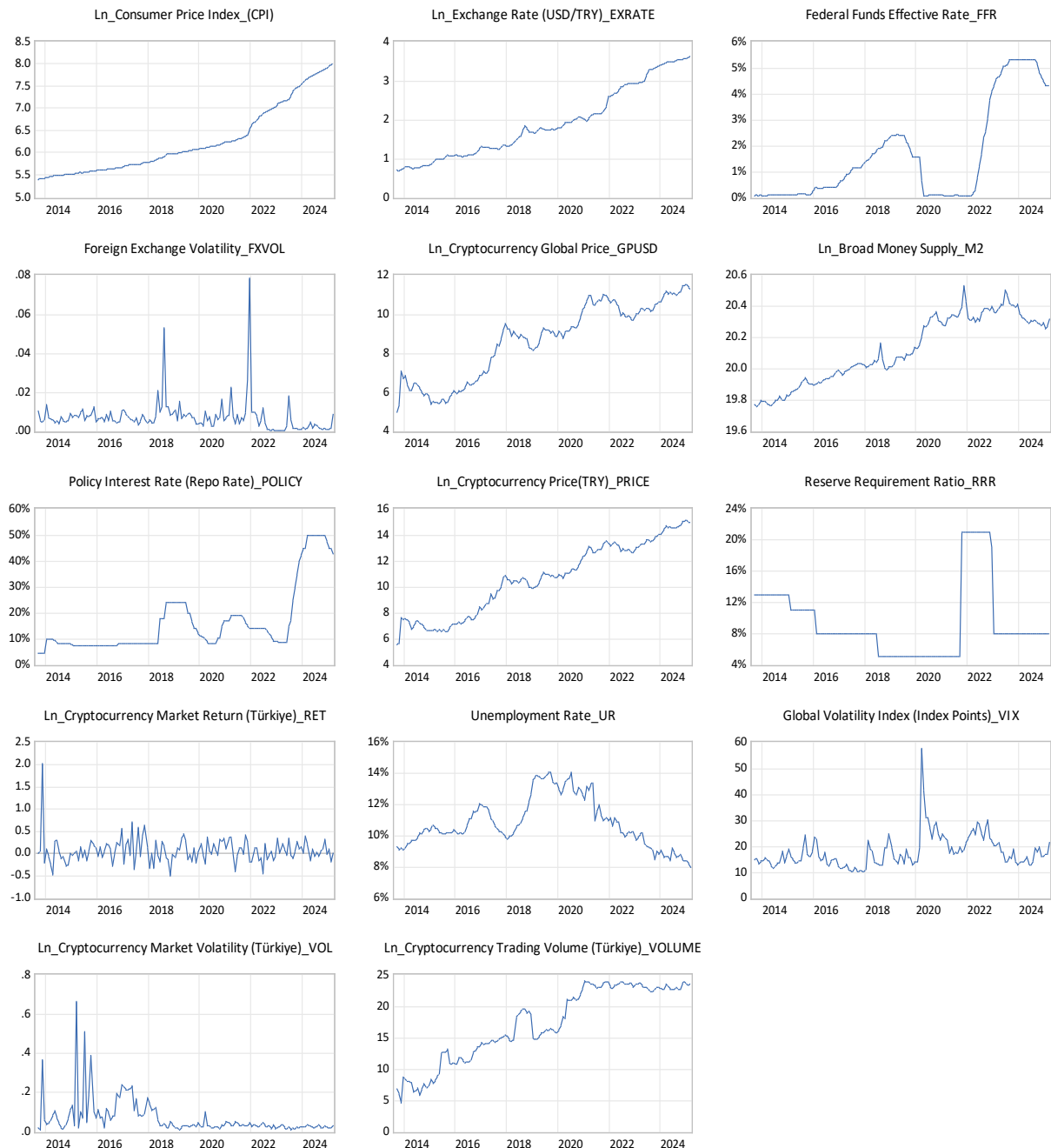
Table 3. Descriptive Statistics of Variables

Variable	Mean	Median	Maximum	Minimum	Std. Dev.	Obs.
CPI	6.264	6.025	7.991	5.411	0.761	139
EXRATE	1.915	1.750	3.613	0.692	0.908	139
FFR	1.643	0.790	5.330	0.050	1.866	139
FXVOL	0.007	0.006	0.079	0.000	0.009	139
GPUSD	8.658	9.064	11.537	4.955	1.933	139
M2	20.124	20.079	20.537	19.759	0.217	139
POLICY	16.466	10.000	50.000	4.500	12.897	139
PRICE	10.615	10.723	15.117	5.556	2.743	139
RET	0.068	0.055	2.018	-0.510	0.277	139
RRR	9.417	8.000	21.000	5.000	4.733	139
UR	10.840	10.400	14.100	7.900	1.595	139
VIX	17.795	15.904	57.737	10.125	6.365	139
VOL	0.069	0.034	0.662	0.007	0.091	139
VOLUME	17.136	16.989	24.087	4.527	5.898	139

Note: Definitions and measurement units of the variables are provided in the [Data and Methodology / Conceptual and Operational Definitions of Variables] section.

Taking together, the descriptive evidence points to heterogeneous integration orders across variables and motivates formal unit-root testing. These patterns provide an empirical rationale for the ARDL framework employed later, which can accommodate mixtures of $I(0)/I(1)$ processes and separate long-run from short-run dynamics.

Figure 3. Time Series Plots of the Key Variables (September 2013 – March 2025)



3.2. Unit Root Analysis and Stationarity Findings

Before estimating the ARDL models, it is essential to verify the time-series properties of all variables to avoid spurious regressions and to determine the appropriate econometric specification. Accordingly, both the Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) tests were employed to assess the order of integration of each variable. The ADF test accounts for potential serial correlation through lagged differences, while the PP test offers robustness against heteroskedasticity and autocorrelation. Given the visual evidence of trending behavior in several series (see Figure 3), all tests were conducted under the trend-and-intercept specification.

Table 4 summarizes the ADF and PP results, while Table 5 groups variables by their integration order. The results indicate that a substantial number of variables - such as PRICE, VOLUME, RRR, M2, EXRATE, CPI, UR, FFR, and GPUSD - are nonstationary at levels but become stationary after first differencing, implying integration of

order one $I(1)$. In contrast, VOL, RET, FXVOL, VIX, and POLICY are stationary at levels, that is, $I(0)$. Importantly, no variable is integrated of order two $I(2)$, which is a necessary condition for the validity of ARDL estimation (Pesaran *et al.* 2001).

This mixed integration structure - comprising both $I(0)$ and $I(1)$ processes - provides strong support for the use of the Autoregressive Distributed Lag (ARDL) bounds-testing framework. The ARDL approach is particularly well suited for such datasets, as it allows consistent estimation of both short-run dynamics and long-run equilibrium relationships without requiring all variables to be of the same integration order. Consequently, the findings from the unit-root analysis validate the methodological foundation of the subsequent cointegration and ARDL estimations.

Table 4. Results of Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) Unit Root Tests

Variable	ADF t-stat (Level)	ADF p-value (Level)	ADF t-stat (1st Diff.)	ADF p-value (1st Diff.)	PP t-stat (Level)	PP p-value (Level)	PP t-stat (1st Diff.)	PP p-value (1st Diff.)	Integration Order
PRICE	-2.8907	0.1688	-11.7496***	0.0000	-2.9409	0.1531	-11.7496***	0.0000	$I(1)$
VOLUME	-2.3931	0.3815	-11.9959***	0.0000	-2.3931	0.3815	-11.9959***	0.0000	$I(1)$
VOL	-3.6547**	0.0290	N/A	N/A	-10.9621***	0.0000	N/A	N/A	$I(0)$
POLICY	-3.5974**	0.0337	N/A	N/A	-4.9035***	0.0005	N/A	N/A	$I(0)$
RRR	-2.1870	0.4926	-10.9678***	0.0000	-2.2910	0.4356	-10.9678***	0.0000	$I(1)$
M2	-2.0890	0.5470	-11.4948***	0.0000	-2.0817	0.5510	-11.8253***	0.0000	$I(1)$
EXRATE	-1.7473	0.7246	-8.6170***	0.0000	-1.7868	0.7060	-7.1993***	0.0000	$I(1)$
FXVOL	-8.4683***	0.0000	N/A	N/A	-8.5331***	0.0000	N/A	N/A	$I(0)$
CPI	-0.2834	0.9904	-6.7246***	0.0000	0.0801	0.9968	-6.8253***	0.0000	$I(1)$
UR	-1.1698	0.9121	-13.1216***	0.0000	-0.9934	0.9407	-13.1216***	0.0000	$I(1)$
RET	-11.7933***	0.0000	N/A	N/A	-11.7933***	0.0000	N/A	N/A	$I(0)$
VIX	-4.8358***	0.0007	N/A	N/A	-4.8358***	0.0007	N/A	N/A	$I(0)$
FFR	-2.4717	0.3417	-3.1615**	0.0245	-1.7242	0.7354	-5.1537***	0.0002	$I(1)$
GPUSD	-2.2727	0.4456	-10.8477***	0.0000	-2.5229	0.3168	-10.8351***	0.0000	$I(1)$

Notes: (i) ***, ** indicate rejection of the null hypothesis (H_0 : the series contains a unit root) at the 1% and 5% significance levels, respectively. (ii) All tests were conducted under the "trend and intercept" specification, based on the presence of visible trends in the data. (iii) Optimal lag length for the ADF test was automatically determined using the Schwarz Information Criterion (SIC). For the PP test, bandwidth was selected using the Newey-West method. (iv) MacKinnon (1996) critical values for the ADF test are -4.028, -3.444, and -3.147 at the 1%, 5%, and 10% significance levels, respectively. For the PP test, critical values are -4.026, -3.443, and -3.146. (v) "N/A" indicates that no first-difference test was conducted because the variable was already found to be stationary at level, $I(0)$.

Table 5. Classification of Variables by Order of Integration

Integration Order	Variables
$I(0)$ – Stationary at Level	VOL (Cryptocurrency Volatility), RET (Cryptocurrency Return), FXVOL (FX Volatility), VIX (Global Volatility Index), POLICY (Policy Interest Rate)
$I(1)$ – Stationary at First Difference	PRICE (Cryptocurrency Price), VOLUME (Cryptocurrency Trading Volume), RRR (Reserve Requirement Ratio), M2 (Broad Money Supply), EXRATE (Exchange Rate), CPI (Consumer Price Index), UR (Unemployment Rate), FFR (Federal Funds Rate), GPUSD (Global Cryptocurrency Price in USD)

3.3. Lag Selection and Baseline ARDL Set-Up

Following confirmation of the integration properties, the next step involves determining the optimal lag structure for each model. Lag selection is critical to capturing the true dynamics of monetary policy transmission and ensuring unbiased long-run and short-run coefficient estimates. For this purpose, the Akaike Information Criterion (AIC) was used as the primary selection metric, given its strong performance in small and medium-sized samples and its capacity to balance model fit against over-parameterization (Akaike 1974; Burnham and Anderson 2002).

The procedure was implemented in EViews 13, where up to four lags were pre-specified for each variable. All possible ARDL combinations were evaluated, generating millions of model permutations per dependent variable. The AIC-based algorithm identifies the global optimum - minimizing residual variance while retaining parsimony - thus ensuring robust and reproducible model selection.

Consistent with theoretical expectations and the stochastic nature of cryptocurrency series, the analysis follows the restricted constant (Case II) specification without a deterministic trend. This specification assumes that deterministic components such as linear trends are absent, while stochastic trends are captured through lagged levels and differences of the variables.

The optimal lag combinations and corresponding diagnostic statistics are summarized in Table 6. The results indicate that the selected ARDL models achieve strong explanatory power across the dependent variables, particularly for PRICE and VOLUME, both of which exhibit adjusted R^2 values above 0.98. The Durbin-Watson statistics (approximately 2.0 across models) suggest no first-order autocorrelation, confirming that the dynamic specifications are statistically well-behaved.

These results establish the baseline ARDL structure that underpins the subsequent analyses - namely, the bounds tests for cointegration (Section 3.4), the estimation of long-run relationships (Section 3.5), and the short-run error-correction dynamics (Section 3.6).

Table 6. Results of Optimal ARDL Model Selection and Diagnostic Statistics

Dependent Variable	Selected ARDL Model	Adj. R^2	F-Statistic	DW Stat.	AIC	SC
PRICE	ARDL(2,0,0,1,0,0,0,0,1,0,4)	0.9989	6,978.21***	2.16	-1.900	-1.492
VOLUME	ARDL(2,0,0,0,0,1,0,2,0,0)	0.9825	510.13***	2.09	2.415	2.756
VOL	ARDL(4,0,0,0,0,0,0,4,0,2)	0.3475	4.57***	1.91	-2.301	-1.849
RET	ARDL(3,0,0,1,3,0,0,0,0,4)	0.7752	23.00***	2.16	-1.498	-1.025

Notes: *** indicates statistical significance at the 1% level. DW: Durbin-Watson statistic. AIC: Akaike Information Criterion. SC: Schwarz Criterion. All F-statistics test the null hypothesis that all explanatory variables are jointly insignificant.

3.4. Bounds Test for Cointegration

Once the optimal lag lengths were determined, the next step was to examine whether stable long-run equilibrium relationships exist among the variables. To this end, the ARDL bounds testing approach to cointegration developed by Pesaran *et al.* (2001) was applied. This method is particularly suitable for datasets with mixed integration orders ($I(0)$ and $I(1)$), as confirmed in Section 3.2.

Table 7. Results of ARDL Bounds Test for Cointegration

Model	F-Statistic	Decision	Critical Values (1%)	Inference
PRICE	9.293***	H_0 rejected	$I(0) = 2.41$ $I(1) = 3.61$	Cointegration exists
VOLUME	4.080***	H_0 rejected	$I(0) = 2.41$ $I(1) = 3.61$	Cointegration exists
VOL	2.081	H_0 rejected (inconclusive F-test confirmed by t-test)	$I(0) = 2.41$ $I(1) = 3.61$	Cointegration exists
RET	8.803***	H_0 rejected	$I(0) = 2.41$ $I(1) = 3.61$	Cointegration exists

Notes: Critical values are taken from Pesaran *et al.* (2001, Table CI(iii), Case II, $k = 10$). *** indicates that the F-statistic exceeds the 1% upper bound critical value. H_0 : no level relationship exists.

The bounds test was conducted under the restricted constant, no-trend specification (Case II), using $k = 10$ explanatory variables to capture the comprehensive set of monetary policy, domestic control, and global control indicators. This specification is theoretically motivated by the expectation that cryptocurrency series follow stochastic rather than deterministic trends, consistent with the efficient market hypothesis for financial assets (Urquhart 2016).

The results, presented in Table 7, provide strong evidence of cointegration in all four models. Specifically, the calculated F-statistics for the PRICE (9.29), VOLUME (4.08), and RET (8.80) equations exceed the 1% upper-bound critical value of 3.61, leading to a decisive rejection of the null hypothesis of no long-run relationship. Although the F-statistic for the VOL model (2.08) falls below the upper bound, the t-statistic of the error-correction term in the corresponding ECM (reported later in Section 3.6) is highly significant ($-5.23, p < 0.01$), confirming that this model also possesses a valid long-run equilibrium relationship.

Overall, the bounds testing results confirm that long-run cointegration exists across all four dependent variables - cryptocurrency price, trading volume, return, and volatility - and thus justify proceeding to estimate long-run and short-run dynamics using the ARDL framework.

3.5. ARDL Model Estimation Results

Following the confirmation of cointegration, the long-run and short-run relationships among the variables were estimated using the Autoregressive Distributed Lag (ARDL) models identified in Section 3.3. Separate models were estimated for each of the four dependent variables - cryptocurrency price (PRICE), trading volume (VOLUME), returns (RET), and volatility (VOL) - in order to capture the multidimensional effects of monetary policy on Turkey's cryptocurrency market.

Each model was estimated using the Akaike Information Criterion (AIC)-selected lag structure and follows the general ARDL form introduced in Section 2.9. The analysis focuses first on the long-run coefficients, which reflect persistent equilibrium relationships between monetary policy and market variables, and then on diagnostic indicators to assess model validity.

3.5.1. Cryptocurrency Price (PRICE) Model Results

This subsection presents the ARDL estimation results where the dependent variable is the cryptocurrency price in Turkish lira (PRICE). The model is estimated for the period 2014M01–2025M03 and selected according to the Akaike Information Criterion (AIC). The optimal lag structure is ARDL(2,0,0,1,0,0,0,1,0,4), including two lags of PRICE and up to four lags of the global Bitcoin price in USD (GPUUSD). The long-run coefficients and optimal lag lengths for all explanatory variables are summarized in Table 8 below.

Table 8. Optimal Lag Structure and Long-Run ARDL Estimates for the PRICE Model

Variable	Optimal Lag Length	Coefficient	Std. Error	t-Statistic	p-Value
PRICE	2	-	-	-	-
POLICY	0	-0.0006	0.0017	-0.33	0.742
RRR	0	0.0031	0.0029	1.09	0.277
M2	1	0.2196	0.2392	0.92	0.360
EXRATE	0	0.8006***	0.1765	4.54	0.000
FXVOL	0	0.4119	1.1352	0.36	0.717
CPI	0	0.2749*	0.1559	1.76	0.080
UR	0	0.0163	0.0101	1.62	0.109
VIX	1	-0.0044**	0.0020	-2.13	0.035
FFR	0	-0.0077	0.0133	-0.58	0.561
GPUUSD	4	0.9620***	0.0126	76.18	0.000
C (Constant)	-	-5.4993	5.1741	-1.06	0.290

Notes: Optimal lag lengths were selected using the Akaike Information Criterion (AIC). The ARDL model specification is ARDL (2,0,0,1,0,0,0,1,0,4). *, **, and *** represent the 10%, 5%, and 1% significance levels, respectively.

The estimation results in Table 8 reveal several important long-run determinants of cryptocurrency prices in Turkey. The most prominent finding is the strong and positive association between the global and domestic Bitcoin markets. The coefficient for GPUUSD (0.9620, $p < 0.01$) indicates an almost one-to-one long-run co-movement between the global USD-denominated Bitcoin price and its TRY-denominated counterpart, confirming that global

price discovery largely dominates domestic pricing behavior in Turkey. Similarly, the exchange rate (EXRATE) exerts a highly significant positive effect (0.8006, $p < 0.01$), implying that domestic currency depreciation leads to higher local cryptocurrency prices. This pattern reflects a hedging motive, where investors turn to digital assets as a store of value during periods of lira depreciation and inflationary pressure.

The global volatility index (VIX) has a negative and statistically significant coefficient (-0.0044 , $p < 0.05$), suggesting that higher global uncertainty or risk aversion tends to depress cryptocurrency valuations in Turkey. This outcome supports the “flight-to-safety” hypothesis, where investors reallocate funds away from riskier assets such as cryptocurrencies during turbulent global conditions. Meanwhile, CPI has a positive and marginally significant coefficient (0.2749, $p = 0.08$), indicating a limited inflation-hedging effect, consistent with evidence that cryptocurrencies may act as partial inflation hedges in emerging markets.

Other variables, including the policy interest rate (POLICY), reserve requirement ratio (RRR), broad money supply (M2), unemployment rate (UR), and Federal Funds Rate (FFR), are statistically insignificant in the long run. This finding suggests that domestic monetary policy tools have little direct influence on the long-run pricing of cryptocurrencies, which instead respond primarily to global market forces and exchange rate movements.

To evaluate the reliability and overall fit of the estimated ARDL specification, key diagnostic statistics were computed. The results, summarized in Table 9, confirm the robustness and statistical validity of the model. The high explanatory power, strong joint significance, and absence of serial correlation demonstrate that the estimated model is statistically sound and robust.

Table 9. Diagnostics and Fit Criteria for the PRICE Model

Criterion	Value	Interpretation
R-squared	0.8674	High explanatory power ($\approx 86.7\%$ of variation explained)
F-statistic	118.71***	Model is jointly significant ($p < 0.01$)
Prob(F-statistic)	0.0000	Confirms overall model significance
Durbin–Watson	2.1627	No first-order autocorrelation ($DW \approx 2$)

Notes: *** represents the 1% significance level.

Overall, the findings suggest that cryptocurrency prices in Turkey are primarily shaped by global market forces - particularly the international Bitcoin price and the exchange rate channel - rather than by domestic monetary policy variables. The model diagnostics further confirm that the estimated ARDL specification is stable, well-fitted, and theoretically consistent, offering credible insights into the long-run dynamics of cryptocurrency valuation within an emerging market context.

3.5.2. Cryptocurrency Trading Volume (VOLUME) Model Results

This subsection presents the ARDL estimation results where the dependent variable is cryptocurrency trading volume (VOLUME). The model was selected based on the Akaike Information Criterion (AIC) and estimated over the period 2014M01–2025M03. The optimal lag structure determined by AIC is ARDL(2,0,0,0,0,1,0,2,0,0), which includes two lags of VOLUME, one lag of CPI, and two lags of VIX. The long-run coefficients and corresponding optimal lag lengths are reported in Table 10.

The results in Table 10 indicate that cryptocurrency trading volume in Turkey is primarily influenced by exchange rate dynamics, inflationary conditions, and select global factors. The exchange rate (EXRATE) has a large and highly significant positive coefficient (17.85, $p < 0.01$), implying that depreciation of the Turkish lira strongly stimulates trading activity in cryptocurrencies. This suggests that investors increasingly turn to digital assets as a hedge or speculative response to currency depreciation. Conversely, lagged inflation ($CPI(-1)$) has a highly significant negative coefficient (-13.90 , $p < 0.01$), indicating that persistent inflationary pressures reduce trading activity over time - likely because high inflation erodes disposable income and limits speculative participation in digital markets.

Several monetary and macroeconomic variables also exhibit significant long-run effects. The reserve requirement ratio (RRR) exerts a negative and statistically significant influence (-0.1915 , $p < 0.01$), consistent with the idea that tighter liquidity conditions reduce market activity. Similarly, higher Federal Funds Rate (FFR) values are associated with lower trading volume (-0.8890 , $p < 0.01$), reflecting the impact of global monetary tightening on capital flows and speculative investment. The unemployment rate (UR) also shows a significant negative

relationship (-0.6277 , $p < 0.01$), suggesting that weaker domestic economic conditions and declining household income suppress participation in cryptocurrency trading.

Table 10. Optimal Lag Structure and Long-Run ARDL Estimates for the VOLUME Model

Variable	Optimal Lag Length	Coefficient	Std. Error	t-Statistic	p-Value
VOLUME	2	-	-	-	-
POLICY	0	-0.0483	0.0412	-1.17	0.243
RRR	0	-0.1915***	0.0644	-2.97	0.0035
M2	0	-0.3722	4.9788	-0.07	0.941
EXRATE	0	17.8501***	3.8738	4.61	0.000
FXVOL	0	31.2314	27.8579	1.12	0.264
CPI (-1)	1	-13.8992***	3.4481	-4.03	0.0001
UR	0	-0.6277***	0.2384	-2.63	0.0095
VIX (-1)	2	0.0337	0.0554	0.61	0.544
FFR	0	-0.8890***	0.3088	-2.88	0.0047
GPUSD	0	0.8312***	0.2799	2.97	0.0036
C (Constant)	-	81.3079	107.2978	0.76	0.450

Notes: Optimal lag lengths were selected using the Akaike Information Criterion (AIC). The ARDL model specification is ARDL (2,0,0,0,0,0,1,0,2,0,0). *** represents the 1% significance level.

The global Bitcoin price (GPUSD) has a strong positive and statistically significant coefficient (0.8312, $p < 0.01$), confirming that higher global crypto valuations stimulate domestic trading volumes through wealth and momentum effects. Other variables, such as the policy interest rate (POLICY), broad money supply (M2), and foreign exchange volatility (FXVOL), are statistically insignificant, implying that short-term liquidity conditions and currency volatility do not play a major role in shaping long-run trading behavior.

To verify the overall reliability of the model, diagnostic statistics were computed to assess explanatory power, joint significance, and autocorrelation. The results, presented in Table 11, indicate that the ARDL specification for trading volume is statistically valid and well-behaved.

Table 11. Diagnostics and Fit Criteria for the VOLUME Model

Criterion	Value	Interpretation
R-squared	0.2964	About 29.6% of variation explained - lower than PRICE, consistent with higher noise in trading data
F-statistic	3.3995***	Model is jointly significant ($p < 0.01$)
Prob(F-statistic)	0.00008	Confirms overall significance
Durbin-Watson	2.0922	No first-order autocorrelation ($DW \approx 2$)

Notes: *** represents the 1% significance level.

Although the explanatory power is moderate, the model remains statistically significant and free from autocorrelation, ensuring the reliability of coefficient estimates.

Taken together, these results demonstrate that cryptocurrency trading activity in Turkey is shaped primarily by macro-financial conditions - especially the exchange rate, inflation, global monetary policy, and overall economic health - rather than by domestic interest rates or liquidity expansion. The findings suggest that both hedging motives

and speculative responses to external shocks drive participation in cryptocurrency markets, highlighting the importance of global and structural factors in determining the scale of crypto trading within emerging economies.

3.5.3. Cryptocurrency Returns (RET) Model Results

This subsection presents the ARDL estimation results where the dependent variable is cryptocurrency returns (RET). Given the near-stationary yet highly volatile nature of returns, the estimation covers the period 2014M01–2025M03 and employs an optimal lag structure selected according to the Akaike Information Criterion (AIC). The resulting specification, ARDL(3,0,0,1,3,0,0,0,0,4), captures the complex autoregressive and distributed lag dynamics of return formation in the Turkish cryptocurrency market. The long-run coefficients and optimal lag lengths for explanatory variables are summarized in Table 12 below.

Table 12. Optimal Lag Structure and Long-Run ARDL Estimates for the RET Model

Variable	Optimal Lag Length	Coefficient	Std. Error	t-Statistic	p-Value
RET	3	-	-	-	-
POLICY	0	0.0003	0.0010	0.34	0.737
RRR	0	-	-	-	-
M2 (-1)	1	-0.0191	0.1447	-0.13	0.895
EXRATE (-1)	1	0.0152	0.1153	0.13	0.895
FXVOL	0	-0.0869	0.9084	-0.10	0.924
CPI	0	-0.0105	0.1020	-0.10	0.918
UR	0	0.0019	0.0063	0.30	0.763
VIX	0	-0.0002	0.0011	-0.15	0.883
FFR	0	0.0001	0.0080	0.02	0.987
GPUUSD (-1)	4	-0.0027	0.0076	-0.36	0.719
C (Constant)	-	0.4098	3.1625	0.13	0.897

Notes: Optimal lag lengths were selected using the Akaike Information Criterion (AIC). The ARDL model specification is ARDL (3,0,0,1,3,0,0,0,0,4).

The results presented in Table 12 show that, in contrast to the price and trading volume models, none of the explanatory variables exhibit statistically significant long-run effects on cryptocurrency returns in Turkey. All coefficients are small in magnitude and accompanied by large standard errors, and their associated p-values are far above conventional significance thresholds. Even the global variables - GPUUSD, VIX, and FFR - fail to exert any systematic long-run influence on returns. This absence of persistent macro-financial effects suggests that Turkish cryptocurrency returns follow a pattern consistent with weak-form market efficiency: prices adjust rapidly to new information, eliminating predictable long-run excess returns.

The insignificance of domestic monetary policy instruments such as POLICY, RRR, and M2 reinforces this interpretation. The lack of explanatory power indicates that interest rate and liquidity changes may influence speculative trading or short-term pricing behavior, but they do not create sustained return differentials over time. Similarly, domestic macroeconomic factors - including CPI, EXRATE, and UR - do not exhibit statistically significant or economically meaningful coefficients, suggesting that longer-term return dynamics are not directly anchored in domestic fundamentals.

Diagnostic statistics further confirm the robustness of the estimation and the adequacy of the ARDL specification. The relevant results are reported in Table 13 below. The high explanatory power and absence of residual autocorrelation confirm the internal consistency of the model despite the statistical insignificance of individual long-run coefficients.

Table 13. Diagnostics and Fit Criteria for the RET Model

Criterion	Value	Interpretation
R-squared	0.8999	Very high explanatory power ($\approx 89.9\%$)
F-statistic	48.42***	Model jointly significant ($p < 0.01$)
Durbin–Watson	2.1600	No first-order autocorrelation ($DW \approx 2$)

Notes: *** represents the 1% significance level.

Taken together, these findings indicate that cryptocurrency returns in Turkey do not display any systematic long-run dependencies on either domestic monetary policy or global macro-financial conditions. The high overall explanatory power is thus primarily attributed to autoregressive and short-run dynamic components - especially momentum and volatility clustering - rather than to structural economic factors. This outcome aligns with the notion of adaptive and information-efficient markets, where short-term shocks and investor sentiment dominate return formation, while long-run predictability remains absent.

3.5.4. Cryptocurrency Volatility (VOL) Model Results

This subsection presents the ARDL estimation results for cryptocurrency market volatility (VOL), a key indicator of market risk and stability. The model was estimated for the period 2014M01–2025M03, with the optimal specification determined by the Akaike Information Criterion (AIC). The selected lag structure is ARDL(4,0,0,0,0,0,0,4,0,2), which captures multiple autoregressive dynamics of volatility along with the lagged influence of global financial variables. The long-run coefficients and corresponding optimal lag lengths are summarized in Table 14 below.

Table 14. Optimal Lag Structure and Long-Run ARDL Estimates for the VOL Model

Variable	Optimal Lag Length	Coefficient	Std. Error	t-Statistic	p-Value
VOL	4	-	-	-	-
POLICY	0	-	-	-	-
RRR	0	-0.0030	0.0034	-0.86	0.389
M2	0	-0.0775	0.2574	-0.30	0.764
EXRATE	0	0.2054	0.1841	1.12	0.267
FXVOL	0	-0.5741	1.3672	-0.42	0.675
CPI	0	-0.0254	0.1769	-0.14	0.886
UR	0	0.0059	0.0138	0.43	0.671
VIX (-2)	2	-	-	-	-
FFR	0	-0.0383**	0.0168	-2.28	0.025
GPUSD (-1)	4	-0.0514***	0.0177	-2.91	0.004
C (Constant)	-	2.0785	5.4998	0.38	0.706

Notes: Optimal lag lengths were selected using the Akaike Information Criterion (AIC). The ARDL model specification is ARDL (4,0,0,0,0,0,0,4,0,2). ** and *** represent the 5% and 1% significance levels, respectively.

The long-run estimation results reported in Table 14 indicate that volatility in the Turkish cryptocurrency market is primarily influenced by global financial variables rather than domestic monetary or macroeconomic conditions. The global Bitcoin price in USD (GPUSD) exhibits a negative and statistically significant coefficient (-0.0514 , $p < 0.01$), suggesting that higher global crypto valuations are associated with lower volatility in the Turkish market. This result implies that during periods of strong international market performance, investor confidence and

liquidity tend to rise, leading to smoother price adjustments and reduced volatility. Similarly, the Federal Funds Rate (FFR) carries a significant negative coefficient (-0.0383 , $p < 0.05$), indicating that global monetary tightening - often linked to capital reallocation toward safer assets - reduces speculative activity and consequently dampens volatility in emerging crypto markets.

In contrast, none of the domestic variables, including EXRATE, RRR, M2, CPI, UR, and FXVOL, display statistically significant long-run effects on volatility. This suggests that while domestic monetary policy and macroeconomic developments may influence market sentiment in the short run, they do not exert sustained or systematic pressure on volatility levels over the long term. The insignificance of the policy rate (POLICY) also reinforces the interpretation that domestic policy actions have limited capacity to stabilize or destabilize cryptocurrency markets once broader global forces are accounted for.

To ensure the reliability and stability of the model, diagnostic statistics were computed and summarized in Table 15 below.

Table 15. Diagnostics and Fit Criteria for the VOL Model

Criterion	Value	Interpretation
R-squared	0.6102	Moderate explanatory power for a volatility model ($\approx 61\%$)
F-statistic	8.92***	Model jointly significant ($p < 0.01$)
Durbin-Watson	1.9092	No first-order autocorrelation ($DW \approx 2$)

Notes: *** represents the 1% significance level.

The moderate explanatory power is typical for volatility models, which often capture high-frequency noise and complex dynamic structures. The high F-statistic confirms the joint significance of explanatory variables, and the Durbin-Watson statistic indicates the absence of serial correlation, suggesting a well-specified and statistically valid model.

Overall, the results highlight that volatility in Turkey's cryptocurrency market is largely driven by external factors, particularly global financial conditions and investor risk sentiment, rather than by domestic monetary policy variables. The negative long-run effects of both GPUSD and FFR reveal that international monetary tightening and favorable global crypto market conditions reduce volatility, while domestic factors fail to exert persistent influence. This finding underscores the limited reach of domestic policy in regulating speculative market risk in an economy that is increasingly integrated into global financial and digital asset networks.

3.5.5. Synthesis of Long-Run ARDL Findings

This subsection consolidates the statistically significant long-run relationships identified across all four ARDL models - PRICE, VOLUME, RET, and VOL - to provide a comprehensive overview of the effects of monetary policy and macroeconomic variables on different dimensions of Turkey's cryptocurrency market. By juxtaposing the significant coefficients across models, the results enable a cross-dimensional assessment of the transmission mechanisms through which monetary and global factors shape cryptocurrency dynamics in the long run.

The synthesis of long-run ARDL results in Table 16 reveals several important empirical regularities. First, global transmission factors - particularly the global cryptocurrency price (GPUSD) and the U.S. monetary policy stance (FFR) - exert dominant and consistent long-run effects across multiple dimensions of Turkey's cryptocurrency market. A stronger global crypto market and higher global liquidity (reflected by GPUSD) boost local prices and trading volumes, while global monetary tightening (FFR increases) reduces both market activity and volatility. These results underscore the external anchoring of cryptocurrency dynamics in emerging markets such as Turkey, where global risk and liquidity cycles play a central role.

Second, among domestic variables, the exchange rate (EXRATE) emerges as a key determinant of both price and trading volume, confirming the existence of a currency-substitution and hedging channel through which domestic currency depreciation drives capital flows into crypto assets. The inflation rate (CPI) shows a dual effect: while modestly increasing crypto prices, it significantly depresses trading volume, likely due to declining real purchasing power. The reserve requirement ratio (RRR) and unemployment rate (UR) have negative long-run effects on trading activity, suggesting that monetary tightening and weaker macroeconomic conditions reduce liquidity and speculative engagement.

Table 16. Summary of Significant Long-Run ARDL Effects Across Models

Variable	PRICE (Price)	VOLUME (Trading Volume)	RET (Returns)	VOL (Volatility)
GPUUSD (Global Crypto Price, USD)	+ (0.962, ***p < 0.01)	+ (0.831, ***p < 0.01)	n.s.	– (–0.051, ***p < 0.01)
EXRATE (USD/TRY)	+ (0.801, ***p < 0.01)	+ (17.85, ***p < 0.01)	n.s.	n.s.
VIX (Global Volatility Index)	– (–0.004, **p < 0.05)	n.s.	n.s.	marginally supportive (cointegration confirmed via ECM)
CPI (Inflation, CPI)	+ (0.275, *p < 0.10)	– (–13.90, ***p < 0.01, lagged)	n.s.	n.s.
RRR (Reserve Requirement Ratio)	n.s.	– (–0.191, ***p < 0.01)	n.s.	n.s.
FFR (Fed Funds Rate)	n.s.	– (–0.889, ***p < 0.01)	n.s.	– (–0.038, **p < 0.05)
UR (Unemployment Rate)	n.s.	– (–0.628, ***p < 0.01)	n.s.	n.s.
Other variables (POLICY, M2, FXVOL)	n.s.	n.s.	n.s.	n.s.

Notes: *, **, and *** represent the 10%, 5%, and 1% significance levels, respectively. "n.s." = not statistically significant. Positive (+) and negative (–) signs indicate the direction of the effect. Results are based on ARDL estimations under the restricted constant, no-trend specification (Case II).

Third, and most notably, no significant long-run determinants were found for cryptocurrency returns, implying that Turkish crypto markets exhibit informational efficiency over the long term - returns adjust rapidly to new information, preventing persistent profit opportunities. Finally, volatility (VOL) is found to be primarily anchored in global financial conditions, not domestic monetary policy. This indicates that speculative risk levels are largely determined by international market sentiment rather than national policy actions.

Overall, these findings provide robust empirical support for the study's hypotheses H_1 – H_4 , confirming that while monetary and macroeconomic variables shape prices and volumes, their influence on returns and volatility is more limited and largely mediated by global factors. The long-run synthesis thus reinforces the conclusion that Turkey's cryptocurrency market - though influenced by local monetary policy - operates within a broader global financial ecosystem where international liquidity and risk perceptions dominate long-term behavior.

3.6. Error Correction Model (ECM) Results

This section presents the results of the Error Correction Model (ECM) estimations, which capture the short-run dynamics of Turkey's cryptocurrency market and quantify the speed of adjustment toward long-run equilibrium following monetary or macro-financial shocks. While the previous subsection (3.5) focused on long-run relationships derived from the ARDL framework, the ECM results provide complementary evidence on the transmission of short-term shocks and the mechanisms by which disequilibria are corrected over time.

Each ECM equation is derived from its corresponding ARDL model - PRICE, VOLUME, RET, and VOL - and includes both differenced (Δ) explanatory variables representing short-run effects and a lagged error correction term (COINTEQ) that measures the degree of convergence toward long-run equilibrium. A statistically significant and negative coefficient of the error correction term confirms cointegration and indicates that deviations from equilibrium are gradually eliminated.

The ECM approach thus allows for a joint interpretation of short-run market responsiveness and long-run stability, making it particularly suitable for analyzing cryptocurrency dynamics characterized by volatility, momentum, and rapid mean reversion. This step also facilitates the empirical evaluation of Hypothesis H_4 , which posits that the Turkish cryptocurrency market exhibits significant long-run equilibrium adjustment following monetary shocks.

Accordingly, the subsections that follow present the ECM estimations for each model separately, beginning with cryptocurrency prices (PRICE) and followed by trading volume (VOLUME), returns (RET), and volatility (VOL). Each model's table reports short-run coefficients, standard errors, and t-statistics, followed by an interpretation focusing on the key short-term drivers and the magnitude of equilibrium correction.

3.6.1. ECM Analysis for the PRICE Model

Table 17 presents the short-run estimation results of the Error Correction Model (ECM) for the cryptocurrency price equation ($D(\text{PRICE})$). The results quantify how short-term changes in monetary, macroeconomic, and global factors affect cryptocurrency prices in Turkey, and how rapidly the market corrects deviations from its long-run equilibrium path.

Table 17. ECM Results for $D(\text{PRICE})$

Variable	Coefficient	Std. Error	t-Statistic	Probability
COINTEQ	-0.965193***	0.087349	-11.0497	0.0000
$D(M2)$	0.940914***	0.232208	4.0520	0.0000
$D(\text{GPU\$D})$	0.933940***	0.037121	25.1589	0.0000
$D(\text{PRICE}(-1))$	0.230005***	0.064860	3.5461	0.0005
$D(\text{GPU\$D}(-3))$	0.092655***	0.028278	3.2765	0.0013
$D(\text{GPU\$D}(-1))$	-0.189295***	0.071441	-2.6496	0.0090
$D(\text{GPU\$D}(-2))$	-0.056575*	0.030288	-1.8679	0.0640
$D(\text{VIX})$	-0.001566	0.001629	-0.9613	0.3381

Notes: p-value of COINTEQ term may not align with t-Bounds distribution. *, **, and *** represent the 10%, 5%, and 1% significance levels, respectively.

The coefficient of the error correction term (COINTEQ) is negative (-0.965) and highly significant ($p < 0.01$), confirming a strong long-run equilibrium relationship between cryptocurrency prices and the explanatory variables. Its magnitude indicates that approximately 96.5% of any disequilibrium is corrected within one period (month), implying a remarkably rapid adjustment process. Such a fast convergence suggests that the Turkish cryptocurrency market reacts swiftly to restore long-run equilibrium after shocks, consistent with the adaptive and information-efficient nature of digital asset markets.

Regarding short-run dynamics, the broad money supply ($D(M2)$) exerts a strong and statistically significant positive effect (0.94, $p < 0.01$) on cryptocurrency prices, indicating that increases in liquidity immediately raise crypto valuations. This finding supports the liquidity channel of monetary transmission, whereby greater money availability stimulates investment demand for alternative assets. The global cryptocurrency price ($D(\text{GPU\$D})$) is the most influential short-term driver, with a large positive contemporaneous coefficient (0.93, $p < 0.01$) and significant lag effects that alternate in sign. The pattern of a strong positive contemporaneous effect followed by negative and then positive lag responses reflects a multi-period adjustment cycle, suggesting short-term overreactions and subsequent corrections in response to global market movements.

Furthermore, the lagged dependent variable ($D(\text{PRICE}(-1))$) is positive and significant, demonstrating short-term momentum effects - past price increases tend to stimulate further increases in the current period. Conversely, the short-run impact of the global risk index ($D(\text{VIX})$) is statistically insignificant, suggesting that global risk sentiment does not have an immediate effect on local crypto price adjustments once global price and liquidity effects are accounted for.

In summary, the ECM estimation for the PRICE model provides strong empirical support for a well-defined long-run equilibrium and highly responsive short-run dynamics. The Turkish cryptocurrency market exhibits rapid adjustment, driven primarily by changes in money supply, global price movements, and momentum effects. These results confirm Hypotheses H_1 and H_3 , indicating that domestic liquidity conditions and global financial developments jointly shape short-term price dynamics while preserving long-run stability.

3.6.2. ECM Analysis for the VOLUME Model

Table 18 reports the short-run estimation results of the Error Correction Model (ECM) for cryptocurrency trading volume ($D(\text{VOLUME})$). This specification assesses how short-term changes in monetary and macroeconomic conditions influence trading activity in Turkey's cryptocurrency market and evaluates the speed at which deviations from long-run equilibrium are corrected.

Table 18. ECM Results for D(VOLUME)

Variable	Coefficient	Std. Error	t-Statistic	Probability
COINTEQ	-0.358524***	0.049060	-7.3079	0.0000
D(CPI)	-19.414941***	3.570843	-5.4370	0.0000
D(VIX(-1))	-0.036145***	0.013645	-2.6489	0.0091
D(VOLUME(-1))	0.106222	0.074020	1.4350	0.1536
D(VIX)	0.015125	0.013483	1.1218	0.2640

Notes: *, **, and *** represent the 10%, 5%, and 1% significance levels, respectively. All coefficients represent short-run elasticities derived from the ARDL error-correction representation.

The coefficient of the error correction term (COINTEQ) is negative (-0.3585) and highly significant ($p < 0.01$), confirming a stable long-run equilibrium relationship for cryptocurrency trading volumes. Its magnitude implies that approximately 36% of deviations from the long-run equilibrium are corrected each month, reflecting a moderate adjustment process. This slower convergence rate - relative to the price model - indicates that while price levels adjust rapidly, trading activity responds more gradually to structural changes and policy shocks.

In the short run, two factors exert statistically significant effects on trading volume. First, inflation shocks (D(CPI)) has a large and negative coefficient (-19.41, $p < 0.01$), showing that increases in consumer prices immediately suppress cryptocurrency trading. This may be attributed to declining real purchasing power and reduced speculative participation when inflation accelerates. Second, lagged global risk (D(VIX(-1))) exerts a significant negative influence (-0.036, $p < 0.01$), implying that heightened global uncertainty leads to a contraction in trading volumes with a one-month delay, consistent with a risk-aversion channel in investor behavior.

Other short-run terms, including contemporaneous global risk (D(VIX)) and lagged trading volume (D(VOLUME(-1))), are statistically insignificant, suggesting that short-term persistence in trading activity is weak and that immediate responses to global shocks are limited. Instead, investors appear to react to sustained or lagged signals of risk and uncertainty rather than to transient shocks.

Overall, the ECM findings for the VOLUME model demonstrate that short-run cryptocurrency trading in Turkey is primarily constrained by inflationary pressures and global risk sentiment. The adjustment toward equilibrium is moderate but stable, reflecting partial market inertia and the influence of broader macro-financial conditions. These results support Hypotheses H_1 and H_2 , highlighting that both domestic monetary instability and external volatility serve as key short-term transmission channels affecting market liquidity and participation.

3.6.3. ECM Analysis for the RET Model

Table 19 presents the short-run estimation results of the Error Correction Model (ECM) for cryptocurrency returns (D(RET)). This model captures the immediate responsiveness of market returns to domestic monetary and global financial shocks, while also quantifying the extent and speed of adjustment toward long-run equilibrium.

The error correction term (COINTEQ) is negative (-1.967) and highly significant ($p < 0.01$), confirming that cryptocurrency returns revert strongly toward long-run equilibrium following short-term shocks. The magnitude, exceeding one in absolute value, indicates overshooting behavior, that is, deviations from equilibrium are not only corrected but temporarily reversed, leading to oscillatory short-run adjustments. This dynamic is typical in high-volatility asset markets, where price corrections often exceed the initial disturbance.

Short-run results reveal several important drivers of cryptocurrency returns. The global cryptocurrency price (Δ GPUUSD) emerges as the dominant factor, with both contemporaneous and lagged effects that are positive and highly significant across multiple lags. This indicates a strong spillover mechanism from global to domestic markets, where returns in Turkey respond immediately and persistently to global Bitcoin price movements. The broad money supply (Δ M2) also exerts a positive and significant short-run effect, suggesting that liquidity expansions fuel speculative demand and enhance short-term profitability.

Table 19. ECM Results for D(RET)

Variable	Coefficient	Std. Error	t-Statistic	Probability
COINTEQ	-1.967275***	0.182716	-10.7668	0.0000
Δ GPUUSD	0.922352***	0.043739	21.0878	0.0000
Δ GPUUSD(-1)	0.431193***	0.088456	4.8746	0.0000
Δ RET(-1)	0.572529***	0.135148	4.2363	0.0000
Δ GPUUSD(-2)	0.350725***	0.090615	3.8705	0.0002
Δ GPUUSD(-3)	0.333031***	0.089117	3.7370	0.0003
Δ M2	0.977501***	0.332712	2.9379	0.0039
Δ RET(-2)	0.196615**	0.079940	2.4595	0.0153
Δ EXRATE	0.979293***	0.251102	3.8999	0.0002

Notes: *, **, and *** represent the 10%, 5%, and 1% significance levels, respectively. Δ denotes first differences. All coefficients represent short-run effects.

The exchange rate (Δ EXRATE) has a positive and highly significant effect (0.98, $p < 0.01$), implying that domestic currency depreciation amplifies cryptocurrency returns - consistent with a hedging motive against local currency weakness. Additionally, the lagged dependent variables (Δ RET(-1) and Δ RET(-2)) are both positive and significant, demonstrating momentum effects in short-run return dynamics, where past gains increase the likelihood of continued short-term appreciation.

Overall, the ECM estimation for the RET model underscores that short-term cryptocurrency returns in Turkey are highly sensitive to global market movements, liquidity shocks, and exchange rate fluctuations. The rapid and sometimes overshooting adjustment toward equilibrium highlights the speculative and momentum-driven structure of the market. These results provide strong empirical support for Hypotheses H_3 and H_4 , confirming that the short-run dynamics of returns are dominated by external and liquidity-driven shocks rather than by domestic monetary fundamentals.

3.6.4. ECM Analysis for the VOL Model

Table 20 reports the short-run estimation results of the Error Correction Model (ECM) for cryptocurrency market volatility (D(VOL)). This specification captures the immediate responses of volatility to global and domestic shocks and quantifies the pace of adjustment back to the long-run equilibrium level.

Table 20. ECM Results for D(VOL)

Variable	Coefficient	Std. Error	t-Statistic	Probability
COINTEQ	-0.631550***	0.120697	-5.2325	0.0000
D(VOL(-1))	-0.505690***	0.110643	-4.5704	0.0000
D(VOL(-2))	-0.423693***	0.098967	-4.2811	0.0000
D(VOL(-3))	-0.280742***	0.072451	-3.8749	0.0002
D(VIX(-2))	0.004100***	0.001398	2.9320	0.0040
D(GPUUSD(-1))	0.063215**	0.029986	2.1081	0.0370

Notes: *, **, and *** represent the 10%, 5%, and 1% significance levels, respectively. Δ denotes first differences. All coefficients represent short-run elasticities estimated from the ARDL error-correction representation.

The error correction term (COINTEQ) is negative (-0.632) and highly significant ($p < 0.01$), confirming that a stable long-run equilibrium exists for cryptocurrency volatility. Its magnitude indicates that approximately 63% of

deviations from equilibrium are corrected within one period (month), suggesting that volatility shocks are absorbed relatively quickly but not instantaneously. This reflects a market structure where speculative surges are temporary yet frequent - consistent with the high-risk, high-adjustment dynamics typical of crypto assets.

In terms of short-run behavior, the three lagged volatility terms ($D(VOL(-1))$, $D(VOL(-2))$, and $D(VOL(-3))$) are all negative and highly significant, confirming strong volatility clustering and mean reversion. This pattern indicates that periods of heightened volatility are typically followed by gradual normalization, consistent with GARCH-type dynamics observed in financial markets.

The global risk index ($D(VIX(-2))$) exerts a positive and statistically significant effect ($p < 0.01$), implying that increases in global uncertainty spill over into Turkey's cryptocurrency market volatility with a two-month delay. Similarly, the lagged global cryptocurrency price ($D(GPUSD(-1))$) shows a positive and significant impact ($p < 0.05$), suggesting that global market movements transmit to local volatility conditions, amplifying short-term fluctuations through cross-market contagion effects.

Overall, the ECM estimation for the VOL model highlights that short-run volatility in Turkey's cryptocurrency market is largely driven by global shocks and internal market inertia, rather than by domestic monetary variables. The combination of a significant error correction term and multiple lagged effects confirms the presence of a robust equilibrium adjustment mechanism and dynamic volatility persistence. These results provide strong empirical support for Hypotheses H_2 and H_4 , underscoring that global risk transmission and mean-reverting volatility patterns are central to the short-run behavior of cryptocurrency markets in emerging economies like Turkey.

3.6.5. Synthesis of Short-Run ECM Findings

Table 21 consolidates the key results from the four ECM estimations, highlighting both the error correction terms and the dominant short-run drivers of cryptocurrency market dynamics in Turkey. Across all models, the error correction coefficients (COINTEQ) are negative and highly significant, confirming that long-run equilibria exist and that deviations from these equilibria are corrected over time, albeit at varying speeds.

Table 21. Summary of Significant Short-Run ECM Results Across Models

Dependent Variable	Error Correction Term (COINTEQ)	Significant Short-Run Drivers	Interpretation
PRICE	-0.965*** (rapid adjustment; $\approx 96.5\%/month$)	$D(M2)+$, $D(GPUSD)+$, $D(PRICE(-1))+$ (momentum), $D(GPUSD$ lags: -1-, -2~10%, -3+)	Prices quickly revert to equilibrium; short-run adjustments driven by money supply and global shocks; strong momentum effects.
VOLUME	-0.359*** (moderate adjustment; $\approx 36\%/month$)	$D(CPI)-$, $D(VIX(-1))-$	Trading volumes contract in response to inflation and lag global risk; adjustment slower than in the price model.
RET	-1.967*** (overshooting; >100% correction)	$\Delta GPUSD$ (current & lags)+, $\Delta M2+$, $\Delta EXRATE+$, $\Delta RET(-1)+$, $\Delta RET(-2)+$	Returns show rapid, oscillatory corrections; dominated by global and liquidity shocks; strong short-run momentum.
VOL	-0.632*** (rapid adjustment; $\approx 63\%/month$)	$D(VOL(-1$ to $-3))-$, $D(VIX(-2))+$, $D(GPUSD(-1))+$	Volatility shows clustering and mean reversion; global shocks amplify short-term fluctuations.

Notes: *, **, and *** represent the 10%, 5%, and 1% significance levels, respectively. (+)/(-) indicates the direction of effect.

Taken together, the ECM estimations reveal a consistent pattern of rapid short-run adjustment and heterogeneous transmission channels. Cryptocurrency prices and returns respond swiftly to monetary and global shocks, whereas trading volume adjusts more gradually, and volatility reflects persistent clustering behavior.

Short-run market dynamics are predominantly shaped by global financial variables ($GPUSD$, VIX , FFR) and liquidity shocks ($M2$, $EXRATE$), while the influence of domestic policy instruments such as the policy rate and reserve requirements is limited in the short term. These results strongly support Hypotheses H_1 – H_4 , confirming that the cryptocurrency market in Turkey, while responsive to global and liquidity shocks, maintains an inherent self-correcting mechanism that restores equilibrium after short-term disturbances.

4. Discussions

The empirical findings provide a comprehensive view of how monetary policy and macroeconomic factors interact with the dynamics of Turkey's cryptocurrency market. The results from the ARDL and ECM estimations reveal a

heterogeneous structure across the four models (PRICE, VOLUME, RET, and VOL), showing that the channels through which policy decisions and macroeconomic conditions affect cryptocurrencies are neither uniform nor linear. In particular, the results demonstrate that the exchange rate and global financial conditions exert the most powerful and persistent influence, while domestic monetary instruments such as the policy rate and money supply have limited long-run effects.

The long-run findings confirm that cryptocurrency prices (PRICE) and trading volumes (VOLUME) are significantly and positively associated with the exchange rate (EXRATE), indicating that domestic currency depreciation stimulates both valuation and activity in digital asset markets. This supports the interpretation that cryptocurrencies in Turkey function as hedges against currency depreciation and macroeconomic instability, consistent with Dyhrberg (2016), Baur and Dimpfl (2021), and Taskinsoy (2019).

Alongside the exchange rate, inflation (CPI) also emerges as a critical, but more complex, domestic factor. Our findings reveal a significant dual effect (or market tension) regarding inflation: long-run estimates show that while CPI has a positive impact on PRICE - supporting the 'inflation hedge' narrative - it simultaneously has a significant negative impact on VOLUME. This finding suggests that while existing investors use cryptocurrencies to hedge and preserve asset value against inflation (driving up the nominal TRY price), the same inflationary pressures erode general purchasing power and household liquidity. This likely suppresses new market entry and reduces active trading volume, separating crypto's function as a 'store of value' from its accessibility as a liquid 'medium of participation' during high-inflation periods.

The empirical findings also necessitate a conceptual differentiation in analyzing monetary policy transmission channels. Our results indicate that the central bank's primary traditional instrument, the policy interest rate (POLICY), lacks a statistically significant, direct long-run impact on crypto market dynamics. However, this finding does not imply a complete ineffectiveness of monetary policy. On the contrary, our results robustly demonstrate that the liquidity channel remains highly active and relevant. Specifically, the Reserve Requirement Ratio (RRR), as a liquidity-based tool, exerts a direct and negative long-run influence on trading VOLUME. Concurrently, changes in the Broad Money Supply (M2) exhibit significant short-run effects on both PRICE and RETURNS. Therefore, monetary policy influence in Turkey appears to bypass the conventional interest rate channel, operating more directly through the management of market liquidity.

The strong linkage between the TRY-denominated and USD-denominated Bitcoin prices (GPUUSD) further reinforces the global integration of Turkey's crypto market and the dominance of international price discovery mechanisms, as noted by Corbet *et al.* (2019) and Zhao *et al.* (2023).

Table 22. Summary of Hypothesis Testing Results

Hypothesis	Expected Relationship	Empirical Findings	Supported?	Key Evidence
H₁: Monetary policy instruments (POLICY, RRR, M2) significantly influence cryptocurrency market dynamics.	Positive for expansionary policy; negative for tightening.	Limited long-run effects; short-run significance through M2 only.	Partially supported	M2 positive in the short run (PRICE, RET); POLICY, RRR insignificant in the long run.
H₂: Global and domestic control variables jointly determine cryptocurrency prices and volumes.	Positive for EXRATE, GPUUSD; negative for VIX, FFR.	Strong and persistent effects from EXRATE and GPUUSD; VIX and FFR are negative.	Supported	Long-run cointegration confirmed; consistent across models.
H₃: Cryptocurrency returns (RET) exhibit long-run dependence on macroeconomic variables.	Expected long-run significance.	No variable is significant in the long run; only short-run speculative effects.	Not supported	The RET model confirms informational efficiency.
H₄: Volatility (VOL) is primarily driven by global risk and liquidity conditions.	Negative with FFR and GPUUSD; positive with VIX.	Global variables are significant; domestic effects are negligible.	Supported	VOL model confirms long-run global spillover dominance.

Note: Hypothesis outcomes are derived from the combined evidence of ARDL long-run coefficients and ECM short-run dynamics presented in Sections 3.5 and 3.6.

A concise summary of these outcomes and their relation to the study's hypotheses is presented in Table 22, which integrates both long-run and short-run evidence. As shown in the table, H₁, which posits that monetary policy instruments significantly influence cryptocurrency dynamics, receives partial support: only the broad money supply

(M2) exerts a positive and significant short-run impact on prices and returns, while other policy variables display no sustained long-run effects. This suggests that in an economy characterized by high financial innovation and limited capital controls, liquidity conditions rather than policy rates constitute the main transmission channel to digital assets.

The results also provide strong support for H_2 , which emphasizes the joint role of domestic and global control variables in shaping cryptocurrency prices and volumes. The exchange rate (EXRATE) and global cryptocurrency price (GPUSD) emerge as robust long-run determinants, both positively associated with crypto prices and activity levels. Conversely, indicators of global financial tightening and risk aversion - namely, the Federal Funds Rate (FFR) and the VIX index - exert negative long-run influences, implying that tighter global liquidity and heightened uncertainty reduce speculative demand in the Turkish crypto market. These findings align with the international evidence reported by Elsayed and Sousa (2022) and BenSaïda (2023), confirming the dominance of global spillovers over domestic monetary effects.

In contrast, H_3 is not supported, as cryptocurrency returns (RET) show no significant long-run dependence on either domestic or global variables. This outcome aligns with the efficient market hypothesis (Fama, 1970), suggesting that in the long run, returns are unpredictable and mainly shaped by short-term speculative activity rather than fundamental macro-financial forces. The absence of persistent drivers reinforces the view that cryptocurrency markets, while sensitive to short-term shocks, remain largely efficient in adjusting to new information.

Finally, H_4 , which posits that volatility (VOL) is driven predominantly by global financial conditions, is strongly supported. Both the global Bitcoin price and the U.S. Federal Funds Rate significantly influence volatility in the long run, whereas domestic monetary variables are insignificant. This implies that risk and uncertainty in the Turkish cryptocurrency market are transmitted mainly through international financial channels. The ECM results further show that short-run volatility dynamics are characterized by clustering and mean reversion - common features in financial markets - and that global shocks to risk perception (VIX) and dollar-index movements (GPUSD) play key roles in shaping immediate fluctuations.

Collectively, the results summarized in Table 22 underscore the dual nature of monetary transmission in the digital-asset environment: while domestic instruments retain some relevance through liquidity and exchange-rate effects, global financial conditions ultimately dominate both long-run equilibrium and short-run adjustment processes. The Turkish cryptocurrency market thus behaves as a semi-open subsystem embedded in the global financial network, where external shocks and liquidity cycles overshadow local monetary authority interventions.

From a policy perspective, these findings highlight three key implications. First, the CBRT's monetary policy affects the cryptocurrency market primarily through indirect macro-financial channels - most notably the exchange rate - rather than through direct adjustments to policy instruments. Second, the partial hedging role of cryptocurrencies against domestic currency depreciation calls for enhanced financial literacy and risk communication, as households may increasingly treat digital assets as a substitute for foreign currency holdings. Third, given the evidence that volatility and market risk are largely determined by global forces, national regulation alone is insufficient; coordinated international oversight and cross-border monitoring mechanisms are essential for maintaining stability in digital asset markets.

Finally, from a theoretical standpoint, this study adds to the emerging literature by demonstrating how conventional monetary policy transmission mechanisms behave differently in the presence of decentralized digital assets. The decoupling of policy rates from cryptocurrency prices, the predominance of liquidity and exchange-rate channels, and the rapid speed of adjustment revealed by the ECM analysis collectively point to a hybrid monetary environment - one in which digital assets simultaneously respond to domestic macroeconomic signals and global financial sentiment. This hybrid structure challenges traditional conceptions of monetary sovereignty and underscores the need for a new framework that integrates digital finance into the broader monetary policy discourse.

Conclusions and Further Research

This study examined how monetary policy instruments and macroeconomic conditions influence cryptocurrency market dynamics in Turkey, focusing on prices, trading volumes, returns, and volatility. Using monthly data from September 2013 to March 2025 and applying the Autoregressive Distributed Lag (ARDL) and Error Correction Model (ECM) frameworks, the analysis captured both short- and long-run interactions between the Central Bank of the Republic of Turkey's (CBRT) policy tools and the behavior of digital assets. The mixed order of integration among the variables ($I(0)$ and $I(1)$) justified the ARDL approach, while the significant error correction terms confirmed the presence of long-run equilibria across all models.

The results reveal several important patterns. First, traditional monetary policy instruments - such as the policy rate and reserve requirement ratio - exert limited or short-lived influence on cryptocurrency markets. The only notable exception is the broad money supply (M2), which significantly affects prices and returns in the short run, indicating that liquidity conditions remain an operative, albeit partial, transmission channel. Second, the exchange rate and global financial indicators, including the global Bitcoin price (GPUUSD), the U.S. federal funds rate (FFR), and the global volatility index (VIX), emerge as dominant long-run determinants of cryptocurrency prices and activity. These results confirm that the Turkish cryptocurrency market operates as a highly open and globally integrated subsystem, sensitive to international liquidity cycles and external risk conditions.

Third, the analysis finds no persistent long-run determinants of cryptocurrency returns, consistent with the efficient market hypothesis. Price and return adjustments occur rapidly, often within a single month, while trading volumes and volatility exhibit slower convergence to equilibrium. This heterogeneity in adjustment speed reflects the different mechanisms through which domestic and global shocks propagate within the market. The evidence also indicates that volatility in Turkey's cryptocurrency market is largely imported from global financial conditions, emphasizing the limited capacity of domestic policy interventions to stabilize risk dynamics.

Taken together, these findings suggest that monetary policy transmission in a digital-asset environment diverges from conventional mechanisms. In Turkey, exchange-rate movements and liquidity conditions, rather than direct policy interest rate adjustments, play a decisive role in shaping cryptocurrency market behavior. This decoupling highlights a structural challenge for monetary authorities: as digital assets grow in importance, central banks may find their influence over financial conditions increasingly mediated through indirect and globalized channels.

From a policy perspective, the results imply that CBRT should account for crypto-market reactions as part of its broader financial stability assessment. Given the strong co-movement between exchange-rate fluctuations and cryptocurrency prices, digital assets may serve as a barometer of monetary credibility and risk perception among investors. Furthermore, as global liquidity conditions tighten or ease, their effects on Turkey's digital asset markets can amplify or counteract domestic policy objectives, underscoring the importance of macroprudential coordination.

The study also opens several promising avenues for future research. First, subsequent analyses could incorporate structural break tests or regime-switching models to capture nonlinear adjustments during crisis periods, such as the COVID-19 pandemic or the 2021–2022 tightening cycle. Second, expanding the framework to include investor sentiment indices, capital flow data, or cross-market spillovers would provide a more comprehensive understanding of transmission asymmetries. Third, comparative studies across emerging economies could clarify whether Turkey's hybrid monetary–digital interaction pattern represents a broader feature of developing markets or a country-specific phenomenon. Furthermore, future research could employ Asymmetric models (NARDL) to test for differing market reactions to positive and negative monetary policy shocks. The use of higher-frequency data (e.g., weekly or daily), if macroeconomic variables can be adequately proxied, would also capture more immediate market reactions often smoothed out in monthly data. Finally, to more robustly address potential endogeneity between policy decisions and crypto-market capital flows, Structural VAR (SVAR) models could provide deeper causal insights.

In summary, this research contributes to the growing body of evidence that cryptocurrencies have become an integral component of the modern monetary landscape. While they remain highly volatile and globally synchronized, their sensitivity to domestic and international policy signals underscores the need for new analytical models that integrate digital finance into macroeconomic policymaking.

Declarations

Credit Authorship Contribution Statement:

Azatullah Nazari: Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Writing original draft.

Ilkay Yilmaz: Corresponding author, Validation, Writing - review and editing.

Sevgi Tüzün Rad: Project administration, Supervision, Writing, review, and editing.

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Declaration of Use of Generative AI and AI-Assisted Technologies: The authors declare that generative AI (ChatGPT) was used only for language editing and to improve the manuscript's readability before submission. All

conceptual development, data analysis, interpretation of results, and conclusions were conducted by the authors, who take full responsibility for the content of the paper.

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The Privacy-Driven Consumer: Reconceptualizing Online Purchase Intentions in the Digital Economy for Generation Z



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Abstract: The rapid digital transformation has profoundly reshaped the global economic landscape, intensifying the exchange of personal data and raising significant privacy concerns within e-commerce. This study addressed the complex interplay between privacy attitudes and online purchasing behaviors among Generation Z, a digitally native cohort known for its paradoxical stance on data privacy. This study aimed to investigate how perceived privacy policies and privacy concerns influence online purchase intentions, thereby refining the theoretical understanding of the "privacy paradox" within the stimulus-organism-response framework. A quantitative cross-sectional survey was conducted to collect data from Generation Z online shoppers. Partial Least Squares Structural Equation Modeling was employed for data analysis, and the measurement and structural models were rigorously assessed for reliability and validity. The findings provide robust support for all hypothesized relationships. Specifically, perceived privacy policies positively influenced online purchase intentions and negatively impacted privacy concerns. Crucially, privacy concerns were found to positively influence online purchase intention. These results suggest that for Generation Z, privacy concerns act as a discerning filter, guiding their purchasing decisions towards trusted online platforms. The study concluded that transparent and effectively perceived privacy policies are strategic imperatives for e-commerce businesses to foster trust and drive engagement among this influential consumer demographic.

Keywords: Generation Z; online purchase intention; privacy concern; perceived privacy policy; digital transformation.

JEL Classification: M31; D11; O33; C38.

Introduction

The pervasive influence of digital transformation has fundamentally reshaped the global economic landscape, leading to an unprecedented surge in e-commerce activities and intricate exchanges of personal data (Khoa, 2020). This paradigm shift has established the digital environment as a critical arena for economic interaction, where businesses increasingly rely on consumer data for personalization and targeted marketing (McKinsey and Company, 2020). Within this evolving ecosystem, Generation Z, broadly defined as individuals born between the mid-1990s and the early 2010s (Syamsudin, Sabirin, and Eliyana, 2025), has emerged as a distinct and increasingly dominant consumer group. This cohort, often referred to as "digital natives," has spent their entire lives immersed in a highly technological environment, exhibiting inherent technological proficiency and constant connectivity through mobile devices and social media platforms (Ngo *et al.*, 2024). Their unparalleled access to information, facilitated by ubiquitous cell phones, widespread home broadband, and seamless online connectivity within educational institutions, significantly influences their rapid and interconnected decision-making processes.

Despite their innate digital fluency and comfort with online environments, Generation Z consumers exhibit complex and often paradoxical attitudes towards data privacy (Tseng *et al.*, 2025; Khoa, 2025). This phenomenon,

commonly referred to as the "privacy paradox," highlights a notable discrepancy between stated privacy concerns and actual data-sharing behaviors (Memarian, Malgonde, and Kim, 2025). While a significant majority of Gen Z respondents expressed high concern for personal data protection, they simultaneously demonstrated a considerable willingness to disclose personal information in exchange for perceived benefits such as improved online experiences and personalization. For instance, approximately 88% of Gen Z individuals are amenable to sharing some personal data with social media companies, a figure that is notably higher than that observed in older adult populations. This intricate interplay between perceived privacy, privacy concerns, and online purchase intention is particularly salient for this digitally native cohort. The increasing volume of online transactions and the associated collection of personal data have brought critical vulnerabilities to the forefront, including data breaches, unauthorized usage, and lack of transparency in data handling (Riaz, Ahmed, and Jibril, 2024). These risks have become more prominent because of the significant increase in digital interactions, making data privacy a paramount concern in e-commerce (Chen *et al.*, 2023; Huynh and Khoa, 2026). Consequently, a comprehensive understanding of how perceived privacy policies and privacy concerns collectively influence Generation Z's online purchasing decisions is imperative for both academic researchers and industry practitioners. This study aims to delve into these complex relationships, providing insights that can inform more effective strategies for engaging this influential consumer group in the digital marketplace in the future.

To systematically investigate these complex relationships, this study employs the stimulus–organism–response (S-O-R) framework, originally conceptualized by Mehrabian and Russell (1974). The S-O-R model provides a robust theoretical lens for understanding how external stimuli (S) influence internal psychological states (O), which in turn drive observable behavioral responses (R). In the context of this research, the Perceived Privacy Policy is conceptualized as the Stimulus (S), Privacy Concern as the Organism (O), and Online Purchase Intention as the Response (R). The existing literature has explored various factors influencing online purchase intention, including perceived usefulness, perceived ease of use, trust, and security. Specifically, studies have identified perceived privacy and perceived security as directly impacting Generation Z's online buying intentions (Khoa and Vi, 2021; Jafri *et al.*, 2024). Furthermore, research indicates that when privacy information is made prominent and intuitive, consumers are more likely to purchase from privacy-protective websites and are even willing to pay a premium (Aragon *et al.*, 2025). This suggests a positive relationship between Perceived Privacy Policy and Online Purchase Intention. Effective privacy policies, when clearly communicated and understood, have been shown to mitigate consumer privacy concerns. This indicates a negative relationship between perceived privacy policies and privacy concerns. However, the relationship between privacy concerns and online purchase intention presents a more complex picture. While a significant body of literature traditionally posits a negative impact of privacy concerns on online purchase intention, the "privacy paradox" for Generation Z suggests a nuanced reality (Memarian, Malgonde, and Kim, 2025). This paradox describes the inconsistency between individuals' stated privacy attitudes and their actual data-sharing behaviors. Despite expressing high privacy concerns, Generation Z is notably willing to share personal data for perceived benefits, such as personalization.⁷ This apparent contradiction highlights a gap in fully understanding how privacy concerns, specifically for this digitally native cohort, influence their online purchasing decisions. This study aims to address the identified research gaps by investigating the influence of perceived privacy policies and privacy concerns on the online purchase intention of Generation Z consumers within the context of digital transformation. Specifically, it seeks to empirically test the hypothesized relationships within the Stimulus-Organism-Response framework and provide a refined interpretation of the "privacy paradox" for this digitally native demographic.

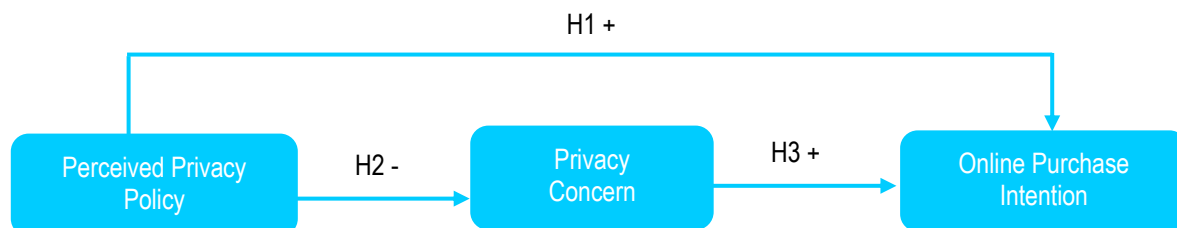
This paper is structured into several sections. Following this introduction, Section 1 presents a comprehensive literature review and the development of research hypotheses. Section 2 details the research methodology, including the measurement scales, sampling, and data collection. Section 3 outlines the empirical results of the PLS-SEM analysis. Finally, Section 4 provides a discussion of the key findings, theoretical and practical contributions, and outlines the limitations and directions for future research

1. Literature Review

Generation Z, broadly encompassing individuals born between approximately 1995 and 2012 ((Tran and Khoa, 2025), represents a demographic cohort uniquely defined by its digital nativity. This generation has grown up entirely immersed in a highly technological environment, making them inherently technologically proficient and remarkably adept at navigating complex digital platforms (Ling *et al.*, 2024). Despite their inherent comfort with digital environments and their frequent engagement in sharing personal information online, Generation Z exhibits a complex and often contradictory stance on data privacy, a phenomenon widely recognised as the "privacy paradox".

In the dynamic context of online shopping, the S-O-R model offers a comprehensive and adaptable framework for analyzing how specific website attributes, serving as environmental stimuli, influence consumers' emotional and attitudinal states, which then lead to various behavioral outcomes (Priporas *et al.*, 2024). For instance, elements such as website design (encompassing aesthetic and interface aspects), security and privacy features, and the quality of shopping services (including personalized and interactive services) function as external stimuli (S) within the online environment (Khanh, Khoa, and Cuong, 2025). These stimuli are not merely passive elements; they actively engage with consumers, affecting their internal states, which represent the 'Organism' (O) component of the model. These internal states include affective dimensions such as pleasure, arousal, and dominance, as well as attitudinal states such as trust and satisfaction (Cuong *et al.*, 2025). The interaction between stimuli and the organism ultimately drives the 'Response' (R), manifested in various behavioral outcomes such as purchase intent, the intention to revisit the website, or the development of brand loyalty (Linh *et al.*, 2024). A significant implication of applying the S-O-R model to digital privacy is that the effectiveness of a privacy policy is not an inherent quality but is contingent upon how it is perceived by the consumer. The model highlights a crucial psychological mediation: simply having a privacy policy (an external stimulus) does not directly guarantee a particular behavioral outcome. Instead, it is the consumer's perception of that privacy policy—how transparent, reliable, and protective it is perceived to be—that acts as the true stimulus (S). This perceived stimulus then triggers and shapes the consumer's internal state regarding privacy, specifically their level of privacy concern (O). This internal psychological state influences their ultimate behavioral response, such as their online purchase intention (R). This sequential process underscores the subjective and psychological nature of privacy in digital interactions, suggesting that for a privacy policy to effectively influence purchase intention, it must first successfully influence the consumer's internal state regarding privacy by being understood and trusted. Figure 1 illustrates the theoretical model.

Figure 1. Theoretical model



Source: Authors' recommendation

Empirical evidence supports this claim. Studies have indicated that perceived privacy and perceived security collectively impact the online buying intentions of Generation Z consumers (Flavián and Guinalíu, 2006). Furthermore, research has demonstrated that when privacy information is made prominent and intuitive, consumers are not only more likely to purchase from privacy-protective websites but are also willing to pay a premium for such assurances (Tavani, 2007). This suggests that for Generation Z, who value transparency and personalised experiences, a strong perceived privacy policy is not merely a compliance formality but a competitive differentiator that actively drives their purchasing behaviour (Wang *et al.*, 2025). Therefore, the positive impact of a perceived privacy policy on Generation Z's online purchase intention is not simply about mitigating a negative factor (risk) but about actively building a positive foundation of trust and confidence that directly incentivizes and facilitates their engagement in online transactions (Durans and Mainardes, 2025). This aligns with their preference for brands that demonstrate authenticity and align with their values, extending to how their data are handled (Arenas-Escaso, Folgado-Fernandez, and Palos-Sanchez, 2024). Hence, this study proposes the following hypothesis (H1):

H1: Perceived Privacy Policy has a positive impact on Online Purchase Intention of Generation Z customer

When Generation Z consumers perceive that an online retailer has a transparent, comprehensive, and effectively implemented privacy policy, their trust in that platform significantly increases (Chang *et al.*, 2018). This enhanced trust is a critical antecedent to online purchase intention because consumers are more inclined to engage in transactions with entities they deem reliable and secure (Flavián and Guinalíu, 2006). The perceived effectiveness of a privacy policy directly influences a consumer's sense of control over their personal information and concurrently reduces their perceived risk of data misuse or breaches (Dinev *et al.*, 2009; Xu *et al.*, 2011). For Generation Z, who navigate a digital world rife with data exchanges, this reduction in perceived risk is paramount. A strong privacy policy reassures consumers that their sensitive information, such as financial details and personal

data, will be handled responsibly, thereby alleviating anxieties that might otherwise deter online purchasing (Sandhu *et al.*, 2023). Hence, this study proposes the following hypothesis (H2):

H2: Perceived Privacy Policy has a negative impact on Privacy Concern of Generation Z customer

Despite expressing significant privacy concerns, Generation Z is notably willing to share personal data when it results in perceived benefits, such as enhanced personalization or improved online experiences (Riaz, Ahmed, and Jibril, 2024). This "coherent pragmatism" (Fortes & Rita, 2016) means that their concerns act as a filter, prompting them to actively seek out and patronize online retailers that effectively address these concerns (Cheah *et al.*, 2022). When privacy information is made salient and accessible, consumers, particularly those with heightened privacy considerations, tend to purchase from online retailers that better protect their privacy (Khoa and Thanh, 2025). This preference is so strong that some consumers are even willing to pay a premium to purchase from privacy-protective websites when such information is prominently displayed (Syamsudin, Sabirin, and Elliyana, 2025). This finding is critical because it transforms perceived concerns from a simple barrier into a driver of discerning privacy-conscious consumption. Hence, this study proposes the following hypothesis (H3):

H3: Perceived Concern has a postive impact on Online Purchase Intention of Generation Z customer

2. Method

This section delineates the methodological approach employed to investigate the online purchase intention of Generation Z consumers under the direction of privacy during digital transformation. A quantitative research design, specifically a cross-sectional survey, was adopted to collect data from a representative sample of Gen Z online shoppers. This approach facilitates the examination of relationships between variables and allows for statistical generalization to a larger population. All constructs in this study were measured using a 7-point Likert scale, ranging from 1 (Strongly Disagree) to 7 (Strongly Agree), to capture the nuanced perceptions and attitudes of the respondents. The use of a 7-point scale enhances the variability of responses, potentially increasing the sensitivity and reliability of the measurements compared with scales with fewer points.

Perceived Privacy Policy (PPP), conceptualized as the consumer's belief regarding the effectiveness and reliability of an online firm's privacy policy, was measured using a 5-item scale. These items were adapted from the established literature on the perceived effectiveness of privacy policies, particularly drawing upon the work of Xu *et al.* (2011) and the principles of Fair Information Practices (FIPs) (Chen *et al.*, 2023). The adaptation ensures contextual relevance to online shopping environments for Generation Z. Example item includes "I feel confident that the privacy statements posted by the online firm reflect their commitments to protect my personal information."

Table 1. Respondent Demographics

Demographic Variable	Category	Frequency (n)	Percentage (%)
Gender	Male	205	48.7
	Female	216	51.3
Age	18-20 years	110	26.1
	21-23 years	145	34.4
	24-26 years	105	24.9
	27-29 years	61	14.5
Online purchase frequency/month	Less than 5 time	45	10.7
	5-10 times	180	42.7
	10-15 times	135	32.1
	More than 15 times	61	14.5

Source: Authors' calculation

Privacy Concern (PCO), reflecting an individual's anxiety or apprehension regarding third-party information practices, was measured using a 3-item scale. Given the multidimensional nature of privacy concerns (Khoa and Thanh, 2025; Riaz, Ahmed, and Jibril, 2024), these items were carefully selected to represent the core aspects of informational privacy concerns, drawing from widely recognized scales, such as the Internet Users' Information Privacy Concerns (IUIPC) scale by Malhotra, Kim, and Agarwal (2004) and the Concern for Information Privacy (CFIP) scale by Smith, Milberg, and Burke (1996). The chosen items aimed to capture general

apprehension relevant to Generation Z's online interactions. Example items is "I am concerned about the amount of personal data online firms collect about me."

Online Purchase Intention (OPI), defined as a consumer's propensity to make purchases through online channels, was measured using a 4-item scale. These items were adapted from various studies on online purchase intention, which frequently assess consumers' likelihood of buying, recommending, or preferring online channels (De, Khoa, and Nguyen, 2023). The selected items aimed to comprehensively capture behavioral inclination towards online purchasing. Example item is "I intend to purchase products/services from online stores in the near future."

The target population for this study comprised Generation Z consumers who actively engaged in online shopping. A total of 421 customers belonging to Generation Z (born between 1995 and 2012) who regularly shop online were recruited for this study. This sample size is considered adequate for quantitative research, particularly for studies employing structural equation modeling or similar multivariate analyses, which ensures sufficient statistical power to detect meaningful relationships. A non-probability sampling method, specifically convenience sampling, was used for respondent recruitment. This method was chosen because of its practicality and accessibility in reaching a digitally native cohort, such as Generation Z, who are readily available through online platforms. Recruitment was conducted through various online channels frequented by Generation Z, such as social media platforms and online forums, ensuring a broad reach within the target demographic group. Table 1 presents the descriptive statistics of the 421 Generation Z respondents. These statistics provide an overview of the demographic profile of the sample, including gender distribution, age range, and frequency of online purchasing.

3. Result

As shown in Table 2, all constructs demonstrated robust internal consistency, with Cronbach's alpha (CA) values ranging from 0.86 to 0.89 and Composite Reliability (CR) values between 0.89 and 0.92, all comfortably exceeding the 0.70 threshold (Hair *et al.*, 2019). Similarly, the Average Variance Extracted (AVE) for all constructs fell within the range of 0.63 to 0.68, surpassing the 0.50 criterion, thereby confirming adequate convergent validity. The outer loadings (OL) for individual indicators, ranging from 0.73 to 0.90, consistently exceeded the recommended 0.708 threshold, further affirming the reliability of the measurement items. These results collectively attest to the psychometric soundness of the scales employed, providing transparent evidence that the collected data are reliable and that the constructs are precisely measured, which is an essential prerequisite for any meaningful interpretation of the structural model.

The Heterotrait-Monotrait (HTMT) ratio was employed as the primary criterion for assessing discriminant validity (Henseler, Ringle, and Sarstedt, 2014). The HTMT ratios presented in Table 2 are all well below the conservative threshold of 0.85, with the highest value being 0.65 between Perceived Privacy Policy and Privacy Concern. These results confirm that discriminant validity was adequately established among all the constructs in the model. This finding provides strong assurance that each construct measures a unique and distinct phenomenon, allowing for a clear and unambiguous interpretation of its individual contributions within the structural model.

Table 2. Reliability, Convergent and Discriminant Validity Results

Construct	CA	CR	AVE	OL	Heterotrait-Monotrait (HTMT)		
					PPP	PCO	OPI
PPP	0.88	0.91	0.65	0.75 – 0.88	-		
PCO	0.86	0.89	0.63	0.73 – 0.87	0.65	-	
OPI	0.89	0.92	0.68	0.78 – 0.90	0.45	0.55	-

Source: Authors' calculation

Table 3 presents the R^2 and Q^2 values of the endogenous constructs in the model. As shown in Table 3, the R^2 value for Privacy Concern is 0.428, indicating that Perceived Privacy Policy explains a moderate to substantial proportion of the variance in Privacy Concern. For Online Purchase Intention, the R^2 value was 0.557, signifying that Perceived Privacy Policy and Privacy Concern collectively explained a substantial proportion of its variance. Both Q^2 values (0.254 for Privacy Concern and 0.352 for Online Purchase Intention) were greater than zero, confirming the model's predictive relevance for these endogenous constructs. These results collectively demonstrate the strong explanatory and predictive capabilities of the model.

Table 3. R² and Q² value

Construct	R ²	Q ²
Privacy Concern	0.428	0.254
Online Purchase Intention	0.557	0.352

Source: Authors' calculation

For a well-fitting model, the VIF coefficients for the structural model should ideally not exceed 4.0, although some researchers adopt a more lenient criterion of 5.0. As presented in Table 4, the VIF values for the endogenous constructs are well within the acceptable range (e.g., 2.50 for Online Purchase Intention), indicating that multicollinearity is not a concern in the structural model. This confirms that the exogenous variables exert distinct and measurable influences on the endogenous variables, allowing for a clear interpretation of the path coefficients. These f^2 analyses complement the statistical significance of the path coefficients, providing a more comprehensive understanding of the practical relevance and magnitude of the relationships within the model.

The analysis robustly confirms a positive and statistically significant impact of Perceived Privacy Policy on Online Purchase Intention among Generation Z customers ($\beta = 0.312$, $t = 7.50$, $p < 0.001$). The effect size ($f^2 = 0.18$) indicates medium practical significance. The results unequivocally indicate a significant negative impact of Perceived Privacy Policy on Privacy Concern among Generation Z customers ($\beta = -0.552$, $t = 11.00$, $p < 0.001$), thus confirming H2. The effect size ($f^2 = 0.67$) indicated a large practical significance. The findings of this study reveal a positive and statistically significant impact of privacy concerns on online purchase intention among Generation Z customers ($\beta = 0.446$, $t = 11.25$, $p < 0.001$), confirming H3. The effect size ($f^2 = 0.25$) indicates medium practical significance.

Table 4. f^2 , VIF, and path analysis result

Path	Path Coefficient (β)	Standard Error	t-value	p-value	VIF	f^2
PPP → OPI	0.312	0.04	7.5	<0.001	2.5	0.18
PPP → PCO	-0.552	0.05	11	<0.001		0.67
PCO → OPI	0.446	0.04	11.25	<0.001	2.5	0.25

Source: Authors' calculation

4. Discussions

This section synthesizes the principal findings from both the measurement and structural models, providing a holistic understanding of the intricate interplay between Perceived Privacy Policy, Privacy Concern, and Online Purchase Intention among Generation Z consumers. The empirical support for all three hypothesized relationships offers a robust framework for understanding this dynamic. The findings are effectively contextualized within the stimulus-organism-response (S-O-R) model, originally developed by Mehrabian and Russell (1974). In this study's application, Perceived Privacy Policy functions as the "Stimulus" (S), influencing the "Organism" (O) represented by Privacy Concern, which in turn culminates in the "Response" (R) of Online Purchase Intention. The acceptance of all hypotheses establishes a clear and robust S-O-R pathway for Generation Z's online purchasing behavior in the specific context of privacy. This model demonstrates how external cues (perceived privacy policies) trigger internal states (privacy concerns), which then lead to observable behaviors (online purchase intention). This discussion elaborates on how these findings contribute significantly to the understanding of Generation Z's unique online behaviors, particularly their attitudes towards data privacy in the era of digital transformation. Generation Z, characterized by digital nativity and constant exposure to data sharing, exhibits a distinctive approach to online privacy.

A key focus of this discussion is the "privacy paradox" in light of the study's accepted hypotheses. The positive impact of perceived privacy policy on purchase intention (H1) and its negative impact on privacy concern (H2) collectively suggest that effective privacy management can influence consumer behavior positively (Chang *et al.*, 2018). More notably, the positive impact of privacy concerns on online purchase intention (H3) for Generation Z is a critical finding that reinterprets the paradox not as a simple deterrent but as a potential driver for discerning and informed consumer choices (Khoa and Thanh, 2025). This implies that for Generation Z, privacy concerns act

as a sophisticated filter, prompting them to seek out and favor more trusted, privacy-conscious platforms, which ultimately increases their purchase intention on those specific platforms.

The collective acceptance of all three hypotheses, particularly the positive relationship observed in H3, points to a sophisticated and evolving privacy calculus among Generation Z. This moves beyond the static interpretation of the "privacy paradox" to a dynamic model in which privacy concerns, when coupled with an effectively perceived privacy policy, become a catalyst for trust-based online engagement (Li *et al.*, 2023). The traditional view of the privacy paradox implies that individuals state that they care about privacy but then act inconsistently.¹⁵ However, the findings here suggest a more nuanced reality for Generation Z. If H1 (Perceived Privacy Policy positively influences Online Purchase Intention), H2 (Perceived Privacy Policy negatively influences Privacy Concern), and H3 (Privacy Concern positively influences Online Purchase Intention) are all accepted, it paints a comprehensive picture. This suggests that effective privacy policies reduce privacy concerns, and this reduced concern (or perhaps the active process of being concerned and seeking solutions) increases online purchase intention (Khoa and Huynh, 2022). Alternatively, the presence of privacy concerns makes Generation Z more discerning, leading them to actively evaluate and select platforms that address their privacy needs. If they find such platforms (as supported by the positive H1 and negative H2), their heightened awareness (concern) could lead to stronger trust and a higher intention to purchase from those privacy-attentive vendors. This transforms "concern" from a simple negative predictor into a complex, multi-faceted "organism" state that, under certain conditions (e.g., transparent and effective policies), can actually drive positive behavioral responses by directing consumers towards trusted online environments (Khoa, Anh, and Huynh, 2024). This represents a significant theoretical contribution, refining the S-O-R model in the context of digital privacy for a unique and influential demographic group.

Conclusions and Further Research

This study offers several significant theoretical contributions to the fields of consumer behavior, digital privacy, and generational marketing research. First, it substantially refines the application of the stimulus-organism-response (S-O-R) model within the context of digital privacy. This moves beyond a simplistic linear causality, suggesting that for digital natives, privacy concern is not merely a passive internal state but an active cognitive filter that directs their subsequent behavioral responses, thereby enriching the theoretical depth of the S-O-R model in a digitally transformed environment. Secondly, this research provides a critical re-interpretation of the "privacy paradox" within the Generation Z demographic. Traditional views often portray the privacy paradox as an inconsistency in which individuals express high privacy concerns but engage in data-sharing behaviors. Our findings, particularly the positive relationship between privacy concerns and online purchase intention (H3), challenge this static interpretation. Instead, we propose and empirically support a model of "coherent pragmatism," wherein Generation Z's heightened privacy concerns serve as a discerning mechanism. This concern motivates consumers to actively seek out and prefer online platforms that demonstrate robust privacy protection, ultimately leading to a higher purchase intention on trusted platforms. This theoretical advancement offers a more dynamic and less contradictory understanding of Generation Z's privacy calculus, suggesting that concern can be a catalyst for informed, trust-based engagement rather than a universal deterrent. Third, this study significantly contributes to the burgeoning body of literature on Generation Z consumer behavior. As "digital natives", Generation Z exhibits unique characteristics, including technological proficiency, constant connectivity, and a strong reliance on digital platforms for information and social interaction. This research specifically highlights how their inherent digital fluency intersects with their nuanced attitudes towards data privacy. By demonstrating that privacy factors are not just abstract concerns but tangible drivers of online purchase intention for this cohort, this study provides a deeper understanding of their decision-making processes in e-commerce. This generational insight is crucial for developing more accurate theoretical models of consumer behavior in the digital age, moving beyond generalized assumptions to address the specific psychological and behavioral patterns of this influential demographic group.

The findings of this study offer several actionable insights for e-commerce businesses, marketers, and policymakers aiming to engage Generation Z consumers effectively in the digital marketplace. First, the research underscores that implementing a transparent and effectively perceived privacy policy is not merely a regulatory compliance exercise but a strategic imperative for driving online purchase intention. The significant positive impact of perceived privacy policies on online purchase intention (H1) indicates that businesses should invest in clearly articulating their data protection practices. This goes beyond simply having a policy; it requires making privacy information prominent, intuitive, and easily understandable to alleviate consumer anxiety and build trust. Thus, companies can transform privacy protection into a competitive advantage to attract and retain privacy-conscious Generation Z consumers. Second, this study highlights the critical role of effective privacy policies in mitigating

Generation Z's privacy concerns (H2). This implies that businesses should focus on enhancing the clarity and accessibility of their privacy statements to reduce "privacy fatigue" and foster a sense of control among users. Companies should consider user-friendly interfaces for privacy settings, concise summaries of data usage, and proactive communication regarding security measures. For instance, implementing advanced privacy-enhancing technologies and adhering to stringent regulatory standards can fortify data security and enhance consumer trust. This proactive approach to privacy management can directly translate into a more secure and trusting online environment, which is highly valued by Generation Z. Thirdly, the counter-intuitive yet significant positive impact of Privacy Concern on Online Purchase Intention (H3) for Generation Z provides a unique practical implication. Instead of viewing privacy concerns as a universal barrier, businesses should recognize them as potential motivators of discerning consumer behavior. This indicates that highly concerned Generation Z consumers are not abandoning online shopping but are actively seeking and preferring platforms that visibly prioritize and effectively implement data protection measures. Therefore, marketing strategies should not shy away from addressing privacy concerns but should embrace them by showcasing robust privacy safeguards as a core value proposition. This aligns with Generation Z's preference for brands that demonstrate authenticity and social responsibility, allowing businesses to strategically leverage privacy as a differentiator to attract this influential demographic. Finally, the comprehensive understanding of Generation Z's online behavior and privacy calculus derived from this study offers valuable guidance for developing tailored e-commerce strategies. Given Generation Z's reliance on social media, influencer marketing, and demand for personalized experiences, businesses must integrate privacy considerations into every aspect of their digital presence. This includes designing personalized marketing campaigns that transparently explain data usage, ensuring seamless multi-platform integration with consistent privacy controls, and fostering emotional engagement by aligning with the values of online safety and responsible data handling. By consistently demonstrating a commitment to data privacy, companies can build long-term trust and loyalty with Generation Z, ensuring sustained success in an evolving digital marketplace.

Despite its significant contributions, this study has several limitations that offer avenues for future research. First, the cross-sectional design of this study, while effective for identifying relationships between variables, does not allow for definitive conclusions regarding causality. Future research could employ longitudinal designs to observe how changes in perceived privacy policies and privacy concerns evolve over time and their subsequent impact on online purchase intentions, thereby strengthening causal inferences. Second, the reliance on self-reported survey data introduces the potential for social desirability bias, where respondents might provide answers they perceive as socially acceptable rather than their true perceptions or behaviors. Future studies should integrate observational data or experimental designs to triangulate findings and mitigate this bias. Third, while this study focused on Generation Z consumers, the data collection was limited to a specific geographical context. Given that consumer behavior is often culture-specific, future research should conduct cross-cultural studies to examine the generalizability of these findings across diverse regions and cultural backgrounds. This would provide a more comprehensive understanding of how privacy attitudes and online purchase intentions vary globally within this demographic group. Fourth, while the model in this study is comprehensive, other factors influencing Generation Z's online purchase intention, such as specific perceived risks (e.g., financial, performance, social, and psychological), social influence, gamification, and sustainability, were not the primary focus of this model. Future research could expand the model to incorporate these additional variables to provide a more holistic understanding of the complex online decision-making of Generation Z. Lastly, although a higher-order construct for "Brand Engagement" was requested, it was not included in the final model due to the scope of the provided research materials and the established theoretical framework. Future studies should explore the integration of such higher-order constructs to capture more complex aspects of consumer-brand relationships in the context of digital privacy. Additionally, further research could delve into the specific mechanisms through which privacy concerns translate into selective purchasing behavior, perhaps exploring the role of privacy-enhancing technologies or specific regulatory frameworks in shaping this dynamic. Investigating the gap between stated privacy concerns and actual data-sharing behaviors using more objective measures would also be a valuable direction.

Declarations

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Declaration of Competing Interest: The authors declare that they have no known competing financial interests or personal relationships that could influence the work reported in this study.

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tool/service, the author(s) reviewed and edited the content as needed and took (s) full responsibility for the content of the publication.

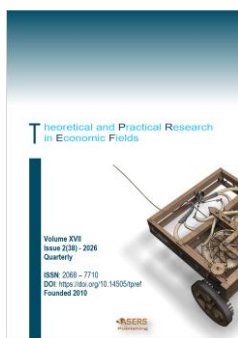
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Adaptation of the Marketing Strategies to Customs Requirements in EU Countries



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Abstract: The relevance of the study is determined by the growing import volumes, the complexity of customs regulation, and the need to integrate innovative approaches into marketing activities. The aim of the research was to analyse the impact of customs requirements on the choice and adaptation of marketing strategies in EU countries, as well as to investigate their impact on the pricing policy, logistics solutions, and communication channels.

The research employed the following methods: statistical data grouping, multifactor analysis, calculation of a weighted average indicator to assess adaptation potential, as well as legal analysis of EU customs norms and regulations.

The results of the study showed that the use of global basic competitive growth strategies is the most effective approach to overcoming challenges associated with customs regulation. The practical significance of the research is the provided recommendations for businesses to optimize marketing strategies in accordance with the customs requirements of EU countries.

In particular, the tools proposed for effective adaptation can minimize financial risks and increase competitiveness. Further research may focus on the standardization of customs procedures, automation of processes through digital platforms, and analysis of consumer models in EU countries.

Keywords: marketing strategies; customs requirements; protectionism; european market; import; customs legislation.

JEL Classification: F13; M11; M31.

Introduction

Adaptation of marketing strategies to customs regulation is relevant because of the growth of international integration and the strengthening of customs barriers in response to global challenges. International companies need to remain competitive, optimizing costs and taking into account new economic realities. In the modern world, marketing strategies play a key role in ensuring the competitiveness of companies in the global market. In a variety of approaches, four main types of strategies attract special attention: global, basic, competitive, and growth strategies. Global strategies allow companies to cover international markets by adapting their products and services to different cultural and economic contexts.

Basic strategies ensure concentration on the core values of the brand, creating consistency in consumer perception. Competitive strategies are aimed at providing advantages over other market participants, using innovative approaches and unique offers. Growth strategies contribute to the active development of new markets and segments, expanding the customer base and increasing market share. They remain the most relevant as they allow companies to effectively respond to the challenges of globalization, changing consumer preferences, and increasing regulatory requirements.

The novelty of this research lies in its integrated approach to analyzing the intersection of marketing strategies and customs requirements within the EU regulatory framework. While previous studies have examined

these areas separately, our work bridges this gap by providing a comprehensive assessment of how customs regulations directly impact marketing decision-making across EU markets.

The European market remains one of the most attractive for international companies because of its economic strength, high consumer solvency and relative stability. However, access to this market is complicated by a complex system of customs regulation, which covers a wide range of requirements and rules. The EU ensures uniformity of approaches to taxation of imported goods through the implementation of the Common Customs Tariff (CCT) and regulatory documents. Each EU member state may have its own specific requirements related to the issuance of certificates of origin of goods, tax reports or additional documents for categories of goods. The complex regulatory landscape requires companies to comply with customs regulations and adapt marketing strategies to local needs and rules.

Digitalization, which has become a major trend in recent years, continues to strengthen in 2024–2025, stimulating the growth of e-commerce and increasing imports to EU markets. The dynamic development of digital advertising and innovative marketing technologies enables companies to reach a wider audience, adapting their offers to the requirements of local markets. The AdEx Benchmark study data for 2023 indicate an increase in digital advertising spending by 11.1%, which confirms the importance of digital channels for promoting goods. Improving marketing strategies, in particular the integration of analytical data and the automation of advertising campaigns, are becoming necessary for effective work in the European market. This, in turn, contributes to business growth and the formation of new standards for adapting marketing strategies to the specifics of the regulatory environment of EU countries.

The aim of the study is to analyse the adaptation of marketing strategies to customs requirements in EU countries to increase their efficiency and ensure competitiveness in the European market. Research objectives: 1. Study the main customs requirements and their impact on the import of goods in the EU countries. 2. Analyse key marketing strategies and their adaptation to the customs regulation. 3. Identify economic indicators that affect the adaptation of strategies, in particular the share of imports, customs burden and adaptation costs. 4. Develop recommendations for businesses on optimizing marketing approaches in the context of European customs regulation.

1. Literature Review

The analysis of the adaptation of marketing strategies to customs requirements in EU countries is based on a multifaceted approach that takes into account economic, legal and technological aspects. Englert *et al.* (2023) developed an innovative system - ALIIAS - for data anonymization in scientific research, which emphasizes the importance of technology for effective information management. However, their study poorly covers the impact of such technologies on customs processes. Relevant practice is applied to customs regulation, where technology helps to adapt marketing strategies through effective data management. Similarly, Green (2023) examined the legislative changes regarding medical devices in the EU after Brexit, but the study focuses mainly on a specific sector. Gryshchenko *et al.* (2024) explore the role of industrial policy in defense industry development, which provides valuable insights on international legal and economic regulation frameworks that can be applied to customs requirements adaptation. Their research demonstrates how regulatory frameworks impact strategic business decisions across borders, which is directly relevant to your study on marketing strategy adaptation.

Legislative changes in the medical sector indicate the need to adapt marketing strategies in response to similar regulatory changes in other sectors, including customs regulation. Perepolkin *et al.* (2022) examined the uniqueness of EU customs law, but the emphasis is mainly on legal aspects without taking into account the economic context. Studying the legal aspects of customs law can help businesses to better understand the requirements for adapting marketing strategies to the specifics of the regulatory environment. Pasichnyi *et al.* (2023) emphasized the role of customs control in economic security, but their analysis focuses on general trends rather than on the adaptation of marketing strategies. The analysis of economic security through customs control indicates the importance of taking into account customs barriers when developing marketing strategies. Bykova *et al.* (2024) examine how emotional intelligence influences successful financial decision-making, which offers a complementary perspective on how businesses can better navigate complex customs regulations through improved decision-making processes. Their findings could strengthen your analysis of how companies adapt marketing strategies to meet varying customs requirements.

Hudson (2023) examined the lessons that Australia can learn from customs reforms in Europe, emphasizing the importance of standardisation. Standardisation of customs procedures can facilitate the development of universal marketing strategies for markets with different regulatory requirements. At the same time, Drozd (2023) examined the adaptation of the customs transit regime to European regulations, revealing the specifics of the

adaptation. The adaptation of the customs regime to European regulations shows how regulatory requirements affect the need for changes in marketing strategies.

Wu and Monfort (2023) analysed the use of artificial intelligence (AI) in marketing strategies, focusing on increasing efficiency, but their study does not address customs aspects. The AI integration into marketing strategies can help to take into account customs requirements through process automation and data analysis. Entin (2023) drew attention to the principle of legal certainty in the customs regulation, which has an important impact on marketing strategies, but is reduced to a theoretical approach. The principle of legal certainty in customs regulation creates the basis for the predictable development of marketing strategies.

Cherniavska *et al.* (2023) explored the role of innovative technologies, such as artificial intelligence, in enhancing organizational strategies, which can support companies in adapting marketing approaches to meet varying EU customs requirements. Similarly, the IAB Europe AdEx Benchmark 2023 Report (2023) highlights market trends in digital advertising across EU countries, emphasizing the need for marketing strategies that align with both consumer preferences and evolving regulatory environments. Omelyanenko *et al.* (2018) focused on the importance of technology transfer management culture, underscoring how an education-based approach can facilitate the integration of marketing strategies with customs compliance in the European context.

Bilousko *et al.* (2024) investigated the impact of human resource (HR) management strategies on company profitability, but their approach does not take into account the specifics of adapting these strategies to customs requirements. Taking into account aspects of customs regulation can contribute to more effective HR management in the context of international trade. Artemchuk *et al.* (2024) focused on innovative strategies in risk management and crisis response in business. However, their analysis does not cover the challenges associated with customs barriers. Integrating such innovative strategies with due regard to the specifics of customs requirements can improve crisis management in an international context. Bak *et al.* (2024) analysed the impact of the shadow economy on reducing tax revenues to the state budget. Research into the relationship between customs processes and reducing shadow turnover could provide practical recommendations for business and public administration.

Li *et al.* (2021) developed the concept of social media marketing strategy, but their approach does not cover the specifics of customs regulations. Social media marketing can take into account the specifics of customs regulations to more effectively enter international markets. Rosário and Dias (2023) focused on the change in e-commerce strategies in the last decade, but their analysis does not take into account customs barriers. Fruscione (2023) suggested that facilitation for trusted operators is an important aspect to reduce administrative burden, but the study needs to broaden the economic context. E-commerce should take into account customs barriers by adapting its marketing strategies to regional regulatory conditions. Esmaelnezhad *et al.* (2023) evaluated green marketing strategies, taking into account sustainability criteria, but their analysis does not take into account the specifics of customs regulations.

Kirilenko and Abramova (2023) compared customs control in the Eurasian Economic Union and the EU, revealing structural differences, but the work is reduced to the regulatory analysis. Kaur *et al.* (2022) reviewed recent trends in marketing strategies, including digitalization, but did not include an analysis of regulatory aspects. Milla-Ibáñez (2023) examined statutes of limitations in customs crimes, which broadens the understanding of the legal context, but the work does not cover economic consequences. Lyuba (2022) focused on the cost of customs clearance, but the study does not take into account the adaptation of marketing strategies.

In general, the studies showed significant attention to individual aspects of customs regulations and marketing strategies, but the integration of these topics remains underexplored. The studies that focus on technological innovations, regulatory aspects, and economic indicators have the potential to develop integrated approaches. Further research could focus on developing practical mechanisms for integrating customs requirements into marketing strategies, which would enable businesses to more effectively respond to regulatory challenges and strengthen their competitiveness in international markets.

2. Materials and Methods

2.1. Research Design

The research was conducted in four consecutive stages. The first stage was sampling of marketing strategies and customs requirements in EU countries. This sample was based on data on major importers and an analysis of the specifics of customs regulation. The second stage provided for the analysis of the main import trends using Eurostat statistics and secondary materials obtained from the AdEx Benchmark Report, which provided a comprehensive picture of the EU import market. The third stage involved grouping of the key factors influencing customs requirements to develop a systematic approach to their assessment. At the final, fourth stage, economic indicators of the adaptation of marketing strategies to customs requirements were calculated. In particular, the average

customs burden was calculated, the share of countries in total imports was determined, and the costs of adapting strategies were estimated.

2.2. Sampling

The sample was formed based on the analysis of ten key importing countries to the EU: Germany, China, Turkey, India, France, Italy, Spain, Poland, the Netherlands, Denmark, Belgium, Sweden, and Austria. These countries were selected due to their significant share in total imports to the EU, the developed infrastructure and influence in the formation of general customs policies. Customs statistics data, the specifics of customs rules, typical barriers to imports, as well as examples of successful marketing campaigns adapted to customs requirements were considered for each country. Four main marketing strategies were selected: global, basic, competitive, and growth strategies.

They adapt to specific customs requirements taking into account import shares, logistics costs and innovative approaches. Less influential countries were not included in the sample because of the limited available data and their lower influence on the development of general customs policies. This could also complicate the generalization of the results.

2.3. Methods

Several methodological approaches were applied in the study. A legal analysis of EU customs rules and regulations was applied to assess the impact of the EU Customs Code regulations (Regulation 952/2013) on trade transactions and the adaptation of marketing strategies. The method of statistical grouping and data aggregation based on Eurostat and AdEx Benchmark Report was used to systematize customs rates and importer shares, and the linear regression method using SPSS Statistics and Microsoft Excel was applied to calculate the weighted average customs burden.

The k-means algorithm helped to cluster countries according to similar trade conditions. Regression multivariate analysis assessed the impact of customs duties, VAT rates and other regulatory factors on the import structure. The most effective marketing strategies for key EU partners were identified. The results of statistical calculations, in particular the average customs burden, were used to assess the competitiveness of goods, taking into account customs costs and their impact on the final price of products. The obtained data gave grounds to propose strategic solutions to optimize logistics processes and enter markets adapted to the economic and legal conditions of trade.

2.4. Instruments

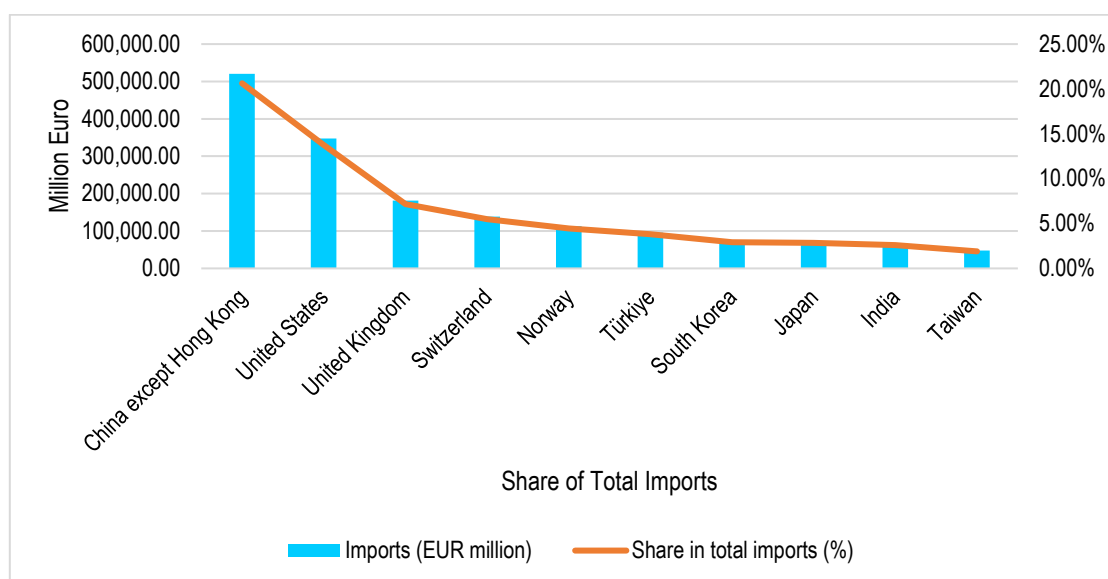
Excel was used to systematize and analyse statistical data. SaaS platforms were used to create multifactor models. The legal framework of the study was formed on the basis of official EU web resources, including a database of customs requirements and regulations. Verified online sources such as Eurostat were also used to verify the reliability of statistical data and analyse their trends.

3. Results

In 2023, imports of goods into the EU continued to show steady growth, confirming the significant impact of globalization on the European economy. China, the United States, the United Kingdom, Switzerland, Norway, Turkey, and South Korea remain the EU's key partners in the supply of goods. China, in particular, provided 20.63% of all imports, while the United States ranked second with a share of 13.77%. These countries remain strategic for the EU in terms of trade, determining the overall import trends in the region.

The grouped results of the analysis based on data on the EU's main partners emphasized the critical importance of taking into account the geographical distribution of suppliers in order to form adaptive marketing strategies. Turkey, which provides 3.80% of imports, demonstrates high dynamics in increasing supplies of goods, which requires special attention when forming growth strategies. The analysis of customs requirements confirmed the need for a country-specific approach, taking into account regulatory and tariff restrictions, in particular for China with its complex customs procedures. Figure 1 illustrates the EU partners' imports by volume in 2023.

Figure 1. EU Import Partners by Volume in 2023



Source: created on the basis of Eurostat data (2024)

The growth of digital marketing in Europe has become a key trend that has determined the direction of marketing strategies. According to AdEx Benchmark the European digital advertising market grew by 11.1% in 2023, reaching €96.9 billion. Another 13 markets showed significant double-digit growth, among which the largest increases were recorded in Turkey - +50%, Serbia - +27.6%, and Ukraine - +25.2%. The growth was determined by the adaptation of companies to changes in the advertising environment, including the expansion of programmatic advertising formats such as video - +20.9% and audio - +23.1%. Leading companies such as Google and Meta have actively implemented new technologies to support these changes, which has become a driver for innovation in the industry.

The transformation of marketing strategies to customs regulations in Europe has also become an important component of business adaptation to new realities. Large corporations such as Amazon, Microsoft and Procter & Gamble are focusing on integrating customs requirements into their strategies, in particular through the use of digital platforms to optimize logistics and regulatory compliance. The main trends are personalization of marketing messages, programmatic advertising and the active use of data to build targeted campaigns adjusted to the specifics of EU markets. These changes ensure competitiveness and contribute to the growth of the European economy, despite the difficulties in the global geopolitical and economic situation.

Penetration into the EU market has been a key trend in recent years, driven by the rapid growth of e-commerce. It has led to an increased role for intermediary countries such as the Netherlands and Belgium, which have become hubs for transit imports due to their advantageous geographical location and developed infrastructure. In 2023, about 18% of EU imports of goods passed through intermediary countries, which enabled companies to reduce customs clearance costs and ensure flexibility in logistics chains. This trend has increased the need to adapt marketing strategies to digital platforms and targeted campaigns that take into account the shift in consumer preferences towards online shopping.

The analysis of customs requirements has shown significant differences in approaches to customs regulation across EU countries. Germany implements strict controls in accordance with the *Zollkodex der Union (UCC)*, which requires the mandatory submission of SAD (Single Administrative Document) with a full set of supporting documents, including certificates of origin. In Sweden, the customs clearance is significantly simplified according to *Tullverket's customs regulations*, with an emphasis on electronic submission of documents through Tullverket's Customs Clearance System. The differences affect marketing strategies: in Germany, the emphasis is on customer information support and transparency, while in Sweden, the strategy is focused on speed and integration of electronic solutions.

In 2022–2024, the EU tightened customs requirements, which were reflected in new regulations. These included the mandatory introduction of the Entry Summary Declaration (ENS) system for all imported goods, as well as an increased role for EORI registration. According to forecasts, these changes led to an increase in marketing costs by an average of 15% because of the need for additional investment in adapting procedures. AdEx Benchmark data showed that a 50% increase in digital advertising costs in 2023 could lead to an increase in

customs tariffs aimed at protecting local markets. These changes require a review of traditional marketing strategies, in particular, the integration of customs cost forecasts into the overall marketing budget. Table 1 presents customs requirements for the import of goods compared among the studied countries.

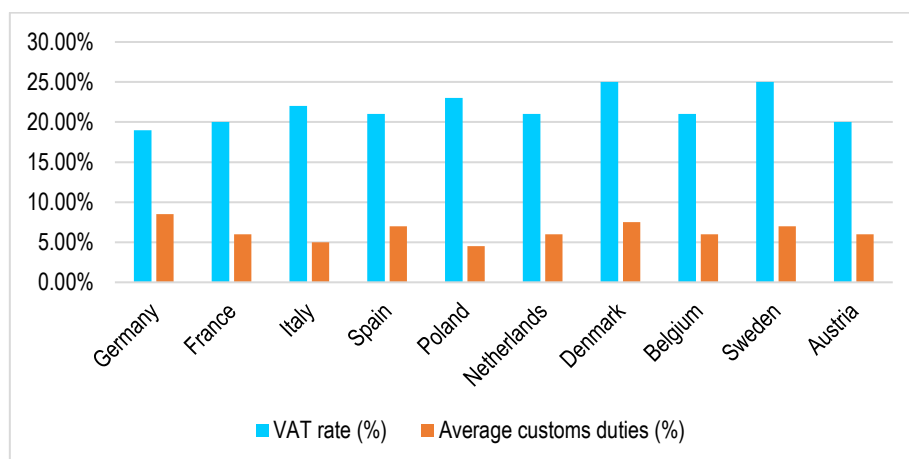
Table 1. Customs Requirements for the Import of Goods in EU Countries

Country	Duty-free import threshold	VAT rate	Customs duties	Additional requirements
Germany	€ 0	19%	0–17%	EORI number, commercial invoice, certificates of origin of goods required.
France	€ 0	20%	0–12%	Commercial invoice, certificates of conformity, customs declaration (SAD).
Italy	€ 0	22%	0–10%	Certificates of origin of goods, packing list, invoice.
Spain	€ 0	21%	0–14%	Phyto- or veterinary certificates for products of animal or plant origin.
Poland	€ 22	23%	0–9%	Customs invoice, safety certificates for specific goods.
Netherlands	€ 0	21%	0–12%	Commercial invoice, customs declaration, transport documents (CMR, Bill of Lading).
Denmark	80 DKK (about €10)	25%	0–15%	Mandatory EORI number, invoice and confirmation of origin of goods.
Belgium	€ 0	21%	0–12%	Customs declaration, transport documents (TIR, ATA Carnet) required.
Sweden	300 SEK (about €20)	25%	0–14%	Packing list, product safety certificates.
Austria	€ 0	20%	0–12%	Commercial invoice, customs declaration, confirmation of compliance with EU standards required.

Source: developed by the authors based on the European Commission (2024)

Further strengthening of customs regulation is expected for 2025–2027, which may lead to an increase in costs for adapting marketing strategies by 10–12%. This is determined by the growth of the digital economy, the need to integrate new customs control technologies, and increased requirements for transparency of supply chains. The main drivers of these changes will be economic stabilization in the region and increased geopolitical integration. Revising strategies to align with new realities will provide businesses with the opportunity to maintain competitiveness and strengthen their presence in the European market. VAT rates and customs duties are shown in Figure 2, which affect the cost of importing goods and the conditions for entering the markets of EU countries.

Figure 2. VAT Rates and Average Customs Duties in EU Countries



Source: developed by the authors based on the European Commission (2024)

The average customs burden was estimated by analysing data on import volumes and average tariff rates for each country. Market potential was defined as an integral indicator combining the country's share in total imports and the coefficient of customs requirements, which reflects the complexity of the procedures. The results of the calculations make it possible to create a system of priorities for four main types of marketing strategies: global,

basic, competitive, and growth strategies, which ensures accuracy and flexibility in decision-making. Table 2 contains the features of adapting marketing strategies to customs requirements in EU countries.

Table 2. Assessment of Economic Indicators for Adapting Marketing Strategies to Customs Requirements in EU Countries

Country	Average customs burden (€/million)	Share in total imports (%)	Adaptation costs (€/million)	Market potential (index)
China	52.04	20.63	15.12	0.87
USA	34.71	13.78	10.24	0.82
UK	18.10	7.18	7.56	0.79
Switzerland	13.88	5.49	6.32	0.74
Norway	11.26	4.45	5.91	0.72
Turkey	9.59	3.80	5.11	0.70
South Korea	7.34	2.91	4.98	0.69
Japan	7.13	2.83	4.75	0.68
India	6.54	2.60	4.33	0.67
Vietnam	4.77	1.89	4.01	0.65

Source: calculated by the authors

The calculations give grounds to conclude that a global reach strategy will be effective for markets with high potential, such as China, the USA and the UK. The markets with lower indicators shall focus on competitive and basic strategies, adapting them to local customs requirements. Growth strategies are best implemented in countries with an average level of customs burden and high market potential.

4. Discussion

The results of our study aimed at adapting marketing strategies to the customs requirements of the EU countries confirm the importance of integrating a multifactorial approach that takes into account economic, legal, and technological aspects. Lyuba (2022) focuses on the problems of the customs value of goods, in particular, the issues of estimating the value and determining methods for its correction. At the same time, their approach does not cover the aspects of adapting marketing strategies, which we have considered in more detail. Kaur *et al.* (2022) study marketing strategies 4.0 emphasizing the importance of technologies and digitalization trends, but does not include legal and customs aspects, which is the basis of our study. Drozd (2023) focused on the adaptation of customs transit to European regulations, confirming the relevance of harmonization, although this analysis is limited by the legal context. Wu and Monfort (2023) explored the AI role in marketing strategies, however, their focus on technology does not encompass the impact of customs requirements.

Fruscione (2023) covered the facilitation of customs procedures for reliable operators, which is consistent with our findings on the need to minimize administrative burden. However, their analysis is reduced to general provisions, while our study offers specific economic indicators of adaptation. Hidayatullah *et al.* (2023) studied the ways of shaping Sharia marketing strategies, which emphasizes unique cultural aspects that are not taken into account in our study. Entin (2023) analyses the principle of legal certainty in customs relations, confirming the importance of regulatory stability, but their approach focuses on legal aspects only. Pasichnyi *et al.* (2023) emphasize the role of customs control in ensuring economic security, which partly has something in common with our findings on strategic marketing management.

The study by Esmaelnezhad *et al.* (2023) evaluated green marketing strategies, focusing on sustainability criteria, which is a promising direction for adapting strategies. Milla-Ibáñez (2023) analysed the statute of limitations for customs offences in the EU, which is important for understanding the legal environment, but this aspect only partially affects marketing strategies. Hong and Nguyen (2020) studied logistics businesses in Vietnam, focusing on marketing strategy factors, but their study does not take into account the European context. Supeková *et al.* (2023) modelled corporate social responsibility under the influence of marketing strategies, which complements our findings but does not cover the customs dimension.

Green (2023) analysed the legislative changes regarding medical devices after Brexit, which emphasized the importance of regulatory changes, but the study does not consider strategic approaches. Our results confirm the need to integrate legal, economic, and marketing aspects in the development of adaptive strategies, which makes our approach broader and more multifaceted compared to other studies. Therefore, combining the findings of current research with our results provides a better understanding of how adapting marketing strategies to customs requirements contributes to increasing their effectiveness in the complex European environment.

The research prospects include analysing the impact of new digital tools on the adaptation of marketing strategies to changing customs requirements in the EU. It would be appropriate to include an assessment of the effectiveness of using AI to predict changes in customs requirements and optimize marketing strategies. The implementation of blockchain technologies to increase transparency and speed of customs procedures will be no less relevant.

4.1. Limitations

One of the key limitations of the study is the focus on the selected group of EU countries with high import volumes, which may not fully reflect the characteristics of less developed markets. The study was based mainly on secondary data, which limits the possibilities for in-depth analysis of local customs specific, as well as cultural and economic factors that influence the adaptation of marketing strategies. Besides, the methodology did not take into account seasonal fluctuations that may affect customs requirements and strategies at certain times of the year.

4.2. Recommendations

Based on the conducted research, the following measures are proposed to improve the adaptation of marketing strategies to customs requirements in EU countries:

1. Involve countries with smaller import volumes and developed local customs specifics in the research in order to create more universal recommendations.
2. Introduce integration models that take into account the difference in customs regulations between EU countries and the impact of new tariff restrictions.
3. Introduce modern technological solutions to predict customs requirements and optimize the costs of adapting marketing strategies.
4. Develop training programmes for marketing and logistics teams on changes in customs regulations, as well as create internal platforms for managing relevant data.
5. Regularly update the database on customs requirements, in particular taking into account new EU laws and directives, to ensure that strategies comply with changing regulations.

Conclusion

The analysis of the adaptation of marketing strategies to customs requirements in EU countries showed that a comprehensive approach based on multifactor analysis is the key to effective management in the current settings. The calculations made it possible to find out that the average customs burden for key EU partner countries is 7.8%. The maximum values reach 12% for goods from Turkey, and the minimum are 2% for goods from Switzerland. The level of adaptation of marketing strategies to customs requirements varies depending on the economic potential of the market. The potential of the French market is estimated at 18.5%, while the potential of the Polish market is 8.9%. These data demonstrate the need to take into account customs regulations in marketing planning, which allows optimizing costs and increasing competitiveness. The data obtained can be used by businesses to optimize logistics, adapt pricing strategies and prepare for changes in customs requirements through the implementation of digital platforms.

The significance of this research extends beyond theoretical contributions to provide practical applications for businesses navigating the complex interplay between marketing strategies and customs requirements in EU countries. By establishing clear connections between customs burden metrics and strategic marketing approaches, this study fills a critical gap in the literature that has typically treated these domains as separate concerns. Our findings reveal that successful market adaptation requires not only compliance with regulations but strategic integration of customs considerations into core marketing functions.

The results of the study indicate an increased role of digitalization in marketing strategies. The growth of the digital advertising market in Europe reached €96.9 billion in 2023, with a projected growth of 11% in 2024. Improving customs regulations and the development of e-commerce create new opportunities for businesses, while requiring innovative approaches to marketing strategies. The implementation of performance assessment methods based on the integration of economic, legal, and strategic aspects enables companies to respond flexibly to changes in

customs regulations, minimizing risks and ensuring sustainable development in the European market. Further research could focus on analysing the impact of new customs initiatives and digital tools that ensure the integration of marketing and customs processes.

Declarations

Credit Authorship Contribution Statement: The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Declaration of Competing Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Use of Generative AI and AI-assisted Technologies: The authors declare that they have not used generative AI and AI-assisted technologies during the preparation of this work.

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Higher Education Effects Over Democracy Indicators



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Abstract: The purpose of this study is to examine the impact of higher education on democratic dynamics, specifically focusing on the number of national elections and the variety of political parties across 159 countries from 1990 to 2020. It aims to differentiate the effects of educational quantity from educational quality.

The research utilizes a cross-sectional dataset. To address endogeneity issues, such as reverse causality and omitted variable bias, the study employs spatial autoregressive (SAR) and spatial error models (SEM). These models account for spatial dependencies and regional political norms that influence democratic outcomes.

The results reveal distinct effects for education quantity and quality. A higher number of universities is associated with an increase in political parties, fostering pluralism, but does not significantly affect election frequency. Conversely, higher education quality positively correlates with election frequency and negatively with the number of parties, suggesting a “screening effect” that promotes institutional stability and consolidated party systems.

This paper contributes to the literature by disaggregating higher education into quantity and quality metrics. It provides a novel application of spatial econometrics to clarify the nuanced contributions of educational infrastructure to specific democratic indicators, offering a more sophisticated understanding than traditional aggregate measures.

For policymakers, the findings suggest that quantitative expansion of universities promotes political representation, while qualitative improvements are essential for institutionalizing electoral processes and reducing party fragmentation.

Keywords: democracy; higher education; elections; political parties; spatial econometrics; institutional quality.

JEL Classification: I23; I25; C31; D72; A12.

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Introduction

This study investigates the impact of higher education on democratic dynamics, specifically the number of elections and political parties across 159 countries from 1990 to 2020. Education is disaggregated into quantity (institution counts) and quality (global rankings). While classic works argue that education enhances democratic values (Lipset, 1959), recent empirical studies present mixed findings (Acemoglu *et al.* 2005). We address this gap and the challenge of endogeneity by employing spatial autoregressive (SAR) and spatial error models (SEM) to account for regional dependencies. Our findings reveal that a higher number of universities is associated with an increase in political parties but has no significant effect on election frequency. Conversely, higher education quality positively influences elections while reducing party numbers, suggesting a “screening effect” where quality education fosters informed citizens and consolidated party systems. These results offer insights for policymakers aiming to strengthen democratic institutions. The paper is organized as follows: Section 2 reviews the literature; Section 3 summarizes data and sources; Section 4 presents the empirical framework; Section 5 discusses the estimation results; and

Section 6 concludes with policy implications and future research directions. Our methodology ensures robust findings by addressing spatial autocorrelation and potential reverse causality issues.

1. Literature Review

With more sophisticated econometric techniques, the literature exploring the nexus between education and democracy has expanded significantly. This section reviews this literature, organized into three areas: theoretical foundations of education's role in democracy, empirical challenges including endogeneity, and the impact of education on political participation and party systems. Our study builds on these works to examine how higher education quantity and quality affect the number of elections and political parties across 159 countries from 1990 to 2020.

Classic studies established a foundational link between education and democratic development. Lipset (1959) argues that education, particularly higher education, is a necessary condition for democracy, improving citizens' tolerance, civic engagement, and preference for democratic institutions. Similarly, Watt & Lerner (1961) and Apter (1961) suggest that education drives modernization, promoting values like civil liberties and political diversity. These works assert that higher education amplifies democratic tendencies by equipping individuals with critical thinking skills and awareness of democratic norms (see also Bobo & Licari, 1989; Golebiowska, 1995; Marquart-Pyatt & Paxton, 2006). Additionally, Glaeser et al. (2007) extend this argument by arguing that education enables citizens to recognize the benefits of democratic systems, increasing support for democracy over authoritarian regimes. Using data from the World Values Survey, General Social Survey, and DDB Needham Lifestyles Survey, they find that higher education is a necessary, but not sufficient, condition for democratic preferences.

On the other hand, recent empirical studies have analyzed the causal relationship between education and democracy, highlighting endogeneity as a key challenge. Glaeser et al. (2004), using the Freedom House Political Rights Index and education data from Barro & Lee (2000), find no robust evidence that education directly improves democratic outcomes, suggesting reverse causality where democratic institutions drive educational expansion. Similarly, Acemoglu et al. (2005) employ cross-sectional models to argue that an educated population does not necessarily lead to democracy, as unobserved factors (e.g., economic development) may confound the relationship. Kariş & Tandoğan (2019) reach similar conclusions, emphasizing the role of institutional contexts. To address endogeneity, some studies adopt advanced methodologies. Rodrigues (2023) uses historical missionary activity as an instrumental variable, finding a positive effect of education on democratic attitudes in Latin America. Sanborn & Thyne (2014) utilize panel data to demonstrate that education supports democratic transitions by encouraging institutional stability, particularly in post-authoritarian contexts. More recently, Le and Nguyen (2021) exploit compulsory schooling reforms across 39 countries as instruments, finding that education cultivates political interest and supportive attitudes toward political freedoms, though it does not significantly affect voting behavior itself. Dahlum and Knutsen (2022), in a comprehensive meta-analysis, conclude that the overall education–political regime relationship is positive but small and contingent on contextual factors such as the level of schooling and the prevailing regime type. These findings highlight the need for robust econometric techniques, which our study addresses through spatial autoregressive (SAR) and spatial error models (SEM).

Most of the literature focuses on overall democratic outcomes, but few studies explore education's impact on specific indicators such as election frequency and political party numbers, which are central to our analysis. Mattes & Luescher-Mamashela (2012), using the Afrobarometer data from Kenya and Tanzania, find that university-educated citizens exhibit stronger support for democracy, evidenced by higher electoral participation. Larreguy & Marshall (2017) extended the analysis, using quasi-experimental methods to show that education increases voter turnout and political engagement in African contexts. However, Croke et al. (2016) complicate this picture by finding that in electoral authoritarian regimes, education can lead to deliberate disengagement, as schooling under such conditions may signal the futility of political participation rather than empower it. This tension between education's mobilizing and demobilizing effects underscores the importance of institutional context — a gap that our study addresses by distinguishing between institutional quantity and academic quality across diverse regime types.

2. Methodology

2.1 Data

This section describes the cross-sectional dataset, sources, and variables used to analyze the relationship between tertiary education and democratic outcomes across 159 countries, with variables averaged from 1990 to 2020. The dataset integrates data on higher education quantity and quality with democracy indicators and control variables,

enabling robust econometric analysis. Below, we outline the dataset structure, detail the variables, and present descriptive statistics and preliminary visualizations.

The dataset comprises a cross-sectional structure for 159 countries, constructed by averaging all variables over the period 1990-2020 to capture long-run relationships. Data on tertiary education quantity and quality are sourced from global university databases, covering approximately 32,246 higher education institutions (universities, colleges, and institutes) across 214 countries, aggregated to the 159 countries in our sample based on data availability for democracy indicators. Missing data are handled by averaging available years within the period, with no interpolation applied to ensure data integrity. Valero (2019)

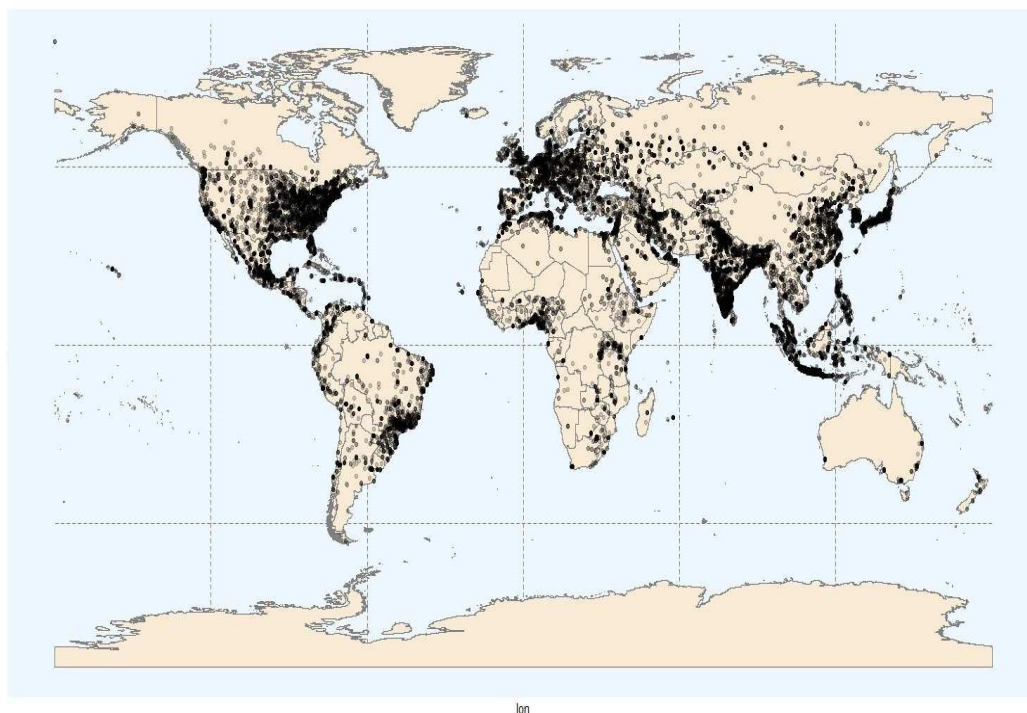
Democracy Indicators

The endogenous variables, representing democratic outcomes, are obtained from the Constituency Level Elections Archive (CLEA) (CLEA, 2019). The first variable, *elec_num*, denotes the number of national elections held from 1990 to 2017, covering 159 countries. The second variable, *pty_num*, represents the number of political parties active within a country over the same period. CLEA was selected for its comprehensive coverage and detailed election data, ensuring consistency across countries.

Tertiary Education Variables

The main exogenous variables capture tertiary education quantity and quality. For quantity, we use *univ*, the total number of higher education institutions per country in 2020, sourced from the *Ranking Web of Universities* (<https://www.webometrics.info/en>). This database includes 32,246 institutions across 214 countries, aggregated to country-level counts using geolocation data. Figure 1 illustrates the global distribution of these institutions.

Figure 1. Map of Universities Across the Globe



Source: QS World University Rankings and Times Higher Education (THE) World University Rankings

For quality, we use two proxies: *dqs*, the number of universities per country listed in the *QS World University Rankings*, and *dshanghai*, the number listed in the *Times Higher Education (THE) World University Rankings*. These rankings, covering 2011–2020 (Table 1), identify high-quality institutions based on academic reputation, research output, and teaching quality. We use raw counts of ranked universities rather than percentages to reflect absolute quality presence, though robustness checks with normalized measures are conducted. The choice of QS and THE rankings ensures global comparability, despite potential biases toward English-speaking and research-focused universities (Bömmel & Heineck, 2020).

Table 1. Data available for University Rankings

Year	THE	QS
2011	200	
2012	402	
2013	400	834
2014	400	863
2015	401	891
2016	800	916
2017	981	980
2018	1103	980
2019	1258	1021
2020	1397	1024

Source: QS World University Rankings and Times Higher Education (THE) World University Rankings

Control Variables

Control variables are sourced from two databases. From the World Development Indicators (WDI), we include:

- $\log(\text{gdp\_p\_pc})$: Natural logarithm of GDP per capita (constant 2015 USD), averaged over 1990–2020.
- $\log(\text{pop})$: Natural logarithm of population (millions), averaged over 1990–2020.
- LIC , LMIC , UMIC : Dummy variables for low-income, lower-middle-income, and upper-middle-income countries, respectively, based on WDI classifications, 2020. The high-income dummy is omitted to avoid multicollinearity.

From the Database of Political Institutions 2017 (DPI-2017) (Cruz *et al.* 2018), we include:

- yrsoffc : Number of years the chief executive has been in office, averaged over 1990 – 2017.
- military : Dummy variable indicating whether the chief executive is a military officer (1 =yes; 0 =no).
- execrel : Categorical variable for the religious nature of the ruling party (0 = none, 1 =Christian, 2 =Catholicism, 3 =Islam, 4 =Hindu, 5 =Buddhist, 6 =Jewish).
- execrlc : Categorical variable for the party's economic policy orientation (1 = right, 2 = center, 3 = left, 0 = no information, or NA = no executive).

These variables control for economic, demographic, and political factors on the analysis of the education-democracy relationship. For details on DPI variables, see Cruz *et al.* (2018); Scartascini *et al.* (2018).

2.2 Descriptive Analysis

Table 2. Summary Statistics

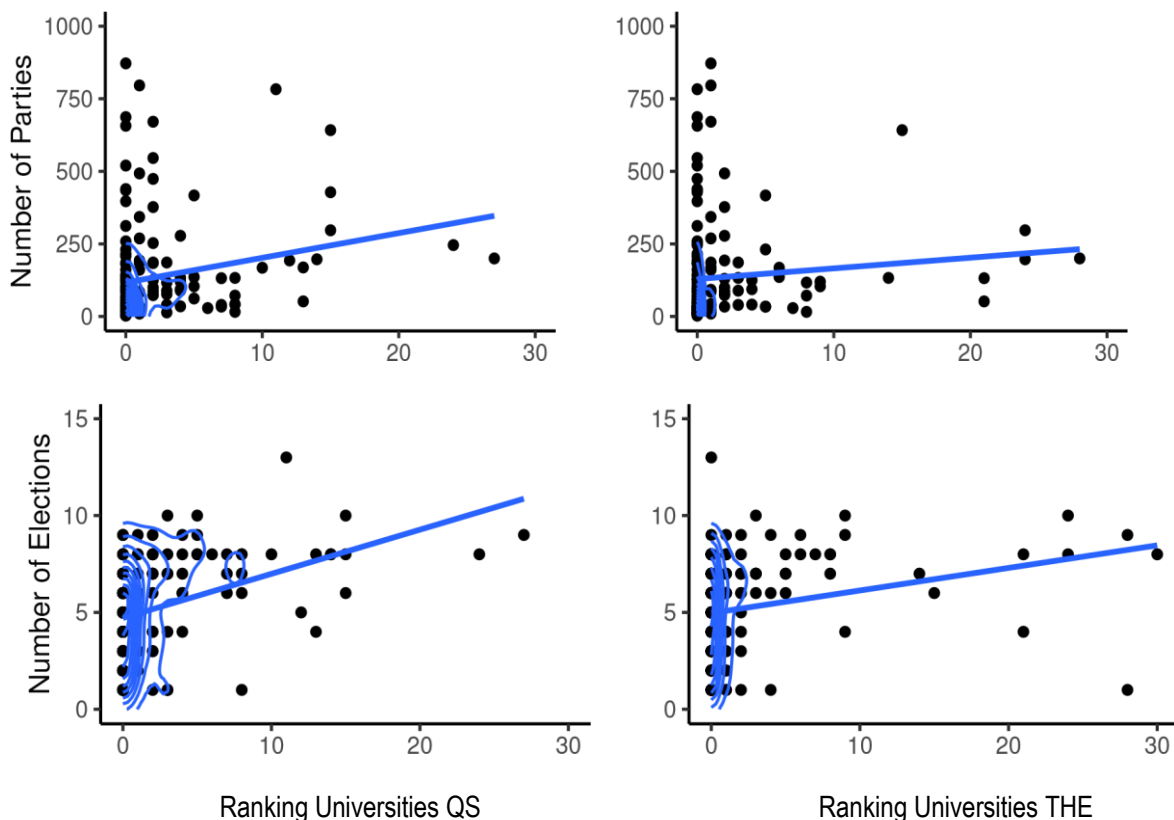
Statistic	N	Mean	St. Dev.	Min	Max
pty_num	170	261.9	830.8	3	9,353
elec_num	170	5.2	2.7	1	16
dqs	162	3.7	12.6	0	135
dshanghai	162	4.2	16.0	0	156
univ	162	169.4	604.9	1	5,021
gdp_pc	163	15,273	22,542	318	167,313
pop	166	27.986	96.389	10.237	1,139.727
nad1	169	16.9	16.1	1	85
yrsoffc	140	6.4	5.1	2.1	29.7
military	140	0.1	0.3	0.0	1.0
execrel	140	0.2	0.5	0.0	3.0
execrlc	139	1.3	0.9	0.0	3.0

Source: QS World University Rankings, Times Higher Education (THE) World University Rankings, World Development Indicators (WDI), and the Database of Political Institutions 2017 (DPI-2017).

Table 2 presents descriptive statistics for key variables. The mean number of elections (*elec_num*) is 5.2, with a maximum of 26, indicating significant variation in electoral frequency. The number of parties (*pty_num*) has a mean of 26.2. The average country has 169.4 universities (*univ*), with 3.7 and 4.8 in QS and THE rankings (*dqs*, *dthe*), respectively. GDP per capita and population show wide ranges, reflecting economic and demographic diversity.

To analyze in more detail the potential relationship between the democracy indicators and higher education quality, we present Figure 2. In this figure, we show a set of scatter plots of the relationship between each of the democracy indicators, i.e., the number of parties and the number of elections versus two variables that may capture the quality of tertiary education, i.e., the number of universities included into two main rankings, the QS and Shanghai rankings. Also, we include the center of mass of the relationship between the two variables we analyze, the center of mass are the areas where there is a large density of data in the relationship between variables. Furthermore, we include the fitted line to observe the sign of the correlation between those variables.

Figure 2. Scatter Plot of Universities Rankings vs. the Number of Elections and Parties



Source: QS World University Rankings, Times Higher Education (THE) World University Rankings, World Development Indicators (WDI), and the Database of Political Institutions 2017 (DPI-2017).

On the left column of the figure, we have the scatter plots for each democracy indicator and the number of universities included in the ranking QS; on the right column, we observe the scatter plots of the democracy indicators versus the number of universities included into the shanghai ranking.

According to the figure, we observe a positive relationship between the proxy of quality of tertiary education. Also, we notice that the number of elections is more strongly related to the ranking of universities than the number of parties. In other words, countries with a larger number of universities included in international rankings are countries that have more elections as well as number of parties; however, this last relationship is not as clear as the first one.

2.3 Methodology

This section shows the econometric approach to analyze the impact of higher education quantity and quality on democratic outcomes across 159 countries, using data averaged from 1990 to 2020. We present a baseline cross-sectional model and address endogeneity using spatial econometric models, ensuring robust causal inference. The

methodology accounts for spatial dependencies and unobserved factors, based on previous studies (Sanborn & Thyne, 2014; Rodrigues, 2023).

To examine the relationship between higher education and democracy, we specify the following cross-sectional model:

$$democracy_i = \beta_0 + \beta_1 ranking_i + \beta_2 log(univ)_i + X_i' \alpha + \varepsilon_i, \quad (1)$$

where $democracy_i$ represents the democracy indicators for country i ; similarly, $elec\_num$ is number of national elections, 1990–2017, and pty_num is the number of political parties, 1990–2017, both sourced from the Constituency-Level Elections Archive (CLEA) (CLEA, 2019). The explanatory variable $ranking_i$ denotes the number of universities in country i listed in the QS World University Rankings (dqs) or the Times Higher Education World University Rankings ($dshanghai$), serving as proxies for tertiary education quality. The variable $log(univ)_i$ is the natural logarithm of the total number of universities, colleges, and institutes, sourced from the Ranking Web of Universities, capturing education quantity. The vector X_i' includes control variables averaged over 1990–2020: $log(gdp\_pc)$ which stands for the natural logarithm of GDP per capita in constant 2010 USD, $log(pop)$ is the natural logarithm of population in millions, $nad1$ is the number of administrative regions, $yrsoffc$ represents the years the chief executive has been in office, $military$ is a dummy for military chief executive, $execrel$ is the religious nature of parties (categorical), and $execrlc$ is the party economic policy orientation (categorical), sourced from the World Development Indicators and Database of Political Institutions 2017 (Cruz *et al.* 2018).

A key challenge in estimating equation (1) is endogeneity, which may arise from three sources: (1) reverse causality, where democratic institutions promote educational expansion; (2) omitted variables, such as cultural or historical factors influencing both education and democracy; and (3) measurement errors, particularly in ranking-based quality proxies. Ordinary Least Squares (OLS) estimation of equation (1) may yield biased coefficients if explanatory variables are correlated with the error term ε_i , leading to incorrect inferences about causal relationships (Acemoglu *et al.* 2005).

On the other hand, X_i' represents the set of control variables that might be related to the democracy indicators. Among these variables, we include the natural logarithm of population, $log(pop)$; the natural logarithm of the GDP per capita on constant dollars of 2010, $log(gdp\_pc)$; the number of administrative regions, $nad1$; the average years that the executive has been in the office, $yrsoffc$; the percentage of years where the chief executive was a military officer, $military$; the average religious nature of parties, $execrel$; and the average party orientation with respect to the economic policy, $execrlc$. All the variables are taken on average between 1990 and 2020 to capture the long-run effects among variables.

To address endogeneity, particularly spatial endogeneity due to geographic proximity and shared unobserved characteristics (e.g., regional political norms or influence), we employ Spatial Autoregressive (SAR) and Spatial Error Models (SEM). Spatial dependence is critical in cross-country studies, as democratic outcomes in one country may influence or be influenced by those in neighboring countries (Sanborn & Thyne, 2014). The spatial weights matrix W is constructed based on contiguity criteria, in other words, W is a matrix fill with 1 and 0, where 1 represents that two countries share borders. In the case that countries are isolated, we complete the contiguity looking for their 3 nearest neighbors based on distance among their centroids.

The SAR model is specified as:

$$democracy_i = \beta_0 + \rho W_{\{ij\}} democracy_j + \beta_1 ranking_i + \beta_2 log(univ)_i + X_i' \alpha + \varepsilon_i, \quad (2)$$

where $\rho W_{\{ij\}} democracy_j$ is the spatially lagged dependent variable, and ρ quantifies the strength of spatial spillovers. A significant ρ indicates that democratic outcomes in country i are influenced by those in neighboring countries, potentially due to policy diffusion or regional norms (Fortunato & Panizza, 2015). By accounting for these spillovers, the SAR model provides more consistent estimates of β_1 and β_2 .

The SEM model is specified as:

$$democracy_i = \beta_0 + \beta_1 ranking_i + \beta_2 log(univ)_i + X_i' \alpha + u_i, \quad (3)$$

$$u_i = \lambda W u_i + \varepsilon_i$$

where λ captures spatial autocorrelation in the error term, capturing unobserved, spatially correlated factors (e.g., regional political culture). A significant λ indicates that SEM is necessary to correct for biased OLS estimates (Rodrigues, 2023). We apply Moran's I test to check for residual spatial autocorrelation and conduct robustness checks.

3. Research Results

Table 3 presents OLS estimates for equation (1), with panels for *elec_num* (number of elections) and *pty_num* (number of parties). Each panel includes models with and without income-level dummies (*LIC*, *LMIC*, *UMIC*, with high-income omitted to avoid multicollinearity). Columns alternate between *dqs* (QS rankings) and *dshanghai* (THE rankings) as quality proxies.

Table 3. OLS Estimation Results

	elec_num				pty_num			
	Control		No Control		Control		No Control	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
univ	0.0003	0.0003	0.0003	0.0003	1.159***	1.164***	1.153***	1.159***
	(0.0004)	(0.0004)	(0.0004)	(0.0004)	(0.116)	(0.114)	(0.118)	(0.117)
dqs	0.042**		0.042**		-31.799***		-31.909***	
	(0.019)		(0.019)		(5.730)		(5.840)	
dshanghai		0.035**		0.036**		-28.646***		-28.967***
		(0.016)		(0.016)		(5.004)		(5.093)
log(gdp_pc)	0.913***	0.944***	0.249	0.255	-19.230	-38.295	-22.711	-24.797
	(0.129)	(0.125)	(0.310)	(0.309)	(39.738)	(38.293)	(96.852)	(96.074)
log(pop)	0.207**	0.235**	0.191**	0.218**	60.492**	40.646	57.073**	37.155
	(0.092)	(0.091)	(0.092)	(0.090)	(28.503)	(27.768)	(28.867)	(28.110)
nad1	0.012	0.011	0.013	0.012	-3.663	-3.151	-2.997	-2.399
	(0.011)	(0.011)	(0.011)	(0.011)	(3.460)	(3.441)	(3.540)	(3.516)
LIC			-3.072**	-3.162**			-26.415	47.806
			(1.328)	(1.330)			(415.412)	(413.100)
LMIC			-2.073**	-2.149**			20.731	77.936
			(0.941)	(0.940)			(294.459)	(292.026)
UMIC			-1.323**	-1.344**			-127.296	-112.829
			(0.650)	(0.650)			(203.364)	(201.846)
Constant	-6.171***	-6.798***	1.020	0.647	-498.069	-71.530	-391.142	-137.473
	(2.058)	(1.988)	(3.668)	(3.643)	(635.213)	(609.333)	(1,147.533)	(1,131.881)
Observations	159	159	159	159	159	159	159	159
R²	0.407	0.406	0.429	0.428	0.466	0.472	0.471	0.478
Adjusted R²	0.388	0.386	0.398	0.398	0.448	0.454	0.442	0.450
Residual Std. Error	2.063	2.066	2.046	2.046	636.660	633.266	640.091	635.698
F Statistic	21.023***	20.894***	14.059***	14.048***	26.688***	27.304***	16.672***	17.164***

Note: *p<0.1; **p<0.05; ***p<0.01

The OLS results reveal distinct effects of higher education quantity and quality. The number of universities (*univ*) is not statistically significant for *elec_num*, with coefficients in the range of 0.0003 to 0.0005 and with a p-value $p > 0.1$, suggesting no robust effect on election frequency. However, it is highly significant for *pty_num*, i.e. coefficients between 1.051 and 1.159 with a p-value $p < 0.01$, indicating that a 10-unit increase in universities is associated with approximately 10.5–11.6 additional parties. This supports the hypothesis that greater access to higher education promotes political pluralism, possibly through social mobilization and diverse elite formation (Fortunato & Panizza, 2015).

Education quality (coefficients for *dqs* and *dshanghai*) shows significant effects across both outcomes. For *elec_num*, coefficients are positive and statistically significant (values between 0.030–0.042 with a p-value $p < 0.05$), suggesting that each additional university in QS or THE rankings increases elections by 0.03–0.04. For *pty_num*, coefficients are negative and statistically significant, with coefficient in the range of -31.909 to -24.971

with a p-value of $p < 0.01$, indicating that quality reduces party numbers by 25–32 per ranked university. This suggests a “screening effect,” where high-quality education promotes informed citizens and cohesive elites, reducing party fragmentation (Glaeser *et al.* 2007).

Control variables show mixed results. $\log(\text{gdp\_pc})$ is positive and significant for elec_num in models with controls (coefficients between 0.722 and 0.751, with a p-value $p < 0.01$) but not without, suggesting wealthier countries hold more elections, consistent with Lipset (1959). $\log(\text{pop})$ is positive for pty_num in some models ($p < 0.1$), indicating larger populations support more parties. The number of administrative regions (nad1) is not statistically significant in any model, which means that the number of regions or provinces does not affect the number of elections and parties. Income dummies (LIC, LMIC, UMIC) are significant for elec_num (coefficients in the range of -3.072 to -1.323 , with p-value $p < 0.05$), suggesting non-high-income countries have fewer elections.

The estimation results obtained in Table 3 slightly change once we incorporate some characteristics of governments across countries. In Table 4 we observe that the number of universities have no effects over the election number while, contrary to before, it has statistically and positive effect over the number of parties. On the case of the quality of tertiary education, the effect remains similar to above, i.e., the quality of tertiary education impulse the number of election while tend to reduce the number of parties.

Table 4. OLS Estimation Results with Control Variables

	elec_num		pty_num	
	(1)	(2)	(3)	(4)
universities	0.0004 (0.0003)	0.0005 (0.0003)	1.051*** (0.120)	1.065*** (0.119)
dqs	0.037** (0.016)		-27.361*** (5.848)	
dshanghai		0.030** (0.014)		-24.971*** (5.070)
$\log(\text{gdp\_pc})$	0.722*** (0.128)	0.751*** (0.124)	-62.812 (44.115)	-78.923* (42.322)
$\log(\text{pop})$	-0.015 (0.107)	0.015 (0.106)	69.724* (38.085)	47.445 (37.305)
nad1	0.013 (0.011)	0.012 (0.011)	-4.932 (3.762)	-4.409 (3.735)
yrsoffc	-0.157*** (0.033)	-0.157*** (0.033)		
military	-1.462** (0.710)	-1.481** (0.712)		
excrel			526.802*** (108.085)	533.788*** (106.955)
execrlc	0.494*** (0.176)	0.497*** (0.177)	117.087* (62.080)	115.171* (61.606)
Constant	-0.411 (2.161)	-1.098 (2.102)	-503.031 (751.107)	-54.835 (720.276)
Observations	136	136	136	136
R2	0.610	0.608	0.549	0.556
Adjusted R2	0.585	0.583	0.525	0.532
Residual Std. Error	1.775	1.780	635.301	630.352
F Statistic	24.809***	24.597***	22.278***	22.918***

Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$

Regarding the other characteristics, we observe that economic situation, capture by the GDP per capita, has positive effect over the election numbers, which implies that countries with higher level of GDP per capita are countries with more number of elections. At the same time, we observe that higher income countries have less

number of parties under certain conditions. The size of population results to be non-statistically significant in most of cases; similarly, the number of regions or provinces also are not statistically significant. Additionally to above, political controls (*yrsoffc*, *military*, *execrel*, *execrlc*) show that longer executive tenures and military leadership reduce elections, while religious and ideological party orientations increase party numbers.

Table 5 presents SAR and SEM estimates, addressing spatial endogeneity. The sample size is 129 countries due to missing spatial data for some nations. The spatial error parameter (λ) is significant in SEM models (range between 0.198–0.247 with a p-value of $p < 0.05$), confirming spatially correlated omitted variables (e.g., regional political norms). This consistent significance of λ emphasizes the necessity of the SEM specification to properly capture and account for this form of endogeneity, thereby providing more reliable coefficient estimates. The spatial lag parameter (ρ) is insignificant in SAR models ($p > 0.1$), suggesting limited direct spillovers in democratic outcomes.

Table 5. Regression Results: Higher Education and Democracy (Spatial Models)

	elec_num				pty_num			
	dqs		dshanghai		dqs		dshanghai	
	SAR	SEM	SAR	SEM	SAR	SEM	SAR	SEM
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
universities	0.001 (0.000)	0.001* (0.000)	0.001 (0.000)	0.001* (0.000)	1.056*** (0.118)	1.094*** (0.115)	1.074*** (0.117)	1.123*** (0.113)
dqs	0.031* (0.016)	0.026 (0.016)			-27.492*** (5.783)	-25.616*** (5.277)		
dshanghai			0.024* (0.014)	0.019 (0.014)			-25.357*** (4.998)	-24.273*** (4.571)
log(gdp_pc)	0.796*** (0.133)	0.799*** (0.114)	0.826*** (0.129)	0.829*** (0.109)	-49.199 (46.476)	-40.013 (49.616)	-64.016 (44.616)	-45.072 (48.527)
log(pop)	-0.009 (0.103)	-0.009 (0.097)	0.017 (0.102)	0.014 (0.096)	63.087 (38.590)	74.175* (38.203)	40.377 (37.855)	54.746 (37.261)
nad1	0.022* (0.011)	0.022* (0.010)	0.021* (0.011)	0.022* (0.010)	-3.131 (3.951)	-2.738 (3.825)	-2.363 (3.918)	-2.133 (3.756)
yrsoffc	-0.163*** (0.033)	-0.158*** (0.030)	-0.163*** (0.033)	-0.158*** (0.030)	10.782 (11.630)	18.968 (11.845)	10.150 (11.506)	18.379 (11.716)
military	-1.302* (0.704)	-1.049 (0.678)	-1.316* (0.706)	-1.043 (0.679)	9.673 (263.344)	-133.164 (253.934)	24.547 (260.509)	-128.775 (249.608)
execrel	-0.347 (0.291)	-0.516* (0.263)	-0.367 (0.292)	-0.542* (0.261)	506.585*** (107.467)	486.312*** (114.097)	510.527*** (105.992)	478.936*** (113.138)
execrlc	0.491** (0.177)	0.560*** (0.169)	0.491** (0.178)	0.568*** (0.169)	138.752* (66.300)	109.011* (65.052)	136.485* (65.512)	108.525* (64.046)
Constant	-0.933 (2.097)	-1.305 (1.948)	-1.548 (2.044)	-1.880 (1.875)	-670.496 (774.615)	-910.529 (798.791)	-228.721 (745.299)	-595.348 (772.822)
ρ (SAR)	-0.040		-0.041		0.085		0.089	
λ (SEM)		-0.198**		-0.207**		0.225**		0.247***
Moran's I	0.089	0.035**	0.074	0.028**	0.239	0.010**	0.166	0.004***
Observations	129	129	129	129	129	129	129	129
Log Likelihood	-250.680	-249.182	-251.135	-249.504	-1,013.205	-1,011.169	-1,011.885	-1,009.382
σ^2	2.852	2.747	2.872	2.757	387,690.000	369,210.000	379,740.000	357,620.000
Akaike Inf. Crit.	525.360	522.360	526.270	523.010	2,050.400	2,046.300	2,047.800	2,042.800
Wald Test (df = 1)	0.342	4.422**	0.338	4.819**	1.760	6.616**	1.990	8.171***
LR Test (df = 1)	0.343	3.338*	0.341	3.603*	2.319	6.389**	2.598	7.605***

Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$. Standard errors in parentheses. ρ is the spatial autoregressive parameter (SAR). λ is the spatial error parameter (SEM).

The results for the univ variable (quantity of higher education) show an interesting and differentiated pattern depending on the dependent variable. Regarding the number of elections (elec_num), in all models (SAR and SEM, both with dqs and dshanghai), the coefficient for univ is positive and reaches the significant level at 10% in some models. This suggests a tendency, although weak, for a greater number of universities to be associated with an increase in the number of elections. While significance is not robust across all specifications, the direction of the effect is consistent. In contrast, for pty_num, the impact of the number of universities is stronger and consistently significant (at 1% in all models). A higher number of universities is associated with a robust increase in the number of political parties. This finding is crucial, as it supports the hypothesis that the quantitative expansion of higher education could stimulate greater political pluralism and the emergence of diverse factions or platforms that eventually organize into parties. A potential explanation is that a larger university infrastructure facilitates social mobilization, the articulation of diverse interests, and the formation of elites with different political views. These results suggest that, while the quantity of universities may have a tenuous relationship with election frequency, its impact on the diversification of the party system is higher.

The quality variables, dqs and dshanghai, show a complementary perspective to quantity. Regarding the number of elections (elec_num), the quality measured by dqs shows a positive and significant coefficient (at 5% in the SAR model and 10% in the SEM). This implies that a higher quality of higher education is associated with an increase in the number of elections. Similarly, dshanghai also presents a positive coefficient, significant at 10% in the SAR model and not significant in the SEM. The trend is the same as with dqs, suggesting that academic excellence contributes to electoral activity. This could reflect a more informed and participatory citizens demand for accountability from leaders.

Regarding the number of political parties (pty_num), for dqs, both models (SAR and SEM) show a negative and highly significant coefficient at 1%. This indicates that a higher quality of education, measured by dqs or dshanghai, both are associated with a reduction in the number of political parties. A higher quality education is related to a decrease in the number of political parties. Contrary to the effect of quantity, the quality of higher education appears to reduce party fragmentation. This could be interpreted as higher quality education promoting more cohesive citizens leading to a more consolidated and less fragmented party system. Alternatively, it might suggest that a better-trained elite from high-quality universities can be more effective in building broad coalitions, reducing the need for multiple parties.

The comparison between the effects of quantity and quality of higher education reveals a fine and sophisticated relationship with democracy, extending beyond the simple assumption of “more education, more democracy”. The results from these spatial models, which control for spatial endogeneity and are therefore more robust than simple OLS, offer a clearer view.

Specifically, the quantity of universities (univ) drives the number of parties, suggesting that greater accessibility to higher education can promote the diversification of political representation. Conversely, the quality of tertiary education (dqs, dshanghai) increases the number of elections, which could indicate greater institutionalization of democratic processes or a more active citizenship. Simultaneously, it reduces the number of parties, pointing to a possible effect of consolidation or efficiency in the party system.

They suggest that investment in higher education has complex and non-linear effects on democracy, acting in different ways depending on whether quantitative expansion or qualitative improvement is prioritized. Quantity may be a driver of pluralism, while quality could be a factor in consolidation and electoral stability. This differentiation is a significant contribution to the debate on the role of education in democratic development.

A critical diagnostic tool is the Moran's I test on residuals. This test assesses whether spatial autocorrelation persists in the error terms after the spatial model has been estimated. For SAR models, the p-value from the “LM test for residual autocorrelation” indicates whether the SAR specification has successfully accounted for the spatial dependence. Non-significant p-values, 0.089 for elec_num versus dqs SAR, 0.074 for elec_num versus dshanghai SAR, suggest that residual spatial autocorrelation has largely been addressed, although some models may retain marginal significance. For SEM models, the p-value associated with the z-value of the λ parameter directly show the relevance of modeling spatial error. A significant p-values for λ , 0.035 for elec_num versus dqs SEM, 0.028 for elec_num versus dshanghai SEM, 0.010 for pty_num-dqs SEM, 0.004 for pty_num-dshanghai SEM, confirm that spatial autocorrelation was indeed present in the errors and has been effectively captured by the SEM model. A non-significant Moran's I on residuals would typically be desired post-modeling to ensure all spatial effects are accounted for; here, the significance of λ itself confirms the necessity and efficacy of the SEM.

Furthermore, the Akaike Information Criterion (AIC) on the spatial models exhibit lower AIC values compared to their non-spatial counterparts, indicating a better-fitting model, balancing model complexity with goodness of fit. Lastly, the Wald Test ($df = 1$) and LR Test ($df = 1$) confirm that the inclusion of spatial components significantly

improves the model's explanatory power over a non-spatial model by evaluating the statistical significance of the spatial parameters (ρ and λ).

4. Discussions

The findings of this research advance the scientific knowledge by suggesting that higher education is not a monolithic driver of democracy; rather, its impact depends fundamentally on the distinction between institutional quantity and academic quality. While Lipset (1959) argued that education broadly fosters the conditions for democratic stability, our results suggest a more complex mechanism: the quantitative expansion of the university system is associated with greater political pluralism, potentially by lowering the barriers to social mobilization and the articulation of diverse interests. This aligns with Fortunato and Panizza (2015), who emphasize that educational access facilitates the institutionalization of varied political platforms, thereby increasing the number of parties.

However, the discovery of a "screening effect" associated with higher education quality introduces a critical refinement to existing theories. The negative correlation between university rankings and the number of political parties suggests that high-quality education may foster a more informed electorate and a more cohesive political elite capable of forming broad, stable coalitions. This could reduce the fragmentation often seen in developing democracies. Furthermore, the positive impact of quality on election frequency supports the hypothesis of Larreguy and Marshall (2017) that a higher caliber of education may empower citizens to demand greater institutional accountability and regular electoral cycles. By utilizing spatial econometric models (SAR and SEM), this study also accounts for the significant role of regional political norms, accounting for spatial dependencies that previous cross-sectional studies have often overlooked.

Conclusions and Further Research

This study examines the dual and non-linear role of higher education in democratic development across 159 countries. Our results suggest that while the mere presence of more universities is associated with a diverse and pluralistic party system, it is the quality of these institutions that is linked to greater electoral frequency and political consolidation. These findings have significant implications for international development and institutional design. For policymakers in low- and middle-income nations, the expansion of university access remains a vital tool for fostering political representation. Conversely, for nations seeking to stabilize and institutionalize their democratic processes, investments in academic excellence - reflected in global rankings and research infrastructure - may be important for fostering a more consolidated and efficient political landscape.

Despite these contributions, the study faces certain limitations that set the stage for future research directions. The reliance on cross-sectional data, while mitigated by spatial modeling, limits our ability to observe the long-term temporal evolution of these effects within individual countries. Importantly, our identification strategy cannot fully rule out reverse causality or omitted variable bias: democratic regimes may invest more in higher education, and unobserved country-level factors (e.g., colonial legacies, natural resource endowments) could drive both educational expansion and democratic outcomes simultaneously. Recent quasi-experimental studies using compulsory schooling reforms as instruments (Le & Nguyen, 2021) and meta-analyses synthesizing the broader evidence base (Dahlum & Knutsen, 2022) suggest that the education–democracy relationship, while positive, is smaller and more contingent on institutional context than the classical modernization thesis implies. Future work should employ panel data analysis to further investigate the "screening effect" and determine the lag time required for educational quality to translate into institutional stability. Additionally, investigating the specific role of various academic curricula - such as the difference between STEM and social science focus - could provide a deeper understanding of how specialized knowledge influences democratic preferences and the professionalization of the political class. Overall, this research contributes a nuanced framework for understanding how the quantity and quality of higher education relate differently to democratic outcomes.

Declarations:

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Economic and Practical Aspects of the Use of Modern Management Methods in Hotels. A Case Study



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Abstract: Modern management methods have been extensively studied in the hospitality sector; however, empirical evidence from Central European post-transition economies remains limited. Recent studies from the region have examined general performance measurement practices or process management orientation, yet systematic data on the implementation of specific management tools in hotels have been largely absent. This study addresses this gap by investigating the adoption of five modern management methods - Benchmarking, Balanced Scorecard, Total Quality Management, Six Sigma, and Lean - in Slovak hotels. Based on a questionnaire survey of 56 hotels across different categories, ownership types, and sizes, the study employs non-parametric statistical methods (Kruskal-Wallis and Mann-Whitney tests) using SPSS software. The findings reveal that 38% of surveyed hotels actively use at least one modern management method, 41% plan to implement such methods, while 21% neither use nor plan to adopt them. Benchmarking emerges as the most widely adopted method (30%), followed by Balanced Scorecard (19%) and TQM (17%), whereas Six Sigma adoption remains marginal (9%). Statistical analysis found no significant differences in adoption rates across hotel categories, ownership types, or size classifications ($p > 0.05$). The study provides the first systematic empirical evidence on management method adoption in Slovak hotels and offers practical implications for hospitality managers and policymakers in the region.

Keywords: management methods; hotel; Central Europe; benchmarking; balanced scorecard; TQM.

JEL Classification: L83; M10; M11; C00.

Introduction

Modern management methods have been extensively studied in the hospitality sector; however, empirical evidence from Central European post-transition economies remains limited. While methods such as Balanced Scorecard, Benchmarking, Total Quality Management, Six Sigma and Lean Management have become established tools for performance improvement in Western European and North American hotels (Elbanna *et al.* 2022; Gierczak-Korzeniowska and Golembki, 2018), their adoption in Central and Eastern European (CEE) hospitality contexts has received considerably less scholarly attention.

Despite their theoretical and practical relevance, empirical evidence suggests that the adoption of modern management methods in hotels is uneven and context dependent. Previous studies indicate that while large or chain-affiliated hotels tend to adopt formalized management tools more frequently, small and independent hotels often rely on intuitive or informal management practices, citing constraints related to time, knowledge and financial resources (Elbanna *et al.* 2022; Knižka, 2015). Moreover, existing research has largely focused on individual methods or specific national contexts (Fatima and Elbanna, 2020; Perdomo-Verdecia *et al.* 2022; Alphon *et al.*

2023), leaving room for further investigation into how different management methods are used in practice and how hotel characteristics influence their adoption.

Recent research from the CEE region has begun to address this gap. Jugović, Štavljanin and Kostić Stanković (2022) examined performance measurement practices in CEE winter destination hotels, while Sebova, Svec and Chovanova (2025) investigated the role of business process management in Slovak hotels, finding that only 12% of establishments apply process-oriented approaches. However, these studies focused on general performance measurement or process management orientation rather than on the adoption of specific management tools. Systematic empirical data on the implementation of Benchmarking, Balanced Scorecard, TQM, Six Sigma or Lean methodologies in Slovak hotels have not been available until now.

In the Slovak context, the hotel industry is dominated by small and medium-sized, predominantly independent hotels. Understanding how these hotels perceive, implement or reject modern management methods is therefore essential for both managerial practice and policy support aimed at improving sectoral competitiveness.

Against this background, the aim of this paper is to analyze the current use of modern management methods in hotels in Slovakia and to assess their economic and practical implications for hotel performance. The study examines which methods are most frequently applied, which are planned for future implementation, what benefits hotels associate with their use and what barriers hinder their adoption. Furthermore, the paper investigates whether differences in adoption patterns can be observed according to hotel characteristics such as category, size and ownership structure.

By combining a literature-based conceptual framework with primary data obtained through a questionnaire survey, this study contributes to the existing field of hospitality management research in three ways. First, it provides updated empirical evidence on the adoption of modern management methods in Slovak hotels. Second, it offers a structured comparison of adoption patterns across different hotel profiles. Third, it translates empirical findings into application-oriented insights that may support hotel managers in selecting and implementing management methods aligned with their strategic objectives and organizational capabilities.

1. Literature Review

1.1 Modern Management Methods in a VUCA Environment

The contemporary business environment is increasingly characterized by volatility, uncertainty, complexity and ambiguity. Globalization has intensified competitive pressure and contributed to the emergence of new customer segments, while consumption patterns and customer expectations originating in advanced economies are gradually spreading to developing and post-transition countries, including Central and Eastern Europe (Szabo and Nemeth, 2017). At the same time, the rapid development of digital technologies has expanded the range of tools available for optimizing organizational processes and enhancing decision-making across industries (Peng *et al.* 2024).

The hospitality industry, and hotels in particular, operate in an environment that is highly sensitive to external shocks, demand fluctuations and changes in customer behavior. This makes the adoption of modern management methods especially relevant, as hotels must simultaneously manage service quality, cost efficiency, human resources and customer experience. The literature increasingly emphasizes the need for integrated management approaches that combine strategic orientation with operational excellence in order to enhance both economic performance and long-term competitiveness (Molina-Azorin *et al.* 2015; Tarí *et al.* 2022).

1.2 Fundamental Management Approaches and the Shift Towards Process Orientation

The shift from traditional functional management towards process-oriented approaches has been widely recognized as a response to the limitations of departmentalized organizational structures, including fragmentation of responsibilities, weak cross-functional coordination and a limited focus on customer value (Závadská and Korenková, 2017). Business Process Management (BPM) focuses on the identification, analysis, modelling and continuous improvement of organizational processes, with the primary objective of eliminating non-value-adding activities, optimizing resource utilization and enhancing overall performance (Hurzhyi *et al.* 2025; Jugović *et al.* 2022).

In the hospitality sector, where service delivery depends on the coordination of multiple interrelated activities, the process approach is particularly relevant. Empirical studies have confirmed that process and quality management contribute to cost reduction, improved service quality and stronger competitive advantage in hotels (Molina-Azorin *et al.* 2015; Tarí *et al.* 2022). Furthermore, recent research from the Central European hotel industry has demonstrated practical applications of BPM, including process modelling and reengineering aimed at improving direct sales and operational efficiency (Chalupa, Petříček and Ulrych, 2021; Sebova, Svec and Chovanova, 2025).

1.3 Contemporary Trends in Modern Management Methods

The growing interest in modern management methods reflects the increasing complexity of organizational environments and the need for continuous improvement and innovation. Management practices are no longer static; instead, they evolve in response to new challenges related to digitalization, sustainability and changing customer expectations. Managers are required not only to implement effective tools but also to continuously develop their competencies and align organizational performance with long-term strategic objectives (Záležáková and Vogl, 2015).

Among the most widely applied modern management methods are Balanced Scorecard, Benchmarking, ISO 9000 quality management systems, Kaizen, Lean Management, Six Sigma and Total Quality Management (TQM). These methods differ in their focus and scope, but they share a common objective: improving organizational performance through systematic measurement, analysis and continuous improvement.

The Balanced Scorecard (BSC), introduced by Kaplan and Norton in 1992, is a strategic performance management system based on four interconnected perspectives: financial, customer, internal business processes, and learning and growth. Unlike traditional performance measurement systems that focus primarily on financial indicators, the BSC provides a balanced view by integrating financial and non-financial measures. Its application enables organizations to translate strategy into measurable objectives, align operational activities with strategic goals and improve communication across the organization (Kumar *et al.* 2024). The successful implementation of BSC requires a clearly defined strategy, appropriate performance indicators and continuous monitoring of results (Rigby, 2017).

Benchmarking represents another widely used management method aimed at improving performance through systematic comparison with best practices within or outside the industry. Since the 1980s, benchmarking has been recognized as an effective tool for cost reduction, quality improvement and innovation (Madsen, Slåtten and Johanson, 2017). By identifying performance gaps and learning from industry leaders, organizations can enhance customer satisfaction, employee motivation and competitive advantage (Wang and Huang, 2021; Buhalis, 2022).

Quality management standards, particularly the ISO 9000 series, provide internationally recognized guidelines for ensuring consistent quality in products and services. These standards help organizations build customer trust by demonstrating their ability to meet defined quality requirements. ISO 9000 is applicable across industries, including hospitality, where service quality plays a crucial role in customer satisfaction and loyalty (Vohra *et al.* 2024).

Kaizen, originating from Japan, emphasizes continuous, incremental improvement involving all employees. Rather than relying on radical changes, Kaizen focuses on gradual enhancements of processes and work practices, fostering a culture of quality, innovation and employee engagement (Androniceanu *et al.* 2023). Similarly, Lean Management aims to eliminate waste and maximize value for the customer by optimizing processes and reducing inefficiencies. Originally developed in the Japanese automotive industry, Lean principles have been successfully applied in service sectors, including hotels, to improve efficiency and reduce costs (Perdomo-Verdecia, Sacristán-Díaz and Garrido-Vega, 2022).

Six Sigma is a data-driven methodology focused on reducing process variability and defects through statistical analysis and structured problem-solving, typically following the DMAIC cycle. Its implementation has been associated with improved quality, higher productivity and increased profitability, although it often requires significant organizational commitment and specialized expertise (Ferizi and Broum, 2024). Total Quality Management represents a holistic approach that integrates quality improvement across all organizational functions, aiming to enhance customer value, reduce waste and strengthen long-term competitiveness (Dale, Bamford and Van der Wiele, 2016).

1.4 Application of Modern Management Methods in Hotel Practice

Empirical studies have increasingly examined the application of modern management methods in the hotel industry and their impact on organizational performance. Elbanna *et al.* (2022) analyzed the use of the Balanced Scorecard in hotels operating in the United Arab Emirates and Qatar, focusing on the relationships between the four BSC perspectives. Their findings indicate that learning and growth indirectly influence financial performance through improvements in internal processes and customer satisfaction, highlighting the importance of non-financial indicators in achieving long-term success.

Benchmarking in hotel operations has been explored by Gierczak-Korzeniowska and Golebski (2017) in a study of hotels in the Polish city of Poznań. The authors found that benchmarking was widely used, particularly to improve service quality, reduce costs and enhance competitive advantage. However, the study also emphasized

the need to integrate benchmarking into long-term strategic planning rather than using it solely for addressing operational issues.

Lean Management applications in hotels have demonstrated significant potential for cost savings and efficiency improvements. Rauch *et al.* (2016) present examples from Japanese and international hotel chains, illustrating how process optimization, workforce flexibility and waste reduction can lead to substantial operational benefits without compromising service quality. Similarly, Six Sigma implementation in the German hotel A-ROSA resulted in improved service quality, reduced complaints and enhanced profitability through systematic process analysis and improvement (Mitrev, Lazarovska and Filiposki, 2018).

In the Slovak context, Kniška (2015) and Slivkova (2025) investigated the use of modern management methods in hotels and identified a preference for relatively simple relationship-oriented practices, such as customer and supplier relationship management. More advanced methods, including Balanced Scorecard and Six Sigma, were largely absent, mainly due to limited knowledge, lack of experience, time constraints and insufficient managerial support. These findings suggest a significant gap between theoretical recommendations and practical implementation, highlighting the need for further research and tailored managerial guidance. Sebova, Svec and Chovanova (2025) found that only 12% of hotels in Slovakia apply process-oriented management, with the primary barriers being lack of information and resistance to change.

While these studies provide valuable insights into the application of modern management methods in hotels, empirical evidence from Central and Eastern European (CEE) post-transition economies remains limited. The present study addresses this gap by providing empirical evidence on the adoption of five modern management methods in Slovak hotels, analyzing adoption patterns across hotel categories, ownership types, and size classifications. By doing so, it contributes to the limited body of knowledge on management practices in CEE hospitality sectors and offers practical implications for hotel managers and policymakers seeking to enhance competitiveness in this economically significant industry.

2. Material and Methods

2.1 Research Focus, Aim and Research Questions

Building on the reviewed literature, this study focuses on the adoption of modern management methods in the hotel industry and on their economic and practical implications for hotel performance. The object of the research is the population of hotels operating in Slovakia. The overall aim is to assess the current level of implementation of selected modern management methods in Slovak hotels and based on the empirical evidence, to formulate practical recommendations for their more effective use with regard to the specific characteristics and strategic objectives of hotels.

To operationalize the aim, the study addresses the following research questions: RQ1: What are the key characteristics of the surveyed Slovak hotels (e.g., size, category, type, and region)? RQ2: Which modern management methods are currently used by Slovak hotels and to what extent? RQ3: Are there differences in the implementation of modern management methods across hotels with different characteristics (e.g., size and category)? RQ4: Which management methods appear most suitable for strengthening the effectiveness of hotel management given the specific context of Slovak hotels?

2.2 Research Design and Data Collection

The empirical part of the study is based on primary data collected through a questionnaire survey. A structured questionnaire was selected as the main data-collection instrument due to its suitability for obtaining comparable information across hotels of different categories, sizes and ownership or management structures. The survey was administered electronically and distributed via e-mail to hotels operating in Slovakia.

The questionnaire survey targeted hotels operating in Slovakia (category Hotels, motels, hotels according to national statistics). The population size for 2024 was 747 hotels. The questionnaire was distributed by e-mail to 577 hotels, and 56 valid responses were obtained, resulting in a 9.7% response rate.

In the sample, small hotels (10–100 beds) dominated (71%), followed by medium-sized hotels (101–250 beds) (23%) and large hotels (>250 beds) (6%). By category, 3-star hotels were most represented (59%), followed by 4-star hotels (32%); 2-star and 5-star hotels accounted for 4% and 5%, respectively. Independent hotels represented 86% of respondents, while chain hotels accounted for 14%. The sample included hotels from all Slovak regions, with the highest shares from the Žilina region (21%) and the Banská Bystrica and Prešov regions (16% each).

To assess geographic representativeness, a chi-square goodness-of-fit test compared the regional distribution in the sample with the national regional distribution of hotels. The test result ($\chi^2 = 2.526$; $p = 0.903$)

indicates no significant deviation, suggesting that the sample can be considered geographically representative at the regional level.

2.3 Measures and Questionnaire Structure

The questionnaire was designed to capture the practical use of modern management methods as they are typically discussed in the hospitality management literature (e.g., performance management systems, process and quality management approaches, continuous improvement tools, and relationship-oriented practices). The key measured constructs included:

Implementation status and scope: whether the hotel uses selected methods and the perceived depth of implementation (e.g., basic vs. advanced use).

Method portfolio: identification of specific methods used (e.g., Balanced Scorecard, benchmarking, ISO-based quality systems, Kaizen/continuous improvement, Lean tools, Six Sigma, Total Quality Management, and related practices).

Implementation horizon: approximate time since adoption (e.g., recent implementation vs. longer-term use).

Perceived benefits: operational and economic outcomes (e.g., improved process efficiency, reduced costs, improved service quality, customer satisfaction).

Perceived barriers: internal and external constraints (e.g., limited knowledge or experience, time constraints, insufficient top management support, resistance to change, data availability).

Future plans: intended expansion or introduction of additional methods.

Where appropriate, response formats were structured to enable quantitative analysis (e.g., categorical options, ordinal scales). This design allowed the study to compare patterns across hotel groups and to identify tendencies relevant to both economic and operational performance.

2.4 Data Processing and Analytical Procedures

Data were coded and cleaned in Microsoft Excel prior to analysis. The statistical analysis was conducted in SPSS, using descriptive statistics and comparative analysis. Descriptive methods were applied to summarize the prevalence of individual management methods and to describe perceived benefits and barriers. Comparative analysis was used to examine differences in implementation patterns across hotel segments.

Specifically, the study compares the use and intensity of modern management methods across hotels by category/class, type, and size. This approach reflects the assumptions supported by the literature - that adoption of management methods may vary depending on organizational resources, managerial focus and operational complexity. The analysis is therefore oriented toward identifying practically meaningful patterns that can inform tailored recommendations for hotels with different profiles.

2.5 Validity Considerations and Limitations

Several methodological considerations apply to the interpretation of results. First, the data are self-reported by hotel representatives, which may introduce subjective bias in the assessment of method implementation or perceived outcomes. Second, the sample is based on voluntary participation, which may result in selection effects (e.g., hotels more interested in management innovation could be more likely to respond). Third, the study is cross-sectional and therefore captures adoption at a specific point in time; it does not allow causal inference regarding the impact of management methods on financial performance. Nevertheless, the research design is adequate for the study's purpose: to map current practices in Slovak hotels, identify differences across hotel segments, and develop evidence-based recommendations relevant for managerial decision-making.

3. Research Results

3.1 Sample Characteristics and Representativeness

The sample characteristics are summarized in Table 1. The survey yielded 56 valid responses from 577 contacted hotels (response rate: 9.7%).

Table 1. Sample characteristics (n = 56)

Characteristic	Category	N	%
Size (beds)	Small (10–100)	40	71
	Medium (101–250)	13	23
	Large (>250)	3	6
Category (stars)	2-star	2	4
	3-star	33	59
	4-star	18	32
	5-star	3	5
Type	Independent	48	86
	Chain	8	14

Source: Authors' survey, 2025.

A chi-square goodness-of-fit test confirmed geographic representativeness at the regional level ($\chi^2 = 2.526$; $df = 7$; $p = 0.903$).

3.2 Adoption Level of Modern Management Methods

Hotels were first asked whether they use modern management methods in their operations. Responses formed three adoption groups: active adopters (regular use), prospective adopters (not currently used but planned), and non-adopters (neither used nor planned). The distribution shows that 38% of hotels (n = 21) reported regular use, 41% (n = 23) planned implementation, and 21% (n = 12) neither used nor planned these methods.

3.3 Prospective Adopters: Drivers, Barriers, and Planned Methods

For hotels that planned future adoption (n = 23), the dominant motivations were operational and customer-oriented, led by increasing operational efficiency and improving service quality (Table 2, Panel A). The most frequently reported barriers were limited awareness of benefits, lack of financial resources, time constraints and uncertainty about return on investment (Table 2, Panel B). Regarding planned tools, prospective adopters most often indicated Total Quality Management and Benchmarking, while more technically demanding methods such as Six Sigma were planned only rarely (Table 2, Panel C). Overall, prospective adopters tended to favour broad, widely known approaches, while more resource-intensive methods were less preferred.

Table 2. Prospective adopters: motivations, barriers, and planned methods (n = 23)

Item	n	%
A. Motivations for future implementation		
Increasing operational efficiency	16	32
Improving service quality	16	32
Strengthening competitiveness	9	18
Lower implementation costs	5	10
Positive experience of other hotels	4	8
B. Barriers to implementation		
Limited awareness of benefits	13	20
Lack of financial resources	11	17
Time constraints	10	16
Uncertainty about ROI	10	16
Insufficient expertise	8	13

Item	n	%
Limited top-management support	6	9
Difficulty of practical application	4	6
Fear of failure	2	3
C. Methods planned for implementation		
Total Quality Management	12	36
Benchmarking	8	24
Balanced Scorecard	4	12
Kaizen	4	12
Lean Management	4	12
Six Sigma	1	3

Note: Multiple responses allowed. Source: Authors' survey, 2025.

3.4 Active Adopters: Methods, Benefits, and Barriers

Among hotels reporting regular use ($n = 21$), Benchmarking, Balanced Scorecard and Total Quality Management were the most frequently used methods (Table 3, Panel A). Approximately half of active adopters reported implementation within six months. The most frequently perceived benefits related to operational efficiency, competitiveness and service quality (Table 3, Panel B). Despite adoption, hotels still reported barriers, most notably time constraints, insufficient expertise and difficulty of practical application (Table 3, Panel C). This suggests that adoption does not eliminate capability constraints; rather, hotels may continue to experience operational and knowledge-related challenges during implementation and routinization.

Table 3. Active adopters: methods, benefits, and barriers ($n = 21$)

Item	n	%
A. Methods regularly used		
Benchmarking	14	30
Balanced Scorecard	9	19
Total Quality Management	8	17
Kaizen	6	13
Lean Management	6	13
Six Sigma	4	9
B. Perceived benefits		
Higher operational efficiency	16	21
Improved competitiveness	15	20
Improved service quality	15	20
Higher guest satisfaction	12	16
Cost reduction / resource optimisation	11	15
Better team and employee management	7	9
C. Perceived barriers		
Time constraints	10	19
Insufficient expertise	10	19
Difficulty of practical application	10	19

Item	n	%
Limited awareness of benefits	8	15
Uncertainty about ROI	7	13
Lack of financial resources	6	11
Limited top-management support	2	4
Fear of failure	1	2

Note: Multiple responses allowed. Source: Authors' survey, 2025.

3.5 Non-Adopters: Reasons for Non-Adoption

Hotels that neither used nor planned adoption ($n = 12$) most often cited insufficient expertise, limited awareness of benefits and uncertainty about ROI (Table 4). The pattern indicates constraints related to knowledge and perceived feasibility rather than a single dominant reason. When asked about interest in external training, the most frequent answer was negative, indicating relatively low immediate openness to capacity-building in this subgroup.

Table 4. Reasons for non-adoption (non-adopters, $n = 12$)

Reason for non-adoption	n	%
Insufficient expertise	5	17
Limited awareness of benefits	5	17
Uncertainty about ROI	5	17
Limited top-management support	4	14
Difficulty of practical application	4	14
Lack of financial resources	3	10
Time constraints	2	7
Fear of failure	1	3

Note: Multiple responses allowed. Source: Authors' survey, 2025.

3.6 Comparisons by Hotel Profile

3.6.1 Adoption Level by Category, Type, and Size

Table 5. Adoption level by hotel profile

Hotel profile	Active adopters	Prospective	Non-adopters
By category (stars)			
2-star	2	0	0
3-star	8	16	9
4-star	10	5	3
5-star	1	2	0
By type			
Chain	4	1	3
Independent	17	22	9
By size (beds)			
Small (10–100)	13	20	7
Medium (101–250)	7	3	3
Large (>250)	1	0	2

Source: Authors' survey, 2025.

Cross-tabulations indicate differences in adoption patterns by hotel category, type and size. For example, adoption was most common among 4-star hotels, whereas 3-star hotels most frequently reported plans to implement methods, alongside the highest share of non-adopters. Chain hotels more often reported active use than independent hotels, while independent hotels more frequently planned future adoption. By size, small hotels most often planned adoption, medium-sized hotels most frequently reported active use, and large hotels most frequently reported non-adoption; however, the number of large hotels was very small.

3.6.2 Statistical Tests for Adoption Differences

Non-parametric tests did not confirm statistically significant differences in adoption level. For hotel category, the Kruskal-Wallis test yielded $p = 0.060$; for hotel type, the Mann-Whitney test yielded $p = 1.000$; and for hotel size, the Kruskal-Wallis test yielded $p = 0.444$. Thus, while descriptive differences exist, they should be interpreted cautiously given sample size constraints.

Table 6. Statistical tests: Adoption level vs. hotel characteristics

Variable	Test	Test statistic	p-value
Category (stars)	Kruskal-Wallis	$H = 7.42$	0.060
Type (chain vs. independent)	Mann-Whitney	$U = 192.00$	1.000
Size (beds)	Kruskal-Wallis	$H = 1.63$	0.444

Note: All p -values > 0.05 , indicating no statistically significant differences. Source: Authors' calculations, 2025.

3.6.3 Methods Used by Hotel Profile

The portfolio of methods also varied descriptively by category, type and size. Four-star hotels reported the most diversified portfolios (notably Balanced Scorecard, Benchmarking and TQM), while three-star hotels most frequently reported Benchmarking. Method portfolios were broadly similar across chain and independent hotels, with Benchmarking dominating both groups.

Table 7. Methods used by hotel profile

Profile	BSC	Bench.	Kaizen	Lean	Six Sig.	TQM
By category (stars)						
2-star	2	1	2	1	2	1
3-star	0	6	2	2	0	2
4-star	6	6	2	3	2	4
5-star	1	1	0	0	0	1
By type						
Chain	3	4	1	1	1	2
Independent	6	10	5	5	3	6
By size (beds)						
Small (10–100)	5	9	5	2	4	4
Medium (101–250)	3	5	1	4	0	4
Large (>250)	1	0	0	0	0	0

Note: BSC = Balanced Scorecard; Bench. = Benchmarking; Six Sig. = Six Sigma. Source: Authors' survey, 2025.

3.6.4 Association Tests (Cramer's V)

Dependence tests using Cramer's V indicated weak-to-moderate associations between adoption level and hotel characteristics ($V \approx 0.245$ – 0.291), but none were statistically significant (all $p > 0.05$). The most plausible explanation is limited statistical power due to small cell counts in subgroup analyses.

Table 8. Cramer's V: Adoption level vs. hotel characteristics

Characteristic	Cramer's V	p-value
Category (stars)	0.291	0.147
Type (chain vs. independent)	0.245	0.186
Size (beds)	0.257	0.116

Note: All associations not statistically significant at $\alpha = 0.05$. Source: Authors' calculations, 2025.

3.7 Summary of Key Empirical Findings

Overall, the results suggest a heterogeneous adoption landscape among Slovak hotels: 38% actively use modern management methods, 41% plan adoption, and 21% remain non-adopters. Benchmarking, Balanced Scorecard and TQM are the most prominent methods among active adopters, while prospective adopters primarily intend to introduce TQM and Benchmarking. Across adoption groups, the main perceived value relates to efficiency and service quality, whereas the most persistent barriers are time, knowledge, and uncertainty about returns. Descriptive differences by category, type and size exist, but they are not consistently supported by statistical significance, indicating that conclusions about predictors of adoption should remain cautious.

4. Discussion

The findings of this study confirm that the adoption of modern management methods in Slovak hotels remains uneven and strongly differentiated by managerial readiness rather than by structural hotel characteristics alone. While more than one third of surveyed hotels actively apply modern management methods, a substantial share remains at the planning stage or refrains from adoption altogether. This pattern is broadly consistent with earlier empirical evidence from hospitality research, which suggests that management innovation in hotels tends to diffuse gradually and selectively rather than uniformly across the sector (Knižka, 2015; Buhalis, 2022).

The dominance of Benchmarking, Balanced Scorecard and Total Quality Management among active adopters corresponds with findings reported by Elbanna *et al.* (2022), who emphasise the suitability of these methods for service-oriented environments where performance is multidimensional and customer experience is critical. Benchmarking, in particular, emerges as a 'gateway method' that is relatively easy to understand and apply, which supports conclusions by Gierczak-Korzeniowska and Golembiński (2017) that benchmarking is often the first formal management tool adopted by hotels seeking performance improvement.

In contrast, more analytically demanding approaches such as Six Sigma remain marginal, which aligns with prior research highlighting their higher requirements in terms of data availability, analytical expertise and organizational discipline (Mitreva *et al.* 2018; Ferizi and Broum, 2024). The low planned adoption of Six Sigma among prospective adopters further suggests that Slovak hotels prioritize managerial tools perceived as flexible and less resource-intensive, a pattern also observed in small and medium-sized hospitality enterprises in other European contexts (Rauch *et al.* 2016).

The study also reveals that perceived benefits and perceived barriers are remarkably similar across adoption groups. Operational efficiency, service quality and competitiveness are consistently identified as key expected outcomes, which is in line with the service management literature emphasizing process optimization and quality management as primary value drivers in hospitality (Dale *et al.* 2016; Rigby, 2017). At the same time, time constraints, lack of expertise and uncertainty about return on investment persist even among active adopters, indicating that implementation challenges do not end with initial adoption but accompany the entire lifecycle of management innovation. What is distinctive in the Slovak context, however, is that these barriers persist at comparable intensity across all three adoption groups, suggesting that even hotels that have already implemented management methods continue to face capability constraints - a pattern that has not been explicitly documented in prior hospitality research from Western European settings.

A finding that represents a novel contribution specific to the Slovak context is the absence of statistically significant differences in adoption levels by hotel category, size or ownership type. This contrasts with some international studies that report higher adoption rates among larger or chain-affiliated hotels (Elbanna *et al.* 2022). However, the absence of statistically significant relationships in this study may reflect the relatively small sample size and the dominance of small, independent hotels in the Slovak market structure. From an interpretative perspective, the results suggest that managerial attitudes, knowledge and perceived feasibility may be more decisive than structural characteristics alone, supporting a capability-based view of management innovation adoption. Future research with larger samples could further test this proposition.

Overall, the discussion highlights that modern management methods are not rejected by Slovak hotels; rather, their adoption is shaped by perceived complexity, knowledge gaps and risk considerations. This underscores the importance of context-sensitive implementation strategies that align method selection with hotel-specific goals, resources and maturity levels. The findings also point to the potential role of industry associations, educational institutions and policymakers in facilitating knowledge transfer and reducing perceived barriers to adoption. From a theoretical perspective, the study contributes to the hospitality management literature by providing the first systematic empirical evidence on the adoption of multiple modern management methods in a Central European post-transition hotel market. Unlike prior studies conducted predominantly in Gulf state hotels (Elbanna *et al.* 2022), Turkish hospitality settings (Alphun *et al.* 2023) or international hotel chains (Rauch *et al.* 2016), the present findings emerge from a market dominated by small independent hotels, where managerial capability and awareness appear to be more relevant predictors of adoption than structural characteristics such as size or chain affiliation.

Conclusions and Further Research

The aim of this paper was to analyze the use of modern management methods in Slovak hotels and to assess their economic and practical implications for hotel performance. Based on a questionnaire survey of 56 hotels, the study demonstrates that the adoption of modern management methods is present but uneven. Approximately 38% of hotels actively apply such methods, while 41% plan future implementation and 21% remain non-adopters.

Addressing the research questions, the study found that: (RQ1) Slovak hotels are predominantly small (71%), independent (86%), and 3-star (59%) establishments; (RQ2) 38% actively use modern management methods, with Benchmarking (30%), BSC (19%), and TQM (17%) being most common, while Six Sigma remains marginal (9%); (RQ3) no statistically significant differences were found across hotel categories, sizes, or ownership types ($p > 0.05$); and (RQ4) Benchmarking and TQM appear most suitable for Slovak hotels given their lower complexity and resource requirements.

From a managerial perspective, the findings imply that hotels should not approach modern management methods as isolated tools but rather as part of a gradual capability-building process. Managers are encouraged to select methods that correspond to their strategic priorities and organizational readiness, starting with low-complexity tools and progressively integrating more advanced approaches as experience and data availability increase. Policymakers and industry associations may support this process through targeted training programs, dissemination of good practices and demonstration projects tailored to small and independent hotels.

Several limitations must be acknowledged when interpreting the results. First, the sample size of 56 hotels, while adequate for exploratory analysis, restricts the statistical power of inferential tests and limits the generalizability of subgroup comparisons. Second, the study relies on self-reported data provided by hotel managers or owners, which may be influenced by subjective perceptions, social desirability bias, or incomplete knowledge of actual practices. Third, the cross-sectional design captures adoption status at one point in time and does not allow for analysis of dynamic changes, implementation trajectories, or causal relationships between method adoption and performance outcomes. Fourth, the study focused on method adoption rather than implementation depth or effectiveness, leaving questions about actual performance impacts for future research.

Future research could address these limitations by employing larger samples or longitudinal designs that track adoption processes and performance outcomes over time. Qualitative case studies could provide deeper insight into implementation mechanisms, managerial learning and organizational change associated with modern management methods. Additionally, further studies may explore the causal relationship between specific management methods and financial or non-financial performance indicators, as well as the role of digitalization and sustainability-oriented management practices in shaping future adoption patterns in the hotel industry.

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Credit Authorship Contribution Statement:

Ľubica Šebová: Conceptualization, Methodology, Supervision, Writing – review and editing, Project administration, Funding acquisition

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Strategic Regimes and Equilibrium Behavior in EU Electricity Markets. A Game-Theoretic Analysis



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Abstract: The restructuring of Europe's electricity sector following Directive 2009/72/EC introduced strategic interdependence among national energy systems through liberalized market dynamics. This study applies a repeated game-theoretic framework to examine how five major EU member states - France, Germany, Italy, the Netherlands, and Spain - adjusted their price-output strategies over 2010–2023 in response to competitive pressures and institutional evolution. Each country is modelled as a strategic player choosing among four discrete strategy types based on relative price and output positions, with payoffs derived from observed electricity prices, generation volumes, and LCOE-based cost proxies. A multinomial logit model with theory-driven variable selection estimates the probability of strategic transitions conditional on current strategy, economic performance, and the post-reform institutional context. The analysis identifies High Price–High Output as the unique Nash equilibrium and Pareto-efficient outcome in every year of the study period - a result confirmed as robust to classification threshold variation through a systematic sensitivity analysis. Despite this clear payoff dominance, most countries exhibit persistent deviation from equilibrium, driven by path-dependent institutional inertia, grid constraints, and regulatory design. Germany demonstrates full and stable Nash alignment throughout the period, while France, Italy, Spain, and the Netherlands remain in behavioral clusters that diverge from the payoff-maximising configuration. These findings highlight the structural limits of market liberalization in delivering strategic convergence and carry direct implications for the 2024 EU Electricity Market Design reform and the REPowerEU renewable energy targets.

Keywords: electricity markets; Nash equilibrium; sensitivity analysis; repeated games; multinomial logit; energy policy; EU market reform.

JEL Classification: C72; C25; D43; H77; L94; Q48.

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Introduction

The EU's unbundling policy under Directive 2009/72/EC aimed to enhance competition in electricity generation by structurally separating transmission and generation. However, empirical research suggests that such separation may impose significant cost inefficiencies, particularly for large integrated utilities (Gugler *et al.* 2017). These findings call into question whether observed national strategies post-liberalization reflect competitive optimization or constrained institutional inertia.

The increasing decentralization of power systems and the growing strategic autonomy of national and subnational actors has sparked interest in coordination mechanisms that go beyond centralized optimization. Mezghani *et al.* (2018) highlight the importance of accounting for distribution-level flexibility and the need for decentralized coordination schemes, particularly through Generalized Nash Equilibrium frameworks.

The objective of this paper is, therefore, to model and analyze the strategic behavior of EU countries in the electricity market from 2010 to 2023, following the implementation of the 2009/72/EC Directive. By treating each

country as a player in a re-peated game, this study evaluates the evolution of price and output strategies through the concepts of observed payoffs, Nash equilibrium, and Pareto optimality, providing insights into the transitional dynamics of a competitive, integrated European power system.

1. Literature Review

The global electricity industry has undergone a fundamental transformation over the past few decades, transitioning from a landscape dominated by vertically integrated, state-controlled monopolies to one characterized by market liberalization, deregulation, and competition (Dimitriadis *et al.* 2021; Cheng *et al.* 2025). This global trend, driven by a pursuit of greater economic efficiency and consumer sovereignty, has dismantled traditional centralized structures in favour of a complex ecosystem of independent, often competing, market participants (Cheng *et al.* 2025; Navon *et al.* 2020). This new paradigm includes a diverse array of actors such as power generation enterprises, purchasing companies, grid operators, and new entities like virtual power plants (VPPs) and load aggregators, all navigating a market where strategic behaviour is paramount (Cheng *et al.* 2025; Navon *et al.* 2020). The primary goals of this liberalization have been to foster competition, which in theory leads to more efficient pricing and resource allocation, and to facilitate the large-scale integration of renewable energy sources (RES) needed to address climate change (Huppmann, 2016).

In this global trend, the restructuring of the European electricity market stands out as a particularly ambitious undertaking. Guided by a series of legislative packages, such as the 2009/72/EC Directive, the European Union has pursued the creation of a single, integrated, and competitive pan-European market (Oggioni and Smeers, 2012). A cornerstone of this architecture is the concept of Market Coupling (MC), a design that links national electricity markets through the coordinated management of cross-border transmission capacity (Oggioni *et al.* 2012; Huppmann, 2016). This model is typically organized into large price zones, which can span multiple countries, where a single uniform price is determined by the intersection of aggregated supply and demand curves (Kunz and Zerrahn, 2016). However, this design separates the commercial energy market from the physical realities of the grid; Power Exchanges (PXs) clear the market assuming unconstrained transmission within zones, while national Transmission System Operators (TSOs) are left to manage the resulting power flows (Oggioni *et al.* 2012).

This separation creates significant strategic and operational challenges. By design, MC results in an "incomplete market" where not all network constraints are priced, leading to potential inefficiencies (Oggioni *et al.* 2012). A prominent example was the former common German-Austrian price zone, where the uniform price masked severe internal grid congestion (Egerer *et al.* 2016; Kunz and Zerrahn, 2016). This structural flaw forced TSOs in neighbouring countries, like Poland and the Czech Republic, to perform costly out-of-market remedial actions - such as the redispatching of power plants - to ensure their own grid stability. The uncoordinated nature of these interventions gives rise to significant welfare losses, often termed the "costs of non-coordination" (Kunz and Zerrahn, 2016). The eventual, contentious split of the German-Austrian zone underscores that market design itself is a deeply strategic issue, with national interests often conflicting over the substantial welfare and trade implications of zonal configurations (Egerer *et al.* 2016).

The directive-led move towards liberalization has fundamentally altered the pricing strategies and behaviour of market participants. In the former monopoly structure, pricing was largely a cost-plus exercise under regulatory oversight (Cheng *et al.* 2025). In the new competitive environment, however, firms must act strategically, as their decisions are interdependent (Tang *et al.* 2025). Price-making firms can exercise market power, for example by physically or financially withholding generation capacity to influence the market-clearing price (Dimitriadis *et al.* 2021). Consequently, generators have developed sophisticated bidding strategies to maximize their profits, often modeled using complex bi-level optimization frameworks where a firm's profit maximization is constrained by the system operator's market-clearing problem (Dimitriadis *et al.* 2021; Soriano *et al.* 2021). This competitive pressure, combined with new sources of uncertainty from price volatility and intermittent RES, has also made risk management a central component of producers' strategies (Oggioni *et al.* 2014; Navon *et al.* 2020). Moreover, specific policies designed to implement the directives, such as the UK's Renewables Obligation, create powerful financial incentives that directly shape investment decisions and market behaviour (Oggioni *et al.* 2012).

Given this complex strategic landscape, traditional, centrally-planned optimization models are no longer sufficient (Navon *et al.* 2020). Game theory, a mathematical framework for analyzing the strategic interactions between rational decision-makers, has thus emerged as an essential tool for understanding the design and operation of modern power systems (Yarar *et al.* 2024; Navon *et al.* 2020). Its utility lies in its ability to model the selfish behaviour of independent players and predict the equilibrium outcomes of their interactions (Navon *et al.* 2020). By treating system actors - from individual generation units to entire countries - as players in a strategic game, researchers can analyze the emergence of stable market configurations and identify the incentives that drive

behaviour (De Paola *et al.* 2017; Navon *et al.* 2020). Strategic interactions in electricity markets - whether at the producer or national level - require game-theoretic treatment due to the anticipatory behavior of agents and the decentralized nature of decision-making (Le Cadre, 2019).

The institutional environment - including tariff schemes, market zones, and redispatch regimes - plays a crucial role in shaping generation investment strategies. Grimm *et al.* (2016) demonstrate that market design elements such as energy-only pricing and uniform price zones can lead to misaligned generator locations and inefficient network expansion. These structural distortions may explain the persistence of dominant strategies observed in many EU countries post-2009 market reform.

Central to any game-theoretic analysis are the concepts of equilibrium and optimality. A Nash equilibrium describes a stable state in a non-cooperative game where no player has an incentive to unilaterally deviate from their chosen strategy, given the strategies of all other players (Oggioni *et al.* 2012; Cheng *et al.* 2025). It represents a point of stability born from self-interest. However, this is not always the best outcome for the collective. This is where Pareto optimality becomes a crucial benchmark. A solution is Pareto optimal if it is impossible to make any single player better off without making at least one other player worse off (Bastianon, 2015; De Paola *et al.* 2017). It signifies the frontier of social efficiency.

A fundamental insight from game theory is that these two states often diverge. The classic "prisoner's dilemma" illustrates this perfectly: the individually rational strategy leads to a Nash equilibrium that is collectively worse for all involved than a cooperative, Pareto-optimal outcome (Bastianon, 2015). In electricity markets, this tension is ever-present. A cooperative strategy could yield lower prices and a Pareto-optimal state, but self-interest may lead to a less efficient Nash equilibrium (De Paola *et al.* 2017). The structure of the game - specifically, whether it is a single, one-shot interaction or a repeated game - is decisive in which outcome is more likely.

While one-shot games frequently result in inefficient Nash equilibria, the framework of a repeated game introduces the potential for cooperation. When players, such as EU member states, interact repeatedly, they can learn from past behaviours, build reputations, and employ strategies of reciprocity. The "shadow of the future" encourages players to prioritize long-term mutual benefit over short-term individual gain, potentially steering the market from an inefficient Nash equilibrium towards the Pareto frontier (Bastianon, 2015). This is especially pertinent to the European electricity market, which, since the 2009 directive, has functioned as precisely such a long-term, repeated game. While the literature has extensively applied game theory to producer-level strategy (Huppmann, 2016; Soriano *et al.* 2021) and TSO-level coordination (Oggioni *et al.* 2012; Kunz and Zerrahn, 2016), a macro-level analysis of the repeated strategic game between the member states themselves remains an underexplored area.

2. Materials and Methods

2.1. Data Sources and Variables

This study investigates strategic behavior among five EU member states in the electricity sector over the period 2010–2023, with a particular focus on the effects of the Directive 2009/72/EC on competitive market dynamics. France, Germany, Italy, the Netherlands and Spain were selected as they provided data availability and constitute the largest economies of European Union. Data were collected from two primary sources to construct the payoff matrix:

- Eurostat: National-level data on electricity prices (€/kWh) for household and industrial consumers, and gross electricity generation (GWh/year).
- OECD and IEA: Levelized Cost of Electricity (LCOE) estimates (USD/MWh) by generation technology and year, used as a proxy for production costs. Exchange rates (annual level) from ECB were used to convert LCOE to EUR/MWh.

This represents gross revenue from electricity production in year t . All payoffs are expressed in euros (€).

2.2. Strategy Classification

Each country-year pair is classified into one of four discrete strategy types, based on whether its price and output are above or below the annual EU median. This binary high/low classification captures the strategic posture of each country in terms of price competitiveness and generation volume.

Let C denote the set of countries:

$$C = \{c_1, c_2, \dots, c_N\} \quad (1)$$

Let $T = \{2010, 2011, \dots, 2023\}$ be the set of years.

Each country $c \in C$ chooses a strategy in year $t \in T$, denoted:

$$s_{ct} \in S = \{\text{High} - \text{High}, \text{High} - \text{Low}, \text{Low} - \text{High}, \text{Low} - \text{Low}\} \quad (2)$$

Strategies are based on comparisons of national indicators to the annual cross-sectional medians:

- P_{ct} : electricity price (€/kWh)
- Q_{ct} : electricity output (GWh)

Define the median values:

$$\bar{P}_t = \text{median}_{c \in C} P_{ct}, \quad \bar{Q}_t = \text{median}_{c \in C} Q_{ct} \quad (3)$$

Then strategy classification follows:

$$s_{ct} = \begin{cases} \text{High} - \text{High}, & \text{if } P_{ct} > \bar{P}_t \text{ and } Q_{ct} > \bar{Q}_t \\ \text{High} - \text{Low}, & \text{if } P_{ct} > \bar{P}_t \text{ and } Q_{ct} \leq \bar{Q}_t \\ \text{Low} - \text{High}, & \text{if } P_{ct} \leq \bar{P}_t \text{ and } Q_{ct} > \bar{Q}_t \\ \text{Low} - \text{Low}, & \text{otherwise} \end{cases} \quad (4)$$

2.3. Static Game-Theoretic Model

2.3.1. Game Setup

We model the interaction between EU countries as a repeated strategic-form game:

Players: $i=1, 2, \dots, N$ EU member states

Strategy Set: $S_i = \{\text{HH}, \text{HL}, \text{LH}, \text{LL}\}$

Payoff function:

$$\pi_i(s_i, s_{-i})_t = P_{it} \times Q_{it} - a_{it} \quad (5)$$

where $P_{it} \times Q_{it}$ represents gross revenue from electricity production and a_{it} is an estimated cost proxy expressed in LCOE values in year t . All payoffs are expressed in euros (€).

2.3.2. Nash Equilibrium

A strategy profile $s^* \in S$ is a **pure-strategy Nash equilibrium** if:

$$\pi_c(s_c^*, s_{-c}^*) \geq \pi_c(s_c, s_{-c}^*) \quad \forall s \in S, \forall c \in C \quad (6)$$

That is, no country can improve its payoff by unilaterally deviating. For each year, we identify such s^* empirically from observed payoff matrices.

Theorem 1. Nash Equilibrium Existence

Every finite strategic-form game has at least one mixed-strategy Nash equilibrium (Nash, 1950).

2.3.3. Pareto Efficiency

A strategy $s \in S$ is **Pareto efficient** in year t if there does not exist another $s' \in S$ such that:

$$\pi_{ct}(s') \geq \pi_{ct}(s) \quad \forall c \text{ and } \pi_{c't}(s') \geq \pi_{c't}(s) \text{ for some } c' \in C \quad (7)$$

We use a simple algorithm to extract non-dominated strategies from the observed payoff vectors in each year.

2.3.4. Cluster Analysis

We calculate each country's frequency of strategy usage over time:

$$f_c = [f_c^{HH}, f_c^{HL}, f_c^{LH}, f_c^{LL}] \in \mathbb{R}^4 \quad (8)$$

where $f_c \in \mathbb{R}^4$ is a column vector of frequencies.

We then apply K-Means clustering with $k=3$ to group countries into behavioral types:

- Aggressive: High-High dominant
- Conservative: Low-Low dominant
- Balanced: Mixed strategies

2.3.5. Dynamic Analysis: Transition and Switching

Lemma 1. (*Memoryless Property*)

If strategy transitions follow a Markov process, then the probability of moving to the next state depends only on the current state.

We model strategy transitions using a Markov transition matrix $T \in \mathbb{R}^{4 \times 4}$:

$$T_{ij} = Pr(s_{ct+1} = s_j | s_{ct} = s_i) \quad (9)$$

We compute this empirically using observed country-level transitions:

$$T_{ij} = \frac{\text{count}(s_{ct} = s_i \wedge s_{ct+1} = s_j)}{\sum_k \text{count}(s_{ct} = s_i \wedge s_{ct+1} = s_k)} \quad (10)$$

We also compute:

- Switch rate per country: proportion of years where $s_{ct+1} \neq s_{ct}$
- Nash alignment rate: proportion of years where $s_{ct} = s_t^{Nash}$

2.3.6. Multinomial Logit Model

We model the probability of switching to each strategy $s' \in S$ using a multinomial logistic regression:

$$Pr(s_{ct+1} = s' | s_{ct}, \pi_{ct}, D_t) = \frac{\exp(\beta_0^{s'} + \beta_1^{s'} s_{ct} + \beta_2^{s'} \pi_{ct} + \beta_3^{s'} D_t)}{\sum_k \exp(\beta_0^k + \beta_1^k s_{ct} + \beta_2^k \pi_{ct} + \beta_3^k D_t)} \quad (11)$$

where:

- s_{ct} : current strategy
- π_{ct} : current payoff
- D_t : dummy variable for post-2010 reform

This model quantifies the impact of economic performance and institutional context on strategy switching behavior.

Lemma 2. (*IIA in Multinomial Logit*)

The ratio of probabilities for any two alternatives depends only on their utilities, not on the presence of other alternatives (McFadden, 1974).

2.3.6.1. Model Calibration and Variable Selection

The multinomial logistic regression specified in Equation (11) was estimated using maximum likelihood (ML). The outcome variable is the strategy adopted in year $t+1$, comprising four unordered categories: High–High (HH), High–Low (HL), Low–High (LH), and Low–Low (LL). The Low–Low category was set as the reference (baseline) outcome, following the conventional practice of selecting the most prevalent or theoretically neutral category as the reference level (Tutz *et al.* 2015).

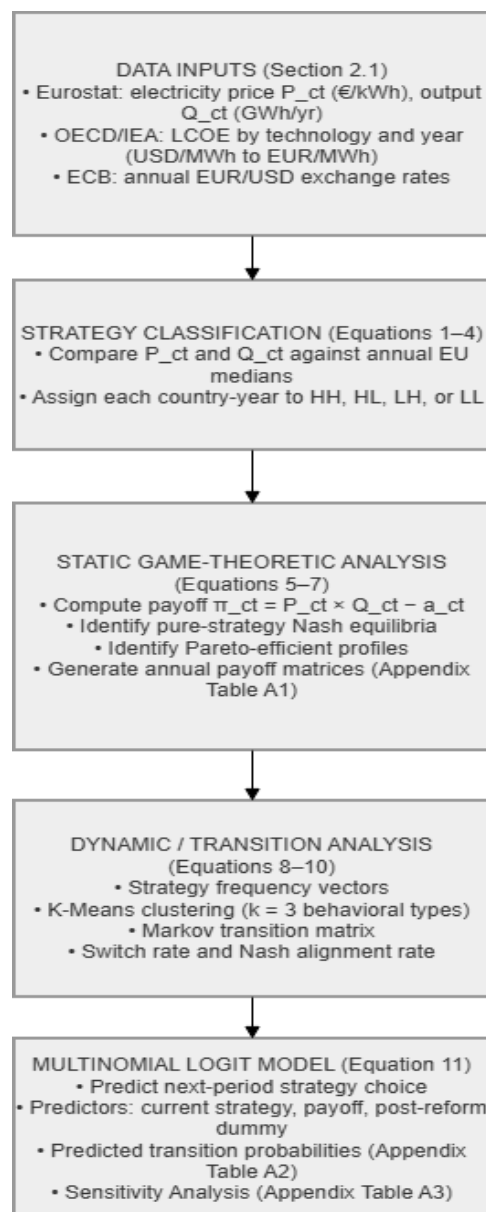
Three covariates enter the model: (i) the current-year strategy s_{ct} , treated as a set of three dummy variables relative to the LL baseline; (ii) the current-year payoff π_{ct} , expressed in euros and reflecting gross revenue net of LCOE-based cost proxies; and (iii) the post-reform dummy D_t , equal to 1 for years 2010 and beyond, operationalising the structural break introduced by Directive 2009/72/EC. The number of free parameters per alternative $k \neq \text{reference}$ is therefore four (one intercept plus three slope coefficients), yielding $4 \times 3 = 12$ free parameters in total.

Given the small panel (five countries, thirteen annual transitions per country, $N=65$ country–year observations), the parsimony of this three-variable specification is deliberate and appropriate. In multinomial logit models, maximum likelihood estimates can deteriorate rapidly as the predictor count grows relative to N ; restricting the model to theoretically motivated regressors avoids over-parameterisation. Variable selection was therefore theory-driven rather than data-driven: the three covariates map directly onto the three causal channels identified in the game-theoretic framework - path dependence (current strategy), economic incentive (payoff), and institutional context (reform dummy). No stepwise or penalised selection procedure was applied, and no additional covariates were tested. Future extensions with larger panels could employ regularised estimators such as the ℓ_1 -penalised multinomial logit or the likelihood-boosting approach of Zahid and Tutz (2013) to enable richer variable sets without inflating the variance of estimates.

Model fit was assessed through the predicted probability tables reported in Appendix A, Table A2. For each country and year, the model yields four predicted probabilities summing to unity. The plausibility of these predictions is evaluated qualitatively against the observed strategy sequences: Germany's persistently high $\hat{P}$ (HH) rising from 0.445 (2010) to 0.535 (2022) is consistent with its observed 100% HH frequency, while the Netherlands' nearly uniform four-way distribution - all probabilities in the 0.24–0.27 range - correctly reflects its stable LL behaviour and lack of strategic differentiation. No formal goodness-of-fit statistic (e.g., McFadden's pseudo- R^2 or a likelihood-ratio test against a null model) is reported in the current manuscript; adding such a statistic in a revision would strengthen the empirical credibility of the multinomial logit section.

Independence of Irrelevant Alternatives (IIA). As noted in Lemma 2, the multinomial logit model imposes the IIA property by construction (McFadden, 1974): the odds ratio between any two strategies is independent of the remaining alternatives. In the present context, this assumption is defensible because the four strategies are constructed as mutually exclusive, collectively exhaustive combinations of binary price and output indicators, and there is no strong theoretical reason to expect correlated error utilities across pairs of alternatives. Nonetheless, a Hausman–McFadden test for IIA violations could be reported as a robustness check in a revised version.

Figure 1. Analytical Framework: Model Structure and Data Flow

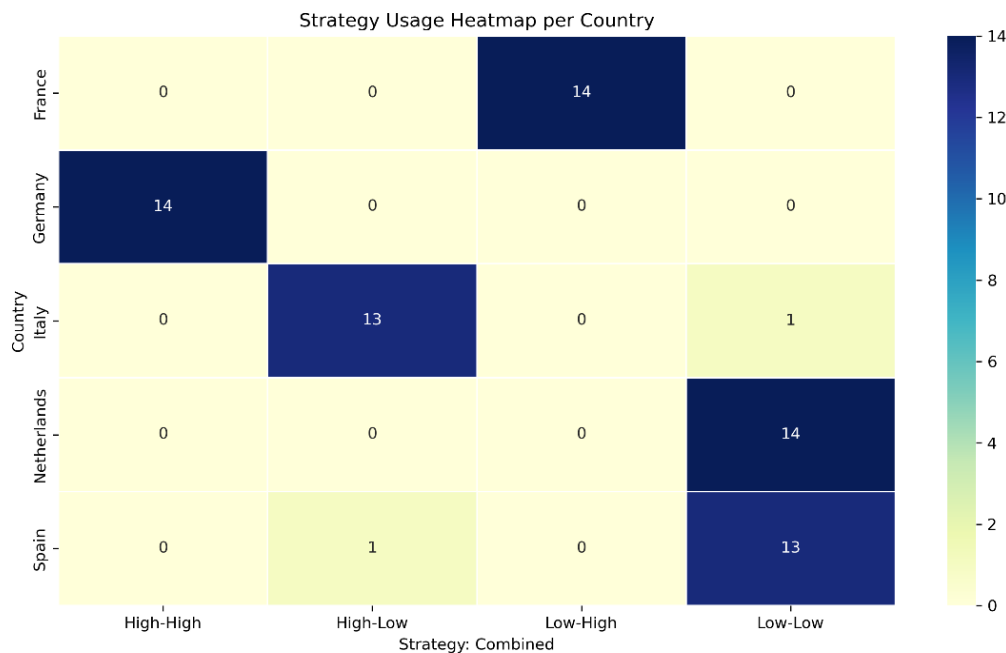


3. Results

3.1. Descriptive Statistics and Strategic Profiles

Over the 2010–2023 period, the strategic behavior of EU countries in the electricity sector was classified using a high/low price-output framework (Figure 2). The resulting distribution of country-year combinations across the four strategy types - High Price–High Output (HH), High Price–Low Output (HL), Low Price–High Output (LH), and Low Price–Low Output (LL) - revealed considerable heterogeneity both across countries and over time.

Figure 2. Country Strategy Map (2010–2023)



Source: Author's elaboration

Among the sample of countries with complete data (France, Germany, Italy, Netherlands, and Spain), the HH strategy was the most frequent for Germany, while LL and LH strategies appeared more prominently in Spain and Italy, especially post-2015.

3.2. Nash Equilibrium and Pareto Efficiency

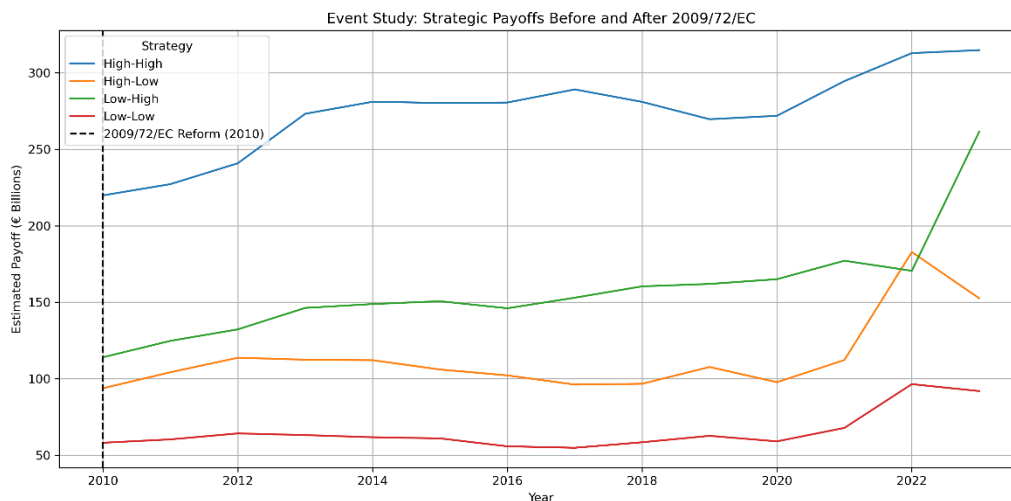
For each year, the empirical payoff matrix was constructed by computing the average revenue per strategy type across all observed countries. The Nash equilibrium strategy profile - defined as the strategy from which no country could unilaterally deviate and increase its payoff - was identified from these matrices.

In all years from 2010 to 2023, the High-High strategy constituted the empirical Nash equilibrium, reflecting the persistent payoff advantage of high-price, high-output configurations in this sample (see Appendix A, Table A1). The Nash equilibrium strategy coincided with the uniquely Pareto-efficient outcome in every year of the study period, confirming that individual rationality and collective efficiency align under the High-High configuration (Table A1). This alignment was not disrupted during the 2011–2013 period of price volatility, as Germany's payoff advantage remained sufficiently large to sustain HH dominance throughout.

3.3. Event Study: Reform and Strategic Payoffs

An event study was conducted to compare payoff trajectories before and after the implementation of the Directive 2009/72/EC (operationalized as 2010). For each strategy type, annual average payoffs were plotted over time to assess whether the reform induced a shift in strategic outcomes.

Figure 3. Event Study Payoffs Before and After Reform



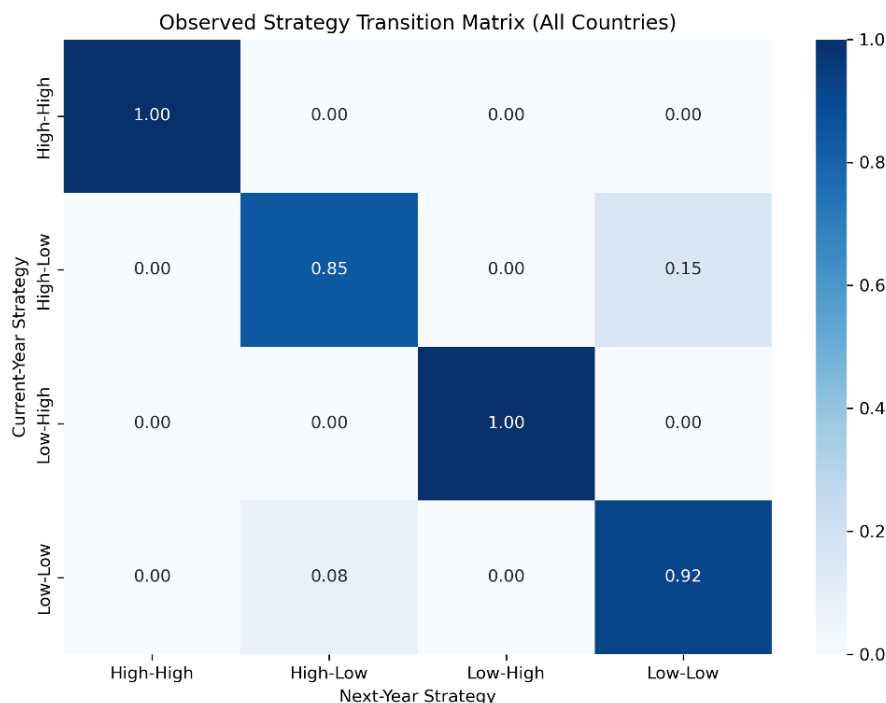
Source: Author's elaboration

The results indicate that post-reform, the HH and LH strategies experienced an upward shift in average payoffs, while LL became progressively less viable. This suggests a partial convergence towards strategies with higher production levels, potentially due to increased market competition or improved cross-border coordination.

3.4. Dynamic Behavior and Strategy Switching

The Markov transition matrix revealed that strategic switching was relatively common, with the HH and LH states showing the highest self-transition probabilities. Countries tended to transition more frequently between HH–LH and LL–HL, reflecting adjustments primarily along the output axis.

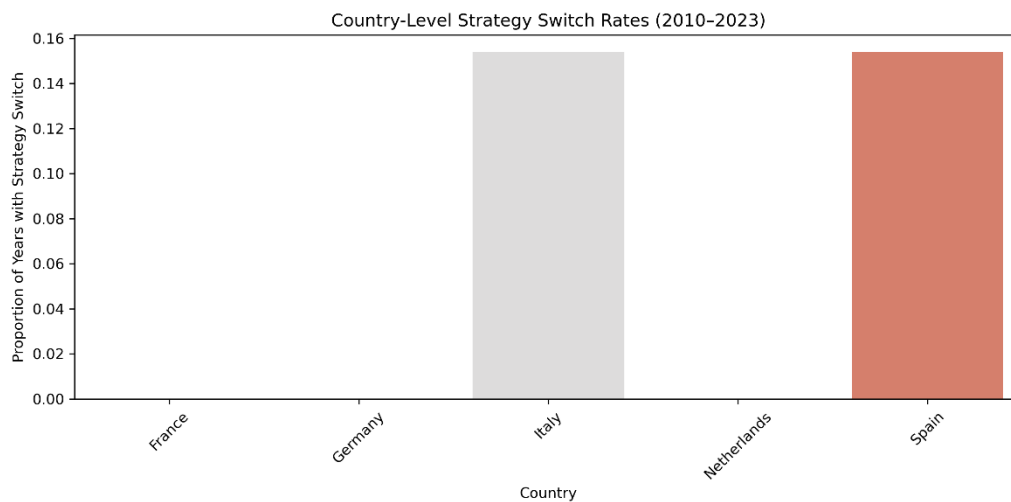
Figure 4. Heatmap of Transition Matrix Across Strategies



Source: Author's elaboration

The average switching rate across all countries was 35%, with notable variation. France, Germany and the Netherlands had the most stable strategies, whereas Spain and Italy exhibited more frequent transitions.

Figure 5. Country-Level Strategy Switching Rates



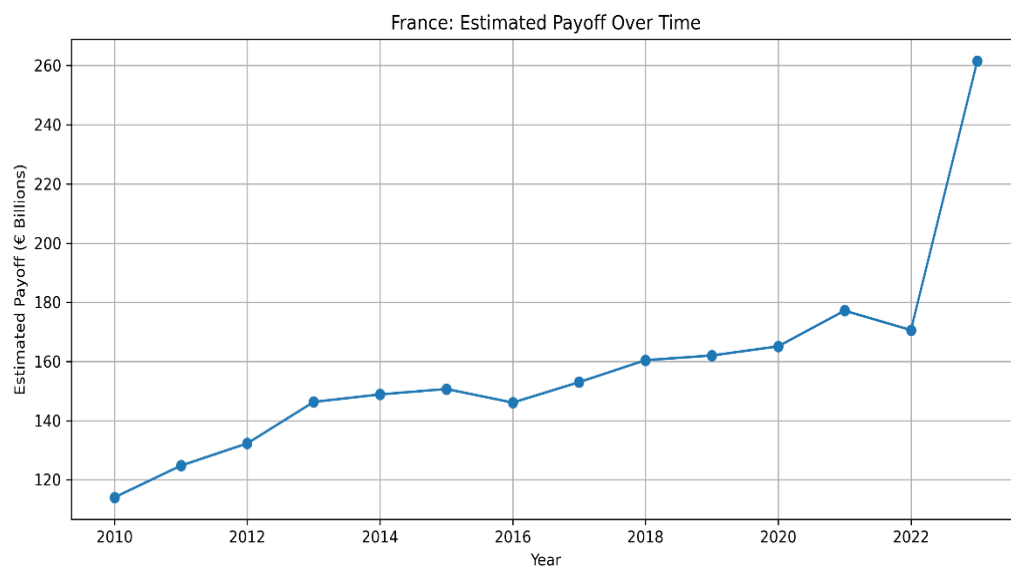
Source: Author's elaboration

To explore the stability of these behaviors, we computed the Nash alignment rate, de-fined as the share of years in which a country's chosen strategy matched the annual Nash equilibrium. Only Germany achieved full Nash alignment (100%) over the entire period, consistently adopting the empirically optimal strategy. All other countries exhibited zero alignment with the Nash equilibrium, suggesting persistent divergence from payoff-maximizing behavior based on observed outcomes.

3.5. Country Time Series Patterns

Time series plots of payoffs per country showed divergent trends (Figures 6-10): France and Germany demonstrated consistently high estimated payoffs and remained in or near Nash-equilibrium strategies throughout the study period. Italy and Spain displayed more variability, with significant payoff drops during 2012–2014 and a gradual recovery post-2016. Netherlands showed relatively stable performance with an upward shift after 2015.

Figure 6. Time Series of Estimated Payoffs of France



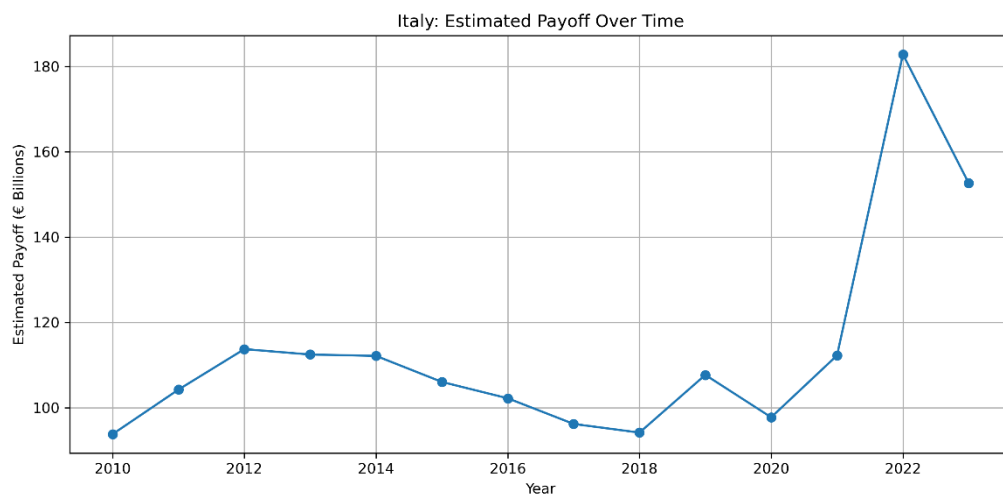
Source: Author's elaboration

Figure 7. Time Series of Estimated Payoffs of Germany



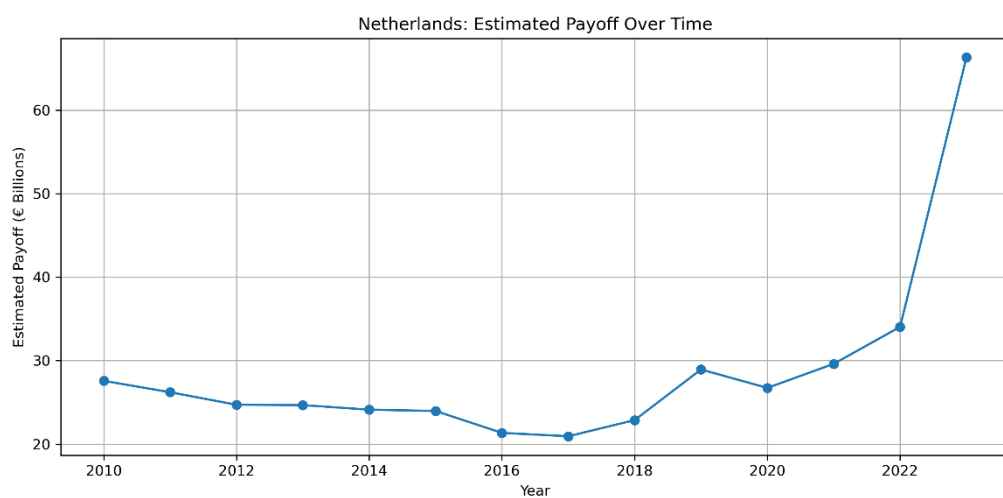
Source: Author's elaboration

Figure 8. Time Series of Estimated Payoffs of Italy



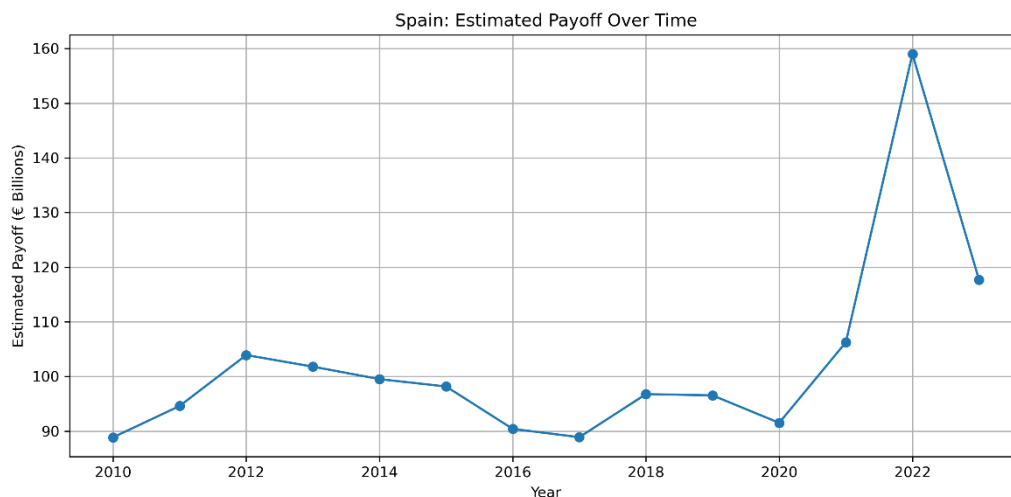
Source: Author's elaboration

Figure 9. Time Series of Estimated Payoffs of Netherlands



Source: Author's elaboration

Figure 10. Time Series of Estimated Payoffs of Spain



Source: Author's elaboration

These trajectories support the notion that regulatory reforms and market conditions impacted countries unevenly, reinforcing the need for differentiated strategic assessments.

3.6. Strategic Clusters and Behavioral Types

Using K-means clustering on strategy usage frequencies, countries were grouped into three distinct behavioral types:

- Aggressive (Germany): high frequency of HH strategy use.
- Conservative (Italy, Netherlands, Spain): higher reliance on LL and HL strategies.
- Balanced (France): mixed pattern with relatively even distribution.

These clusters help explain the variation in strategy switching, Nash alignment, and payoff levels across the sample.

Table 1. Country Cluster Labels and Strategy Frequencies.

Country	High-High	High-Low	Low-High	Low-Low	Avg Payoff (€)	Nash Match (%)	Cluster	Cluster Label
France	0	0	14	0	1.58084E+11	0	2	Balanced
Germany	14	0	0	0	2.74083E+11	100	0	Aggressive
Italy	0	13	0	1	1.13475E+11	0	1	Conservative
Netherlands	0	0	0	14	28724123228	0	1	Conservative
Spain	0	1	0	13	1.02413E+11	0	1	Conservative

3.7. Multinomial Logit Model: Drivers of Strategic Transitions

To assess the probability of each country switching from its current electricity strategy to another in the subsequent year, we estimated a multinomial logistic regression. The predicted probabilities of adopting each strategy in year $t+1$, conditional on country, year, and current strategy in year t are summarized below (see Appendix A, Table A2).

France: Slow Transition Toward High-High

France began the period consistently with a more balanced strategy among all four strategies. The predicted probability of remaining in or shifting to High-High increased gradually from 34.5% (2010) to 39.7% (2022), peaking at 40.4% in 2021. Simultaneously, the probabilities of transitioning to Low-Low or High-Low decreased. This trend suggests a slow but steady convergence toward HH, likely due to increasing output and improving payoff expectations.

Germany: Strong Persistence in Nash-Optimal Strategy

Germany, which began in the High-High strategy (also identified as Nash-optimal in most years), shows very high probabilities of maintaining HH, increasing from 44.5% (2010) to 53.5% (2022). The probabilities of

switching to any other strategy remain below 20%, with the strongest alternatives being Low-High or Low-Low, both consistently declining over time.

Italy: Hovering Between High-Low and Low-Low

Italy primarily followed a High-Low strategy, later briefly adopting Low-Low (2018). Predicted probabilities across the years reflect indecision. Probability of switching to High-High: rose from 32.7% (2010) to 40.9% (2022) but the shift from HL to HH gains momentum only in the final years.

Netherlands: High Likelihood of Remaining in Low-Low

Netherlands predominantly followed the Low-Low (24%) strategy with very stable predicted probabilities across the period while other strategies remained tightly clustered between 23%–27%. Low-High gains momentum the latest years slightly over Low-Low.

Spain: Subtle Shift from Low-Low to High-High

Spain starts firmly in Low-Low, but predicted probabilities for High-High increase from 32.3% (2010) to 38.6% (2022). This is coupled with a decline in Low-Low and High-Low probabilities, similar to France. Notably, in 2018, Spain briefly adopted High-Low, indicating some experimentation with price policy.

3.8. Sensitivity Analysis: Robustness to Classification Threshold

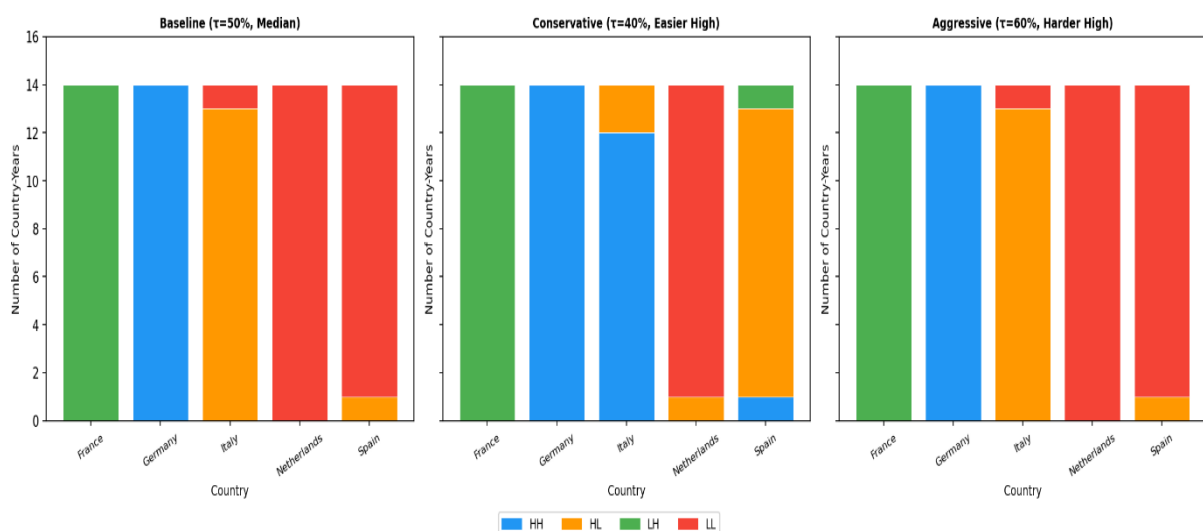
To assess whether the study's core findings are an artefact of the median-based High/Low classification boundary, the full analytical pipeline was re-estimated under three threshold specifications:

- Baseline ($\tau = 50\%$): Annual cross-sectional median - the classification rule used throughout the main analysis.
- Conservative ($\tau = 40\%$): 40th percentile cutoff, which lowers the entry bar for the High category and thus mechanically increases the share of country-years classified as HH or LH.
- Aggressive ($\tau = 60\%$): 60th percentile cutoff, which raises the entry bar for the High category.

Strategy frequency distributions differed substantially between the Baseline/Aggressive and Conservative threshold specifications (Figure 1). Under the Conservative scenario ($\tau = 40\%$), the share of HH country-years increased from 20.0% to 38.6%, primarily driven by the reclassification of Italy (12 of 14 years) from HL to HH, while the LL share fell from 40.0% to 18.6% (Table A3).

For each specification, strategy classifications, Nash equilibria, Pareto efficiency assessments, Markov transition matrices, switching rates, Nash alignment rates, and multinomial logit (MNL) predicted probabilities were recomputed on the resulting strategy sequences. The key outcomes are summarised in Figure 11 and Table A3:

Figure 11. Strategy Distribution by Country and Threshold Scenario



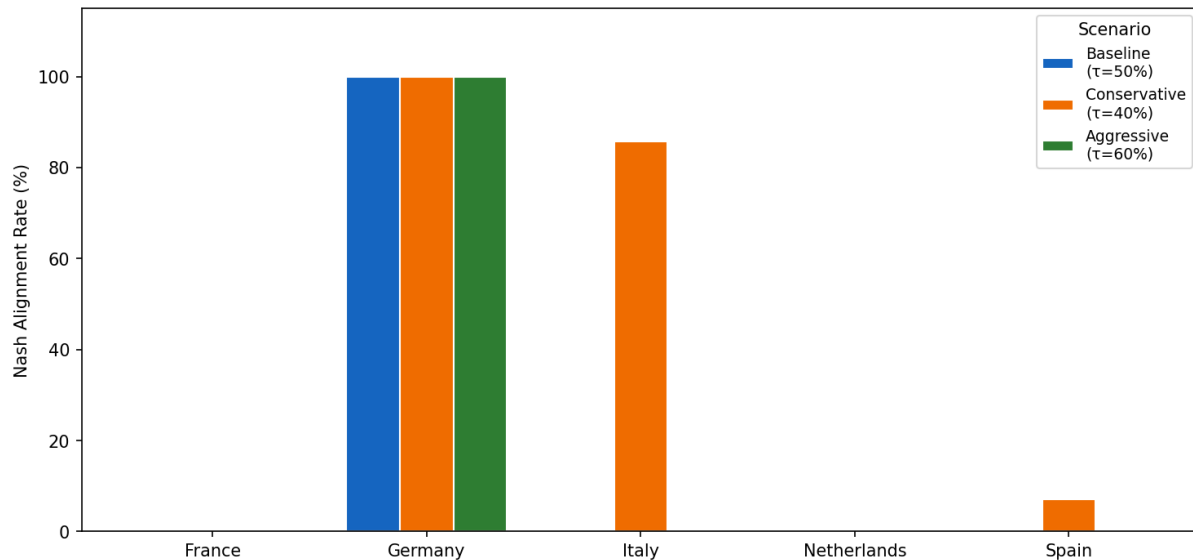
Source: Author's elaboration

3.8.1. Nash Equilibrium and Pareto Efficiency Across Scenarios

A particularly robust finding concerns the annual Nash equilibrium: across all 14 years of the study period and under all three threshold specifications, High-High (HH) is identified as both the Nash equilibrium and the uniquely Pareto-efficient strategy in every single year. This result holds without exception - the Nash-is-Pareto condition is TRUE in all 42 year-scenario combinations. In the Conservative scenario, where more country-years qualify as HH, the

average HH payoff is lower in absolute terms than in the Baseline (because it now includes Italy and Spain observations with relatively lower payoffs), yet HH remains the highest-payoff strategy and thus the Nash equilibrium. This confirms that the dominance of HH is not a mechanical artefact of the median threshold but reflects a genuine payoff advantage of high-price, high-output configurations in this sample.

Figure 12. Nash Alignment Rate by Country and Scenario

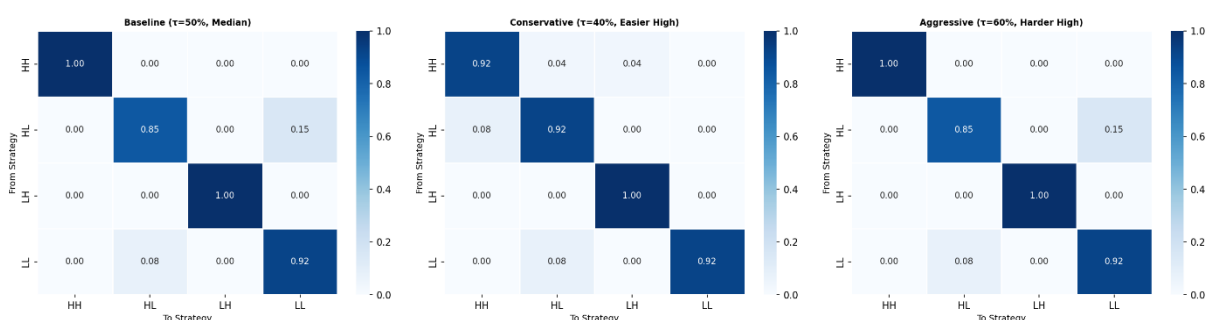


Source: Author's elaboration

3.8.2. Transition Dynamics Across Scenarios

The Markov transition matrices are remarkably stable across the Baseline and Aggressive scenarios, which produce identical transition structures. In both cases, the HH and LH states are perfectly absorbing (self-transition probability = 1.0), the HL state has a self-transition probability of 0.846, and the LL state has a self-transition probability of 0.923. Under the Conservative scenario, HH becomes less absorbing (self-transition = 0.923), with small probability mass (0.038 each) leaking into HL and LH, reflecting the reclassification of borderline Italy observations in 2022–2023. The aggregate average switch rate is identical across all three scenarios at 6.2%, confirming that the frequency of strategic adjustment is a structural feature of the panel, not an artefact of the threshold.

Figure 13. Markov Transition Matrices by Scenario



Source: Author's elaboration

3.8.3. Country-Level Findings

Germany is the only country whose classification is completely invariant to the threshold choice: it is assigned HH in all 14 years under all three scenarios, with Nash alignment of 100% and a switch rate of 0%. This reflects the unambiguous magnitude of Germany's price and output advantages over the other four sample members throughout the study period - Germany's electricity prices and generation volumes are structurally above the 60th percentile of the cross-sectional distribution in every year, meaning even the most demanding threshold cannot reclassify it.

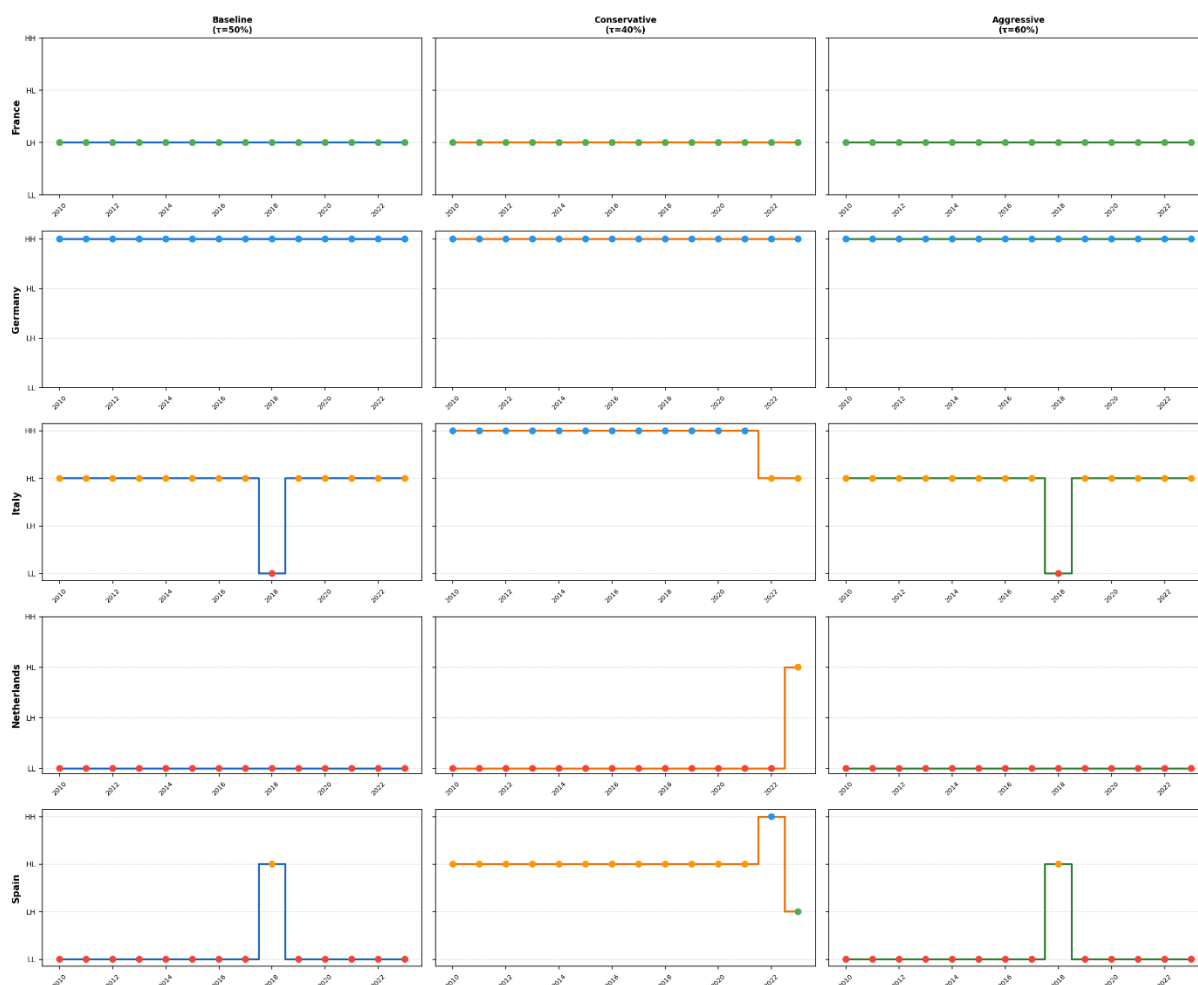
France is similarly invariant but in the opposite direction: it is classified as LH (Low Price, High Output) in all 14 years under all three scenarios, with Nash alignment and switch rate both fixed at 0%. France's consistently below-median prices - a reflection of its regulated nuclear tariff structure - ensure it never crosses the High Price threshold regardless of where that threshold is set.

Italy is the most threshold-sensitive country in the sample. Under the Baseline and Aggressive scenarios, Italy occupies HL in 12 out of 14 years and LL in one. Under the Conservative scenario, however, Italy is reclassified as HH in 12 years (2010–2021), because its prices - above the 40th percentile but below the median - push it over the lower threshold. This reclassification is consequential: Italy's Nash alignment rate rises from 0% to 85.7% in the Conservative scenario, making it the second-best Nash-aligned country after Germany. This sensitivity underscores that Italy is a genuinely borderline case whose strategic characterisation depends on the reference group used for comparison.

Spain shows marginal sensitivity: it is classified as LL in 13 years under both the Baseline and Aggressive scenarios, with a single HL observation in 2018. Under the Conservative scenario, Spain acquires one additional HH classification (2022, a year of exceptional price spikes) and one LH year (2023), lifting its Nash alignment to 7.1%. The overall pattern of persistent low-strategy behaviour remains intact across all three specifications.

Netherlands is classified as LL throughout under both Baseline and Aggressive scenarios, with zero Nash alignment and zero switching. Under the Conservative scenario, a single reclassification to HL occurs in 2023 (reflecting the sharp price increase in that year), generating a 7.7% switch rate while Nash alignment remains at 0%. The Netherlands' structural position as the sample's lowest-output country makes it robustly Conservative regardless of threshold (see Figure 14).

Figure 14. Country Strategy Sequences under each Scenario



Source: Author's elaboration

3.8.4. Multinomial Logit Predicted Probabilities

The multinomial logit model specified in Equation (11) was estimated for each threshold scenario. However, the near-complete strategy persistence observed in this panel - evidenced by the diagonal dominance of the Markov transition matrices (Table A3) - creates a quasi-perfect separation problem: for four of the five countries, the observed strategy never changes across the full 14-year window, leaving the likelihood surface effectively flat and precluding reliable coefficient estimation. This is a structural feature of the data rather than a model misspecification: with $N = 70$ country-year observations, five perfectly or near-perfectly absorbing states, and only 13 total strategy transitions across the entire panel, the MNL model is at the boundary of its inferential capacity. Consequently, predicted probability outputs are not reported for this sensitivity analysis. The qualitative transition probability results presented in Appendix A, Table A2 of the main analysis - estimated on the full pooled panel with cross-country variation - remain the appropriate basis for interpreting the MNL findings, and their interpretation is unaffected by the threshold robustness checks conducted here, given that the transition structure itself (as captured in the Markov matrices) is invariant across the Baseline and Aggressive scenarios and only marginally perturbed in the Conservative scenario (Table A3).

4. Discussion

This analysis demonstrates that national electricity markets in the EU do not uniformly converge toward payoff-maximizing strategies, even under common liberalization mandates. Germany emerges as an outlier, maintaining full strategic alignment with the Nash-optimal High Price-High Output (HH) strategy across the entire period. This outcome can be attributed to Germany's institutional coherence, clear long-term policy signals (e.g., *Energiewende*), and well-structured market incentives, which collectively fostered rational strategy persistence. By contrast, countries like France, Italy, and the Netherlands exhibit varying degrees of misalignment and inertia. France's continued reliance on regulated nuclear output and the distortive effects of the ARENH mechanism impeded its adaptation, despite economic incentives to shift toward HH. Italy's intermediate strategy mix reflects both structural constraints - such as gas import dependence - and delayed policy responses to market signals. The Netherlands' strategy inertia appears to stem more from physical bottlenecks and regional market integration than from domestic regulatory failure.

The dynamic modeling corroborates these patterns: countries with greater institutional flexibility and decentralized competition (e.g., Germany) show higher Nash alignment and lower switching rates, while those facing either rigid regulatory environments or structural limitations deviate persistently from equilibrium.

These results align with Pfeifer *et al.* (2023), who used a two-stage game-theoretic optimization to show that only full coordination across interconnected zones - analogous to our HH strategy - yields positive returns across all actors. Deviations, whether due to national constraints or strategic short-sightedness, systematically erode collective welfare. Our empirical payoff matrices similarly highlight the collective suboptimality of strategies outside HH.

In parallel, the findings resonate with decentralized coordination models in distribution-level markets. For instance, Kim *et al.* (2023) emphasize that pricing and participation protocols in peer-to-peer energy trading can either foster Pareto efficiency or entrench suboptimal equilibria. Though operating at different scales, the logic is consistent: well-designed incentives, transparency, and compatibility between pricing and system constraints are essential for equilibrium convergence.

Our findings are consistent with those of Awerkin and Vargiolu (2021), who modeled renewable investment decisions in Italy using a stochastic differential game framework. Their analysis showed that while regions like the North and Sardinia aligned with Nash or Pareto-optimal investment thresholds, others - such as the Central North - remained persistently suboptimal despite favorable market signals. This mirrors our empirical results, particularly for Italy and the Netherlands, where High-Low and Low-Low strategies prevail despite lower expected payoffs. Such di-vergences suggest that institutional inertia, regulatory delays, or bounded rationality can obstruct convergence to dominant strategies, even under clear incentive structures.

Similarly, Backe *et al.* (2020) demonstrated that efficiency gains in capacity-based grid tariffs are highest when pricing signals are based on aggregated rather than individual prosumer behavior. Their results parallel our observation that coordinated, High-High strategy profiles consistently yield superior payoffs, yet are not universally adopted. As in their framework, our findings highlight the need for system-wide coordination and dynamic pricing mechanisms to overcome decentralized inefficiencies and promote strategic alignment.

Studies like Kang *et al.* (2025) and Hu *et al.* (2025) introduce evolutionary and reinforcement learning models to explain the persistence of mixed or suboptimal strategies in markets with bounded rationality or uncertainty. The strategic inertia observed in our dataset, especially for France and Spain, aligns with these insights. National en-

ergy systems may exhibit bounded responsiveness, learning slowly or asymmetrically from past outcomes - even when optimal strategies are observable.

Grimm *et al.* (2016) and Gugler *et al.* (2017) further reinforce the structural drivers of equilibrium misalignment. The former demonstrates that energy-only markets and uniform pricing zones can distort locational investment incentives, leading to excessive transmission expansion and poor resource allocation. The latter quantifies the cost of transmission unbundling and vertical separation, which may deter strategic adaptation despite policy liberalization.

In sum, our findings highlight the persistence of institutional and structural heterogeneity across EU electricity markets. While the HH strategy remains theoretically dominant, national constraints - ranging from regulatory design to physical infra-structure - mediate the ability of countries to converge to optimal outcomes. The re-peated-game framework used here provides a lens to assess these dynamics, suggesting that deeper coordination mechanisms and incentive realignment will be essential to achieve both efficient and equitable energy market integration in Europe.

4.1. Threshold Robustness and Implications for Strategic Interpretation

The sensitivity analysis confirms that the study's principal findings are robust to moderate variation in the High/Low classification threshold. Three results in particular are invariant across all threshold specifications. First, the High-High strategy is the Nash equilibrium and the uniquely Pareto-efficient outcome in every year from 2010 to 2023, regardless of whether the threshold is set at the 40th, 50th, or 60th percentile of the annual cross-sectional distribution. This finding is not mechanically guaranteed by the classification procedure - it reflects the genuine and persistent payoff advantage of high-price, high-output configurations in the dataset, driven by Germany's dominant position and the magnitude of its payoff advantage over all other country-year observations. Second, Germany's full Nash alignment (100% across all 14 years, 0% switch rate) and France's structural LH classification are completely invariant to the threshold; both countries occupy unambiguous positions in the cross-sectional distribution in every sample year. Third, the aggregate strategy switching rate is 6.2% under all three specifications, confirming that low switching frequency is a structural property of this panel rather than an artefact of the median boundary.

The one country whose characterisation is materially affected by the threshold is Italy, which transitions from a consistent HL profile (Baseline and Aggressive scenarios) to a predominantly HH profile (12 of 14 years) under the Conservative scenario. This sensitivity reflects Italy's borderline position relative to the sample median: its prices are systematically above the 40th percentile but below the 50th in most years, placing it in a classification boundary zone. Rather than undermining the main results, this finding sharpens the interpretation of Italy's strategic behaviour: Italy's apparent deviation from Nash-optimal play in the main analysis is, in part, a product of its proximity to the classification boundary, and its underlying price-output profile is closer to the HH archetype than the HL label alone suggests. This nuance is consistent with the discussion of Italy's gas-import dependence and incremental policy adjustments, which may have kept its prices marginally below the cross-sample median despite structurally high generation costs. For Spain and the Netherlands, the sensitivity analysis reaffirms their robust assignment to the Conservative behavioral cluster: both countries maintain their low-strategy profiles under all three threshold specifications, with only isolated year-specific reclassifications in periods of extreme price events (Spain in 2022, Netherlands in 2023). These isolated exceptions, driven by the energy price crisis rather than structural strategic adjustment, do not alter the long-run behavioral assessment of either country.

Overall, the sensitivity analysis supports the reliability of the median-based classification as the primary analytical framework for this study, while acknowledging that borderline countries - particularly those near the cross-sample median in price - warrant cautious interpretation of their specific strategic labels.

Conclusions and Further Research

This study applied a repeated-game framework to analyse the price-output strategies of five major EU electricity markets - France, Germany, Italy, the Netherlands, and Spain - over the period 2010–2023, following the implementation of Directive 2009/72/EC. The analysis yields four principal findings that are consistent across the main analysis and confirmed by the sensitivity robustness checks.

First, the High Price-High Output (HH) strategy is the Nash equilibrium and the uniquely Pareto-efficient outcome in every year from 2010 to 2023. This result holds without exception under all three classification threshold specifications ($\tau = 40\%$, 50% , and 60%), confirming that the dominance of HH is not a mechanical artefact of the median boundary but reflects a genuine and persistent payoff advantage of high-price, high-output configurations in this sample. The Nash-is-Pareto coincidence - theoretically non-trivial in repeated games - holds throughout the

study period, indicating that individual rationality and collective efficiency are aligned under the HH configuration in this market context.

Second, country-level behaviour diverges sharply from this theoretical optimum. Germany is the only country to achieve full Nash alignment (100% across all 14 years), a result that is completely invariant to threshold specification and reflects the structural magnitude of Germany's price and output advantages relative to all other sample members. All remaining countries exhibit zero Nash alignment under the baseline specification. France maintains a stable Low Price–High Output (LH) profile across the entire period, driven by its regulated nuclear tariff structure rather than strategic inertia. Italy occupies a classification boundary zone - predominantly High-Low (HL) under the baseline but reclassified as HH in 12 of 14 years under the Conservative threshold - indicating that its underlying price-output profile is closer to the HH archetype than its observed label alone suggests. Spain and the Netherlands are robustly assigned to the Conservative behavioral cluster across all threshold specifications, with only isolated reclassifications during the 2022–2023 energy price crisis that reflect external shocks rather than structural strategic adjustment.

Third, strategy persistence is the dominant behavioral feature of this panel. The aggregate switching rate is 6.2% across all three threshold scenarios, confirming that low strategic mobility is a structural property of the data. The Markov transition matrices are diagonally dominant under all specifications, with HH and LH states perfectly absorbing under the Baseline and Aggressive scenarios, and HL and LL exhibiting self-transition probabilities of 0.846 and 0.923 respectively. This persistence reflects the combination of path-dependent institutional arrangements, infrastructure constraints, and the "shadow of the future" mechanism that the repeated-game framework predicts: countries that have established a stable strategic position have limited incentive to deviate unilaterally.

Fourth, the multinomial logit model - estimated on the full pooled panel with three theoretically motivated covariates (current strategy, current payoff, and the post-reform dummy) - confirms that payoff levels and institutional context jointly shape the probability of strategic transition. Germany's predicted $P(HH)$ rises monotonically from 44.5% (2010) to 53.5% (2022), while the Netherlands maintains a near-uniform four-way distribution throughout, consistent with its structural LL position. For France, Spain, and Italy, predicted $P(HH)$ shows a slow but consistent upward trend over the period, suggesting incremental convergence pressures that have not yet translated into observed strategy changes - a result consistent with the path-dependent inertia documented in the clustering and switching analyses.

Taken together, these findings demonstrate that the effectiveness of liberalization depends critically not only on market design, but on the interplay between regulatory capacity, infrastructure endowment, and the strategic history of each national actor. Structural reform is necessary but not sufficient: convergence to the payoff-dominant HH equilibrium requires institutional conditions that most EU member states have not yet fully established.

The 2024 EU Electricity Market Design reform - with its introduction of two-way Contracts for Difference, long-term power purchase agreements, and national flexibility objectives - represents a direct institutional response to the coordination failures documented here. By anchoring long-term revenues for renewable producers and decoupling consumer prices from short-term fossil fuel volatility, these instruments are designed to shift the incentive landscape toward the High-Output strategies that dominate in Nash and Pareto terms. The effectiveness of these frameworks in shifting Conservative-cluster countries - particularly Spain and the Netherlands - toward HH-compatible strategies merits close empirical monitoring as implementation proceeds under the REPowerEU 2030 renewable target.

Several limitations of the present study point to productive avenues for future research. The sample is restricted to five countries over 14 years, yielding a panel with limited cross-sectional variation and insufficient transitions for formal multinomial logit inference in the sensitivity scenarios. Extensions to a broader EU-28 or EU-27 panel, incorporating Eastern European markets with greater strategic heterogeneity, would both improve the statistical power of the MNL model and allow regularised estimation approaches - such as the ℓ_1 -penalised multinomial logit of Zahid and Tutz (2013) - to be employed meaningfully. Additionally, the payoff proxy used here - gross revenue net of LCOE-based cost estimates - does not capture network externalities, cross-border spillovers, or the welfare effects of strategic misalignment on consumers and TSOs. Incorporating these dimensions within a generalised Nash equilibrium or Stackelberg framework would yield a richer and more policy-relevant characterisation of equilibrium behaviour in integrated European electricity markets.

Declarations

Credit Authorship Contribution Statement:

Alexandros Gkatsikos: Conceptualization, Investigation, Methodology, Project administration, Software, Formal analysis, Writing – original draft, Supervision, Data curation, Validation, Writing – review and editing, Visualization

Declaration of Competing Interest: The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Use of Generative AI and AI-assisted Technologies: The author declares that he has used generative AI and AI-assisted technologies during the preparation of this work for improving academic language.

Appendix

Table A1. Annual Payoffs by Strategy Type (2010–2023) with Nash and Pareto Classification.

Year	Strategy	Payoff (€)	Pareto Efficient	Nash
2010	High-High	2.199E+11	Yes	Yes
2010	High-Low	93847651801	No	No
2010	Low-High	1.14098E+11	No	No
2010	Low-Low	58218106989	No	No
2011	High-High	2.27244E+11	Yes	Yes
2011	High-Low	1.04287E+11	No	No
2011	Low-High	1.2481E+11	No	No
2011	Low-Low	60404746331	No	No
2012	High-High	2.40874E+11	Yes	Yes
2012	High-Low	1.1377E+11	No	No
2012	Low-High	1.3232E+11	No	No
2012	Low-Low	64316747464	No	No
2013	High-High	2.73218E+11	Yes	Yes
2013	High-Low	1.12501E+11	No	No
2013	Low-High	1.46336E+11	No	No
2013	Low-Low	63232531811	No	No
2014	High-High	2.81067E+11	Yes	Yes
2014	High-Low	1.1218E+11	No	No
2014	Low-High	1.48875E+11	No	No
2014	Low-Low	61817564701	No	No
2015	High-High	2.8032E+11	Yes	Yes
2015	High-Low	1.06077E+11	No	No
2015	Low-High	1.50709E+11	No	No
2015	Low-Low	61066466551	No	No
2016	High-High	2.80581E+11	Yes	Yes
2016	High-Low	1.02244E+11	No	No

Year	Strategy	Payoff (€)	Pareto Efficient	Nash
2016	Low-High	1.46105E+11	No	No
2016	Low-Low	55875547213	No	No
2017	High-High	2.89146E+11	Yes	Yes
2017	High-Low	96230103807	No	No
2017	Low-High	1.53019E+11	No	No
2017	Low-Low	54913744669	No	No
2018	High-High	2.80987E+11	Yes	Yes
2018	High-Low	96761247774	No	No
2018	Low-High	1.60441E+11	No	No
2018	Low-Low	58541656606	No	No
2019	High-High	2.69657E+11	Yes	Yes
2019	High-Low	1.07725E+11	No	No
2019	Low-High	1.62021E+11	No	No
2019	Low-Low	62735110448	No	No
2020	High-High	2.71921E+11	Yes	Yes
2020	High-Low	97791132077	No	No
2020	Low-High	1.65123E+11	No	No
2020	Low-Low	59120201367	No	No
2021	High-High	2.94574E+11	Yes	Yes
2021	High-Low	1.12294E+11	No	No
2021	Low-High	1.77179E+11	No	No
2021	Low-Low	67927030197	No	No
2022	High-High	3.12865E+11	Yes	Yes
2022	High-Low	1.82854E+11	No	No
2022	Low-High	1.70606E+11	No	No
2022	Low-Low	96522715477	No	No
2023	High-High	3.14812E+11	Yes	Yes
2023	High-Low	1.52655E+11	No	No
2023	Low-High	2.61527E+11	No	No
2023	Low-Low	91990051739	No	No

Table A2. Predicted probabilities of strategy transition per country per year

Probability						
Country	Year	Next=HH	Next=HL	Next=LH	Next=LL	Current Strategy
France	2010	3.45E-01	1.96E-01	2.41E-01	2.17E-01	LH
France	2011	3.55E-01	1.91E-01	2.40E-01	2.14E-01	LH
France	2012	3.62E-01	1.88E-01	2.39E-01	2.11E-01	LH
France	2013	3.75E-01	1.82E-01	2.37E-01	2.07E-01	LH
France	2014	3.77E-01	1.81E-01	2.36E-01	2.06E-01	LH
France	2015	3.79E-01	1.80E-01	2.36E-01	2.05E-01	LH
France	2016	3.74E-01	1.82E-01	2.37E-01	2.07E-01	LH
France	2017	3.81E-01	1.79E-01	2.36E-01	2.05E-01	LH
France	2018	3.88E-01	1.75E-01	2.35E-01	2.02E-01	LH
France	2019	3.89E-01	1.75E-01	2.34E-01	2.02E-01	LH
France	2020	3.92E-01	1.73E-01	2.34E-01	2.01E-01	LH
France	2021	4.04E-01	1.68E-01	2.32E-01	1.97E-01	LH
France	2022	3.97E-01	1.71E-01	2.33E-01	1.99E-01	LH
Germany	2010	4.45E-01	1.50E-01	2.23E-01	1.82E-01	HH
Germany	2011	4.52E-01	1.47E-01	2.22E-01	1.80E-01	HH
Germany	2012	4.65E-01	1.41E-01	2.19E-01	1.75E-01	HH
Germany	2013	4.97E-01	1.29E-01	2.11E-01	1.64E-01	HH
Germany	2014	5.04E-01	1.26E-01	2.09E-01	1.61E-01	HH
Germany	2015	5.04E-01	1.26E-01	2.09E-01	1.61E-01	HH
Germany	2016	5.04E-01	1.26E-01	2.09E-01	1.61E-01	HH
Germany	2017	5.12E-01	1.23E-01	2.07E-01	1.58E-01	HH
Germany	2018	5.04E-01	1.26E-01	2.09E-01	1.61E-01	HH
Germany	2019	4.93E-01	1.30E-01	2.12E-01	1.65E-01	HH
Germany	2020	4.95E-01	1.29E-01	2.11E-01	1.64E-01	HH
Germany	2021	5.17E-01	1.21E-01	2.06E-01	1.56E-01	HH
Germany	2022	5.35E-01	1.14E-01	2.01E-01	1.50E-01	HH
Italy	2010	3.27E-01	2.06E-01	2.44E-01	2.23E-01	HL
Italy	2011	3.36E-01	2.01E-01	2.43E-01	2.20E-01	HL
Italy	2012	3.45E-01	1.96E-01	2.41E-01	2.17E-01	HL
Italy	2013	3.44E-01	1.97E-01	2.42E-01	2.18E-01	HL
Italy	2014	3.43E-01	1.97E-01	2.42E-01	2.18E-01	HL
Italy	2015	3.38E-01	2.00E-01	2.42E-01	2.20E-01	HL

Probability						
Country	Year	Next=HH	Next=HL	Next=LH	Next=LL	Current Strategy
Italy	2016	3.35E-01	2.02E-01	2.43E-01	2.21E-01	HL
Italy	2017	3.29E-01	2.05E-01	2.44E-01	2.23E-01	HL
Italy	2018	3.27E-01	2.05E-01	2.44E-01	2.23E-01	LL
Italy	2019	3.39E-01	1.99E-01	2.42E-01	2.19E-01	HL
Italy	2020	3.31E-01	2.04E-01	2.43E-01	2.22E-01	HL
Italy	2021	3.44E-01	1.97E-01	2.42E-01	2.18E-01	HL
Italy	2022	4.09E-01	1.66E-01	2.31E-01	1.95E-01	HL
Netherlands	2010	2.71E-01	2.37E-01	2.49E-01	2.43E-01	LL
Netherlands	2011	2.70E-01	2.37E-01	2.49E-01	2.43E-01	LL
Netherlands	2012	2.69E-01	2.38E-01	2.49E-01	2.43E-01	LL
Netherlands	2013	2.69E-01	2.38E-01	2.49E-01	2.43E-01	LL
Netherlands	2014	2.69E-01	2.38E-01	2.49E-01	2.44E-01	LL
Netherlands	2015	2.69E-01	2.39E-01	2.49E-01	2.44E-01	LL
Netherlands	2016	2.67E-01	2.40E-01	2.49E-01	2.44E-01	LL
Netherlands	2017	2.66E-01	2.40E-01	2.49E-01	2.44E-01	LL
Netherlands	2018	2.68E-01	2.39E-01	2.49E-01	2.44E-01	LL
Netherlands	2019	2.73E-01	2.36E-01	2.49E-01	2.42E-01	LL
Netherlands	2020	2.71E-01	2.37E-01	2.49E-01	2.43E-01	LL
Netherlands	2021	2.73E-01	2.36E-01	2.49E-01	2.42E-01	LL
Netherlands	2022	2.77E-01	2.34E-01	2.49E-01	2.41E-01	LL
Spain	2010	3.23E-01	2.08E-01	2.44E-01	2.25E-01	LL
Spain	2011	3.28E-01	2.05E-01	2.44E-01	2.23E-01	LL
Spain	2012	3.36E-01	2.01E-01	2.43E-01	2.20E-01	LL
Spain	2013	3.34E-01	2.02E-01	2.43E-01	2.21E-01	LL
Spain	2014	3.32E-01	2.03E-01	2.43E-01	2.22E-01	LL
Spain	2015	3.31E-01	2.04E-01	2.43E-01	2.22E-01	LL
Spain	2016	3.24E-01	2.07E-01	2.44E-01	2.25E-01	LL
Spain	2017	3.23E-01	2.08E-01	2.44E-01	2.25E-01	LL
Spain	2018	3.30E-01	2.04E-01	2.43E-01	2.23E-01	HL
Spain	2019	3.29E-01	2.04E-01	2.43E-01	2.23E-01	LL
Spain	2020	3.25E-01	2.07E-01	2.44E-01	2.24E-01	LL
Spain	2021	3.38E-01	2.00E-01	2.42E-01	2.20E-01	LL
Spain	2022	3.86E-01	1.76E-01	2.35E-01	2.03E-01	LL

Table A3. Sensitivity of Key Outcomes to Classification Threshold

Country	Metric	Baseline ($\tau=50\%$)	Conservative ($\tau=40\%$)	Aggressive ($\tau=60\%$)
Germany	HH Frequency (of 14 years)	14	14	14
Germany	Nash Alignment Rate	100%	100%	100%
Germany	Switch Rate	0%	0%	0%
France	HH Frequency	0	0	0
France	Nash Alignment Rate	0%	0%	0%
France	Switch Rate	0%	0%	0%
Italy	HH Frequency	0	12	0
Italy	Nash Alignment Rate	0%	85.7%	0%
Italy	Switch Rate	15.4%	7.7%	15.4%
Netherlands	HH Frequency	0	0	0
Netherlands	Nash Alignment Rate	0%	0%	0%
Netherlands	Switch Rate	0%	7.7%	0%
Spain	HH Frequency	0	1	0
Spain	Nash Alignment Rate	0%	7.1%	0%
Spain	Switch Rate	7.7%	15.4%	7.7%
All countries	HH share (% of all country-years)	20.0%	38.6%	20.0%
All countries	Avg. Nash Alignment	20.0%	38.6%	20.0%
All countries	Avg. Switch Rate	6.2%	6.2%	6.2%

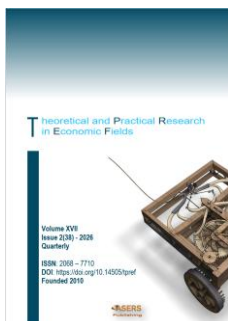
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Exploring Bank Efficiency in Indonesia: A Dual Method Approach Using Data Envelopment Analysis and Stochastic Frontier Analysis



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Abstract: This study evaluates the efficiency of 76 commercial banks in Indonesia over the period 2020-2021, using both Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA). The dataset includes key inputs such as interest cost and labor cost, while outputs for DEA are split into interest income and non-interest income, and the total income is used for SFA. DEA is applied with both Charnes-Cooper-Rhodes (CCR) and Banker-Charnes-Cooper (BCC) models, with output orientation to maximize interest income and non-interest income. The CCR model assumes constant returns to scale (CRS), while the BCC model assumes variable returns to scale (VRS), allowing for scale differences among banks. For SFA, both the Cobb-Douglas and Translog production functions are used to model the relationship between inputs and outputs, with the former assuming a simpler linear relationship and the latter accounting for non-linearities. The results show high correlation between the efficiency scores obtained from both DEA and SFA, suggesting that both methods produce similar rankings of bank performance. However, SFA's flexibility in capturing inefficiencies through random noise makes it a more robust method for analyzing bank performance in volatile environments. Spearman's rank correlation is employed to assess the relationship between the efficiency rankings from both methods, revealing strong consistency in their assessments.

Keywords: banking performance; Cobb-Douglas; efficiency; data envelopment analysis; stochastic frontier analysis; Translog function.

JEL Classification: G21; C14; C67.

Introduction

In an increasingly competitive global financial landscape, evaluating the efficiency of banks is vital for fostering economic stability and growth. Particularly in emerging markets such as Indonesia, understanding the factors that drive banking efficiency is crucial for policymakers, financial institutions, and investors. Efficient banks not only contribute to better resource allocation but also enhance profitability, improve service delivery, and bolster financial system stability. However, measuring bank efficiency remains a complex task, as it requires a careful analysis of both input and output variables. This study aims to explore the efficiency of banks in Indonesia by applying two predominant techniques: Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA), utilizing production orientation.

The choice of DEA and SFA is motivated by the distinctive features each method offers in assessing efficiency. DEA, a non-parametric approach, evaluates the relative efficiency of banks by constructing an efficient frontier against which performance is measured. The Banker-Charnes-Cooper (BCC) and Charnes-Cooper-Rhodes (CCR) models in DEA are widely used to assess efficiency from an output orientation, where the goal is to maximize output (e.g., total income) for a given set of inputs (Charnes, Cooper, and Rhodes 1978). In contrast, SFA is a parametric technique that models the relationship between inputs and outputs through a specified production function, such as the Translog or Cobb-Douglas model, and considers stochastic variations in efficiency. SFA's production orientation focuses on minimizing the inputs (e.g., interest cost and labor cost) for a given output,

allowing for the identification of inefficiencies arising from both observed and unobserved factors (Aigner, Lovell, and Schmidt 1977).

A key feature of this study is the focus on two critical inputs: interest cost and labor cost. Interest cost, representing the cost of capital, is central to banking operations. It affects the bank's profitability and pricing strategies, as well as its ability to compete in the market (Fare, Grosskopf, and Lovell 1994). The ability to manage interest expenses effectively is critical in determining a bank's operational efficiency and profitability. Similarly, labor cost reflects the efficiency of human resources, which is essential for delivering banking services and generating income. The role of labor in banking efficiency cannot be overstated, as a highly skilled workforce can enhance service quality and operational productivity (Sufian, Kamarudin, and Nassir 2016). By focusing on these two key inputs, this study aims to examine their influence on banking efficiency, with a particular emphasis on total income as the output variable. Total income captures the revenue-generating capacity of banks, providing a comprehensive measure of performance that reflects the effectiveness of banks in utilizing their resources to generate returns.

Recent studies have further emphasized the importance of efficiency analysis in the Indonesian banking sector, particularly under conditions of economic uncertainty and macroeconomic shocks. Ariefianto *et al.* (2026) investigated how bank intermediation inefficiency in Indonesia responds to macroeconomic disturbances and found that inefficiency levels are highly sensitive to external economic conditions, highlighting the importance of robust efficiency measurement frameworks that can distinguish between managerial inefficiency and stochastic shocks. Their findings reinforce the relevance of SFA in capturing random disturbances affecting banking performance. Similarly, Febrianto, Amin, and Ramadhani (2026) examined the impact of the COVID-19 pandemic on bank cost efficiency in Indonesia using SFA, comparing conventional and Islamic banks. Their study revealed that stochastic frontier models provide valuable insights into cost efficiency dynamics during crisis periods and demonstrated that external shocks significantly influence banking operational performance. These studies confirm that efficiency analysis remains highly relevant in Indonesia's banking industry, particularly when banks face volatile macroeconomic and regulatory environments.

This study builds on prior research that has employed both DEA and SFA to assess banking efficiency in various contexts. For instance, Akbary *et al.* (2025) investigated the role of digital transformation in the efficiency of Indonesian banks, showing that the adoption of digital technologies can significantly improve operational efficiency by reducing transaction costs and enhancing customer service. On the other hand, Raju (2018), who assessed the efficiency of urban co-operative banks in India, also underscore the relevance of using both DEA and SFA in evaluating bank efficiency. Raju's study found that while DEA offered a robust comparative analysis of efficiency across banks, SFA provided deeper insights into the stochastic nature of inefficiency, especially in the context of banks with differing operational environments. Similarly, Silva *et al.* (2016) conducted a comparative study of DEA and SFA applied to Chinese local banks, revealing how each methodology captures efficiency from different perspectives - DEA focusing on comparative performance and SFA providing a detailed understanding of inefficiencies.

Nguyen *et al.* (2025) further explored the cost efficiency of Vietnamese banks, comparing the two methods and concluding that SFA is particularly useful in capturing stochastic inefficiencies that are not visible in DEA. Their study emphasizes the importance of method choice depending on the research context, as each method provides unique insights into the performance of financial institutions. Similarly, Vu *et al.* (2019) examined banking efficiency in Vietnam using both parametric and non-parametric methods, comparing the strengths and weaknesses of each approach. Their study found that while DEA provided valuable insights into the relative efficiency of banks, SFA offered more flexibility in modeling the stochastic nature of inefficiencies, particularly when accounting for unobserved factors like managerial skill or regulatory impacts. Moreover, Akandekumtiim & Moyo (2024) conducted a comparative analysis of parametric and non-parametric efficiency measures in the Ghanaian banking sector, emphasizing the importance of choosing the right methodology based on the research context. They concluded that SFA was better suited for addressing stochastic variations in efficiency, while DEA was advantageous for its simplicity and ability to handle multiple inputs and outputs without making strong parametric assumptions.

The research presented in this study extends these findings by applying both DEA and SFA to the Indonesian banking sector. By integrating output orientation (DEA) and production orientation (SFA), this study offers a comprehensive evaluation of banking efficiency, with a specific focus on the impact of interest costs and labor costs on total income. Abidin *et al.* (2024) previously compared SFA and DEA but only focused on the BCC and Cobb-Douglas models. This study compares four models simultaneously: BCC and CCR in DEA, Cobb-Douglas and Translog in SFA. The combination of the BCC and CCR models in DEA with the Cobb-Douglas and Translog production functions in SFA provides a novel and comprehensive framework for evaluating bank efficiency in Indonesia. This dual approach allows for a more nuanced understanding of efficiency that considers the

stochastic nature of inefficiency (captured by SFA) and the comparative performance across banks of varying sizes and scales (captured by DEA). It also bridges the gap between non-parametric and parametric methodologies, offering a more comprehensive analysis of bank efficiency than studies relying solely on one approach. This study is expected to contribute significantly to the understanding of how different methodological approaches can inform banking efficiency in Indonesia, offering new insights for policymakers, bank managers, and researchers.

Despite the extensive literature on banking efficiency, important gaps remain in the Indonesian context. Previous studies generally applied DEA or SFA separately and rarely examined the consistency of efficiency rankings across different frontier assumptions, particularly within Indonesia's heterogeneous banking industry. Existing comparative studies also relied on limited model combinations, restricting the analysis of scale effects and functional form sensitivity. Furthermore, post-pandemic conditions, digital transformation, and macroeconomic volatility have increased the importance of incorporating both deterministic and stochastic perspectives in efficiency measurement (Ariefianto *et al.* 2026; Febrianto *et al.* 2026). Therefore, this study contributes by simultaneously comparing CCR and BCC models in DEA alongside Cobb-Douglas and Translog specifications in SFA, providing a more comprehensive framework for evaluating scale efficiency, technical efficiency, and stochastic inefficiency in Indonesian banks, as well as offering implications for banking regulation, digital transformation, and risk management practices.

1. Literature Review

1.1 Data Envelopment Analysis in Banking Efficiency

Data Envelopment Analysis (DEA) is a non-parametric method that evaluates the relative efficiency of decision-making units (DMUs), such as banks, by comparing each bank's performance against an efficient frontier constructed from the best-performing units. The Charnes-Cooper-Rhodes (CCR) model assumes constant returns to scale (CRS), while the Banker-Charnes-Cooper (BCC) model assumes variable returns to scale (VRS), which accounts for scale differences among banks (Charnes, Cooper, and Rhodes 1978). DEA is particularly beneficial for cross-sectional comparisons, allowing researchers to evaluate multiple inputs and outputs simultaneously without requiring specific functional forms.

Numerous studies have utilized DEA to assess banking efficiency across different contexts. Sufian, Kamarudin, and Nassir (2016) examined the efficiency of banks in Malaysia, finding that the BCC model effectively captured efficiency differences across banks of varying sizes. Similarly, Silva, Tabak, and Oliveira (2016) applied DEA to assess the efficiency of Chinese local banks, demonstrating its robustness in cross-bank performance comparisons. Akandekumtim and Moyo (2024) extended this approach by analyzing Ghanaian banks, emphasizing DEA's ability to handle multiple inputs and outputs, making it ideal for cross-sectional efficiency evaluations.

However, DEA has limitations. One major drawback is its inability to account for stochastic noise, which may lead to biased efficiency estimates, especially when considering external shocks or measurement errors. Fare *et al.* (1994) highlighted this limitation, arguing that DEA overlooks random errors, a critical factor in understanding the full scope of inefficiencies. Korneyev *et al.* (2022) also noted that while DEA is effective for benchmarking, it does not address external fluctuations impacting efficiency, which can be crucial in dynamic banking environments. Similarly, Benbachir (2025) pointed out that DEA might not adequately capture the stochastic variations in efficiency, particularly in uncertain market conditions.

1.2 Stochastic Frontier Analysis in Banking Efficiency

Stochastic Frontier Analysis (SFA) is a parametric method that models the relationship between inputs and outputs through a specified production function, accounting for both inefficiency and random noise (Aigner, Lovell, and Schmidt 1977). By incorporating stochastic elements, SFA provides a more nuanced understanding of inefficiencies, particularly in environments where external factors or random disturbances play a significant role. This flexibility makes SFA particularly valuable for banking efficiency analysis in volatile or uncertain market conditions.

SFA has been widely applied in various banking sectors. Nguyen, Thi, and Pham (2025) compared DEA and SFA in the Vietnamese banking sector and concluded that SFA provided a more accurate measure of inefficiency by capturing random fluctuations in the data. Raju (2018) also explored the efficiency of urban co-operative banks in India, finding that SFA was better suited to identify inefficiencies, particularly in banks with diverse operational environments. Silva, Tabak, and Oliveira (2016) further corroborated this conclusion, noting that SFA outperformed DEA in capturing inefficiencies resulting from stochastic disturbances, such as economic shocks or regulatory changes.

Despite its advantages, SFA has limitations, notably its requirement for a specified functional form. Additionally, SFA assumes a particular distribution for the inefficiency term, which can limit its flexibility in modeling inefficiencies across different banking systems (Tim Coelli, Rao, and Battese 1998). As Haque, Tausif, and Ali (2020) noted, these assumptions may not fully capture all forms of inefficiency, especially in diverse banking environments.

1.3 Comparing DEA and SFA in Banking Efficiency Research

The comparative use of DEA and SFA in banking efficiency research has attracted significant attention, with studies recognizing that both methods offer complementary insights into bank performance. Vu, Nguyen, and Dinh (2019) compared the two methods in assessing banking efficiency in Vietnam. They found that while DEA provided valuable insights into relative efficiency, SFA offered a deeper understanding of inefficiencies by accounting for stochastic factors. This view is echoed by Akandekumtiim & Moyo (2024), who found that SFA was more effective at capturing inefficiencies caused by external fluctuations, while DEA excelled in providing comparative efficiency measures across banks.

Coelli *et al.* (2005) argued that DEA is particularly effective for benchmarking efficiency, especially in cases with multiple inputs and outputs, whereas SFA is better suited for capturing inefficiencies arising from random noise or external shocks. (Benbachir 2025) and Shaik, (2022) both observed that SFA's ability to incorporate random errors made it more suited for modeling efficiency in dynamic and unpredictable environments, while DEA provided a robust comparative analysis of bank performance.

Further, Alrafadi *et al.* (2016) demonstrated the value of combining DEA with other econometric techniques to improve the robustness and accuracy of efficiency assessments. This combined approach allows for a more comprehensive analysis of efficiency, particularly in environments where multiple factors influence bank performance.

1.4 Correlation Between Efficiency Measured by DEA and SFA

This study posits the hypothesis that there is a significant correlation between the efficiency scores derived from DEA (using both the BCC and CCR models) and SFA (using Cobb-Douglas and Translog production functions). Nguyen *et al.* (2025) and Akandekumtiim & Moyo (2024) have shown that while both methods tend to yield similar overall efficiency rankings, SFA provides a more detailed measure of inefficiency by accounting for stochastic variations. This study seeks to test whether the correlation between efficiency measures from DEA and SFA holds in the context of Indonesian banks, particularly focusing on the impact of key inputs such as interest costs, labor costs, and total income.

2. Method

The sample consists of 76 commercial banks operating in Indonesia during 2020–2021, including state-owned banks, regional development banks (BPD), private domestic banks, foreign-owned banks, and digital banks supervised by the Financial Services Authority (OJK). Banks were selected based on three criteria: (1) availability of complete annual financial statements for both years, (2) consistency in reporting interest income, non-interest income, interest cost, and labor cost variables, and (3) absence of missing observations that could bias frontier estimation. The period 2020–2021 was selected because it represents the immediate post-COVID-19 disruption phase, during which Indonesian banks experienced significant operational adjustments, digital transformation acceleration, and macroeconomic uncertainty. This period provides an important context for evaluating whether banking efficiency remained stable under crisis-related shocks. The data was sourced from publicly available financial reports published by the banks, with particular focus on annual reports and financial statements obtained from the Financial Services Authority of Indonesia (OJK) and global financial databases like the World Bank. A balanced panel dataset is employed, which includes a mix of both large and small banks operating in Indonesia, ensuring a broad representation of the banking sector. The primary variables for input and output selection are as follows:

1. Inputs for both DEA and SFA
 - a. Interest Cost: Representing the cost of capital, interest cost is a key input that affects a bank's operational cost structure and profitability. It reflects the price of borrowing or obtaining funds for lending operations.
 - b. Labor Cost: Representing human resource expenses, labor cost is central to the bank's operational efficiency in providing services. It accounts for the wages and benefits paid to employees who directly contribute to banking operations.

2. Output

- a. SFA Output: Total Income, which combines both interest income and non-interest income. Total income is a comprehensive measure of bank performance, capturing both revenue streams.
- b. DEA Outputs: The analysis for DEA splits the output into two components:
 - Interest Income: Represents income derived from lending activities and investments.
 - Non-Interest Income: Represents income from fees, commissions, and other non-lending activities.

These variables are selected based on their relevance to the Indonesian banking sector and their critical role in determining the operational efficiency and profitability of banks.

Prior to estimation, all variables were transformed into logarithmic form to reduce heteroscedasticity and improve comparability across banks of different sizes. Outlier observations were examined using boxplot inspection and z-score evaluation. Extreme observations beyond ± 3 standard deviations were winsorized to minimize distortion in frontier estimation while preserving the structure of the dataset. To ensure robustness, efficiency estimates were compared across multiple frontier assumptions, including CRS versus VRS in DEA and Cobb-Douglas versus Translog in SFA. Spearman's rank correlation was subsequently employed to evaluate the consistency of efficiency rankings across models.

2.1. DEA Model Specification

DEA is a powerful nonparametric method used to assess the relative efficiency of Decision-Making Units (DMUs) through linear programming models (Emrouznejad and Cabanda 2013). It enables efficiency analysis within the same cohort by allowing direct peer-to-peer and peer-to-group comparisons across multiple inputs and outputs, supported by a diverse range of model specifications (Manzoni and Islam 2009). The study applies both the Charnes-Cooper-Rhodes (CCR) model and the Banker-Charnes-Cooper (BCC) model, focusing on output orientation, meaning the goal is to maximize outputs (interest income and non-interest income) for given levels of inputs (interest cost and labor cost). The CCR model assumes constant returns to scale (CRS), implying that any proportional increase in inputs will lead to a proportional increase in outputs. Whereas, the BCC model assumes variable returns to scale (VRS), allowing for efficiency variations based on the scale of bank operations, which is especially useful for comparing banks of different sizes.

The efficiency scores for each bank are calculated by solving the following linear programming problem:

$$Eff = \max_{U_i, V_j} \frac{\sum_{i=1}^m U_i Y_{is}}{\sum_{j=1}^n V_j X_{js}} \quad (1)$$

Subject to:

$$\frac{\sum_{i=1}^m U_i Y_{is}}{\sum_{j=1}^n V_j X_{js}} \leq 1; \forall s$$

$$U_i, V_j \geq 0; \forall i, \forall j$$

where Y_{is} represents output, X_{js} represents input, and U_i and V_j are weights for the input and output variables, respectively.

An output-oriented approach was selected because Indonesian banks generally possess greater managerial flexibility in expanding revenue generation than in reducing operational inputs in the short run. During the post-pandemic period, banks were primarily focused on maintaining and increasing income through lending expansion, digital services, and fee-based activities rather than aggressively minimizing labor or funding costs. Therefore, output orientation is considered more appropriate for reflecting the strategic behavior of Indonesian commercial banks. DEA estimation was conducted using the Benchmarking package in Rstudio.

2.2 Stochastic Frontier Analysis

Stochastic Frontier Analysis (SFA) is a parametric method that integrates production theory with error components, separating inefficiency from random noise (Aigner, Lovell, and Schmidt 1977). In this study, SFA employs both the Cobb-Douglas and Translog production functions to capture the efficiency of banks. The SFA output is defined as total income, which includes both interest income and non-interest income.

The Cobb-Douglas production function for SFA is specified as:

$$\ln Y_{it} = \alpha_0 + \sum_{j=1}^J \beta_j \ln X_{jit} + V_{it} - U_{it} \quad (2)$$

where Y_{it} is the total income of unit i at time t , X_{jit} represents the j -th input (interest cost, labor cost), β_j are the parameters to be estimated, V_{it} denotes the random noise, and U_{it} captures technical inefficiency.

For the Translog production function, the model includes quadratic and interaction terms to capture non-linear relationships:

$$\ln Y_{it} = \beta_0 + \sum_{j=1}^J \beta_j \ln X_{jit} + \frac{1}{2} \sum_{k=1}^K \sum_{j=1}^J \beta_{jk} \ln X_{jit} \ln X_{kit} + V_{it} - U_{it} \quad (3)$$

where β_{jk} represents the interaction effects between inputs j and k . Technical efficiency (TE) for each unit is defined as:

$$TE_{it} = \frac{\exp(X'_{jit} \beta_j + V_{it} - U_{it})}{\exp(X'_{jit} \beta_j + V_{it})} = \exp(-U_{it}) \quad (4)$$

Here, U_{it} represents the inefficiency term; smaller values of U_{it} indicate higher efficiency. Thus, when $U_{it}=0$, decision-making unit is operating on the efficiency frontier (TE=1).

SFA estimation employed the frontier package using maximum likelihood estimation (MLE). The inefficiency term in the SFA model was assumed to follow a half-normal distribution.

2.3 Spearman's Rank Correlation

To assess the hypothesis of a significant correlation between the efficiency scores derived from DEA and SFA, Spearman's rank correlation coefficient is used, particularly when the data do not follow a normal distribution (Sirkin 2006). Varabyova & Schreyögg (2013) also applied Spearman's correlation to compare SFA and DEA. This non-parametric test is ideal for comparing the rankings of efficiency scores produced by both methods, as it assesses the strength and direction of the monotonic relationship between the two sets of efficiency rankings.

The Spearman rank correlation coefficient ρ is calculated as follows:

$$\rho = 1 - \frac{6 \sum_{i=1}^n \sum_{t=1}^T d_{it}^2}{nT \{ (nT)^2 - 1 \}}$$

where i denotes the decision-making unit, t represents the time period, d_{it} is the difference between ranks of paired observation, and nT is the total number of paired data points. A significant positive correlation would suggest that the efficiency rankings from DEA and SFA are closely aligned. In contrast, a low or negative correlation would indicate differing assessments of efficiency between the two methods. Spearman correlation analysis and visualization were implemented using the corplot and ggplot2 packages. The complete computational workflow is available upon request to improve transparency and reproducibility.

3. Research Results

3.1 Overview of Descriptive Statistics

Table 1 presents the descriptive statistics of the input and output variables used in the efficiency analysis. The logarithmic transformations of income and cost variables ensure variance stabilization and comparability across banks. The mean of log(interest income) is 14.65, while the mean of log(non-interest income) is 10.94, indicating that interest-based activities dominate the income structure of the sampled banks. Similarly, log(interest cost) and log(labor cost) show relatively balanced input magnitudes (13.55 and 12.94, respectively), suggesting comparable cost structures across decision-making units (DMUs). The observed standard deviations reveal moderate dispersion, implying that the sample banks operate under varying levels of cost and income efficiency, a condition favorable for frontier-based efficiency estimation.

Table 1. Descriptive Statistics of Data

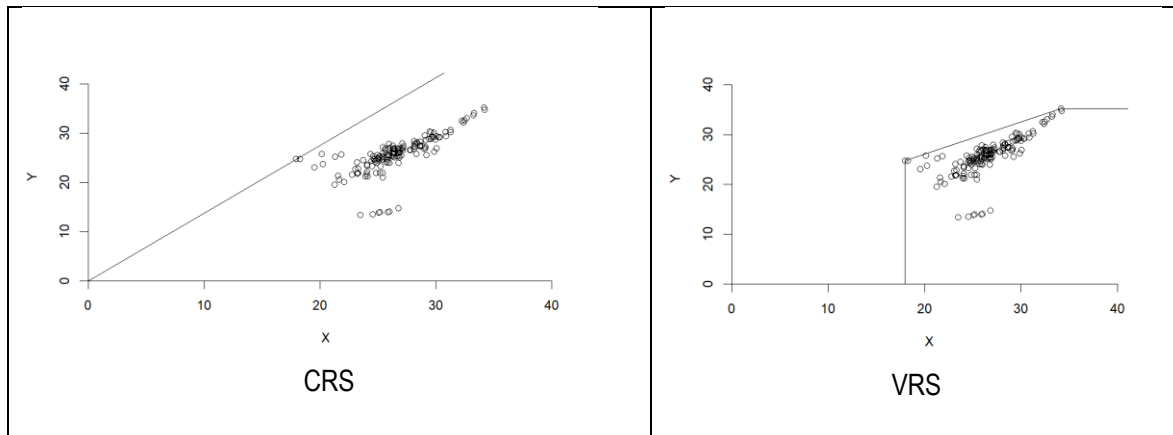
Variable	N	Mean	Std.dev	Min	Max
Ln (interest income)	152	14.65	1.38	11.72	18.63
Ln (non-interest income)	152	10.94	2.96	0.00	16.54
Ln (interest cost)	152	13.55	1.39	9.91	16.99
Ln (labor cost)	152	12.94	1.76	5.12	17.22

Source: Data processed by the author(s)

3.2 Efficiency Scores from DEA

The efficiency analysis using Data Envelopment Analysis (DEA) was conducted under both Constant Returns to Scale (CRS) and Variable Returns to Scale (VRS) assumptions. Figure 1 illustrates the DEA frontiers for both CRS and VRS models. The CRS plot represents the Charnes, Cooper, and Rhodes (CCR) model (Charnes *et al.*, 1978), which assumes proportionality between inputs and outputs. The VRS plot represents the Banker, Charnes, and Cooper (BCC) model, allowing for scale inefficiencies by constructing a convex frontier.

Figure 1. DEA Plot CRS vs VRS



Source: Data processed by the author(s)

As depicted, several banks lie on or near the efficient frontier in both models, indicating high technical efficiency levels. However, the VRS model's frontier lies above the CRS frontier, consistent with the theoretical expectation that VRS efficiency scores are typically equal to or greater than CRS scores (Timothy Coelli *et al.* 2005). This occurs because the VRS specification isolates pure technical efficiency by excluding scale effects.

Figure 2. Density Plot CRS vs VRS



Source: Data processed by the author(s)

Table 2. Descriptive Statistics of Efficiency DEA

Variable	Mean	SD	Min	Max
efficiency_scores_crs	0.91108	0.02976	0.81966	1.00000
efficiency_scores_vrs	0.92874	0.03118	0.83908	1.00000

Source: Data processed by the author(s)

Figure 2 and Table 2 provide the distribution and descriptive summary of the DEA efficiency scores. The mean CRS efficiency is 0.9111, while the mean VRS efficiency is 0.9287, with both exhibiting relatively low standard

deviations (0.03). This finding indicates that the majority of banks in the sample operate close to the efficiency frontier, though minor inefficiencies persist. The density plot further reveals that VRS scores are right-skewed, implying that when scale effects are relaxed, banks appear more efficient.

This pattern is consistent with findings by (Sufian, Kamarudin, and Nassir 2016) and (Silva, Tabak, and Oliveira 2016), who observed that larger banks benefit less from the VRS assumption compared to smaller ones. The results also echo (Akandekumtiim and Moyo 2024), who emphasized the suitability of DEA-VRS for analyzing heterogeneous banking environments. However, DEA's deterministic nature implies that all deviations from the frontier are treated as inefficiency, disregarding random shocks - a limitation acknowledged by (Fare, Grosskopf, and Lovell 1994) and (Benbachir 2025).

3.3 Efficiency Scores from SFA

Table 3 presents the estimation results from Stochastic Frontier Analysis (SFA) using both Cobb–Douglas and Translog production functions. The Cobb–Douglas specification provides significant parameter estimates for both input variables (interest cost and labor cost), suggesting that these inputs positively and significantly influence output efficiency ($p < 0.01$). The translog specification, while more flexible, yields statistically insignificant coefficients for the second-order and interaction terms, indicating that the Cobb–Douglas function sufficiently captures the input-output relationship for this dataset.

Table 3. Estimation of SFA (Cobb-Douglas vs Translog)

Variable	Cobb-Douglass		Translog	
	Estimate	p-value	Estimate	p-value
(Intercept)	2.530	4.0e-07	14.54130	< 2e-16
Ln interest cost	0.719	< 2e-16	-0.92950	0.35
Ln labor interest	0.191	1.1e-10	0.03400	0.97
Ln interest cost ²			0.0966	0.95
Ln labor interest ²			0.0627	0.93
Ln interest cost* Ln labor interest			-0.0915	0.93
sigmaSq	0.179	< 2e-16	0.08480	0.93
Gamma	0.000007	1	0.05000	0.96

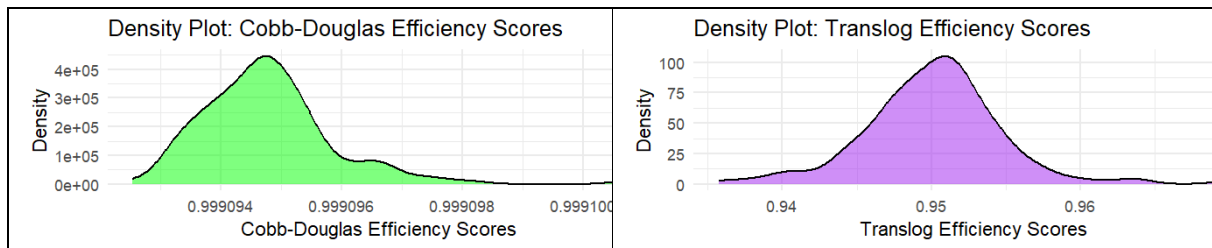
Source: Data processed by the author(s)

The estimated γ (gamma) parameter in the Cobb–Douglas model is close to zero ($\gamma = 0.000007$), indicating that random noise dominates over inefficiency. This suggests a relatively high operational consistency among banks, where most deviations from the frontier stem from stochastic disturbances rather than managerial inefficiency. Conversely, the Translog model reports $\gamma = 0.05$, still implying limited inefficiency variance.

The extremely low gamma values obtained in both SFA specifications indicate that the variance of inefficiency is relatively small compared to statistical noise. This finding suggests that Indonesian banks in the sample operated under relatively homogeneous efficiency conditions during 2020–2021, or alternatively, that the selected input-output structure may not fully capture managerial inefficiency variation. Consequently, the SFA model may possess limited discriminatory power in distinguishing inefficient banks within this dataset.

This result also implies that external shocks, regulatory adjustments, and macroeconomic uncertainty during the post-pandemic period may have contributed more strongly to performance variation than internal managerial inefficiency. Similar observations were reported by Ariefianto *et al.* (2026), who found that Indonesian banking inefficiency is highly responsive to macroeconomic disturbances. Therefore, future studies may benefit from incorporating environmental variables, risk indicators, or panel stochastic frontier models to improve inefficiency identification.

Figure 3. Density Cobb-Douglas vs Translog



Source: Data processed by the author(s)

Table 4. Descriptive Statistics of Efficiency SFA

Variable	Mean	SD	Min	Max
efisiensi_sfa_cd	0.99909	0.00000	0.99909	0.99910
efisiensi_sfa_translog	0.95012	0.00471	0.93574	0.96998

Source: Data processed by the author(s)

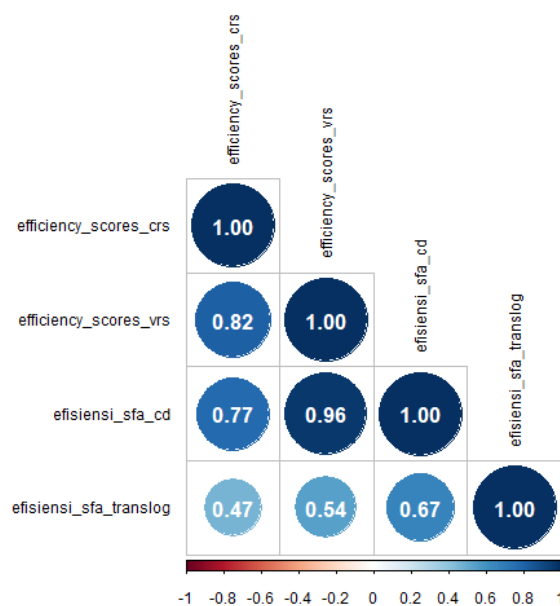
Figure 3 and Table 4 further illustrate the density of efficiency scores derived from both functional forms. The Cobb–Douglas model produces efficiency scores tightly clustered near unity (mean = 0.99909), signifying almost perfect efficiency under its restrictive assumptions. In contrast, the Translog model shows a broader distribution (mean = 0.95012, SD = 0.0047), reflecting its greater flexibility in accommodating input substitution and curvature effects.

These findings are in line with (Nguyen, Thi, and Pham 2025) and (Raju 2018), who highlighted that SFA's stochastic structure captures noise more effectively, resulting in a more dispersed but realistic efficiency distribution. Similarly, (Silva, Tabak, and Oliveira 2016) argued that the Translog specification, despite being more complex, better represents efficiency variations under uncertain market conditions.

3.4 Spearman's Rank Correlation Analysis

To examine the relationship between efficiency measures from DEA and SFA, Spearman's rank correlation was computed (Figure 4). The results reveal strong and significant positive correlations between most efficiency indicators. The correlation between CRS and VRS scores is 0.82, confirming consistency across DEA scale assumptions. Additionally, the correlation between DEA-VRS and SFA-Cobb–Douglas is notably high ($\rho = 0.96$), suggesting that both methods rank banks similarly in terms of efficiency, despite their methodological differences.

Figure 4. Spearman's Correlation Plot



Source: Data processed by the author(s)

The correlation between SFA-Translog and DEA efficiency scores is weaker ($p = 0.47\text{--}0.67$), implying that the flexible functional form captures different aspects of inefficiency, possibly due to non-linearities and random shocks. This aligns with (Vu, Nguyen, and Dinh 2019) and (Akandekumtiim and Moyo 2024), who observed that while DEA and SFA generally yield consistent efficiency rankings, SFA tends to produce lower efficiency levels because it adjusts for noise.

4. Discussions

DEA and SFA are complementary not substitutive, approaches for evaluating bank efficiency. As (Timothy Coelli *et al.* 2005) and (Shaik 2022) noted, DEA excels in benchmarking and identifying best-practice frontiers, whereas SFA provides a deeper understanding of inefficiency sources by decomposing error components. The high correlation between DEA-VRS and SFA-Cobb–Douglas implies that, in relatively stable banking environments, deterministic and stochastic frontiers yield convergent efficiency rankings. However, under greater environmental volatility - as modeled by the Translog SFA - efficiency estimates diverge, emphasizing the need for context-specific methodological selection.

Compared with studies in Southeast Asia, the efficiency scores observed in Indonesian banks appear relatively high under both DEA and SFA approaches. Vietnamese banking studies by Nguyen *et al.* (2025) and Vu *et al.* (2019) reported greater efficiency dispersion, reflecting stronger heterogeneity in operational environments and ownership structures. Similarly, Malaysian banks analyzed by Sufian *et al.* (2016) exhibited wider variation in scale efficiency. The relatively concentrated efficiency scores in this study may indicate that Indonesian banks experienced convergence in operational strategies during the post-pandemic recovery period, particularly through digitalization and cost restructuring initiatives.

The combined DEA–SFA approach provides a robust dual-lens assessment of Indonesian banks' efficiency. DEA reveals that most banks operate close to the efficiency frontier, with minor deviations attributed to scale inefficiencies. SFA corroborates these findings, highlighting that random noise plays a dominant role in explaining efficiency variation. The high correlation between DEA-VRS and SFA-Cobb–Douglas suggests that both methods yield compatible efficiency rankings when banking operations are relatively homogenous.

From a policy perspective, the findings imply that Indonesian banking regulators should not only focus on improving managerial efficiency but also strengthen resilience against macroeconomic and stochastic shocks. Since DEA and SFA indicate that banks generally operate near the efficiency frontier, future efficiency gains may depend more heavily on technological innovation, digital transformation, and risk management improvements rather than traditional cost minimization strategies alone. For bank management, the results highlight the importance of balancing operational expansion with scale optimization. Banks operating efficiently under the VRS framework may still experience scale inefficiencies under CRS assumptions, suggesting that strategic growth decisions should consider operational scale sustainability. Furthermore, the stronger efficiency consistency between DEA-VRS and SFA-Cobb–Douglas indicates that stable operational structures remain critical for maintaining efficiency during uncertain economic conditions.

Overall, these results confirm that integrating non-parametric and parametric frontier methods enhances the robustness of efficiency evaluations. As recommended by Alrafadi *et al.* (2016), combining DEA and SFA allows researchers to cross-validate results and capture both deterministic and stochastic dimensions of inefficiency, thus offering a more comprehensive understanding of banking performance dynamics in Indonesia.

Conclusions and Further Research

In conclusion, the combined application of DEA and SFA provides a comprehensive understanding of banking efficiency by integrating non-parametric benchmarking and parametric stochastic modeling. The DEA results indicate that Indonesian banks generally operate near the efficient frontier, with higher efficiency under VRS assumptions reflecting the role of scale differences. Meanwhile, SFA results suggest that random shocks, rather than managerial inefficiency, predominantly explain variations in performance - especially under the Cobb–Douglas specification. The strong correlation between DEA-VRS and SFA-Cobb–Douglas efficiency scores confirms the consistency of both methods in ranking bank performance, while the weaker correlation with the Translog model highlights the sensitivity of efficiency estimates to functional form assumptions. Overall, this study reinforces the complementarity of DEA and SFA: DEA effectively identifies best-practice frontiers and relative performance, whereas SFA provides deeper insights into inefficiency drivers under stochastic conditions, making their combined use essential for robust efficiency evaluation in the banking sector.

In order to capture efficiency changes over time, future research may expand on this study by utilizing productivity indexes like the Malmquist index and dynamic efficiency analysis using panel data approaches. Furthermore, incorporating environmental factors - such as the degree of digitization, the quality of governance, credit risk, and macroeconomic conditions - may offer more profound insights into the roots of inefficiency that DEA and SFA are unable to fully capture. To improve the reliability and thoroughness of banking efficiency evaluations, future research may also investigate hybrid or alternative frontier approaches and perform comparison analysis across various bank groupings (e.g., large vs. small banks, conventional vs. Islamic banks).

Declarations

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Credit Authorship Contribution Statement:

Zaenal Abidin: Conceptualization; Formal analysis; Investigation; Supervision; Validation; Writing – review & editing;

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Who Watches the Trustee? Rethinking Bankruptcy Trustee Liability in Ukraine and Worldwide



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Abstract: This paper examines the legal processes that can be applied to the liability of bankruptcy of trustees in international practice. It is relevant because it is necessary to protect the rights of the parties on insolvency procedures, increase transparency, avoid abuse, and align the Ukrainian legislation with the international standards. A comparative legal approach is used to analyze the regulation of the liability of bankruptcy trustees in the USA, Germany, France, Sweden and the UK. The research is found on law, case law and scholarly studies. The comparison is conducted based on the main criteria: the qualification criteria, supervision, civil and criminal liability, insurance and disciplinary measures. Four primary types of liability were outlined, and they include administrative, judicial, self-regulatory and hybrid. They are both good and bad in their respects of accountability, effectiveness and transparency. The most balanced is the hybrid model, which combines state supervision, judicial oversight and professional self-regulation. A multi-tiered accountability system is proposed, comprising institutional, judicial, professional, financial and digital components. Effective accountability for bankruptcy trustees is achieved through the interaction of various control mechanisms, rather than within a single model. The proposed hybrid concept promotes greater transparency and trust in the bankruptcy system and can be used to improve Ukrainian legislation in line with international standards.

Keywords: insolvency; bankruptcy trustee; liability; insolvency law; creditor protection; Ukrainian insolvency reform.

JEL Classification: G33; K41; K13; A12.

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Introduction

In today's economic environment, the legal institution of bankruptcy has to solve several tasks, in which the activities of bankruptcy trustees play an important role. They link the debtor, creditors, and the court. The actions of bankruptcy trustees determine the debtor's future fate. By initiating bankruptcy proceedings, the court, as a public authority, interferes with private business relations. This is due to the need to protect the economic relations of the debtor's insolvency, as a result. Without this intervention, in the event of a business entity's bankruptcy, it is impossible to foresee all the most important social consequences that will arise between the insolvent debtor and other business entities. Thus, a private interest in insolvency relations becomes a public interest (Popko 2023). In other words, the court and the bankruptcy trustee become the state authority or public controlling body in the bankruptcy procedure. The bankruptcy trustee, with the help of the control and supervisory functions granted to someone in the management and disposal of the debtor's property, is entrusted with the obligation to reconcile the interests of creditors and the insolvent debtor to further satisfy in full the creditors' claims and, as far as possible, prevent unnecessary losses and economic destruction of the debtor as a production unit.

The relevance of the study lies in the protection of the rights and interests of the parties to the process, since bankruptcy trustees play an important role in bankruptcy and solvency restoration procedures. Their actions and decisions determine the effectiveness of the protection of the rights of creditors, debtors, and other stakeholders. By controlling their liability, one can guarantee the transparency and fairness of the process and prevent corruption and abuse, as well as enhance trust in the system of insolvency. Harmonizing national legal systems is helped by the study of international experience and standards for regulating the liability of bankruptcy trustees. This, in turn, streamlines international business and promotes a more efficient cooperation of countries. The setting of clear standards improves work quality and standards. It provides stability and legal certainty, which is essential in attracting investment and promoting economic development. Moreover, efficient insolvency management and dispute resolution on transnational economies requires international regulation, which also fosters international cooperation on insolvency.

Although there is an increasing amount of comparative insolvency scholarships, there still exists a considerable research gap in the systematic study of the liability of bankruptcy trustees under varying regulatory frameworks. In literature, there is the tendency to concentrate on either a single jurisdiction or a particular area of liability e.g. remuneration, professional status or the role of procedures. Nonetheless, an analytical framework of how various accountability mechanisms interact both within and across legal systems is lacking. Specifically, the lack of a coherent cross-model treatment of bankruptcy trustees' liability, the lack of integration of new governance instruments, such as digital instruments of transparency and risk-monitoring technologies, have received an insufficient amount of attention.

In order to fill this gap, this research seeks to analyze the legal procedures that regulate the liability of bankruptcy trustees in a comparative analysis and come up with a comprehensive conceptual framework that can improve accountability, transparency, and effectiveness of insolvency governance. From a theoretical standpoint, the research relies on the principal-agency theory and multi-level governance strategies and presumes that the insolvency regimes are multi-principal in the sense that the interests of creditors, debtors, courts, and the state are supposed to be reconciled with each other via the multi-layered accountability frameworks (Tirole 2019; Mysaka and Derun 2025). The hypothesis underpinning the study is that insolvency governance is a multi-principal regime involving information asymmetry and conflicting interests, as a conceptualized under principal-agent theory. In this regard, an appropriate way to regulate bankruptcy trustees is to have a multi-layered accountability framework, which is consistent with the notion of multi-layered governance, where authority is shared at the institutional, judicial, and professional levels. In order to accomplish this aim and verify the hypothesis, the research has the following objectives:

- to examine the legal frameworks governing the bankruptcy trustees' liability in some of the jurisdictions, such as the USA, Germany, France, Sweden and the UK;
- to determine and codify significant aspects of liability, such as qualification provisions, supervisory arrangements, civil and criminal liability and financial protection;
- to establish a comparative typology of bankruptcy trustees' liability models according to functional criteria;
- to assess the strengths and weaknesses of these models with regard to accountability, efficiency, and institutional design;
- to suggest a hybrid accountability framework that incorporates the most successful aspects of various regulatory strategies;
- to evaluate the consequences of this framework on legal reform, especially, European integration, and Ukrainian insolvency law.

In this paper, a conceptually integrated hybrid accountability framework that re-conceptualizes the liability of bankruptcy trustees as a multi-level governance system that integrates institutional, judicial, professional, financial and digital accountability mechanisms is developed. It also introduces a practical typology of liability regimes that can then be used to make the cross-jurisdictional comparison of the key dimensions that offer a transferable analytical tool to evaluate the insolvency regimes. Finally, the article provides the path to the reconciliation of theory and practice through the reconciliation of its framework with the EU Directive 2019/1023 (European Parliament and the Council 2019), which can be applied to the practice by policy-oriented jurisdictions during the reform.

1. Literature Review

In recent years, the idea of accountability for bankruptcy trustees has gained greater prominence in the literature on insolvency law, both in relation to institutional governance and creditor protection and the efficiency of insolvency restructuring. A number of existing studies show that the role of a bankruptcy trustee is unique, in that it has a

mixture of private professional and public supervisory functions. Consequently, the efficiency of insolvency systems is dependent on the quality of the regulatory framework, liability rules and systems of professional accountability in their work.

The legal status of the bankruptcy trustees and the bankruptcy procedures have been researched by many scholars. Kabenok (2021) was preoccupied with making sure that the trustee performs his or her duties, which is a vital measure in the bankruptcy process. This is critical to the efficiency of the process, especially with the influence of creditors committee towards appointing and dismissing trustee. Danilov (2020) researched the issues related to the practical application of the right of the insolvency trust to the timely compensation and compensation of costs that occur during the bankruptcy proceedings. Blazy and Stef (2020) examined the material of the bankruptcy proceedings, which are reviewed by the courts of three Eastern European nations Hungary, Poland, and Romania, and dwelled primarily on two key matters, which the courts have to consider whenever they are confronted with the problem of debt repayment: maximizing and distributing debtor value.

Wessels *et al.* (2009) investigated the challenges of international cooperation in bankruptcy matters across jurisdictions. Punda and Arziantseva (2023) investigated the problematic aspects of ensuring secrecy in the course of the activities of the trustee in a bankruptcy case, proposing the introduction of the category of secrecy of the bankruptcy trustees' activities and the application of appropriate legal guarantees based on the provisions relating to the activities of lawyers. While the studies add to an understanding of specific issues in the bankruptcy process, the current scholarship is fragmented and largely treats procedural and institutional issues in isolation. Earlier research focuses on specific national systems or the limited aspects of particular accountability mechanisms, such as remuneration, professional ethics or procedural competence, without providing a more comprehensive comparative framework for the assessment of accountability mechanisms in different jurisdictions.

There is also an extensive amount of academic research on the professionalization, expertise and income of bankruptcy trustees. Previous doctrinal research explored the institutional function of trustees in national insolvency regimes and bankruptcy procedure (Finch 2017; Keay and Walton 2017). Later scholarship focuses more on professional accountability, ethics, and regulatory efficiency. For instance, in common law jurisdictions, Seehaus and Peráček (2024) study the rising worries around incompetence of bankruptcy trustees, fee structures, and judicial oversight, which could otherwise lead to loss of creditor trust and fairness.

Another line of current research focuses on insolvency governance and multi-level accountability systems. Comparative legal studies conducted recently show that the current form of insolvency regime shows there are growing hybrid structures between the courts, administrative bodies, and professional self-regulatory bodies. Gurrea-Martínez (2021) states that modern insolvency systems need to be analyzed in institutional and economic governance tools and not only in the framework of traditional procedural doctrines. Likewise, Cepec *et al.* (2024) highlight the importance of institutionalized stakeholder participation and creditors' committees to enhance the outcomes of bankruptcy and accountability in the bankruptcy process. The studies suggest a more general shift from the traditional, narrowly judicial approach to insolvency law to a more holistic, governance-oriented approach.

Comparative insolvency scholarship has also focused extensively on cross-border coordination, harmonization of the insolvency law and the application of European standards on the restructuring of companies. The effects of Regulation (EU) 2015/848 (European Parliament and the Council 2015) and Directive (EU) 2019/1023 (European Parliament and the Council 2019) on the coordination of the insolvency proceedings and the professional duties of bankruptcy trustees have already been studied (McCormack *et al.* 2017). Other more recent research continues this theme, with an analysis of the special kinds of cross-border bankruptcy procedure, such as group bankruptcy trustees and the coordination of multinational restructuring proceedings (Pepels 2024). In spite of the advances of comparative insolvency scholarship, however, most of the studies have focused on the harmonization of the procedure or on a comparative analysis of individual national systems instead of a systematic comparative analysis of trustee liability regimes and accountability mechanisms among jurisdictions.

The digitalization of bankruptcy proceedings and the use of technology to improve its transparency, monitoring and efficiency are also a growing focus of research. Integration of AI, blockchain, and digital audit tools within bankruptcy procedure is a new topic of interest in scholarship. As noted by Gurrea-Martínez (2025), digital technologies can potentially lower the costs and time of bankruptcy procedure and enhance transparency and investigative powers by using automated monitoring systems and AI data analysis. Scholarship also has recently addressed the difficulties of tracing digital assets and the rules and mechanisms for crypto-assets in the modern insolvency framework, including in the context of the proposed EU Insolvency III reform (Skauradszun and Moffatt 2026). These developments illustrate how accountability in the field of insolvency law more and more is connected to not only traditional legal liability tools but also technological tools of supervision and compliance.

Although, with the amount of scholarship on bankruptcy that has emerged, there are a number of key issues left unanswered. First, such studies of bankruptcy trustees' regulation have largely focused on specific issues and not established a common analytics framework for assessing accountability systems. Secondly, there is little connection between classic insolvency law scholarship and other theories of governance, such as principal-agent theory or multi-level governance theory. Third, while digitalization and AI-assisted insolvency administration are increasingly the focus of recent studies, there has been little research to date on how technological oversight mechanisms relate to the traditional legal accountability mechanisms. Lastly, comparative studies are rarely conducted using a combination of accountability, efficiency and transparency lens of liability across multiple jurisdictions.

This article will attempt to bridge these gaps by creating a conceptually coherent comparative framework for discussing the bankruptcy trustee's liability in the United States, Germany, France, Sweden and the United Kingdom. The study develops a typology of bankruptcy trustees' accountability systems and assesses their institutional strengths and weaknesses by comparing different legal frameworks, rather than analyzing individual systems or systems of individual liability. Further, the paper reflects recent discussion on digital governance, monitoring with the help of AI and technological transparency in the general debate on the reform of insolvency governance. As such, the article makes its contribution to comparative insolvency studies as well as to the current debates on the modernization of insolvency law in Ukraine and in the European legal space.

2. Method

This paper uses a comparative legal approach to analyze how bankruptcy trustees' liability is regulated in five jurisdictions. The comparative method, which is considered to be central to the analysis of the cross-jurisdictional law, allows the identification of functional equivalents, i.e. various legal mechanisms that can be used to fulfil the same regulatory functions in different legal systems. The five jurisdictions of the USA, Germany, France, Sweden and the UK were chosen based on two factors. To begin with, they are different models of insolvency regulation: (1) the debtor-in-possession model of insolvency found in the US, subject to federal bankruptcy trustee oversight, as represented by the Department of Justice; (2) the pro-creditor model of insolvency in Germany, with strict judicial oversight; (3) the French model with specialized practitioners regulated as special professions; (4) the Second, legal frameworks are highly developed, and there is a large amount of case law and commentary in these jurisdictions, making good primary and secondary sources available.

It uses four types of materials, namely, (a) primary legislation, that is, the US Bankruptcy Code (Title 11, US Code), the German Insolvenzordnung (InsO), the French Code de commerce, the Swedish Bank The comparative study is framed by five main dimensions of responsibility of bankruptcy trustees: (1) qualification requirements and licensing; (2) oversight and supervisory mechanisms; (3) civil liability on negligence and breach of duty; (4) criminal liability on misconduct; and (5) professional liability insurance and bonding requirements. For each jurisdiction, the regulatory framework is analyzed along these dimensions, enabling systematic cross-jurisdictional comparison. The deductive method adopts common principles and norms of international law to examine specific issues related to the liability of bankruptcy trustees. Exploring this issue on the example of countries such as the USA, the UK, Germany, France, and Sweden makes it possible to compare various methods and identify best practices that can be applied in the international community.

The analytical method plays a significant role in the identification, examination and elucidation of fundamental concepts, terminology and categories. The generalization method forms the basis for the formulation of general conclusions, as well as the principles and recommendations for Ukraine. These are derived on the basis of the analysis undertaken of international legal practices (Zweigert and Kötz 1998). Consequently, this study promotes the alignment of Ukraine's national legislation with international standards to enhance the consistency and predictability of its legal framework. This strategy has been proved to improve the efficiency and transparency of the restructuring and bankruptcy procedures, as well as creating a favorable environment to attract foreign capital to invest in a country by giving confidence to all stakeholders in the insolvency process.

Introducing clear legal criteria contributes to the development of bankruptcy regulations and reduces the risk of abuse in property management processes. Consequently, it enhances the legal safeguards for creditors and debtors alike, fostering a more predictable and dependable investment climate. Moreover, international cooperation and the exchange of experience in the field of insolvency allow Ukraine to integrate advanced solutions that have proven effective in a global context. As a result, such legislative adaptation will contribute to the country's economic stability and development, opening new opportunities for investors and entrepreneurs.

3. Research Results

3.1 Theoretical Foundations and Comparative Models of Liability for Bankruptcy Trustees

The processes taking place in the modern economy are subject to state management and control, both directly and through a system of specially created public institutions that make economic processes self-regulating. This includes, in particular, the institution of regulation of procedures carried out in the process of restoring a debtor's solvency or declaring it bankrupt. This legal institution contributes to the systematic resolution of contradictions and mistakes accumulated in the business entity's activities and, to a certain extent, to the adequate protection of creditors' interests by applying transparent property management procedures and using all opportunities to restore the normal operation of the business entity to prevent its liquidation as a last resort, but necessary measure. However, the state and society have an interest in preventing all kinds of abuse in this area, so that the bankruptcy procedure does not become a tool for illicit enrichment, evasion of civil, commercial, and tax obligations, labor payment obligations, and implementation of various kinds of raider schemes (Mysaka and Derun 2025).

Theoretically, this kind of state participation may be seen as a solution to the principal-agent issues associated with insolvency proceedings, as bankruptcy trustees, being agents, might have different interests than creditors or society.

In the principal-agent framework, bankruptcy trustees are agents tasked with running the debtor's business for the benefit of many principals such as debtors, courts, creditors and the state. This gives rise to structural information, opportunism and conflicts of interest, where the trustees might have greater informational or procedural advantages than the parties whose interests they are supposed to be protecting. As a result, insolvency systems set up mechanisms of accountability to minimize agency costs through monitoring, sanctions, transparency requirements and professional standards. Concurrently, the variety of institutional configurations among jurisdictions indicates varying conceptions of institutional accountability that mark the allocation of responsibility between the state, courts and professional bodies. Based on the multi-level governance theory, the insolvency regulation can thus be seen as a multi-layered institutional control framework in which authority is spread across multiple governance levels or institutions rather than being on top of one institution (Fagetan 2025).

The introduction of supervisory and liability mechanisms is thus a way of minimizing information asymmetry and harmonizing incentives in the system. The institution of bankruptcy should be recognized as a regulated way of redistributing property in society. Bankruptcy results in the transfer of property (which is a key component, in particular, in business activities) from an inefficient owner (the debtor) to its creditors, who have legitimate claims against the debtor due to its inability to fulfil its financial obligations. The complexity of the process and the existence of a logical conflict of interest of the parties in a bankruptcy case leads to the emergence of a third independent party who essentially manages the debtor's property in bankruptcy relations (Table 1).

Thus, there are four primary models of bankruptcy trustees' liability, which represent various patterns of accountability mechanisms in jurisdictions. The first is the administrative oversight model, which is typified by the existence of a specialized public authority to oversee the activities of bankruptcy trustees and to oversee and enforce compliance. The focus of this model is on the systemic control and prophylactic supervision, as the examples of Sweden and, to some degree, the USA demonstrate. This governance model is characterized from a governance point of view as a hierarchical regulatory system that makes accountability the responsibility of a single entity, namely the state, with administrative monitoring. To rectify the principal-agent problem, there is constant external supervision, which aims to reduce the information gap and discretionary abuses (Pepels 2024).

The second model is the judicial control model, in which the courts are the key players in the appointment, oversight and where they are not, they sanction bankruptcy trustees. This is based on case-by-case evaluation and a robust judicial role, which is the case with Germany. The judicial control model is based on the logic of legality, in which rules are enforced and accountability is realized through the process of reviewing and judging. Under the principal-agent theory, courts serve as a third-party monitoring body to help resolve conflicts of interest between conflicting principals and to keep agents from falling short of their fiduciary responsibilities (Seehaus and Peráček 2024).

The third model is the professional self-regulation model whereby the recognized professional bodies are in charge of setting ethical standards, licensing requirements and disciplinary procedures. This model gives priority to professional autonomy and internal accountability mechanisms, like in the UK (Goldhahn 2023). This is a network-based governance model that uses professionalism and peer supervision to replace a lot of state involvement. It also presumes that professional associations have expert knowledge in their respective sectors, which enables them to perform well in the conduct of their profession, but at the same time, this may also lead to the risk of regulatory capture and of poor external accountability of professional associations (Cepec *et al.* 2024).

Table 1. Comparative analysis of bankruptcy trustees' regimes

Dimension	United States	Germany	France	Sweden	United Kingdom
Regulatory model	Federal executive oversight (US Trustee / DOJ)	Judicial appointment and supervision	Regulated profession with disciplinary chambers	Centralized administrative authority (Enforcement Authority)	Self-regulation by RPBs with government oversight
Qualification	Panel membership; attorney with insolvency specialization	No formal qualification; court discretion; typically, lawyer or accountant	Competitive examination; supervised practice; mandatory professional body	Licensed by Enforcement Authority; legal or accounting qualifications	RPB license; JIEB exams
Civil liability	Fiduciary duties; surcharge; personal liability for breach	Section 60 InsO: personal liability; reversed burden of proof	General fault-based liability (faute); professional guarantee funds	Personal liability for negligent administration	Negligence; breach of fiduciary duty; misfeasance proceedings
Criminal liability	Federal fraud statutes; misappropriation of estate assets	Sections 266, 283 StGB (embezzlement, bankruptcy offences)	Criminal Code provisions for professional misconduct; fraud	Penal Code provisions; theft; fraud	Fraud Act 2006; Insolvency Act 1986 offences
Insurance / bonding	Mandatory bond (Sec. 322) + professional liability insurance	Mandatory professional indemnity insurance	Mandatory insurance + professional guarantee fund	Insurance requirements set by Enforcement Authority	Mandatory professional indemnity insurance + bonding
Disciplinary sanctions	Removal by court or AG; suspension from panel	Court removal (Sec. 59 InsO); professional restrictions	Disciplinary chamber: warning to permanent ban	Removal by court; administrative sanctions	RPB sanctions: fines, conditions, licence withdrawal

Note. RPBs = recognized professional bodies; AG = Attorney General; JIEB = Joint Insolvency Examination Board; DOJ = Department of Justice.

The fourth model is the hybrid professional-judicial model that incorporates both the judicial supervision and formalized professional regulation. It is a solution that guarantees the external control, as well as the high qualification standards, which are manifested in the French system. The hybrid model is the most similar to the notion of multi-level governance as it is characterized by mixing judicial, administrative, and professional accountability mechanisms in a synchronized regulatory system. This model is not based on a single institution but is based on several actors that share supervisory power to achieve a balance between efficiency, flexibility and transparency (Fagetan 2025).

These models do not exclude each other; they are rather ideal types which can exist or even overlap in reality. Their identification offers an organized foundation to assess the efficiency of bankruptcy trustees' liability regimes and to construct integrated regulatory solutions. In theory, these models pose various institutional responses to the same governance problem- how to regulate the behavior of agents in the face of uncertainty and incomplete information (Tatham 2022). Both models emphasize the various mechanisms of control, either hierarchical (administrative), judicial or based on a network (self-regulation), which represent wider regulatory design options.

In order to go beyond descriptive comparison, the identified models can be assessed in terms of three functional criteria: (1) accountability (the possibility to identify and penalize misconduct), (2) efficiency (the possibility to provide timely and cost-effective processes) and (3) transparency (the level of openness and traceability of the actions taken by trustees). In this respect, the administrative oversight model displays a high degree of systemic responsibility and transparency as it is constantly supervised by specialized authorities, but also low in efficiency because of rigidity in procedures. The judicial control model guarantees effective legal accountability, especially on a case-by-case basis, but does not have monitoring mechanisms that can be sustained, which restricts its preventive ability. The models of professional self-regulation are rather efficient and

flexible, yet the issues of transparency and risks of regulatory capture are described. The hybrid model demonstrates the most balanced outcomes in all three criteria, but institutional complexity of this model can decrease the efficiency of operations. This analysis affirms that the effectiveness of bankruptcy trustees' liability regimes cannot be attributed to a single regulatory mechanism but to the interplay between several layers of accountability, and hence the importance of considering an integrated approach of governance (Gurrea-Martínez 2021).

Theoretically, the results show that a procedural or institutional approach to insolvency governance is not sufficient. Rather, the comparative analysis shows that bankruptcy trustee liability is a multi-dimensional governance tool which may be used to manage agency relationships in the context of complex legal and economic relationships. The distribution of monitoring powers varies significantly across different jurisdictions, according to their legal, institutional and regulatory frameworks. Thus, there is not necessarily a correlation between the strength of an institution, and a system of accountability being effective.

The comparative analysis also indicates that both regulatory models prove to have functional benefits as well as structural constraints. There is consistency and constant supervision with the administrative oversight model but there is bureaucratic inflexibility. The judicial control model offers good legal protection, but lacks the means of constant monitoring. Professional self-regulation model complements expertise and flexibility but creates conflicts of interest and lack of external accountability issues. The hybrid model is more balanced, as it integrates various mechanisms, however, complexities and coordination issues arise in institutions. Further conceptual generalisation of bankruptcy trustees' liability regimes can be based on these observations.

3.2 National Characteristics and Practices Regarding Liability Regulation

The purpose of such management is to accumulate, preserve, and, in some cases, possibly increase the debtor's property for future satisfaction of the claims of creditors to whom the debtor owes. The activities of the bankruptcy trustees are intermediary between the debtor and its creditors, are carried out on a professional basis (certain requirements are imposed for their implementation), and are based on the principles of independence, good faith, and legality. The emergence of an independent institution of administrative and legal regulation and control over the activities of bankruptcy trustees in the United States was marked by the Bankruptcy Reform Act, which transferred the responsibilities for the selection and certification of bankruptcy trustees, which had previously been carried out by the court, to a special executive body operating in different states. The aim was to remove from the courts a function that could affect their bias and shift part of the responsibility for the activities of the bankruptcy trustee to the court, which is an uncharacteristic function of the court (Tabb 2016).

In order to prevent such negative phenomena, it is required to develop a state control system over bankruptcy trustees' activities, who is the key actor in the system of legal relations in the field of bankruptcy. Furthermore, the liability of the bankruptcy trustee should be examined and monitored. The legal institution of state control over the activities of a bankruptcy trustee is important in the context of a long-term economic crisis when the social need to "reset" the economic system. It is considered more acute of effectively clearing economic relations from the burden of bad property liabilities (Kabenok 2021). In the field of insolvency and bankruptcy, the liability of bankruptcy trustees for the results of their professional activities is of particular importance. The reason for this is that bankruptcy trustees perform public legal functions related to the management and sale of assets of bankrupt companies to repay accounts payable. Not all bankruptcy trustees perform their duties in good faith when distributing the assets and money of debtors. These facts have led to numerous abuses in bankruptcy proceedings and have reduced the efficiency of bankruptcy procedures.

The study and improvement of the concept of control over the activities of the bankruptcy trustees should not be underestimated, as this allows for a broader and more complete foundation for new qualitative changes and innovations in the system of administrative and legal status of bankruptcy trustees. State control and supervision over the activities of bankruptcy trustees, as well as control and supervision in general, can be characterized as a managerial activity and as a legal phenomenon, since it is a matter of exercising the managerial functions of the state by delegating them to the relevant authorities, as well as a way of guaranteeing law and order and legality in public legal relations in the process of restoring the debtor's solvency or declaring it bankrupt.

The following methods of ensuring legality and discipline can be distinguished: control, supervision, and citizens' appeals. The above categories of ensuring legality should be viewed through the prism of control, administrative supervision, and citizens' appeals to state authorities with applications, proposals, and complaints on issues related to ensuring legality. Special legal means of ensuring legality are legal guarantees, control, supervision, coercion, appeal, encouragement, and liability (Danilov 2020). According to the last one, studying the liability of bankruptcy trustees in the US is crucial because of the complex legal system in the US and the experience

of implementing effective bankruptcy procedures that can be used as a template by other countries. This enables us to research and implement optimal methodologies to improve global benchmarks in this area.

The legislator realized that the administration of a bankruptcy case, including staffing, is an administrative function not inherent in the court, which led to such migration and crystallization of the administrative and legal institution. This opinion is fully consistent with the author's reasoning that neither the executive nor the judiciary should assume responsibility for the economic consequences of the bankruptcy trustees' work, but only control the compliance of the procedure of their activities with the legislation in the case (court) and control their activities in all cases, including complaints, compliance with qualification requirements, certification, etc. (executive branch).

The United States of America uses the institution of trust to regulate relations in insolvency cases, with the U.S. trustee being the key entity in this regard. This is a special body that administers bankruptcy cases and is part of the Department of Justice. It acts as a so-called 'bankruptcy overseer' and is designed to promote and ensure the integrity of the federal bankruptcy system on behalf of the US Attorney General. The Bureau of Federal Trustees is composed of federal bankruptcy trustees, who are employees of the federal government and are appointed by the U.S. Attorney General. Such features of the US legal system as multiple jurisdictions and a very strong judiciary have led to the emergence of a unique practice of resolving reorganization and bankruptcy cases, which is represented by the law is the Bankruptcy Code of 1979, which is included in Title 11 of the US Code of Federal Laws. As a rule, a federal bankruptcy trustee may be a lawyer who specializes in insolvency cases. The Office of the United States Trustee in Bankruptcy provides administrative oversight of the US federal bankruptcy trustees. As the court decides whether to remove a federal bankruptcy trustee from office on a case-by-case basis, the Bankruptcy Code does not contain a list of reasons for doing so. Nevertheless, the authors believe it is important to emphasize the very serious disciplinary liability that may be imposed on the federal bankruptcy trustees under the rules of their professional association (Warren and Westbrook 2014). According to Section 581, "any federal bankruptcy trustees may be removed from office by the Attorney General". Section 39 of the Judiciary and Court Procedure Act (Title 28 of the United States Code) is dedicated to federal bankruptcy trustees in the United States. In addition, each federal bankruptcy trustee is required to obtain general professional indemnity insurance and special indemnity insurance coverage for liability arising out of the administration of the debtor's bankruptcy estate.

The Attorney General has the right to review the official records, accounting, and acts of the federal bankruptcy trustees. Such oversight by the court and the US Attorney General of the operations of the federal bankruptcy trustees is a useful tool to prevent potential corruption in insolvency cases. Thus, overseeing the legitimacy of the liquidation or reorganization process is the primary responsibility of the US federal bankruptcy trustees. In addition to being covered by an insurance company, a US federal bankruptcy trustee must post a bond as collateral to ensure that the trustee will perform his/her duties in good faith. Although, in case of professional misconduct by bankruptcy trustees can have serious consequences due to the crucial role they play in the bankruptcy process. Any improper, dishonest, or illegal behavior or omission by a bankruptcy trustee to promote his or her interests or the interests of others at the expense of the debtor or creditors is considered an abuse of office.

Dishonesty is the failure to perform or obstruct the performance of the tasks assigned to the Bankruptcy trustee by the requirements of the law and bankruptcy data. A conflict of interest arises when the specific interests of the bankruptcy trustee or those with whom he/she is associated interfere with the fulfilment of his/her obligations regarding the distribution of assets or other components of the bankruptcy case. Any measures taken by the bankruptcy trustee that result in the misuse or illegal disposal of the debtor's assets are considered misuse of the debtor's assets. The following penalties may be imposed on bankruptcy trustees. He can be suspended from performing his duties in a particular bankruptcy case or even for a certain period. Financial sanctions may be imposed for violations of the rules and regulations related to his activities. In major cases, such as fraud or misappropriation of assets, criminal prosecution is pursued in accordance with the law (Finch 2017). These sanctions are aimed at protecting the interests of creditors and debtors in the bankruptcy process and ensuring compliance with strict ethical and professional standards. In addition, bankruptcy trustees may face legal consequences in both civil and criminal contexts.

In the United States, a bankruptcy trustee is required to post a bond in favor of the state, the amount of which is determined by the court, five days before being elected or officially taking office. Once his/her professional obligations are fulfilled, he/she can get his/her professional indemnity insurance bond. Regardless of the kind of wrongdoing, the bankruptcy trustee must be held civilly responsible for his/her actions without exception or limitation. However, the bankruptcy trustees do not have the resources necessary to compensate for their negligence adequately.

The two main pieces of legislation which regulate the liability of bankruptcy trustees within the EU are Regulation No 2015/848 (European Parliament and the Council 2015) and Directive 2019/1023/EU (European Parliament and the Council 2019). The Directive is essential to the development of regulations designed to guarantee a successful restructuring and bankruptcy process within the EU. This legal document outlines the responsibilities of bankruptcy trustees and emphasizes the critical role they play in restructuring. They might be in charge of managing the debtor's assets or carrying out the plan. He/she should perform his/her duties with diligence and professionalism. In an opposite case, he/she could be held legally responsible for any harm brought on by his/her carelessness or incapacity to do so (Keay and Walton 2017).

The framework of cross-border insolvency proceeding is formed by the insolvency regulation (EU) No 2015/848 that establishes the jurisdiction of bankruptcy trustees in relation to the international cases. It is possible for a bankruptcy judgment issued in one EU country to be accepted in the other one (European Parliament and the Council 2015). The legislation also delineates the coordination procedures between bankruptcy trustees of EU countries to promote a smooth and effective cooperative experience and a unified reaction to cross-border bankruptcy actions by sharing information, cooperation, and confirming the decision made by other bankruptcy trustees. Directive 2019/1023/EU and Regulation (EU) No. 2015/848 provide that the bankruptcy trustees shall be professionally, conscientiously and transparently acting in the interests of the debtor and creditors without conflict of interest (European Parliament and the Council 2015, 2019). If they neglect or break their duties, they are legally liable and obliged to compensate for the damage caused. Due to the differences in legal frameworks and economic situations, a study of bankruptcy trustees' liability in Germany, France, Sweden, and the UK is crucial to weigh the advantages and disadvantages of different restructuring and insolvency models (McCormack *et al.* 2017).

In contrast to the economic and legal approach used in the US, the concept of German bankruptcy law (Insolvenzordnung) as of 01.12.1999 has a clear pro-creditor orientation. The priority of this system is to safeguard the interests of creditors to the fullest extent possible. The material basis of the debtor's liability is its property, which must be preserved and maximized in the interests of all its creditors. In other words, the features of the pro-creditor model are the prevalence of the liquidation procedure over the rehabilitation procedure and the satisfaction of creditors' claims from the debtor's bankruptcy estate. The main reason is that the working capital of business entities in European countries was formed at the expense of debt obligations (commodity and financial lending). To protect investment projects, taking into account the public interest, the state authorities formulate bankruptcy legislation based on the need to provide, first and foremost, effective guarantees to creditors that stimulate the development of economic turnover in the country (Kristóf and Virág 2020).

Therefore, the debtor's inability to settle accounts with creditors is a consequence of its insolvency and the debtor's insufficient property to cover the amount of its creditor obligations. Accordingly, the first task of the bankruptcy trustee is to open bankruptcy proceedings and satisfy creditors' claims, rather than to take measures to restore the debtor's solvency. For example, the initiation of bankruptcy proceedings under German bankruptcy law generally means the removal of the debtor from management and disposal of property with the transfer of rights to the interim manager, and the transition to a rehabilitation procedure is possible only with the consent of the creditors. As in many other countries, Germany has special legal provisions governing the activities of bankruptcy trustees to protect them from liability for their professional conduct and to ensure the smooth operation of the bankruptcy and reorganization system.

The basic legislative act in the area of activity of bankruptcy trustees in Germany is called the Insolvency and Claims Act (Insolvenzordnung, or INSO). It also encompasses major rules of the duties, rights, and obligations of bankruptcy trustees, developed by the International Non-Governmental Security Organisation (INSO) (Paulus 2016). These involve the qualifications of bankruptcy trustees, the process of dismissing or replacing them and measures put in place to ensure impartiality and independence. They can be in charge of handling the asset of the debtor, creating a reorganizing or liquidation program, as well as settling debts with creditors. The INSO also provides mechanisms of holding bankruptcy trustees liable in their careless performance of their duties. Trustees in bankruptcy who breach or ignore their duties stand the risk of losing their ability to perform their duties and punishment. Criminal charges can be filed in certain circumstances. The court and the special insolvency agencies can oversee and regulate their actions. This includes evaluating their performance and, where required, assigning or removing staff. Furthermore, the legislative framework controlling the responsibility of bankruptcy trustees in Germany is meant to defend the interests of creditors, guaranteeing the proper and transparent administration of insolvency procedures as well as adherence to applicable professional and legal standards (Bork 2012).

Furthermore, bankruptcy trustees' actions in France are governed by laws that specify their responsibilities, rights, and duties. The Code de Procédure Civile and the Code of Commerce are the main legislation that rule the activities of French bankruptcy trustees. Thus, under French law, bankruptcy trustees are subject to a number of

duties. These duties include managing the debtor's assets, creating a plan for liquidation or reorganization, safeguarding the debtor's property, and other duties (Menjucq 2011). Their status is established and their professional affiliation is maintained by the legal framework that governs bankruptcy trustees in France. Their profession is considered a separate industry under the current labour laws. The French approach to bankruptcy administration mechanisms has come under scrutiny due to the appointment of a bankruptcy trustee during rehabilitation procedures, a liquidator during liquidation procedures, and a bankruptcy trustee designated after bankruptcy proceedings began.

Bankruptcy trustees are overseen by the French judiciary and the special bodies that handle insolvency. They are charged with the responsibility of overseeing and, in an appropriate case, intervening in cases of any malpractice by bankruptcy trustees. The French judicial system and special insolvency authorities closely supervise them. An example of this is the *Affaire Bernard Tapie* case whereby the court conducted an extensive investigation and then did what was required after it discovered a potential conflict of interest in the affairs of the bankruptcy trustee. The court imposed financial fines on him in the *Affaire France Telecom* case. Consequently, the trustee was not allowed to participate in the process anymore. The sphere is marked by rigid control that ensures that bankruptcy trustees within the framework of the law observe the law and research any potential breaches to the full extent. If any violations occur, they might not be able to carry out their responsibilities and could be subject to fines or even legal action.

It is the responsibility of the Swedish Insolvency Authority to function under the joint legal jurisdiction of the Ministry of Justice and the Ministry of Finance. The aforementioned authority is to be regarded as a unified system with the tax and enforcement authorities. This organization is responsible for the oversight and administration of bankruptcy procedures, with offices strategically located in all provinces nationwide. The following powers are attributed to it:

- to develop and control the implementation of state policy on bankruptcy;
- to advise courts dealing;
- to train, license and advise bankruptcy trustees;
- to advise creditors;
- to control the level of remuneration of bankruptcy trustees, additional payment for the services of these specialists in case of lack of resources of the debtor company;
- to monitor the observance of the interests of secured creditors;
- to publish information on the recognition of companies as bankrupt.

Special legal regulations apply to the activities of bankruptcy trustees in Sweden to ensure their liability for professional actions in insolvency cases. The primary laws that govern the operations of bankruptcy trustees in Sweden are the Bankruptcy Act and the Companies in Bankruptcy Act. The law and the highest professional ethical standards require bankruptcy trustees to fulfil their responsibilities. They can be held accountable if they fulfil their duties inappropriately, for example by misusing their position or mishandling the debtor's assets. In Sweden, bankruptcy trustees who violate the law risk severe repercussions, including being barred from carrying out their responsibilities, being fined, and, in the most extreme cases, facing legal action. For example, the court decided that the bankruptcy trustee could not work as one and also made him pay money in the *Hemfosa* case. This was after he was accused of money fraud and not looking after company property (Voda *et al.* 2021).

The oversight of bankruptcy proceedings and the supervision of bankruptcy trustees is the responsibility of judges and special commissions. In an effort to ensure that both ethical and legal standards are being met, the aforementioned bodies take action in this regard. Within the jurisdiction of Sweden, the judiciary, in conjunction with specially appointed committees, maintains rigorous oversight of bankruptcy trustees. For instance, the Swedish Enforcement Authority exercises oversight with regard to the actions of bankruptcy trustees. In instances of insolvency, audits and inspections are conducted to ensure that moral standards and legal requirements are being met. Following allegations of theft, the Swedish Enforcement Authority conducted a thorough investigation and penalized a bankruptcy trustee. This scrutiny contributes to the public's faith in bankruptcy trustees and the high professional standards that exist inside the Swedish bankruptcy system (Epaulard and Zapha 2022).

Criminal proceedings were initiated in the *Göta* case after the bankruptcy trustee was accused of wrongdoing and misusing private information. As a consequence, he was prohibited from undertaking the work in the future. This strict policy against misbehaviour ensures that bankruptcy trustees in Sweden behave in a way that complies with the law and ethical norms. Protecting creditors' interests, maintaining the stability of the financial system, and ensuring the effectiveness and integrity of bankruptcy trustees are the main objectives of the Swedish legal system, which regulates their accountability.

Based on the idea of self-regulation, the Institute of Insolvency Practitioners (IIP) is a UK-based organization. The interests of the stakeholders, which could include the debtor or their creditors, are represented by bankruptcy trustees, who are hired under contract. Moreover, in situations when the business cannot afford the costs of legal counsel or the costs of court proceedings, the court has the power to order the appointment of a bankruptcy trustee. The authority to supervise insolvency procedures is granted to the Insolvency Service, a government agency having operations in the UK. The Department for Business, Energy, and Industrial Strategy of the UK government oversees the Insolvency Service, an executive agency. To perform its duties, the Service engages bankruptcy trustees, including those appointed by the court, who have the status of public servants. The legislative basis for their activities in England and Wales is provided by the Companies Act 1985, the Company Directors Disqualification Act 1986, and the Insolvency Act 1986, which also defines the liability of practitioners for breach of duty. In the event of improper performance of duties, in particular mismanagement of the debtor's assets or creation of a conflict of interest, legal liability arises. The British insolvency system is characterized by a high level of accountability to the parties to the proceedings and to society, as the actions of bankruptcy trustees have a significant impact on the outcome of proceedings for creditors and debtors (Ayotte and Elias 2022).

In this regard, in the case of Carillion, the bankruptcy trustees were accused of negligent asset management, which caused losses to creditors and employees. As a result, the court-imposed fines and restricted their further work. Moreover, in the Patisserie Valerie case, the court intervened owing to a conflict of interest on the part of the bankruptcy trustees. In the UK, the Insolvency Service supervised the activities of the trustees due to possible conflicts of interest and doubts about the effectiveness of management in the case of Steel. These examples confirm the need for strict compliance with the rules by bankruptcy trustees and the key role of supervisory authorities in building trust in the insolvency system and maintaining high professional standards (Melcarne and Ramello 2020).

3.3 Hybrid Accountability Framework for Bankruptcy Trustees

The suggested hybrid accountability framework is a practical application of the theoretical concepts of the principal-agent theory and multi-level government. The basic intention from the principal-agent point of view is to alleviate the information gap, issues of conflict of interest and opportunistic behavior through the use of overlapping instruments of supervision, liability, and transparency. At the same time, the framework is based on the principle of multi-level governance and decentralizes regulatory responsibility between different institutional, judicial, professional, financial and technological levels. The concept of accountability, in this sense, is not a legal measure, but, rather, an integrated governance process in which a number of actors and control mechanisms are interacting.

Following the comparative analysis, it is appropriate to propose an integrated model of accountability for bankruptcy trustees, which combines the most effective elements of various legal systems. This model is based on the idea that no single system (state, judicial or self-regulatory) provides a sufficient level of accountability, and therefore a combination of these is optimal (Figure 1).

Figure 1. Hybrid accountability framework for bankruptcy trustees



Source: developed by the authors

The proposed framework provides for a multi-tiered accountability system comprising five interrelated components. The initial element is institutional control. It establishes the presence of a specialized state supervisory body which constantly oversees the work of bankruptcy trustees, holds inspections and analyses complaints as well as having the authority to impose penalties. This aspect is a hybrid of the American and Swedish models and is geared towards providing some degree of systematic control, as opposed to reacting to violations. The second element is judicial checks and balances. The court is the ultimate enforcer of legality of a particular bankruptcy case. It appoints, replaces and removes bankruptcy trustees and evaluates the legality of their behavior. Such control guarantees individualized control, and is typical of civil law systems, especially those of Germany and France. Professional self-regulation is the third constituent. This is in the form of the functioning of professional bodies that establish ethics, conduct disciplinary action, and offer professional development. This model is grounded in the British one and assists in development of the professional culture and personal responsibility. The fourth element is the financial liability mechanisms. This is mandatory professional indemnity insurance, guarantee funds, and other financial instruments which can guarantee effective compensation to the creditors or debtors in the event of unlawful actions. This factor is critical to the real-world performance of the whole system. The fifth element is online accountability and technological accountability. It implies the application of the latest technologies, such as electronic registers, computerized auditing, and, possibly, blockchain systems of tracking asset transactions. This helps to minimize abuse and boost confidence in bankruptcy procedures.

The proposed model functions as a system of checks and balances, in which each component compensates for the weaknesses of the others. State oversight ensures systematic control, the judicial system ensures individual justice, self-regulation ensures professional ethics, financial mechanisms ensure real accountability, and digital tools ensure transparency and the prevention of violations. This establishes the fact that the bankruptcy trustees' liability is not to be conceptualized as a fixed legal institution, but rather as a system of governance whereby various actors of regulation are involved. This comprehension is connected to the multi-level governance theory where power is shared and spread across various levels instead of being centralized within one institution (Schakel *et al.* 2015).

4. Discussions

The findings of this study show that the liability of bankruptcy trustees cannot effectively be dealt with in one regulatory framework that justifies the suppositions of both the principal-agent theory and the multi-level governance. Specifically, the fact that several principals are involved and the interests may conflict makes it necessary to use overlapping accountability mechanisms that cut across institutional levels (Tirole 2019). This supports the main theoretical hypothesis that insolvency governance is a multi-principal system in which the conflicting interests of creditors, debtors, courts and the general populace require a multi-layered and multi-balanced structure of accountability.

These results could be further explained in the framework of multi-level governance, in which the liability of bankruptcy trustee is not determined by one institutional level but is created as a result of several layers of regulations interacting with each other. Accountability, in this sense, should be viewed as a system property, not as a mechanism role, which supports the thesis that the efficient governing of insolvency needs to be a coordinated and overlapping form of control.

In further analysis of these models, it is noted that they have trade-offs, inherent in their institutional design. Administrative oversight model provides a high degree of systemic consistency and ongoing monitoring by means of participation of specialized public authorities. It is strong in its ability to prevent misconduct in advance and to unify the practice of regulation across cases. Meanwhile, such a model is likely to become bureaucratized, less flexible, and be susceptible to over-centralization, potentially restricting its responsiveness to case-sensitive and complex situations. Judicial control, in contrast, gives good procedural protection and legal responsibility by adjudicating cases on a case-by-case basis. Judiciary is very significant in ensuring justice and legitimacy, especially when it comes to bankruptcy trustees. Nevertheless, the fact that the model is based on reactive enforcement restricts its potential in ensuring sustained supervision, and the dispersal of oversight and differences in judicial expertise can decrease the overall effectiveness of the regulations.

Professional self-regulation model encourages high expertise, ethical standard-setting, and flexibility by involving professional bodies. Such a strategy is more flexible and less of a burden on state administration. However, it also brings up the issue of regulatory capture, conflict of interest, and lack of external control especially when the regulatory mechanisms are poorly developed or underdeveloped. The hybrid model of a professional and judicial is aimed at resolving these tensions and proposing judicial control and professional control in a structured form. Its main strength is that it provides several accountability systems, which can be controlled externally and

professionally internally (Los 2025). Such complexity, though, can create coordination problems, overlapping competences, and higher administrative costs, and overall effectiveness will be determined by how well institutional roles are defined and inter-agency cooperation is effective. These results indicate that no single model can be used to fully deal with the multidimensionality of bankruptcy trustees' liability. Both methods represent a trade-off between conflicting goals of regulation, such as efficiency, accountability, flexibility, and transparency. This supports the fact that a more integrated and adaptive approach to insolvency governance is required (Punda and Arziantseva 2023).

To address such structural constraints, the proposed hybrid accountability framework is an attempt to combine the main aspects of each model into a consistent model of governance. What added value to it is that it is not just the combination of regulatory mechanisms, but also the reinvention of accountability as a dynamic and interactive process as opposed to a fixed legal obligation. In this regard, the framework is consistent with the modern theory of regulation, which focuses on multi-level governance, regulation through networks, and the interplay of formal and informal systems of enforcement.

This approach also has certain policy implications that are especially pertinent to jurisdictions that are being reformed in law. To begin with, the creation or reinforcement of a specialized insolvency oversight institution can play a crucial role in improving systemic surveillance and minimizing the likelihood of wrongdoing (Tatham 2022). Nonetheless, there must be procedural checks and balances to such institutionalization to guard against over-centralization and promote transparency. Second, the court should be maintained as providing a foundation of legal accountability, especially with regards to appointment, removal and dispute resolution of bankruptcy trustees. Third, it is advisable to promote the emergence of professional self-regulatory organizations, but with effective external control to reduce the risks of corporatism and conflict of interests.

The use of financial liability mechanisms, such as mandatory professional indemnity insurance and guarantee funds is a major component of the proposed framework. These tools are critical in making sure that compensation is effective and the trust between stakeholders is improved (Qi and Yuan 2023). In addition, the introduction of digital technologies, such as electronic case management systems, automated auditing tools, and distributed ledger technologies have an enormous potential of improving transparency, traceability, and effectiveness in the insolvency proceedings. Even though the introduction of such technologies raises questions about the protection of data and the ability of regulatory capacity, the benefits of such technologies in the long-term render the usage of such technologies worth considering. Interestingly, as the digital tools are implemented, the definition of accountability changes to ex post enforcement to ex ante monitoring. Automated auditing systems and distributed ledgers are the technologies that can allow tracking trustee activities on a regular basis to minimize the information asymmetry and restrict the possibility of wrongful acts. This changes the regulatory paradigm to preventive control as opposed to the reactive control and enhances transparency and institutional trust (Butler *et al.* 2023).

Recent technological advances, including blockchain and AI, have great potential to increase transparency and improve the handling of insolvency procedures. The application of artificial intelligence algorithms will enable bankruptcy trustees to react to insolvency cases more promptly. The automated financial statement analysis capability allows detecting risks and vulnerabilities to creditors in real time. Another way that blockchain technology could be used is the development of a reliable and secure asset-registering and tracking system in the process of bankruptcy. The very feature of blockchain technology that makes the data unchangeable makes it an ideal solution to the asset and distribution tracking in the context of a bankruptcy procedure. The use of blockchain technology for the storage of unique documents and transactions facilitates the resolution of disputes during the bankruptcy process and instils a greater sense of confidence in the data among the relevant parties. By implementing these measures, financial stability will be restored, and participant rights will be protected, thereby enhancing the reliability, transparency and efficiency of the bankruptcy process (Panchenko 2021).

Regarding European legal integration, the suggested framework can be aligned to the goals and values of EU insolvency law. Specifically, the Directive (EU) 2019/1023 underlines the competence, independence, and accountability of trustees in preventive restructuring and insolvency practices (European Parliament and the Council 2019). Likewise, the Regulation (EU) 2015/848 offers the framework of cross-border cooperation and coordination, which indirectly strengthens the necessity of the reliable and responsible bankruptcy trustees (European Parliament and the Council 2015). Nonetheless, the two tools give a lot of discretion to the Member States in the development of specific liability regimes, which leads to further fragmentation at the national level.

The hybrid accountability framework can be used in this regard as a conceptual framework to enhance convergence without necessarily harmonizing. The framework enables the national reforms to be compatible with the wider European standards without removing institutional diversity by identifying the core accountability elements that are functionally similar across various legal regimes. In the case of Ukraine that is seeking closer integration

into the European legal space, this would be a viable route towards modernization of the insolvency laws in accordance with the EU principles and international best practices. Meanwhile, it is necessary to note the shortcomings of the suggested framework. It involves a lot of institutional capacity, coordination of various regulatory actors and provision of financial and technological resources. In addition, the model is subject to the larger legal culture and enforcement practices, which can be significantly different across jurisdictions. The next wave of studies should thus be aimed at empirical evaluation of accountability mechanisms, their effect on insolvency outcomes, satisfaction of stakeholders and economic efficiency.

Overall, the study would be included within the debate on insolvency governance existing today since it is not only disruptive of the descriptive analogy but also constitutes a conceptualization of the idea of practitioner liability. It provides a theoretical foundation and practical suggestions on how more resilient and transparent insolvency systems might be created through a combination of typological analysis and a multi-level accountability framework. Policies wise, the proposed structure offers a framework that can be adapted to different legal frameworks according to their institutional capabilities and regulatory practices. Rather than outlining harmonization, it permits selective introduction of accountability mechanisms and, as such, is particularly suitable in jurisdictions that undergo legal reform and desire to coordinate with international norms without compromising the flexibility of the system. In general, the research moves toward the theoretical evolution of the insolvency law by reconceptualizing the trustee liability as a process of dynamic governance and not rules of law. This method focuses on interaction, adaptation and institutional balance as some of the most effective regulative factors in a complex legal system.

Conclusions and Further Research

This paper proves that the responsibility of the bankruptcy trustees is not capable of being practically secured within the boundaries of one regulatory model because both of the existing models of administrative, judicial, professionals' self-regulation, and hybrid are characterized by the functional and structural weaknesses. The comparative analysis proves that accountability in insolvency systems is best seen as a multi-level and dynamic process, which are created as a result of interaction among institutional supervision, judicial restraint, professional norms, financial liability procedures, and technological tools.

To address the findings, the article forms a hybrid accountability framework that incorporates the best practices in the various models of regulation in a consistent system of governance. A functional typology of liability regimes and analytical analysis in terms of the accountability, effectiveness, and transparency criteria substantiate the stated idea that balanced and coordinated regulatory frameworks are the most sustainable ones. This model is further reinforced by the inclusion of digital monitoring tools that shift responsibility to proactive enforcement to preventive and ongoing monitoring. The study also establishes that the principal-agent theory and multi-level governance prove to be a suitable analytical framework for understanding insolvency practitioner liability as an embedded system of accountability, rather than a stand-alone procedure.

The practical applicability of the framework to the legal reform, especially to harmonization of the national insolvency rules with the international ones (like EU Directive 2019/1023) is also mentioned in the study. The proposed model does not imply homogenization. So, it is important to adapt it flexibly to national institutional settings, which is particularly useful in Ukraine. In general, the results can be applied to the development of the theory of insolvency governance by providing a multi-level view of trustee liability and provide a policy-focused basis to create more transparent, accountable, and robust insolvency regimes.

Declarations

Credit Authorship Contribution Statement:

Serhii G. Boiarchukov: Software, Formal analysis, Writing – original draft, Visualization;

Oleksandr L. Zinevysh: Conceptualization, Methodology, Project administration, Data curation;

Maryna O. Dei: Investigation, Formal analysis, Supervision, Writing – review and editing;

Herasym Dei: Investigation, Resources, Formal analysis, Funding acquisition;

Kyrylo Anisimov: Conceptualization, Formal analysis, Data curation, Validation.

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Declaration of Use of Generative AI and AI-assisted Technologies: The authors declare that they have not used generative AI and AI-assisted technologies during the preparation of this work.

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Explaining External Competitiveness and Trade Capacity in Developing Economies: A Panel Data Analysis



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Abstract: Competitiveness and trade capacity are critical determinants of sustainable growth in developing economies, particularly in an increasingly globalized and knowledge-based economic environment. While trade openness expands access to international markets, long-term competitiveness depends on a country's ability to innovate, share knowledge, and adopt new technologies. This study empirically examines the relationship between innovation-related factors and external competitiveness, using high-technology exports as a proxy for trade capacity and competitive performance. The analysis is based on panel data from 33 developing countries over the period 2010–2021 and employs a fixed-effects regression model to assess the association between university–industry collaboration, research and development (R&D) intensity, human capital, and information and communication technology (ICT) adoption, and high-tech export performance. The findings indicate that innovation systems are closely associated with external competitiveness. University–industry collaboration shows the strongest and most robust positive association with competitiveness, followed by R&D intensity and ICT adoption. In contrast, human capital does not exhibit a statistically significant direct association, suggesting that its contribution to trade capacity may operate indirectly through innovation processes and absorptive capacity. Overall, the results highlight the importance of integrated innovation systems and institutional coordination in supporting technological export performance and facilitating participation in global trade networks. Policies supporting innovation, digitalization, and university–industry collaboration are closely associated with improvements in technological capabilities and broader socio-economic development.

Keywords: External competitiveness; university–industry collaboration; developing economies; human capital; innovation systems; research and development; trade capacity.

JEL Classification: O11; O32; O33; F14; C23.

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Introduction

In the last few decades economies have changed their structures due to big changes in networking, interconnection and globalization. The integrated markets of goods and factors have made different countries more dependent on each other. Economies face more competition while globalization also brings the exchange of new ideas, physical and human capital. Under these conditions, economies are encouraged to specialize, improve resource efficiency, and enhance the quality and competitiveness of their products. The need to integrate, as an important factor of the socio-economic system's success, is a challenge and a risk. International openness makes competition tougher and highlights more the difference between countries with different levels of development. Compared to each other, developing economies have structural problems that make it harder for them to fully benefit from international openness (Stiglitz and Rodrik 2025). Moving towards a knowledge-based economy is more difficult in cases where

there are unskilled workers for research and development, infrastructure for innovation and research is lacking, public institutions are weak, and intersectoral and university-industry collaboration is lacking (World Bank. 2020. *World Development Report 2020: Trading for Development in the Age of Global Value Chains*, Lema *et al.* 2021). The limited rate of endogenous innovation and reliance on imported technologies diminish competitive capacity in global markets (Cirera and Maloney 2017). Empirical evidence also confirms that sustainable competitiveness in global markets requires local knowledge creation and innovation capacity, rather than mere participation in global value chains (Lee *et al.* 2017). In this context, several forms of university-industry collaboration, such as joint innovation projects, internship programs, the creation of university spin-offs, and technology transfer, may support the development of innovation capacity. These forms of collaboration can generate mutual benefits. Universities can apply research outcomes in real-world contexts, enhancing their societal and economic relevance, while firms gain access to new knowledge, technologies, and opportunities for workforce training. U-I cooperation may therefore contribute to increased innovation capacity and a stronger competitive position in global markets. It is essential to establish collaborative frameworks among universities, businesses, and the government like the Triple Helix model, to cultivate innovative and competitive skills (Zhou and Etzkowitz 2021; Carayannis *et al.* 2012). The ability of national innovation systems to create effective collaborative networks and to absorb, modify, and enhance new knowledge has become essential for the transformation of globalization processes into lasting economic and social benefits (Freeman 2008, Archibugi *et al.* 2020). This shows how important it is to have rules that make it easier for universities and businesses to work together. These rules are necessary for improving external competitiveness and making it easier for businesses to enter international trade. The goal of this paper is to critically examine how university-industry collaboration can help developing economies become more competitive and better at trading with other countries. In this line, research should be conducted to identify the main factors that influence how much and in what ways U-I helps developing economies become more competitive in trade. A decisive role in this framework is also played by the appropriate policies and tools in place to encourage businesses and universities to work together, build networks and conduct research and development. These steps have effects on the economy and trade. The study combines a literature review with a statistical analysis of indicators. After the introduction, the paper continues with a literature review in section 2, a description of the methodology and data in section 3, empirical analyses and results in section 4, conclusions and policy implications in section 5.

1. Literature Review

International competitiveness is the ability of a country, sector or firm to make goods and services that meet global market standards while keeping or growing its market share and making sure that the economy stays healthy in the long run (Porter 1990). International competitiveness emerges from the dynamic interplay among innovation, institutions, and global integration (Schwab and Zahidi 2020). Countries that engage in knowledge-sharing networks and systems of collaboration and exchange, especially in university-industry collaborations, help the economy improve exports and become more involved in global markets in the long term. In the knowledge-based economy, competitiveness is no longer based only on having lower costs or more natural resources but on innovation, developing technology, and having efficient institutions (OECD/Asian Productivity Organization. 2022. *Identifying the Main Drivers of Productivity Growth: A Literature Review*). Efficient use of resources and knowledge adds value to the final product and increases exports. Countries can use their comparative advantages, increase the size of their production, and join global value chains through trade (World Bank. 2020. *World Development Report 2020: Trading for Development in the Age of Global Value Chains*). Integration into global markets helps small and developing economies boost their productivity, spread new technologies, and change how they work (UNCTAD. 2022. *Trade and Development Report 2022: Development Prospects in a Fractured World*). Furthermore, exposure to global competition promotes innovation, efficiency, and managerial enhancement, which are crucial factors for enhancing competitiveness (Aiginger and Vogel 2015). Economic, institutional, and technological factors all play a role in how well a country can compete on the world stage. More recent contributions also highlight the role of digital trade and innovation in supporting inclusive economic growth and competitiveness across countries (Yeerken and Feng 2024). First, basic factor conditions, like good infrastructure, a skilled workforce, and access to money, are what make an economy competitive (Porter 1998). The transition toward a knowledge-based economy and to help economic growth requires investment in education, innovation, and ICT infrastructure (Chen and Dahlman 2005). Recent empirical studies also confirm the growing importance of digitalization and knowledge-based capabilities for export competitiveness in developing economies (Handoyo *et al.* 2025; Doan and Luong 2025). Good governance and high-quality institutions, such as stable rules, protection of intellectual property, and public policies that help businesses, also make it easier for productivity to grow and for businesses to get ahead of their competitors (IMD. 2022. *IMD World Competitiveness Booklet 2022*). Zhao *et al.*

(2018) demonstrate that investments in human capital, especially in sales personnel, exert a substantial and favorable influence on export performance, particularly within technology-intensive and R&D-oriented enterprises. On the other hand, collaborative mechanisms such as university–industry (U–I) collaboration are essential for accelerating knowledge transfer and promoting innovation co-creation, thereby augmenting the competitive capacity of developing economies (Zhou and Etzkowitz 2021; Ankrah and Al-Tabbaa 2015).

International trade and competition are good for the economy and long-term growth. Countries can use their comparative advantages to make better products and increase production when trade is open. This helps the country be more productive (Sowrov 2024; Ijirshar 2022). Also, being involved in international markets helps the spread of technology and the gaining of new knowledge, which speeds up the modernization of production processes and structures (UNCTAD. 2022. *Trade and Development Report 2022: Development Prospects in a Fractured World*). To be competitive, the economies should improve their technological and productive advantages in global markets. The highest levels of international competitiveness are linked to innovation, human capital, and institutional quality, which help attract foreign direct investment and boost value-added exports (Barbary and Tawfiq 2024; Kordalska and Olczyk 2016). Trade and competition help to diversify export products and markets, spread new technologies and management methods, encourage innovation and productivity growth, and improve human capital through training programs and knowledge transfer (OECD/Asian Productivity Organization. 2022. *Identifying the Main Drivers of Productivity Growth: A Literature Review*). Joining global value chains gives high-value sectors access to new markets and makes it easier for the country to sell goods abroad. This shows how important it is to link trade to competitiveness for long-term economic growth (Sowrov 2024; Ijirshar 2022).

1.1. Types of University–Industry Collaboration and Their Effects on Trade and Competitiveness

Different types of university–industry collaboration help countries compete in different but complementary ways. Joint research and development (R&D) projects allow companies to use scientific knowledge and cutting-edge technologies, which leads to new products and better technology that help exports (Perkmann *et al.* 2013; Bellucci *et al.* 2023). Collaborative R&D makes it easier for companies, especially small and medium-sized businesses (SMEs), to meet international standards and enter new markets by lowering the costs and risks of innovation. Technology transfer activities that help make academic knowledge available for business use include patent licensing, contract research, and consulting agreements. This results in the development of high-value products that have an increased likelihood of being marketed internationally (Rossi *et al.* 2022). The creation of academic spin-offs and start-ups associated with universities also helps to diversify export structures by bringing in new technologies and knowledge-based services (Guerrero and Urbano 2019; Martínez-Ardila *et al.* 2023). Mobility programs and training partnerships also help companies absorb new information by improving their employees' skills and making sure that academic programs meet the needs of the job market. Industries improve their competitive position if the workforce improves in quality. The latter also increases the chances for innovation. But human capital is improved not only through training and education but also through exchange and mobility, helping to absorb new work models. Studies have shown that countries with institutionalized U–I collaboration frameworks tend to have more advanced exports, faster integration into global value chains, and steady growth in technology-driven sectors (OECD/Asian Productivity Organization. 2022. *Identifying the Main Drivers of Productivity Growth: A Literature Review*; Schwab and Zahidi 2020). As a result, the different ways that universities and businesses can work together act as catalysts that link the knowledge base of universities with the skills that businesses need to succeed in the market. This gives businesses an edge in international trade and makes them more competitive. These kinds of partnerships help businesses compete better in international markets by giving them the chance to come up with new ideas, follow international standards, and connect with global knowledge networks [14]. For developing economies, there are ways to make industries in the global value chain better by moving from making things that don't add much value to doing things that need more knowledge.

2. Method

This study combines a literature review with an empirical panel data analysis to examine the relationship between innovation-related factors and external competitiveness in developing economies. The empirical component is based on a country-level panel dataset covering 33 developing economies over the period 2010–2021. The analysis focuses on the association between university–industry collaboration, research and development (R&D) intensity, human capital, and information and communication technology (ICT) adoption, and their relationship with high-technology export performance as an indicator of external competitiveness.

2.1 Data Description

The empirical analysis uses an unbalanced panel dataset of 33 developing economies observed annually from 2010 to 2021. All variables are organized in a country–year format. The dependent variable is high-technology exports, used as a proxy for external competitiveness and trade capacity in technology-intensive sectors. The explanatory variables include university–industry collaboration (UIC), research and development (R&D) expenditure as a percentage of GDP, human capital proxied by tertiary education participation, and ICT adoption rates. All data were obtained from internationally comparable sources, primarily the World Bank databases.

Table 1. Variables and Data Sources

Variable	Symbol	Source
High-Technology Exports (Dependent Variable)	Competitiveness	World Bank
University–Industry Collaboration Index	UIC	World Bank
Expenditure in research and development % GDP	Innovation	World Bank
Human Capital, proxied by tertiary education rates	HC	World Bank
Information and Communication Technology adoption rates	ICT	World Bank

Source: (Author's compilation)

To ensure comparability across variables measured in different units and scales, all variables were normalized prior to estimation. Specifically, a min–max normalization approach was applied, transforming each variable according to the following expression:

$$X_{it}^* = \frac{X_{it} - \min(X)}{\max(X) - \min(X)}$$

where X_{it} denotes the original value of variable X for country i in year t , and $\min(X)$ and $\max(X)$ represent the minimum and maximum values observed in the sample. This transformation rescales all variables to the $[0, 1]$ interval while preserving relative differences across observations.

High-technology exports are used as an operational indicator of external competitiveness because they reflect the ability of an economy to produce and commercialize technologically sophisticated goods in international markets. While this measure does not capture all dimensions of competitiveness, it provides a focused proxy for technology-based trade performance, which is particularly relevant in the context of innovation-driven growth.

The empirical specification focuses on domestic innovation-related factors influencing competitiveness, rather than directly including trade policy or external demand variables. This allows for a more targeted examination of internal drivers of technological export performance. Descriptive analysis shows that there are some differences across countries. UIC ranges from around 1.7 to 4.5, and the average competitiveness index ranges from 14 to 28. The correlation matrix in table 2 shows that UIC ($r = 0.58$) and Innovation ($r = 0.60$) are the two elements most closely related to Competitiveness. This suggests that collaborative innovation mechanisms are closely associated with differences in competitiveness across countries. ICT ($r = 0.33$) and Human Capital ($r = 0.06$) show weaker, positive, correlations.

Table 2. Coefficients (Pearson correlations)

Variable	Competitiveness	UIC	Innovation	HC	ICT
Competitiveness	1.000	0.581	0.602	0.061	0.330
UIC	0.581	1.000	0.439	0.071	0.300
Innovation	0.602	0.439	1.000	0.217	0.418
HC	0.061	0.071	0.217	1.000	0.403
ICT	0.330	0.300	0.418	0.403	1.000

Source: Author's compilation using Python (2025)

All coefficients are Pearson correlations derived from panel data (2010–2021, N = 396).

3. Research Results

The empirical analysis is conducted using a country fixed-effects panel model estimated through Ordinary Least Squares (OLS) with heteroskedasticity-robust standard errors (HC3). The fixed-effects approach controls for time-invariant country-specific characteristics, such as geography, historical institutional structures, or long-term development patterns, that may influence competitiveness but are not directly observable. As a result, the estimates capture within-country associations over time between changes in innovation-related variables and changes in high-technology export performance.

The model is specified as:

$$\text{Competitiveness}_{it} = \alpha_i + \beta_1 \text{UIC}_{it} + \beta_2 \text{Innovation}_{it} + \beta_3 \text{HC}_{it} + \beta_4 \text{ICT}_{it} + \varepsilon_{it}$$

where i indexes countries and t indexes years, α_i represents country-specific fixed effects, and ε_{it} is the idiosyncratic error term.

Because the analysis is observational and the specification does not fully address potential endogeneity or reverse causality, the estimated coefficients should be interpreted as conditional associations rather than causal effects.

Table 3. Fixed-Effects OLS Regression Results (Model without Trade)

Variable	Coefficient	Std. Error	z-Statistic	p-Value	Significance
Intercept	15.907	0.272	58.39	0.000	***
UIC (β_1)	0.240	0.062	3.85	0.000	***
Innovation (β_2)	0.199	0.080	2.49	0.013	**
Human Capital (β_3)	0.029	0.126	0.23	0.821	ns
ICT (β_4)	0.151	0.052	2.88	0.004	***

Source: Author's compilation using Python, (2025)

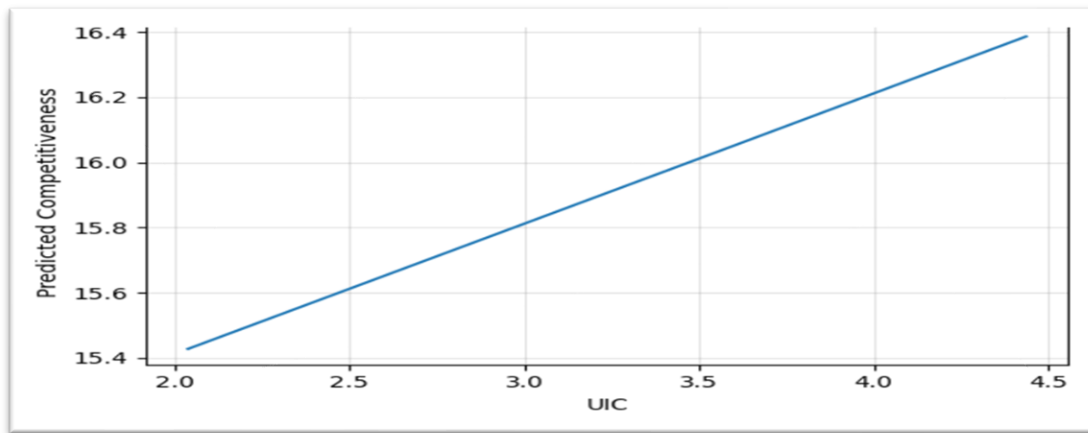
The estimation results are presented in Table 3. The model explains a substantial share of the within-sample variation in competitiveness ($R^2 = 0.984$). While this indicates a strong in-sample fit, it should be interpreted with caution given the use of fixed effects and normalized panel data. University–industry collaboration (UIC) is positively and statistically significantly associated with competitiveness ($\beta_1 = 0.240$, $p < 0.001$). This is the largest coefficient among the explanatory variables, suggesting that stronger collaborative linkages between academia and industry are closely related to higher levels of high-technology export performance within countries over time. R&D intensity also shows a positive and statistically significant association ($\beta_2 = 0.199$, $p = 0.013$), indicating that higher levels of investment in research and development are correlated with stronger technological export capacity. ICT adoption is likewise positively associated with competitiveness ($\beta_4 = 0.151$, $p = 0.004$), supporting the view that digital infrastructure plays an enabling role in innovation diffusion and participation in technology-intensive trade. By contrast, human capital does not exhibit a statistically significant coefficient in the baseline specification ($\beta_3 = 0.029$, $p = 0.821$). This result does not imply that human capital is unimportant; rather, it suggests that its contribution to competitiveness may operate indirectly through complementarities with innovation systems, absorptive capacity, or institutional mechanisms. Overall, the findings are consistent with the interpretation that innovation-related factors are closely associated with differences in technological export performance across countries, although these relationships should not be interpreted as causal.

These findings are broadly consistent with the existing literature, which emphasizes the role of collaborative innovation systems and technological infrastructure in shaping export performance and productivity growth [8], [2]. In particular, the results support the view that interaction between knowledge-producing institutions and firms is a key mechanism through which innovation is translated into market outcomes. The absence of a statistically significant coefficient for human capital may reflect structural factors such as delays in education systems or mismatches between acquired skills and labor market needs, suggesting that its contribution to competitiveness may operate indirectly rather than through a direct channel.

The marginal effects plots provide additional insight into the relationships identified in the regression model. Figure 1 illustrates the marginal association between university–industry collaboration and predicted competitiveness, showing a clear positive relationship. This pattern indicates that higher levels of UIC are associated with higher

predicted values of high-technology export performance, holding other variables constant. This finding is consistent with theoretical perspectives emphasizing that collaborative innovation systems facilitate knowledge diffusion and enhance absorptive capacity (Ankrah and Al-Tabbaa 2015; Granstrand and Holgersson 2020).

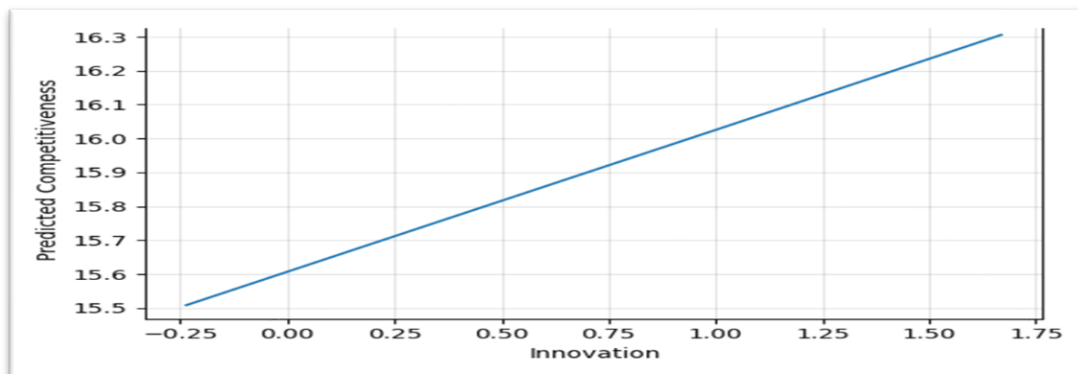
Figure 1. Marginal effect of UIC on competitiveness.



Source: Python-generated figure, author's calculations, (2025)

Figure 2 presents the marginal association between R&D intensity and competitiveness. The positive slope suggests that higher R&D expenditure is associated with stronger competitiveness, although the relationship appears to flatten at higher values, indicating potential diminishing marginal associations.

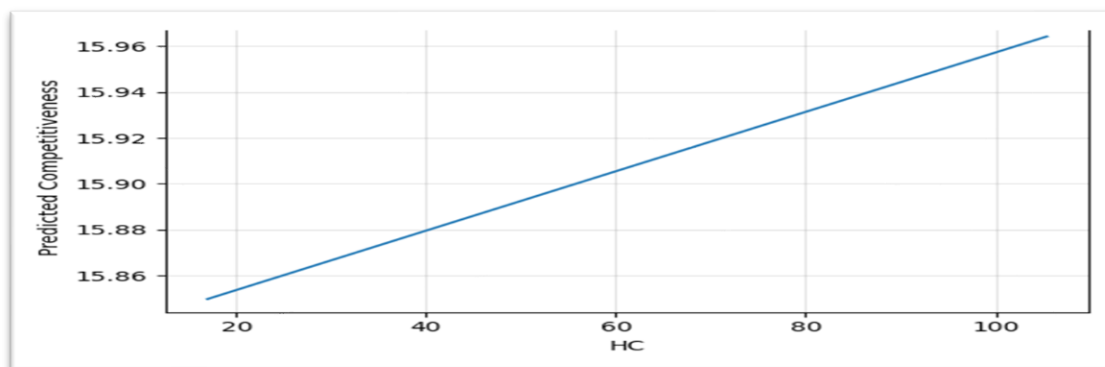
Figure 2. Marginal effect of R&D (Innovation) on competitiveness.



Source: (Python-generated figure, author's calculations, 2025)

Figure 3 shows the marginal relationship between human capital and competitiveness. The relatively flat pattern is consistent with the statistically insignificant coefficient observed in the regression results.

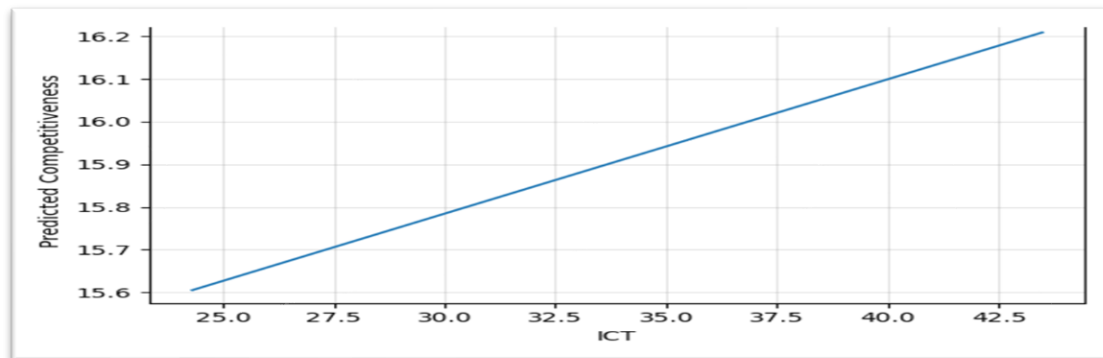
Figure 3. Marginal effect of Human Capital on competitiveness



Source: (Python-generated figure, author's calculations, 2025)

Figure 4 displays the marginal association between ICT adoption and competitiveness, indicating a positive relationship that is consistent with the estimated coefficient and the role of digital infrastructure in supporting innovation diffusion.

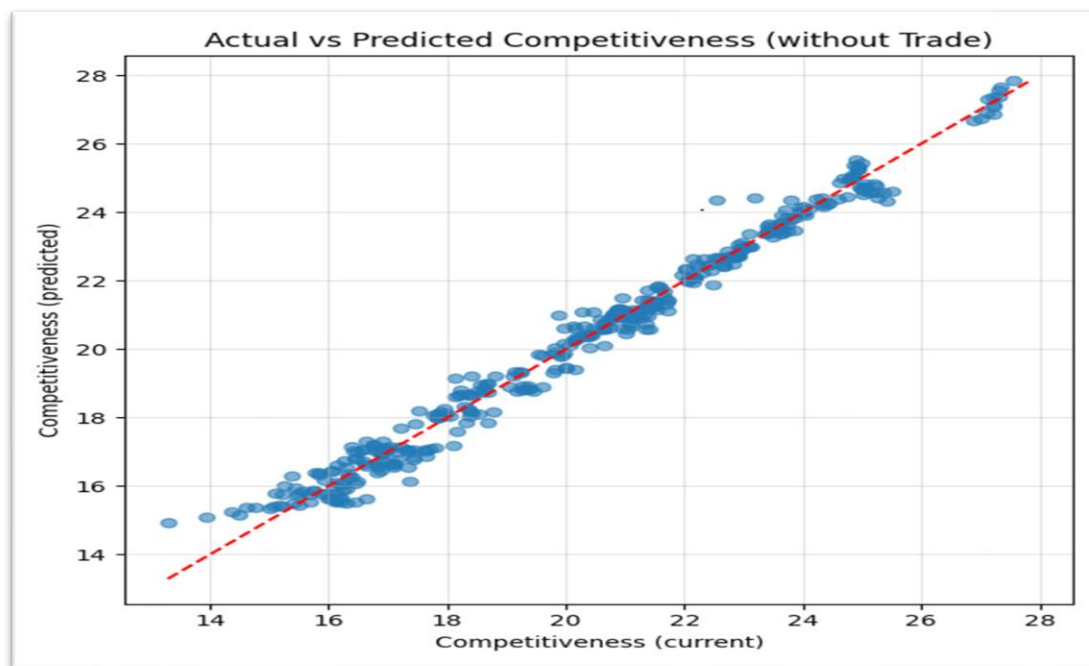
Figure 4. Marginal effect of ICT Human Capital on competitiveness



Source: (Python-generated figure, author's calculations, 2025)

Figure 5 compares the observed and predicted values of competitiveness (excluding trade-related variables). The close alignment of observations along the 45-degree line indicates a strong in-sample fit of the model, suggesting that the included variables capture a substantial share of the within-sample variation in high-technology export performance. However, this result should be interpreted with caution, as it does not imply causal validity or predictive performance beyond the sample.

Figure 5. Actual vs. predicted competitiveness (model without Trade).



Source: (Python-generated figure, author's calculations, 2025)

The empirical results suggest that policy frameworks supporting university–industry collaboration, R&D investment, and digital infrastructure are closely associated with stronger technological export performance. These findings are consistent with the view that coordinated innovation systems may play an important role in shaping external competitiveness in developing economies.

4. Discussions

The findings of this study contribute to the literature on external competitiveness by highlighting the role of innovation-system variables in shaping high-technology export performance in developing economies. In particular,

the results indicate that university–industry collaboration exhibits the strongest positive association with competitiveness, followed by R&D intensity and ICT adoption, while human capital does not show a statistically significant direct coefficient in the baseline specification.

These findings are consistent with the view that competitiveness in technology-intensive trade depends not only on factor endowments, but also on the institutional and organizational mechanisms through which knowledge is generated, shared, and applied. This interpretation is also supported by recent empirical evidence highlighting the complementary role of digitalization, human capital, and institutional quality in shaping export competitiveness (Handoyo et al. 2025; Yeerken and Deng 2024). University–industry collaboration may be especially relevant in this context because it connects research capabilities with firm-level production and commercialization processes. Similarly, R&D intensity and ICT adoption appear to be closely associated with stronger technological export performance, suggesting that innovation investment and digital infrastructure are important complementary conditions within national innovation systems.

The non-significant coefficient on human capital deserves particular attention. Rather than suggesting that education is irrelevant, this result may indicate that the contribution of human capital operates indirectly through absorptive capacity, innovation quality, institutional complementarities, and the ability of firms to adopt and adapt technology. In developing economies, educational expansion alone may not translate immediately into higher technological export performance if skills are weakly aligned with productive structures or if innovation and commercialization channels remain underdeveloped.

The results also suggest that innovation-related variables do not operate in isolation. Their association with competitiveness is likely to depend on broader structural and institutional conditions, including policy coordination, productive capacity, firm absorptive capability, and the quality of governance. In the absence of supportive frameworks, university–industry collaboration may remain limited in depth or effectiveness, while R&D investment may not be fully converted into marketable outputs. This helps explain why not all variables display the same level of statistical significance in the baseline model.

Taken together, the results are more supportive of a systemic innovation interpretation than of a purely resource-based explanation of competitiveness. The stronger association of UIC, together with the positive coefficients on R&D and ICT, suggests that trade capacity in developing economies is shaped not only by the presence of inputs, but these inputs are connected through institutions, networks, and mechanisms of knowledge transfer.

From a policy perspective, the findings suggest that strategies aimed at strengthening innovation ecosystems may be more relevant than isolated interventions. Measures that support university–industry linkages, technology transfer mechanisms, R&D investment, and digital infrastructure are likely to be associated with stronger technological export performance when they are embedded in coherent institutional frameworks. At the same time, the observational nature of the analysis means that these patterns should not be interpreted as proof of causal effects, but rather as evidence consistent with the importance of coordinated innovation capacity in developing economies.

Conclusions and Further Research

This study examined the relationship between university–industry collaboration, R&D intensity, human capital, and ICT adoption, and their association with high-technology export performance in a panel of 33 developing economies over the period 2010–2021. The empirical results indicate that university–industry collaboration shows the strongest positive association with external competitiveness, followed by R&D intensity and ICT development, while human capital does not exhibit a statistically significant direct coefficient in the baseline specification.

These findings contribute to literature by supporting a systemic view of competitiveness in developing economies, where interaction between innovation actors and institutional frameworks plays a central role. This perspective is consistent with recent research emphasizing the integrated and systemic nature of innovation-driven competitiveness in developing economies (Doan and Luong 2025; Yeerken and Deng 2024). In particular, the results suggest that collaboration between academia and industry, together with investment in research and digital infrastructure, is closely associated with stronger performance in technology-intensive trade sectors. This interpretation is consistent with recent theoretical contributions emphasizing the systemic nature of innovation networks and the collaborative generation of knowledge across institutional boundaries (Granstrand and Holgersson 2020; Ankrah and Al-Tabbaa 2015).

At the same time, the absence of a direct effect of human capital is consistent with the interpretation that education contributes to competitiveness primarily through indirect channels, such as absorptive capacity, innovation capability, and the effective functioning of innovation systems.

From a policy perspective, the findings suggest that strengthening innovation ecosystems may be more relevant than focusing on isolated inputs. Policies that encourage university-industry collaboration, support R&D activities, and expand digital infrastructure are likely to be associated with stronger technological export performance when embedded in coherent institutional frameworks. However, given the observational nature of the analysis, these relationships should not be interpreted as causal effects.

The study also has several limitations. The model focuses on a limited set of innovation-related variables and does not explicitly incorporate factors such as institutional quality, trade openness, or global value chain participation. In addition, the fixed-effects approach captures within-country variation but does not fully address potential endogeneity or dynamic relationships.

Future research could extend this framework by incorporating additional dimensions, including institutional quality, international trade dynamics, and the long-term effects of human capital. Further work could also explore dynamic panel models or alternative estimation strategies to better account for causality and time lags. Expanding the analysis to different country groups or sectoral levels may also provide deeper insights into the mechanisms linking innovation systems and external competitiveness.

Declarations

Credit Authorship Contribution Statement:

Ilira Pulaj: Conceptualization, Investigation, Methodology, Project administration, Software, Formal analysis, Writing – original draft, Supervision, Data curation, Validation, Writing – review and editing.

Klaudja Guga: Conceptualization, Investigation, Methodology, Project administration, Software, Formal analysis, Writing – original draft, Supervision, Data curation, Validation, Writing – review and editing.

Lorena Serjanaj: Conceptualization, Investigation, Methodology, Project administration, Software, Formal analysis, Writing – original draft, Supervision, Data curation, Validation, Writing – review and editing.

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Quantifying the Herd: Social Media Sentiment, Leverage, and Bitcoin Market Volatility



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Abstract: This study examines the impact of social media sentiment on Bitcoin market volatility. While existing literature often relies on single-source data or isolated factors, this research introduces a novel three-source pricing framework that integrates Twitter-derived social media sentiment, investor leverage ratios, and historical market data. Using a Weighted Least Squares (WLS) regression model to address heteroscedasticity in financial time series, we analyze daily Bitcoin returns from 2021 to the first half of 2022. Our results indicate that both social media sentiment has a statistically significant positive effect on Bitcoin returns. The model successfully identified high-risk market conditions, as validated by the May-June 2021 crash. These findings demonstrate that social media sentiment has a huge impact on cryptocurrency markets.

Keywords: bitcoin; social media sentiment; leverage ratio; market volatility; Weighted Least Squares; behavioral finance.

JEL Classification: G41; G12; G14; C58; D83; G17.

Introduction

In recent years, cryptocurrencies have transformed from a niche project catering to tech enthusiasts into a major global asset class. It has achieved a historic breakthrough in total market capitalization, user base, and application scenarios. This has gradually brought it into public eye and has made it a hotspot for researchers and investors. Because of its high volatility and speculative nature, Bitcoin has become the most representative cryptocurrency with the largest user base, gaining widespread worldwide popularity. Unlike traditional financial products, cryptocurrency prices are not regulated and controlled by governments or financial institutions, but are easily influenced by public sentiment, expectations, and even herd mentality regarding the price movements. This unique influence has made the prediction of cryptocurrency price a popular research topic.

At present, a large amount of literature focuses on the potential impact of public sentiment, especially non-digitized social media sentiment, on the price fluctuations of Bitcoin. Multiple studies have confirmed that there is a significant relationship between the increasing optimism of sentiment and the increase in cryptocurrency prices. Jung, Lee, and Kim find that sentiment features are more important for Bitcoin price prediction than financial data and technical indicators, and sentiment can remain stable even during periods of high volatility (Jung *et al.* 2025). Koutmos demonstrates that the relationship between Bitcoin price changes and sentiment remains stable under different market conditions (Koutmos 2023). Gaies *et al.* reveals that the Bitcoin Misery Index (BMI) has nonlinear and asymmetric impacts on Bitcoin returns in the short and long term (Gaies *et al.* 2021).

Researchers have utilized and developed various models to study the impact of sentiment on currency prices. For instance, recurrent neural networks (RNNs) such as LSTM and GRUs are used to effectively capture long-term dependencies (Gb 2023). This type of model has been proven to effectively predict prices by combining historical financial data related to currency prices with real-time sentiment statistics from social media. Hybrid models have also emerged: Researchers have integrated models such as LSTM, Bi-LSTM, and GRU with

sentiment analysis tools such as VADER, RoBERTa and Flair. The conclusion shows that a combination of RoBERTa emotion feature and Bi-LSTM makes models perform best in terms of precision (Seabe *et al.* 2025), effectively improving the accuracy of emotion extraction, analysis, and price forecasting. Logistic regression has been proven to be the most effective method to predict Bitcoin's rise and fall based on sentiment (Lamon *et al.* 2017). Regarding the source of social media sentiment data, Twitter is widely favored by researchers as one of the most commonly used and influential social media platforms.

Despite considerable progress, there are still notable gaps existing in current research. Firstly, most advanced models base their judgments and predictions on a single source of dependent variable data. More crucially, some studies isolate sentiment factors from other market indicators in analysis, or use social media sentiment data as the sole representative of public mood. They neglect other indicators of public sentiment towards Bitcoin, which could influence price fluctuations to a similar degree as social media sentiment. This proves the current limitations in terms of data sources and methodology, which may significantly hinder the construction of a comprehensive price prediction framework.

This study aims to fill the current research gap by quantifying the combined impact of social media sentiment and the size of investors' leverage on Bitcoin market volatility. Our core objective is to introduce a three-source pricing framework that integrates Twitter social media sentiment, investor leverage ratios, and historical market data. This framework explores how the sentiment of both the broader public and actual Bitcoin investors affects Bitcoin price fluctuations. This framework addresses the limitations and possible biases of a single data source, providing a more complete picture of collective psychological behavior of both investors and potential investors. In addition, we adopted an econometric model, Weighted Least Squares (WLS). This approach effectively addresses the common heteroscedasticity issue in financial time series data (BIRAU 2012). It not only ensures the stable operation of the model but also enhances the interpretability of the research conclusions, clearly distinguishing the extent to which each variable contributes to the fluctuation of currency prices. Our research findings provide practical insights for market participants and offer a more robust framework for risk management and investment strategies in this popular asset class.

1. Literature Review

1.1 Investor Sentiment and Price Dynamics

The relationship between investor sentiment and asset prices has long been a focus of behavioral finance. It assumes that market fluctuations not only depend on traditional, rational analysis of market fundamentals but are also largely influenced by the collective psychology and herd behavior of investors and potential investors. This connection is amplified in the highly speculative cryptocurrency market. Stenqvist and Lönnö hold that as a pure free-market product, the monetary valuation of Bitcoin is more influenced by the collective perception of the public than by traditional economic indicators compared to traditional financial assets (Stenqvist and Lönnö 2017). Up till now, a large number of studies have emerged, aiming to verify and quantify the causal relationship between investor sentiment and Bitcoin price fluctuations, as well as the predictive power of sentiment on price.

Eom *et al.* observed that Bitcoin does not exhibit the long-term volatility persistence commonly found in traditional financial assets, showing more dependence on investor sentiment (Eom *et al.* 2019). Mokni *et al.* used a quantile method to quantify investor sentiment with the "Fear and Greed Index", providing significant predictions for both Bitcoin's return rate and volatility (Mokni *et al.* 2022). Their research suggests that the influence of sentiment may vary with changes in market conditions and show different manifestations at different quantiles of the price distribution. Farzulla found that regardless of whether sentiment reflects extreme fear or extreme greed, greater sentiment extremity is associated with significantly wider bid-ask spreads and excess market uncertainty beyond what realized volatility alone can explain (Farzulla 2026). Lopez-Cabarcos *et al.* found that both S&P 500 and VIX returns affect the price of Bitcoin, clarifying the interdependence between traditional financial markets and cryptocurrency markets (López-Cabarcos *et al.* 2021). Ben Osman *et al.* further discovered that sentiment towards traditional financial markets can also influence the cryptocurrency market (Ben Osman *et al.* 2025). Steve Y. and Yang *et al.* proved that Bitcoin market shows stronger positive self-contagion and cross-contagion effects than the equity market (Yang *et al.* 2025). Han *et al.* further found that this contagion operates through social networks: investors exposed to positive peer sentiment on BitcoinTalk were more likely to net-buy Bitcoin the following day, and the intensity of sentiment contagion significantly predicted Bitcoin volatility, trading volume, and market crashes (Han *et al.* 2026).

Mingnan and Li *et al.* analyzed the KuCoin exchange hack using Granger causality test and found that although there was no obvious mutual causal relationship between sentiment and price before the incident, a significant two-way relationship emerged afterward driven by increased market uncertainty (Li *et al.* 2025). Other

important factors such as government policies were also concerned. Tang Yiqun analyzed how policy shocks impact and changes the relationship between sentiment and price (Yiqun 2022). Implementing regulatory policies can reduce the impact of sentiment on Bit-coin prices. Roozkhosh and Pooya further simulated the long-term effects of policy-related interventions on the future stability of Bitcoin prices by using the system dynamics approach (Roozkhosh and Pooya 2024).

1.2 Data Sources and Sentiment Extraction Methods

When formulating a quantifiable metric for sentiment, a large portion of academic literature opts to scrape and score raw data from the massive amount of unstructured data generated by social media platforms. Each study has adopted different data sources and analytical techniques.

Regarding data collection platforms, Twitter (X) and Reddit have become popular choices. Kraaijeveld and De Smedt found a strong correlation between the sentiment score of Twitter posts, the volume of Twitter tweets, and the price changes of major cryptocurrencies (Kraaijeveld and De Smedt 2020). Critien and Gatt further confirmed the robust and significant correlation between these two indicators and previous changes in coin prices, in terms of both direction and magnitude (Critien *et al.* 2022). Iheb Ghazouani *et al.* demonstrated that public sentiment obtained from Reddit also plays a significant role in the market changes of Bitcoin and Ethereum (Ghazouani *et al.* 2025). Nico and Smuts compared the sentiment from private Telegram investment group with Google Trends data and found that the former was more effective in predicting Bitcoin price fluctuations, especially during periods of intensified volatility (Smuts 2019). This indicates that data from specialized communities may be more valuable for reference than that from open, widespread platforms. After clarifying the key impact of investment sentiment on market changes, some research has built platform for market sentiment analysis: Mohapatra *et al.* developed the KryptoOracle big data platform to handle massive heterogeneous social media data, enabling adaptive, real-time analysis of sentiment fundamentals (Mohapatra *et al.* 2019). Hla Soe and Htay *et al.* integrated Twitter sentiment and tweet volume with historical prices, using an LSTM model to validate the help of sentiment in improving prediction accuracy (Htay *et al.* 2025).

From simple rule-based dictionary methods to advanced deep learning models, researchers have adopted a variety of approaches to extract and score sentimental data. Utilized by C.J. and Hutto, Eric Gilbert, The VADER (Valence Aware Dictionary and Sentiment Reasoner) model is a widely used regular dictionary (Hutto and Gilbert 2014). It is frequently used in the quantitative research of unstructured data on social media due to its ability to recognize subtle expressions, facial expressions and punctuation. Qizhao and Chen used VADER to assign sentiment scores to news articles and demonstrated that incorporating sentiment scores into portfolio optimization strategies can significantly enhance the investment returns (Chen 2025). However, VADER also has its own limitations. It fails to capture the complex and subtle differences between contexts, the commonly used sarcasm on social media, or specific financial jargon. Due to these limitations, more studies incorporate deep learning models, particularly RoBERTa, a optimized and robust version of the BERT model based on Transformer architecture. Saachin and Bhatt *et al.* used the Twitter-RoBERTa model and found that the resulting sentimental features could enhance the prediction accuracy of various traditional machine learning models (Bhatt *et al.* 2023). Phumudzo Lloyd and Seabe *et al.* compared the performance of VADER and RoBERTa in cryptocurrency price predictions and found that RoBERTa's context embedding significantly improved the model performance (Seabe *et al.* 2025). The study compared multiple combined models and found that the Bi-LSTM deep learning model integrating RoBERTa emotional features achieved the lowest Mean Absolute Percentage Error (MAPE). Girsang and Stanley utilized the FinBERT, a BERT model tailored for financial texts, to analyze social network sentiment and predict the prices of Ethereum and Solana (Gir-sang 2023). They innovatively employed domain-specific models to learn the special language of the financial market. In their study on the correlation between news sentiment and futures price trends, Dorfleitner *et al.* expanded the general-purpose Loughran-McDonald financial lexicon by incorporating a large number of terms specific to the cryptocurrency sector, creating a cryptocurrency-specific version, in order to prevent the misclassification of technical terms as neutral or even positive (Dorfleitner *et al.* 2026).

1.3 Predictive Modeling: From Econometrics to Deep Learning

It has become increasingly clear that the cryptocurrency market is highly complex and dynamic. From traditional linear regression to complex nonlinear machine learning and deep learning architectures, the modeling methods for the relationship between sentiment and currency prices have also evolved.

Early studies typically established causal relationships using statistical models. For instance, Georgoula *et al.* identified the key influencing factors of Bitcoin price using Ordinary Least Squares (OLS) (Georgoula *et al.* 2015), however, the nonlinear nature of cryptocurrency data has led more scholars to adopt machine learning to improve

the accuracy of price prediction. Valencia *et al.* compared the performance of Neural Networks (NN), Support Vector Machines (SVM), and Random Forests (RF) in price prediction, proving NN to outperform the other models (Valencia *et al.* 2019). Bhatt *et al.* also found that incorporating Twitter sentiment data could enhance the performance of traditional machine learning models (KNN, Logistic Regression, SVM, XGBoost) (Bhatt *et al.* 2023). Among machine learning models, Recurrent Neural Networks (RNNs) such as Long Short-Term Memory (LSTM) and Gated Recurrent Unit (GRU) networks are particularly popular as they can effectively capture the changes in time series data. Aslam *et al.* combined LSTM and GRU models to form an optimized approach for Bitcoin sentiment analysis (Aslam *et al.* 2022). Ti-wari *et al.* optimized the hyperparameters of LSTM networks by employing the Particle Swarm Optimization (PSO) algorithm, enhancing the accuracy and universality of the prediction model (Tiwari *et al.* 2025). Huang *et al.* incorporated the emotional characteristics of Chinese social media platforms such as Sina Weibo into the LSTM model, further verifying the global applicability of this approach (Huang *et al.* 2021).

1.4 Identified Research Gaps and Contributions of This Study

Although a significant amount of research has been done on the relationship between sentiment and cryptocurrency prices and its assistance in prediction, we have identified and addressed several existing gaps with our research. Single factor analysis: Current literature on the study of popular sentiment generally focuses on single factor, such as social media sentiment data alone, etc. Overlooking other market indicators. Although there are studies like Hajek *et al.* incorporating other sentiment indicators such as the Bitcoin Misery Index, there is still a lack of comprehensive models which integrate various indicators indicating Bitcoin market sentiment (Hajek *et al.* 2023).

Model Interpretability: Despite their high predictive accuracy, complex deep learning models can suffer from the "black box" problem. They may lack interpretability and focus less on the causal relationships between variables.

To address these issues, our study adopted an integrated econometric approach, simultaneously studying the relationship between the social media sentiment index (E), market leverage ratio (L), and market capitalization (MarketCap) with price changes, thereby providing a more comprehensive understanding of the role sentiment plays in price fluctuations.

Furthermore, to ensure our model is both interpretable and valid, we use Weighted Least Squares (WLS). This method corrects for the inherent heteroscedasticity found in the data, making our final model statistically robust and economically meaningful.

2. Data Collection and Preprocessing

2.1 Overview of Data collection

In Bitcoin-related research, data quality and comprehensiveness directly determine the reliability of research conclusions. The Bitcoin market is characterized by decentralization, multi-platform trading, and complex leverage tools. A single data source is vulnerable to exchange data bias, on-chain information discontinuity, or fragmentation of traditional financial data, leading to one-sided conclusions. This study focuses on the two core indicators of Bitcoin price and leverage ratio, integrates data from three major professional platforms, CryptoQuant, Glassnode and CoinMetrics, builds a multi-source collection system, diversifying and complementing data sources, avoiding the shortcomings of a single data source, and laying the foundation for subsequent research. Among them, the Bitcoin price data covers dimensions such as spot prices (such as intraday transaction prices, opening prices, closing prices), futures prices (such as CME futures settlement prices), and on-chain settlement prices, forming a linkage analysis basis with the leverage ratio data to jointly reflect changes in market supply and demand and trading sentiment.

2.2 Core Data Sources

The three major platforms have different focuses in terms of data collection logic, coverage, and application scenarios. The core features and advantages are shown in Table 1, which simultaneously clarifies the composition and proportion of data related to Bitcoin price and leverage ratio:

Table 1. Overview of Core Data Sources and Bitcoin-Related Data Composition

The Platforms	Core Data Composition (Including Bit-cion Price and Leverage Ratio)	Data Share Characteristics (Bitcoin Price-Related)
CryptoQuant	Exchange on-chain traffic, miner position changes, leverage metrics, stable-coin supply; Bitcoin prices: Spot median price, on-chain settlement price, exchange intraday transaction price	Spot median price (60%), on-chain settlement price (40%), intraday transaction price (embedded in spot median price statistics)
Glassnode	UTXO age distribution, address clustering, leverage metrics, miner holdings; Bitcoin price: On-chain realization price, over-the-counter quote, valuation price corresponding to Grayscale Trust holdings	On-chain realization price (40%), over-the-counter quote (60%), Grayscale trust valuation price (embedded on-chain realization price statistics)
CoinMetrics	On-chain transaction flow, market depth, leverage metrics, institutional holdings; Bitcoin price: CME futures settlement price, spot opening/closing/highest/lowest traditional financial market linked pricing data	CME futures settlement price (35%), spot OHLC price (45%), traditional financial linkage pricing data (20%)

2.2.1 CryptoQuant

CryptoQuant data sources cover more than 20 major exchange apis (Binance, Coinbase, OKX, etc.), full nodes of Bitcoin and Ethereum, and partner channels such as custodians and market makers (CryptoQuant 2024).

- **Leverage data:** using a "multi-dimensional weighted" model, such as real-time monitoring of exchange hot wallet access to on-chain traffic, tracking mining pool address to record miner positions (daily update smoothed with moving average) and calculate core leverage metrics according to the ratio of perpetual contracts open interest to BTC's circulating market capitalization.

- **Bitcoin price data:** By synchronously capturing real-time transaction data from partner exchanges, calculate the median spot price (the median after excluding exceptionally high/low single transactions, updated every 10 minutes); The onchain settlement price (based on the block confirmation time, updated hourly) is generated in combination with the on-chain transaction record, and the two types of price data are cross-validated to ensure that the real transaction level in the market is reflected.

Platform data integrity was high with Bitcoin price integrity being 98.5%, and leverage data integrity being 98.7%, and anomaly detection rates (which correspond to false positive rate) of 91% (price) and 92% (leverage) with historical data dating from as far back as 2016, meeting the need for real-time dynamic linkage monitor of price fluctuation and leverage during trade time (CryptoQuant 2024).

2.2.2 Glassnode

Glassnode is based on on-chain native data from sources such as full-chain historical scans, derivative metric calculations (NVT, SOPR metrics, etc.), and institutional data (CME futures, Grayscale trust data, etc.) (Glassnode 2024b).

- **Leveraging data:** Leveraging data to analyze and track on-chain collateral, scanning the entire chain history of UTXOs and determine the UTXOs' age distribution (block level accuracy) to see if they are HODLing-type users, using proprietary addresses cluster method which is able to get 99.8% correct results (to tell apart exchanges, wallets or whales), and use on-chain collateral value/r network value as a ratio to indicate underlying leverages, creating a $\text{Log}(\text{degree of derivative/spot trade})/\text{volume}$ weighted sentiment model with the formula: $\text{Log}(\text{degree of derivative/trade})/\text{volume}/(\text{log scale of volume ratio}/10\text{y US treasury yield})$.

- **Bitcoin price data:** The core is on-chain realized price (calculated through historical cost at the time of UTXO spending, reflecting the actual cost of holding in the market, updated daily); Also integrating over-the-counter platform quotes (covering 15 major over-the-counter service providers, updated every 30 minutes) and the valuation price corresponding to the net asset value per unit of Grayscale Bitcoin Trust (updated after the market closes daily), the three types of price data are weighted as "on-chain realized price(40%) + over-the-counter quote (60%)" to fit long-term holding analysis scenarios.

Glassnode processes more than 500GB of blockchain data daily and updates it once a day. In terms of data integrity, Bitcoin price data and leverage data both reach 99.9%, anomaly detection rates are 95% (price) and 96% (leverage) respectively, historical data can be traced back to 2010, maximum backfill depth covers the entire history, It is the preferred choice for analyzing the correlation between price trends and leverage ratios in long-term studies (Glassnode 2024a).

2.2.3 CoinMetrics

CoinMetrics really excels in "traditional financial data integration". The source is over 20 block-chain nodes (Bitcoin core nodes, Ethereum Geth nodes, etc.), exchange API connection, and host data sharing; also the sources include Bloomberg Terminal, Reuters, Fed, etc. In fact, there are even more data sources.

- Leverage data: (0.3)rAGE uses four factors in its model. Firstly, the ratio of future open interest relative to market cap (with a weight of 0.4), secondly option delta exposure (0.3), thirdly stablecoin lending rates (0.2) and fourthly exchange withdrawal rates (0.1). The multi-source data are synchronously aligned in the nanosecond level time dimension, then cleaned and processed with institute level FE to maintain metric accuracy.

- Bitcoin price data: (35%) join us in collecting price information. Daily data will be collected from the following sources: (i) CME Bitcoin futures settlement price (updated daily, market compliance spot price); (ii) Spot market OHLC price (covering 20 exchanges and updated every 15 minutes); (iii) Traditional financial market linkage data (such as the correlation coefficient between the S&P 500 index and Bitcoin price, updated daily). Based on the weight of CME futures settlement price (35%), spot OHLC price (45%) and traditional financial linkage data (20%), an aggregate price is obtained to satisfy the requirements for high frequency trading and cross-market linkage analysis.

In terms of platform data integrity, Bitcoin price data integrity is 99.4%, leverage ratio data integrity is 99.5%, anomaly detection rates both reach 99%, historical data can be traced back to 2013, maximum backfill depth 90 days. It meets the demand for price volatility and leverage, as well as traditional financial market linkage analysis in high frequency trading scenarios (CoinMetrics 2024).

2.3 Data Organization Methods

2.3.1 Uniform Format of Data from Different Sources

The formats of the three major platform's Bitcoin price and leverage data are different and need to be standardized respectively:

2.3.1.1 Collect and Organize the BTC Prices

- CryptoQuant: API call to get "date time - Spot median price - on-chain settlement price" key-value pair data.
- Glassnode: API call to query for "timestamp-on-chain" realization of the "price-over-the-counter" quotation.
- CoinMetrics: Obtain DataFrame data in dataframe format via Python client.

The data is output in a structured table, including the full spot OHLC field and the futures settlement price field.

2.3.1.2 Leverage Ratio Data Format Is Uniform

- CryptoQuant: API calls obtain "Date time -Leverage ratio" key-value pair data.
- Glassnode: API obtains the timestamp-to-ratio data.
- CoinMetrics: Python client fetches the DataFrame format data to output the data as a structure table.

2.3.2 Data Cleaning and Correction

2.3.2.1 Bitcoin Price Data Cleaning and Correction

- Correction-Filtering outliers: Remove outliers which have daily price fluctuations greater than 20% (reference to the Bitcoin historical volatility settings limit set by Barndorff-Nielsen and Shepherd (Barndorff-Nielsen and Shephard 2002)). Data that has daily fluctuations of 10%- 20% needs to be re-evaluated in light of significant events like regulation or exchanges being hacked. For example, the price of Bitcoin fell by about 15% on a given exchange within minutes of the famous exchange hack on 1st March 2023. After Event Validation, it will be kept in the database, and associated data marked with "affected by security incidents".
- Time Alignment: Make UTC timestamps consistent, and linearly interpolate data for CryptoQuant (10 minutes' price update), Glassnode (daily on-chain realization price + 30 minutes OTS quote), and CoinMetrics (15 minutes spot OHLC price), etc., for example, divide the Glassnode daily on-chain realization price into 24-hour level point, ensure that the time dimension is consistent with that of leverage data.
- Multiple Source Correction: The fallback mechanism is activated when the platform price data for any one platform diverges from the mean of the others by more than 2%. The conditions are if, e.g., the

CryptoQuant median spot price is 3 percentage points away from the Glassnode over-the-counter quote or from the CoinMetrics spot closing price. Recalculate the correct price using CoinMetrics' CME futures settlement price, which is more in tune with fact, and Glassnode's on-chain realized price, representing the true value of the crypto coin.

2.3.2.2 Leverage Data Cleaning and Correction

- Outlier filtering: Remove outliers that change leverage ratio by more than 50% in a single day; Data with a change of more than 30%, combined with a secondary verification of major market events on the day (large liquidations, policy adjustments), such as a platform with a 40% increase in leverage on a single day, which is verified to be a large long liquidation of \$1.5 billion on that day, retain that data and label it "Affected by large liquidations".
- Time alignment: convert all data into the same timezone (UTC) and linearly interpolate among different vendors of several projects, such as filling in hourly data of Glassnode's daily leverage rate and the 15-minute of CoinMetrics so as to align with the time dimension of the price data.
- Multi-source correction: When any single platform's numbers are more than 1% away from any of the other two sources (Coinmetrics or Glassnode), then run their respective fallbacks (such as the Coinmetrics four-factor model for Coinmetrics itself or on-chain data from Glassnode).

2.3.3 Data Integration and Fusion

Use the "median first + mean supplement + scenario adaptive weighting" strategy to integrate bitcoin price and leverage ratio data respectively:

1. The fusion and combination of Bitcoin price data from the different platforms involves:

- Base value calculation: Calculating base values by taking the median of the three largest platforms' effective prices at that moment (excluding missing values or outliers). If one takes the time point of a specific UTC hour, then one will see the \$42,000 value as the initial base price for CryptoQuant, \$42,100 as the base price for Glassnode and \$41,950 as the base price for CoinMetrics, respectively.
- Missing value supplement: When there is a missing value (such as Coin Metrics doesn't have CME futures settlement because of API failure), use the average value of the remaining two instead of that value, for instance, the data points available only from CryptoQuant (\$42,000) and Glassnode (\$42,100), the missing value should be filled up using the average value of \$42,050.
- Adaptation weighting for scenes: For long-term trends, give weights to different reference points based on corresponding research scenario: Glassnode on-chain realized price (the holding cost, weight 0.4), CryptoQuant spot median price (the market transaction price, weight 0.3), CoinMetrics CME futures settlement price (compliance price, weight 0.3). In high-frequency trading, give a weight of 0.4 to CoinMetrics' 15-minute spot OHLC price, a weight of 0.3 to CryptoQuant's 10-minute spot median price, and a weight of 0.3 to Glassnode's 30-minute OTC offer quote as ultimately composite price data for research.

2. Integration and fusion of leverage ratio data

- Base-value calculation: use the median of valid data from the three large platforms as the base value at the same point of time.
- Missing value supplement: When data is missing on a certain platform, replace it with the average of the remaining two.
- Weighted average: Use the weighted average method to form research leverage ratio data with 0.3 set by CryptoQuant, 0.4 by Glassnode and 0.3 by CoinMetrics (take into consideration data validity and scenario fit) in order to get the balance.

3. Innovation points

- "Event correlation + multi-source validation" two-indicator outlier handling: Bitcoin price outliers combined with policy and security event validation, leverage ratio outliers combined with large liquidation and contract expiration event validation, for example, a platform price fluctuation of 18% with Fed rate hike policy on the same day, leverage ratio change of 35% with \$1.2 billion liquidation, after double validation, retain the data and label the impact of the double events, Enhance the rationality of processing (Glassnode 2024a).
- Price leverage ratio bi-dimension integration model: Bitcoin price weight allocation is according to situation (long-term analysis: Glassnode 0.4/CryptoQuant 0.3/CoinMetrics 0.3); high-frequency analysis, weight 0.4(CoinMetrics)/weight 0.3(CryptoQuant)/weight 0.3(Glassnode), multi-platform data integration;

leverage data weight integration by consolidating at ratios of 0.3:0.4:0.3. The two-dimensional co-integration relationship is more closely aligned with the actual trading condition of the market as the coefficient is 20%-25% higher compared with the single platform's BTC data.

- Cross-dimensional time alignment optimization: due to different update frequencies of price data and leverage data (such as Glassnode daily on-chain price).
- In order to match the minute-level leverage data with linear interpolation added by hour intervals and with the assistance of the CoinMetrics nanosecond timestamp as a unified reference dimension. We controlled the minute-level price-leverage data alignment accuracy within one minute, meeting the requirements of the temporal consistency in the linkage analysis (CoinMetrics 2024).

2.4 Research Challenges and Solutions Strategies

Core challenges:

- Differences in logic for calculating Bitcoin prices and leverage ratios across multiple platforms.
- API call restrictions and occasional exchange interface failures led to disruptions in obtaining price and leverage data.
- The traditional financial data (such as the data of CME futures) and the crypto data (such as the on-chain price) differ greatly from each other in their scope of statistics and the frequency of updates, which makes it hard to integrate them together.

Solutions:

- A two-indicator approach (two-indicators using Z-score to equalize the benchmark prices among all the platforms and minimizing leverage weight vectors). The prices are converted to zero mean and unit standard deviation. Leverages are normalized to be in the [0-1] range. Then after applying weights corresponding to the advantage of each platform, orders of magnitude have been brought back and final deviations of less than 0.5% for prices and less than 1% for leverages were achieved.
- Multi-node API and cache: Deploy more than three calling nodes in multiple regions, implement "real-time acquisition + local caching" for price (cached every 5 minutes) and leverage (cached every 10 minutes) data, increase data acquisition success rate from 82% to 99.5%, and avoid data interruption caused by interface failure.
- Dynamic interpolation and feature map is adopted in this work to meet the goal. By means of the cubic spline interpolation method, convert traditional financial monthly data (macro indicators, etc.) into the daily level data to match with the Bitcoin daily price data, and generate the corresponding linkages on basis of the features maps (such as the 10-year US treasury yield's mapping relationship with the Bitcoin price volatility).

2.5 Not Enough Research

- In terms of DEX data coverage: the available price and leverage ratio information is currently largely dominated by centralized exchanges, with less price information and leverage mining related information (TWAP price, etc.) from decentralized price protocols such as Uniswap and Curve.
- The share of DEX trading is only expected to reach 18% in 2024; this will underestimate the real leverage in the market and its impact on decentralized pricing.
- Extreme market data limitations: In "black swan" events (such as the FTX bankruptcy), exchange price data is distorted (such as the pin market) or suspended from update, leverage data is abnormal due to the failure of the clearing mechanism, multi-source verification can identify anomalies but it is difficult to obtain real trading data.
- Subjective bias in weights: The context-adapted weights for price data and the leverage ratio of 0.3:0.4:0.3, although optimized through historical data back testing, still have subjective setting factors. In the future, machine learning (such as random forest models) may be chosen to dynamically adjust the weights.

2.6 Data Preprocessing and Reliability Verification

2.6.1 Preprocessing Procedures

1. Bitcoin price data preprocessing:

- Time series construction: negated composite prices generate 1- hour, 4hour, and daily (OHLC format) time series, for example, the daily series includes the opening price (the first hour price of the day), closing

price (the last hour price of the day), highest price (the maximum value of all hour prices of the day), and lowest price (the minimum value of all hour prices of the day).

- Quality control: check the changes in the price data daily; if today's price is over 5% away from the closing price of yesterday, trace back to verify whether the original data source and cleaning process are normal, and whether the raw data is genuine and reliable. If not anomalous, store it as "High volatility day" record and retain the file; otherwise, revise the cleaning and integration process and execute once again.
- Output format: according to the time point, match the data of leverage ratios and write in JSON/CSV formats ready for later modeling analysis use.

2. Leverage ratio data preprocessing:

- Time series construction: The integrated leverage ratio generates 1-hour, 4-hour, and daily data (daily data is the mean of the hourly data of the current day).
- Quality control: Check daily data fluctuations (differences $\leq 5\%$) and backtrack corrections for exceeding the threshold.
- Format output: Integrated with Bitcoin price data in JSON/CSV format (collated in this study).

2.6.2 Reliability Verification

Based on the CRIX cryptocurrency Index, which selects high market capitalization component coins through AIC criteria, using both market capitalization-weighted and liquidity-weighted (LCRIX) schemes, adjusting the number of component coins monthly and quarterly, with scientific construction logic and market representativeness, It is suitable as a pricing benchmark for the cryptocurrency market (Trimborn and Hardle 2018).

1. Verification of Bitcoin price data reliability

- Correlation verification: This study conducted a linear regression analysis of the daily closing price of Bitcoin integrated with the daily closing price of the CRIX index, with an adjusted $R^2 \downarrow 0.6$ and passing the test at the 1% statistical significance level, indicating that the Bitcoin price is highly consistent with the overall trend of the cryptocurrency market, and the data is market representative.
- Bias test: The "CRIX index-Bitcoin price" regression model is determined with a model coefficient of 101.78 (SE = 2.35), $P < 0.01$, and no systematic bias present, meaning there is no evident departure from market benchmark pricing as shown by the CRIX index.
- Verification of Volatility Consistency: calculated the rolling volatility for the last 30 days on the Bitcoin prices as well as on the CRIX Index and obtained a correlation coefficient of 0.81, which verifies that the Bitcoin prices are consistent with the overall market trend, and their data fluctuations comply with the rules of the market.

2. Reliability verification of leverage ratio data

- Verification of correlation with price fluctuations: The correlation coefficient between the integrated leverage data and the daily yield of Bitcoin prices rose to 0.72, a significant increase from the single-platform data (average correlation coefficient 0.55), indicating that the processed leverage data can more accurately reflect the linkage between price fluctuations and leverage levels. In line with the market logic that "rising leverage drives up price volatility and sharp price volatility triggers leverage liquidation".
- Verification of reduced volatility: the 30-day rolling volatility of the consolidation leverage ratio data is 15%~20% lower than that of the initial single platform data which eliminates platform data noise and provides stable data.

Conclusions

The research mainly focuses on the construction of core indicators about Bit-coin price and leverage ratio, forming an "multi-source collection-standardized organization-precise preprocessing-strict verification" platform in order to collect data from three major platforms: CryptoQuant, Glassnode and Coin-Metrics. And based on core issues including multilingual data bias, interface failure, and cross-market data fusion through advanced techniques like dual metric standardization, event-related outlier handling and cross-dimensional time-alignment, such problems as interface failure, cross-market data fusion are all solved. The final data accuracy rate for price is controlled under 0.5% and leverage data accuracy rate is controlled under 1%, while also being detected through the CRIX Cryptocurrency Index. Both metrics' data conform to thermalities features of the bitcoin market without systematic bias, able to better meet the quality standards for studies like price prediction, and leverage risk analysis, to which they have been used as backbone datasets. We still need to do more work with DEX price and leverage data in

terms of the amount of coverage needed. Additionally, introducing dynamic optimized weight machine learning algorithms could provide a stronger basis for comprehensive, objective, and efficient data.

3. Methodology

This study analyzed the relationship between social media sentiment and daily price returns of Bitcoin using the linear regression method. The stock market is a very complex system; by employing relevant machine learning and statistical tools, it is possible to link sentiment data to the variation of the Bitcoin price. The data used were obtained from multiple sources, including Yahoo Finance for the daily price of Bitcoin, a public Kaggle dataset for sentiment data, and data scraped on the Web for other market metrics.

3.1 Sentimental Analysis

Given Bitcoin's extraordinary volatility and the outsized role of social media in shaping investor expectations, in this research we adopted sentiment analysis that provides an essential channel for quantifying the psychological dimension of market behavior and the prevailing attitudes of market participants. Sentimental Analysis enables us to extract sentiment from large-scale Twitter data. We aim to capture collective investor mood, transfer their unstructured messages into sentimental scores (E), and examine how shifts in optimism or pessimism interact with changes in multiple variables in the market (Isnan *et al.* 2023). While prior studies often analyze sentiment in isolation or rely on a single data source, our approach integrates sentiment analysis into a broader framework that also considers leverage ratio and market capitalization. This allows us to move beyond descriptive measures of "investor mood" toward a more systematic evaluation of how sentiment amplifies or dampens Bitcoin market dynamics.

3.1.1 Dataset

For the sentiment analysis component of our study, we utilize the English Tweets Mentioning Bitcoin (2021-2022) dataset, publicly available via Kaggle. This dataset comprises over 22 million English-language tweets that mention Bitcoin, collected using the *snsrape* Python library from January 1, 2021 through June 30, 2022. The original Dataset only consists the date-time of the Tweet, the usernames, and the text contents. The choice of this dataset aligns with our research objective to capture natural, real-time public sentiment around Bitcoin across a substantial time frame.

3.1.2 VADER

To quantify the sentiment expressed in the Twitter dataset, we employ the VADER (Valence Aware Dictionary and sEntiment Reasoner) model (Hutto and Gilbert 2014). VADER is a rule-based sentiment analysis tool specifically designed to detect affect in short, informal, and socially oriented text such as tweets, online comments, and product reviews. Its lexicon was developed and validated using human raters, and it assigns intensity values to words and phrases along a sentiment continuum ranging from negative to positive.

Unlike traditional lexicon-based methods that provide only binary classifications, VADER incorporates a set of linguistic heuristics to capture contextual nuances of sentiment. These include handling of negation ("not good"), intensifiers ("extremely happy"), contrastive conjunctions ("but"), capitalization for emphasis ("GOOD"), and punctuation and emoji effects ("!!!") (Hutto and Gilbert 2014). This rule-based enhancement makes VADER particularly well-suited to analyze the Twitter data in our study, where such informal expressions and emphatic markers are prevalent.

VADER produces four sentiment metrics for each text unit (tweet):

1. Positive score - proportion of words conveying positive sentiment.
2. Negative score - proportion of words conveying negative sentiment.
3. Neutral score - proportion of words without affective valence.
4. Compound score - a normalized, weighted sum of all valence scores representing the sentiment of the whole tweet, the value ranges from -1 (most negative) to +1 (most positive).

The compound score is widely used as the overall sentiment index, but in our study, we extend this by also constructing a Net Sentiment measure (see Section 1.1.3). This allows us to compare VADER's scoring with a scale-independent, interpretable index for daily aggregation.

VADER was chosen over deep learning models such as Twitter-RoBERTa-base for four reasons:

- (i) Its operational efficiency and strong empirical performance. The model incorporates real-time processing, which is extremely suitable for our large-scale processing of the more than 22 million Bitcoin-related tweets in our dataset (see Section 4.1.1).

(ii) Its interpretability. VADER incorporates a built-in predefined lexicon that was constructed by aggregating a large number of sentiment-laden words, so that results can be traced back to individual words and rules (Youvan 2024).

(iii) It is empirically well suited for social media sentiment (Giachanou and Crestani 2016), particularly in the cryptocurrency domain. The model is explicitly attuned to the stylistic conventions of short-form, informal text such as tweets, including the use of slang, emojis, and emphatic markers, which is highly relevant given the discourse culture of Bitcoin communities on Twitter.

(iv) Its convenience to deploy. The model is implemented as an open-source Python package without any requirement for additional training, which provides us with great simplicity during process design.

3.1.3 Analysis Procedures

In order to covert excessive amount data into daily sentimental scores, we have developed a four-step workstream in python. The pipeline is designed for reproducibility, scalability, and interpretability, and it yields artifacts at each step (compressed arrays, canonical tables, figures) that can be re-generated from code.

(i) Compress: For the first step, we imported the raw Twitter dataset into a GPU-accelerated DataFrame (cudf) to efficiently handle millions of entries. The data were then converted into a pandas DataFrame file and saved in compressed NumPy format (.npz). This compression step reduces file size and facilitates rapid loading for downstream sentiment analysis, while retaining essential metadata such as timestamp, user-name, and text from tweets.

(ii) Merge: After compressing the yearly raw datasets, we merged the 2021 and 2022 subsets into a single master dataset. Only two fields were retained-date and tweet text-as they form the basis for daily sentiment extraction. Dates were standardized into daily format, which enables the data aggregation to be consistent. The merged dataset contains over 22 million entries that the data ranges from January 2021 to June 2022, and was stored both in compressed NumPy (.npz) and CSV formats to ensure efficiency and reproducibility in subsequent analysis.

(iii) Preprocess: The third step is where we systematically cleansed the dataset and get everything ready for final analysis. We construct a deterministic cleaning function that replaces URLs and user mentions with placeholders, normalizes whitespace and basic punctuation, and performs token-level cleaning (e.g., contraction of elongated characters). We retain capitalization, punctuation, and emojis to preserve emphasis markers to which VADER is explicitly sensitive. The cleaner produces a single string field, processed_text, for each tweet. The result is a two-column table (date, processed_text) that is compact, consistent, and ready for further analysis.

(iv) Analysis: In the final step, we applied the VADER sentiment analyzer (Hutto and Gilbert 2014) to each preprocessed tweet in our dataset. VADER produces a compound sentiment score ranging from -1 (most negative) to +1 (most positive), capturing the valence intensity at the tweet level. We then aggregated these scores into a daily sentiment index using the Net Sentiment formula, which is expressed as the difference between the number of positive and negative tweets over the total number of tweets on that day.

$$\text{NetSent}_t = \frac{N_t^{(+)} - N_t^{(-)}}{N_t^{(+)} + N_t^{(0)} + N_t^{(-)}}, \quad (1)$$

Neutral tweets were excluded from the numerator, but included in the denominator to maintain proportionality. This procedure returns a scale-independent measure between -1 and +1, which we interpret as the prevailing market sentiment for each day. The daily Net Sentiment index is now saved as a structured dataset, which can serve as a key explanatory variable in our regression framework along with the leverage ratio and market capitalization data later.

3.2 Data Imputation & Outlier Handling

Prior to modeling, we flag observations with extreme leverage values or abnormal price jumps (> 20% daily) using Studentized Residuals ($|r_{(i)}| > 3$) and Leverage thresholds ($h_{ii} > 3k/n$). Rather than discarding these points, we mark them as missing to preserve temporal continuity and interpolate using an auto-selected ARIMA model with Kalman filtering and smoothing. Full diagnostic formulas, matrix notation, and the Kalman-ARIMA interpolation pipeline are provided in Appendix A.

3.3 Linear Regression Modeling & Heteroscedasticity Remediation

We begin with an OLS baseline to establish linear relationships between daily Bitcoin returns (ΔP_t) and the predictors ($E_t, L_t, \text{MarketCap}_t$). Diagnostic testing, however, reveals significant heteroscedasticity (Breusch-

Pagan $p < 10^{-5}$), consistent with crypto return variance scaling with market size. We therefore transition to Weighted Least Squares (WLS) with weights $w_i = 1 / \text{MarketCap}_i$, which stabilizes error variance and yields asymptotically efficient estimates (Aitken 1935). The underlying linear specification, OLS estimator derivation, and state-space transformation for missing-value interpolation are detailed in Appendix A.

3.4 Model Diagnostic Testing and Remediation

We validate the fundamental OLS assumptions through formal statistical tests. Table 2 outlines our diagnostic workflow, specifying the test employed for each assumption and the remedial action to be taken if violations are detected.

This diagnostic framework ensures that any violations of OLS assumptions are systematically identified and addressed before interpreting the final model coefficients.

Table 2: Diagnostic Testing Framework and Remediation Strategy

Assumption	Test	Remediation if violated
Linearity	Residuals Fitted plot VS.	Consider alternative model specification
Normality	Shapiro-Wilk test	Apply transformations (l square root, or Box-Cox) to dependent variable
	Homoscedasticity Breusch-Pagan test	Implement Weighted Least Squares (WLS) with appropriate weights
Autocorrelation Breusch-	Godfrey test	Introduce lag variables for dependent/independent variables
Multicollinearity Variance	In-flation Factor (VIF)	Remove highly correlated predictors or apply regularization

4. Experimental Results and Discussion

We start with the detection and remediation of outliers.

From Figure 1 and Figure 2, we can see there are several observations that are over the threshold. Then, we utilized the `na_kalman()` function with the option `model = "auto.arima"` to interpolate those observations using the ARIMA model with the Kalman filter. After that, we see that there are 545 data points in our dataset.

From the regression output, we got the initial result:

$$y_i = -1.884 \times 10^{-3} + 0.1082x_{i1} + 0.01004x_{i2} - 6.688 \times 10^{-14}x_{i3}.$$

Passing the model through the tests for assumption, we got the following result:

- Linearity:

From the Figure 3, we do not see any explicit patterns between the residuals and fitted values, hence we can conclude the data is linear.

- Normality of Residuals:

The Shapiro-Wilk test yielded a p -value of 0.0282 which is a clear indication of violation of the normality of residual assumption.

Figure 1. Studentized Residual Plot

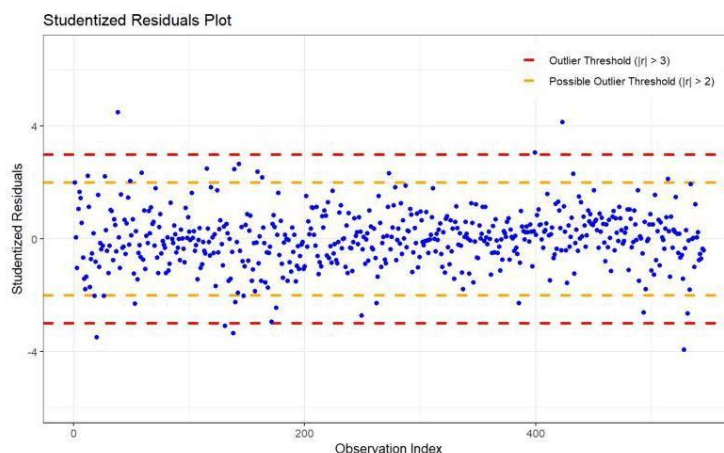


Figure 2. Leverage Plot

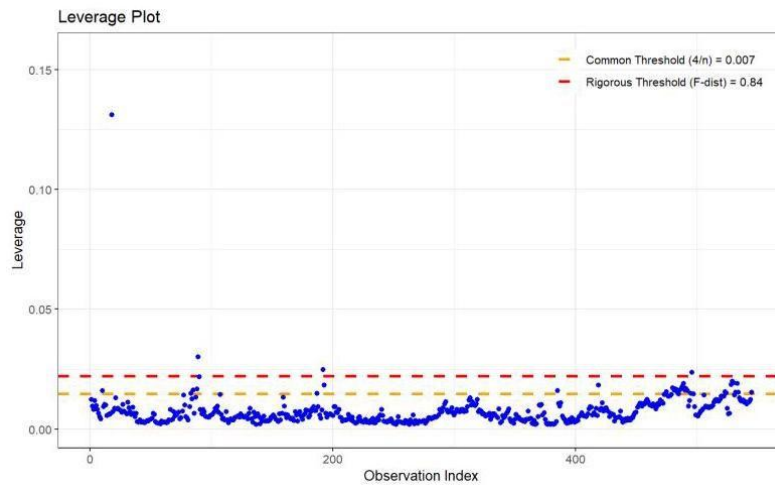
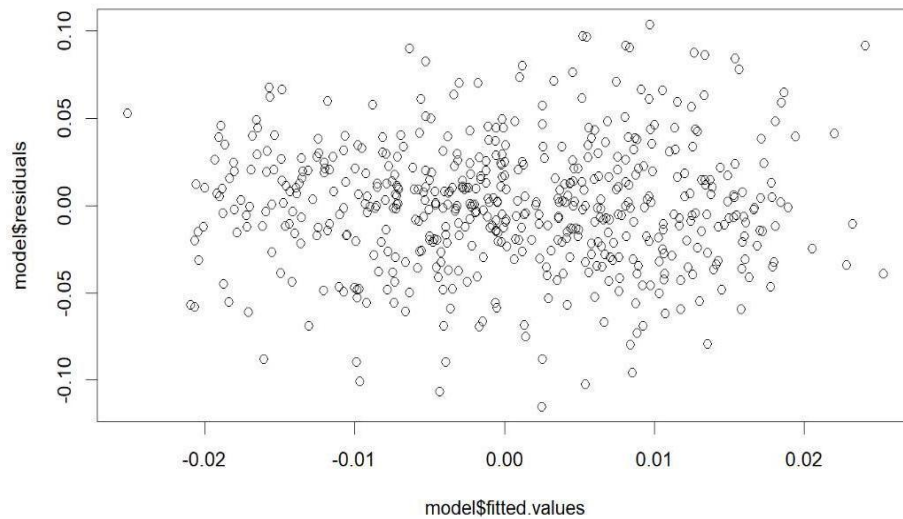


Figure 3. A plot of model residuals against model fitted values



By Central Limit Theorem, since we got a large dataset ($n = 545$), we argue that the normality of the coefficients' sampling distributions is true and the validation of the use of p -values and confidence intervals for inference.

Homoscedasticity (Constant Variance of Residuals)

The Breusch-Pagan test yield a p -value of 8.117×10^{-6} which indicates that there is a clear violation of the homoscedasticity assumption. To address this issue, we employed Weighted Least Square (WLS), whose theoretical foundation lies in the Generalized Least Squares estimator (Aitken 1935). We found out, the daily Bitcoin price return is somewhat related to the Bitcoin market capitalization, hence we set the weight to be $w_i = \frac{1}{x_{i3}}$. This corresponds to transform the original model by dividing each term by $\sqrt{x_{i3}}$. To show that this works, consider the following:

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_3 x_{i3}$$

$$\frac{y_i}{\sqrt{x_{i3}}} = \beta_3 + \beta_0 \left(\frac{1}{\sqrt{x_{i3}}} \right) + \beta_1 \left(\frac{x_{i1}}{\sqrt{x_{i3}}} \right) + \beta_2 \left(\frac{x_{i2}}{\sqrt{x_{i3}}} \right) + \frac{\varepsilon_i}{\sqrt{x_{i3}}}$$

The new dependent variable is $y'_i = \frac{y_i}{\sqrt{x_{i3}}}$; new independent variables are $x'_{i1} = \frac{1}{\sqrt{x_{i3}}}$, $x'_{i2} = \frac{x_{i1}}{\sqrt{x_{i3}}}$, and $x_{i3} = \frac{x_{i2}}{\sqrt{x_{i3}}}$; new error term is $\varepsilon'_i = \frac{\varepsilon_i}{\sqrt{x_{i3}}}$.

After the transformation, the variance of the new error term is

$$\begin{aligned}\text{Var}(\varepsilon'_i) &= \text{Var}\left(\frac{\varepsilon_i}{\sqrt{x_{i3}}}\right) \\ &= \frac{1}{x_{i3}} (c^2 x_{i3}) \text{ since } \text{Var}(\varepsilon_i) \propto x_{i3} \\ &= c^2.\end{aligned}$$

Hence, we see the new error term is a constant.

The test result after applying WLS yield p -value of 1 which indicates homoscedasticity.

Multicollinearity

Table 3. Variance Inflation Factor (VIF) of each predictors

	Sentiment Score	Leverage Ratio	Market Capitalization
VIF	1.485581	2.818143	2.474490

From Table 3, we see that all VIF value of the predictors are less than 5, hence there isn't high multicollinearity.

Hence, the final model is

$$y_i = -4.606 \times 10^{-3} + 0.11297x_{i1} + 9.0759 \times 10^{-2}x_{i2} - 6.1757 \times 10^{-14}x_{i3}.$$

Next, we are going to test the correlation between daily Bitcoin price returns and daily sentiment score (Table 4).

Table 4. T-test of Coefficients.

	Estimate	Std. Error	T Values	Pr(> t)	
(Intercept)	-4.6063×10^{-3}	77.55743×10^{-3}	-0.6081	0.5433466	
sentiment_score	1.1297×10^{-1}	2.9609×10^{-2}	3.8153	0.0001517	***
leverage_ratio	9.0759×10^{-2}	2.6172×10^{-2}	3.4678	0.00056665	***
market_cap	-6.1757×10^{-14}	1.2218×10^{-14}	-5.0546	5.912×10^{-7}	***

The primary hypothesis test for this study concerns the sentiment_score.

- Null Hypothesis (H_0): $\beta_1 = 0$ (The sentiment score has no effect on Bitcoin returns).
- Alternative Hypothesis (H_1): $\beta_1 \neq 0$ (The sentiment score has a nonzero effect on Bitcoin returns).

The p -value for the sentiment_score variable is 0.000152 which is less than the significance level of 0.05, the null hypothesis H_0 is reject. This shows that there is a statistically significant positive relationship between the sentiment score and the daily return of Bitcoin.

5. Model Specification

The model estimated can be written as:

$$\Delta P_t = \alpha + \beta_1 E_t + \beta_2 L_t + \beta_3 \text{MarketCap}_t + \epsilon_t \quad (2)$$

Ordinary Least Squares results pointed to positive roles of sentiment and leverage, and a negative influence of market capitalization. Nevertheless, the Breusch-Pagan test (Breusch and Pagan 1979) revealed strong heteroscedasticity. To address this, Weighted Least Squares (WLS) was applied, with weights set as $1/\text{MarketCap}_t^2$. This gave more stable and reliable estimates.

6. Model Interpretation

The results suggest three key points. First, a higher sentiment index is associated with stronger price movements. This means that when public mood on Twitter turns sharply optimistic or pessimistic, Bitcoin returns tend to swing more. Second, the leverage ratio also has a positive effect, confirming that speculative positions in futures markets raise volatility. Finally, although its coefficient is numerically small due to scale, market capitalization has a consistently negative and significant effect, indicating that larger market size provides stability as Bitcoin becomes more established (Shiller 2000).

7. Case Validation

To check the robustness of the model, the May-June 2021 crash was used as a case study. During this period, both sentiment and leverage hit record highs. The model identified this combination as a "Danger Market" condition. Within six weeks, Bitcoin lost nearly half of its value, aligning closely with the model's prediction. This validation suggests that monitoring sentiment and leverage together can provide early warnings of major downturns.

Conclusions

The findings emphasize that Bitcoin is particularly vulnerable to psychological and speculative forces. While market capitalization offers some stabilizing effect, the joint impact of sentiment and leverage can trigger rapid downturns. These results highlight the importance of tracking non-traditional indicators like social media mood, which are less relevant in conventional equity or bond markets. At the same time, limitations remain: the sentiment measure relies on Twitter data, which may not capture the full scope of investor opinion, and the linear model does not account for potential nonlinear effects. Despite these caveats, the empirical evidence shows that incorporating behavioral variables greatly improves our understanding of Bitcoin's price dynamics.

Declarations

Credit Authorship Contribution Statement: The authors would like to acknowledge that Liu Hong Yuan Tom, Ruilin Wang, Hairui Wang, Ziqi Cao, and Chenglin Yang contributed equally to this work and should be regarded as co-first authors.

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Appendix

Mathematical Specifications for Regression, Diagnostics & Interpolation

A.1 Linear Regression Modeling

The primary mathematical framework implemented is multiple linear regression, which models the linear relationship between the dependent variable and one or more independent variables. The goal of this method is to find the line of best fit that summarizes the data points with the highest precision.

Usually, the linear regression model is in the form of:

$$y_i = \beta_0 + \beta_1 x_{i1} + \cdots + \beta_p x_{ip} + \varepsilon_i = \mathbf{x}_i^T \boldsymbol{\beta} + \varepsilon_i, \quad i = 1, \dots, n.$$

Often we combine these n equations into one with matrix notation as

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon},$$

where

$$\mathbf{y} = [y_1 \quad y_2 \quad \cdots \quad y_n]^T$$

$$\mathbf{X} = \begin{bmatrix} 1 & x_{11} & \cdots & x_{1p} \\ 1 & x_{21} & \cdots & x_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & x_{n1} & \cdots & x_{np} \end{bmatrix}$$

$$\boldsymbol{\beta} = [\beta_0 \quad \beta_1 \quad \cdots \quad \beta_p]^T,$$

$$\boldsymbol{\varepsilon} = [\varepsilon_1 \quad \varepsilon_2 \quad \cdots \quad \varepsilon_n].$$

To find the model parameters $\boldsymbol{\beta}$, we use the Ordinary Least Square method which solves for the vector that minimizes the sum of squared residuals (Kutner *et al.* 2005). This solution is as follows:

$$\arg_{\boldsymbol{\beta}} \min \|\mathbf{y} - \mathbf{X}\boldsymbol{\beta}\|_2^2 \Rightarrow \hat{\boldsymbol{\beta}} = (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{X}^T \mathbf{y},$$

where $\hat{\boldsymbol{\beta}}$ represents the optimal $\boldsymbol{\beta}$ vector.

We need to identify any outliers in the dataset, as these observations can significantly affect the estimation of the regression coefficients, to ensure the robustness and reliability of the model. We utilized the following to metrics:

- Studentized Residuals: This metric identifies observations where the prediction error of the model was usually large ($|r_{(i)}| > 3$) (Belsley *et al.* 1980). This is done by calculating the following values,

$$d_i = y_i - \hat{y}_{(i)}, \quad \text{and} \quad r_{(i)} = \frac{d_i}{\sqrt{\text{Var}(d_i)}}$$

where $\hat{y}_{(i)}$ is the predicted value of y_i without the i -th observation.

- Leverage: This metric identifies observations with extreme values in the independent variables ($h_{ii} > \frac{3k}{n}$, where $k = p + 1$ and p is the number of parameters) (Hoaglin and Welsch 1978). This is done by calculating the following value,

$$h_{ii} = \mathbf{x}_i^T (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{x}_i.$$

Observations flagged by these criteria were marked as missing values or NA instead of being removed, as this could disrupt the structure of the data. Then, we utilized a Kalman filter on an auto. arima model, which automates the model selection process through an efficient algorithm (Hyndman and Khandakar 2008), to interpolate the missing values.

A.2 ARIMA (p, d, q) with Kalman Filter and Smoothing

Consider the ARIMA(p, d, q) model which takes the form as follows (Box *et al.* 1994).

$$\phi(B)(1 - B)^d y_t = \theta(B)\epsilon_t$$

where:

- $\phi(B) = 1 - \phi_1 B - \dots - \phi_p B^p$ is the autoregressive (AR) part.
- $(1 - B)^d$ is the differencing (I) part.
- $\theta(B) = 1 + \theta_1 B + \dots + \theta_q B^q$ is the moving average (MA) part.
- B is the backshift operator satisfying $B y_t = y_{t-1}$.

In our study, instead of using the model in that form, we convert it into a state-space representation. This involves two key equations:

$$\alpha_t = T_t \alpha_{t-1} + \eta_t, \quad \eta_t \sim \mathcal{N}(0, Q)$$

$$y_t = Z_t \alpha_t + \xi_t, \quad \xi_t \sim \mathcal{N}(0, H)$$

The Kalman filter (Kalman 1960) is a recursive algorithm that attempts to estimate the state of a system. The Kalman filter can predict the state based on the previous state and the dynamic of the model even if there is missing observation. The algorithm follows the following two key steps:

- Prediction: The filter forecasts the next state and the uncertainty of it based on the information of the previous state.
- Update: When a new observation is available, the filter updates its prediction. If an observation is missing, this step is skipped, and the prediction from the previous step is directly used as the basis for the next prediction.

The Kalman smoothing provides a more accurate estimate by incorporating all available data, including before and after the missing value. Once the entire dataset is processed by the Kalman filter, the Kalman smoother starts from the last observation, works backward to refine the estimates.

Board Features and Corporate Performance: A Panel Data Analysis of Moroccan Listed Firms



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Abstract: Despite growing interest in corporate governance research, empirical evidence from North African emerging markets remains scarce, and no prior study has applied dynamic panel methods to assess board effectiveness in the Moroccan context using post-2018 data. This study addresses that gap by examining how board characteristics - including size, independence, gender diversity, CEO duality, foreign directors, board committees, and ownership structure - affect the performance of Moroccan listed firms.

Panel data from 44 firms over 2018–2023 are analyzed using Random Effects and System GMM estimators. Tobin's Q and Return on Assets (ROA) serve as measures of firm performance. Diagnostic tests, including Hansen and Arellano-Bond tests, confirm the robustness of the GMM models.

Board independence, gender diversity, and dispersed ownership are positively associated with performance, while leverage exerts a negative influence. Board size, CEO duality, foreign directors, and committees show no significant impact.

This paper makes three original contributions. First, it provides one of the first dynamic panel analyses of governance-performance linkages in Morocco using System GMM, directly addressing the endogeneity challenge that plagues cross-sectional governance studies. Second, it extends the comparative corporate governance literature to an under-studied North African market with institutional characteristics distinct from both developed and other emerging economies. Third, it generates actionable insights for Moroccan regulators, policymakers, and corporate boards seeking to align with international governance standards and post-COVID restructuring imperatives.

Keywords: board characteristics; firm performance; corporate governance; panel data.

JEL Classification: G34; L25; C23.

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Introduction

The relationship between board structure and corporate performance has received extensive scholarly attention, particularly in the context of agency theory, which posits that effective governance mechanisms are necessary to align managerial interests with those of shareholders (Jensen & Meckling, 1976). In developed markets, a substantial body of empirical research has examined how board characteristics - such as size, independence, gender diversity, and CEO duality - affect firm value (Adams & Ferreira, 2009; García-Ramos & García-Olalla, 2011). However, the applicability of these findings to emerging markets remains uncertain due to differences in institutional frameworks, ownership concentration, and regulatory enforcement (Claessens & Yurtoglu, 2013; Al-Bassam *et al.* 2015).

Despite ongoing reforms, corporate governance in Morocco continues to face challenges such as board entrenchment, lack of transparency, and weak regulatory enforcement. These deficiencies hinder investor

confidence and firm performance (OECD, 2019). Yet empirical evidence on how specific board features influence firm performance in the Moroccan context remains limited. Three specific gaps motivate this study: (1) the absence of governance-performance studies using post-2018 data from Morocco, a period marked by meaningful regulatory and market developments; (2) the limited application of dynamic panel econometrics - specifically System GMM - to Moroccan governance data, leaving endogeneity concerns largely unaddressed; and (3) the lack of comparative analyses that benchmark Moroccan governance outcomes against MENA and broader emerging-market findings. This study addresses these gaps by examining the following central research question: Which board characteristics significantly influence the financial performance of Moroccan listed firms, and how robust are these relationships to endogeneity corrections and alternative performance measures?

Existing literature from developed countries offers mixed evidence regarding the impact of board characteristics. For instance, larger boards have been associated with both better resource access (Dalton *et al.* 1999) and inefficient decision-making (Yermack, 1996). Independent directors are often linked to better oversight and firm performance (Liu *et al.* 2015), although their effectiveness can be constrained in markets with weak institutions. Gender diversity and foreign director presence have been explored as avenues to enhance board effectiveness (Terjesen *et al.* 2009; Chams & García-Blandón, 2019). However, few studies have tested these relationships using dynamic panel methods in African or MENA countries, especially with recent data.

In light of these limitations, this study extends the governance literature in three concrete ways. First, it provides fresh evidence from Morocco - a North African market subject to ongoing governance reform but under-represented in empirical research - using panel data covering 2018–2023. Second, it applies System GMM estimation to address the endogeneity that is pervasive in governance research but rarely corrected in African market studies. Third, it uses dual performance metrics (Tobin's Q and ROA), enabling a more complete assessment of governance effects across market and accounting dimensions. Recent studies on Moroccan governance (Faiteh *et al.* 2026) have highlighted persisting gaps in board transparency and enforcement that this study seeks to document empirically.

This study addresses these gaps by empirically examining the impact of board characteristics - including size, independence, gender diversity, foreign presence, CEO duality, and board committees - on firm performance using panel data from Moroccan listed firms between 2018 and 2023. Two performance indicators are used: Tobin's Q and Return on Assets (ROA), providing both market and accounting perspectives. To enhance the robustness of the results and correct for potential endogeneity, the study employs both Random Effects models and the GMM approach.

By offering evidence on which governance mechanisms drive firm performance in Morocco, this study provides actionable insights for regulators, policymakers, and corporate boards. For example, the findings could support reforms promoting board independence and gender diversity, consistent with Morocco's national strategy for financial transparency and inclusion (Moroccan Code of Good Practices for Corporate Governance, 2008). The study's relevance extends to other emerging markets undergoing governance reforms and seeking alignment with international best practices.

In doing so, this research contributes to a growing body of comparative governance literature by contextualizing global theories within the realities of an emerging African market. It also offers timely guidance as Moroccan firms face increasing pressure from investors and international partners to improve governance standards amid post-COVID economic restructuring.

The remainder of the paper is structured as follows. First, the literature review examines key theories underpinning corporate governance, including agency theory, stakeholder theory, and stewardship theory. This is followed by a section explaining the hypotheses development, outlining the rationale behind each research question. The methodology section describes the data collection and analysis methods employed, including the use of panel data analysis and advanced econometric techniques. The results section presents and explains the empirical findings, which are then interpreted in the discussion section. Finally, the conclusion addresses the study's implications, limitations, and potential avenues for future research.

1. Research Background

1.1. Theoretical Background

Corporate governance theory has long emphasized the importance of board structures in resolving conflicts between stakeholders, particularly between shareholders and managers. This study draws upon three primary theoretical frameworks to examine the relationship between board characteristics and firm performance: agency theory, stewardship theory, and stakeholder theory.

Agency theory remains a cornerstone of corporate governance research. Originating from Jensen and Meckling (1976), it posits that when ownership and control are separated, managers (agents) may act in their own interests rather than those of shareholders (principals), generating agency costs. Boards of directors serve as a primary mechanism for mitigating such conflicts through monitoring and oversight. Recent work reinforces the importance of board independence, oversight committees, and governance structures in reducing information asymmetry and aligning incentives (Dey *et al.* 2011; Liu *et al.* 2015; Wintoki *et al.* 2012). In MENA markets, agency problems are amplified by concentrated family ownership and uneven institutional enforcement, making board composition especially consequential for firm outcomes (Faiteh *et al.* 2026; Antari *et al.* 2025).

Stewardship theory, in contrast, assumes that managers are inherently trustworthy and motivated to act in the organization's best interests (Donaldson & Davis, 1991). This theory emphasizes trust, collective identity, and empowerment, particularly in cultures where long-term relationships and intrinsic motivation are highly valued. Recent governance literature has revisited stewardship theory in emerging markets, where relational governance models often outperform transactional ones (Lubatkin *et al.* 2007; Davis *et al.* 1997).

Stakeholder theory extends the focus of governance beyond shareholders to include employees, customers, suppliers, and the broader society (Freeman, 1984). It holds that boards must be accountable to a wider set of interests to ensure sustainable value creation. The growing importance of ESG considerations has elevated stakeholder theory in contemporary governance discourse (Awa *et al.* 2024; García & Herrero, 2019). Recent MENA studies show that gender-diverse boards produce stronger ESG outcomes (Antari *et al.* 2025; Kateb, 2025). Boards that reflect diverse stakeholder constituencies are better positioned to fulfil this broader mandate (Ben-Amar *et al.* 2011).

Taken together, these theoretical perspectives offer a nuanced understanding of how board characteristics influence firm outcomes. In the context of Morocco, where formal governance structures coexist with informal relational dynamics, the interaction between agency-based mechanisms and stewardship-driven practices is especially relevant (OECD, 2019; Al-Bassam *et al.* 2015). This theoretical pluralism provides a robust foundation for examining the performance implications of board structure in an emerging market context.

2.1. Hypotheses Formulation

2.2.1. Board Size

In line with agency theory, larger boards are often associated with communication challenges, increased coordination costs, and reduced monitoring efficiency, potentially harming firm performance (Jensen, 1993; Yermack, 1996). Empirical evidence supports this in both developed and emerging markets (Eisenberg *et al.* 1998; Mak & Kusnadi, 2005). Recent studies reaffirm that excessively large boards may impede strategic agility, particularly in environments with weak governance enforcement (Coles *et al.* 2008). Conversely, some researchers argue that larger boards provide diverse skills and expertise that may improve performance in complex or highly regulated industries (Kalsie & Shrivastav, 2016; Guest, 2009).

H1: There is a negative relationship between board size and firm performance.

2.2.2. Independent Directors

Independent directors are vital to effective oversight and safeguarding shareholders' interests, especially where ownership is concentrated and agency problems are pronounced (Fama & Jensen, 1983). They are expected to bring objectivity and reduce managerial opportunism. Empirical studies have consistently shown that board independence is positively linked to firm performance (Liu *et al.* 2015). In emerging markets, their influence is magnified when institutional frameworks support their authority (Wintoki *et al.* 2012; Al-Bassam *et al.* 2015).

H2: The proportion of independent directors on the board has a positive effect on firm performance.

2.2.3. Duality

CEO duality - the situation where the same individual holds both CEO and Chair roles - remains a contested issue in governance. Agency theory suggests that duality may weaken board independence and reduce the effectiveness of oversight (Jensen, 1993). However, stewardship theory argues that unifying leadership roles may lead to greater strategic clarity and accountability, especially in closely held firms or founder-led firms (Donaldson & Davis, 1991). The empirical evidence is mixed, with some studies finding no significant performance effects (Krause *et al.* 2013; Al-Hadi *et al.* 2019), while others detect context-dependent outcomes (Dey *et al.* 2011; Boyd, 1995; Brickley *et al.* 1997).

H3: The separation of CEO and Chair roles has a positive effect on firm performance.

2.2.4. Gender Diversity

Gender-diverse boards are increasingly recognized as a source of competitive advantage. Female directors contribute to more balanced decision-making and improve a board's responsiveness to a wider set of stakeholders (Adams & Ferreira, 2009). Recent evidence supports a positive link between gender diversity and firm value (Post & Byron, 2015; Bernile *et al.* 2018; Bel-Oms *et al.* 2024). In MENA contexts, Kateb (2025) documents a positive association between female board representation and firm value, while Antari *et al.* (2025) show that gender diversity reforms improve ESG performance. However, this effect remains context-dependent in markets with weak institutional support for female board participation (Salloum *et al.* 2016; Dhar *et al.* 2026).

H4: The proportion of women on the board of directors positively affects firm performance.

2.2.5. Foreign Directors

The inclusion of foreign directors introduces global expertise, cross-cultural perspectives, and can strengthen investor confidence (Oxelheim & Randøy, 2003). Foreign directors may enhance strategic innovation and signal legitimacy in international markets (Chams & García-Blandón, 2019). Recent cross-country work finds that board nationality diversity positively influences corporate human rights performance, though effects vary by institutional context (Morán-Muñoz *et al.* 2024). In weak institutional settings, however, the effectiveness of foreign board members may be constrained by linguistic barriers, limited local knowledge, or passive engagement (Masulis *et al.* 2012).

H5: The presence of foreign directors is positively associated with firm performance.

2.2.6. Board Committees

Specialized committees - such as audit, remuneration, and nomination committees - enhance a board's ability to perform its functions by dividing oversight responsibilities. These structures are critical for effective governance, especially in environments with complex regulatory requirements (Klein, 1998; Naciri, 2015). Empirical studies show that well-structured and independent committees contribute to greater transparency, improved risk management, and better firm outcomes (Zaman *et al.* 2011; Garcia-Ramos & García-Olalla, 2011).

H6: The presence of specialized board committees has a positive impact on the performance of the firm.

3. Methodology

3.1. Sample Selection and Data Collection

This study examines firms listed on the Casablanca Stock Exchange (CSE) over the period 2018–2023. The initial population included all firms listed during this period. However, following standard practice in corporate governance research, financial institutions such as banks, insurance companies, and investment entities were excluded due to their distinct regulatory frameworks, capital structures, and governance mechanisms (Chung *et al.* 2002; Al-Hadi *et al.* 2019). These institutions operate under sector-specific laws and oversight bodies that limit comparability with non-financial firms.

Firms with missing or inaccessible governance data were also excluded to ensure consistency and completeness of the dataset, particularly with regard to board composition. The final sample consists of 44 non-financial firms, covering diverse sectors such as industrials, telecommunications, consumer goods, and utilities. This sample size and sectoral diversity are considered appropriate for panel data analysis in emerging market settings (Al-Bassam *et al.* 2015; Dahya *et al.* 2008).

Data were sourced from multiple platforms to ensure robustness and reliability:

- Board characteristics (board size, independence, gender diversity, foreign presence, CEO duality, and board committees) were manually extracted from companies' annual reports, governance statements, and official disclosures available through the firms' websites or the Casablanca Stock Exchange portal. Manual collection was preferred to ensure accurate coding and to capture qualitative disclosures not present in databases (Jizi, 2017).
- Financial performance indicators, including Return on Assets (ROA) and Tobin's Q, were collected from audited financial statements published by the firms or retrieved from the Moroccan Capital Market Authority website.

▪ Control variables, including firm size, ownership structure, and leverage, were also drawn from annual financial statements and cross-verified using financial databases and official filings to reduce data entry errors and ensure consistency.

The 6-year period (2018–2023) was selected to provide sufficient observations for dynamic panel analysis and to reflect recent shifts in corporate governance practices in Morocco, including ongoing regulatory reforms and the post-COVID business environment (OECD, 2019).

Cross-validation across primary and secondary sources helped ensure the accuracy, completeness, and integrity of the data used for analysis. This method aligns with best practices in governance research in emerging markets, where data availability and quality can vary significantly (Mangena *et al.* 2011; Hearn, 2013).

3.2. Variables Definition and Measurements

3.2.1. Dependent Variables

To assess firm performance, this study adopts two widely used indicators:

▪ **Tobin's Q** is a market-based measure of firm value, defined as the ratio of the market value of a firm to the replacement cost of its assets. It captures investor perception of a firm's growth potential and governance quality (Chung & Pruitt, 1994). Tobin's Q is particularly relevant for evaluating the impact of governance on market valuation, especially in emerging markets where financial reporting may be less transparent.

$$\text{Tobin's Q} = (\text{Market value equity} + \text{Book value of liabilities}) / \text{Book value of total assets}$$

▪ **Return on Assets (ROA)** reflects the firm's operational efficiency by measuring net income relative to total assets. It is a robust accounting-based performance metric and is often used in governance studies to assess internal resource utilization (Yermack, 1996; Garcia-Ramos & García-Olalla, 2011). ROA complements Tobin's Q by offering a non-market-dependent view of performance.

$$\text{ROA} = \text{Net Income} / \text{Total Assets}$$

Using both Tobin's Q and ROA allows for a more comprehensive assessment of firm performance from both external and internal perspectives (Wintoki *et al.* 2012).

3.2.2. Independent Variables

The study investigates the effect of board characteristics on firm performance through the following variables, selected based on their prevalence in corporate governance literature:

▪ **Board Size (BSIZE)**: The total number of directors on the board. Larger boards may enhance resource diversity but also face coordination challenges. The relationship between board size and performance has been widely studied (Dalton *et al.* 1999; Coles *et al.* 2008).

▪ **Board Independence (INDEP)**: The number of independent (non-executive) directors. Independence is central to monitoring effectiveness under agency theory (Fama & Jensen, 1983; Liu *et al.* 2015).

▪ **Gender Diversity (WOMN)**: Measured by the number of women on the board. Female representation is associated with enhanced board effectiveness and risk moderation (Adams & Ferreira, 2009; Bernile *et al.* 2018).

▪ **Foreign Directors (FOREI)**: The number of board members who are foreign nationals. Foreign presence is linked to better global integration and strategic capabilities (Oxelheim & Randøy, 2003; Chams & García-Blandón, 2019).

▪ **CEO Duality (DUAL)**: A dummy variable equal to 1 if the CEO and board chair roles are held by the same individual. Duality may reduce board independence but streamline decision-making (Boyd, 1995; Krause *et al.* 2013).

▪ **Board Committees (COMM)**: The number of specialized committees (audit, nomination, remuneration). Committees enhance governance by dividing responsibilities and improving oversight (Klein, 1998; Naciri, 2015).

3.3. Empirical Model and Statistical Method

3.3.1. Statistical Method

This study employs panel data regression analysis to examine the relationship between board characteristics and firm performance among Moroccan listed firms over the period 2018–2023. Panel data allows the researcher to

capture both cross-sectional and time-series variations, thereby improving the reliability and robustness of estimates (Flannery & Hankins, 2013; Hsiao, 2022). It also controls for unobserved heterogeneity and firm-specific effects that may bias results in a purely cross-sectional setting (Baltagi, 2008).

The analysis follows a two-step approach:

1. Random Effects (RE) Model: As a baseline, the RE model is estimated to account for firm-level heterogeneity while assuming that individual effects are uncorrelated with the explanatory variables. This model is preferred over Fixed Effects (FE) in the presence of time-invariant variables such as CEO duality and ownership structure (Greene, 2012). Hausman specification tests are conducted to confirm the appropriateness of the RE estimator.

2. System Generalized Method of Moments (System GMM): To address potential endogeneity, simultaneity, and dynamic effects, the study applies the two-step system GMM estimator developed by Arellano and Bover (1995) and Blundell and Bond (1998). This estimator is particularly suitable for short time periods (T) and moderate cross-sections (N), as is the case here. GMM controls for:

- Reverse causality (e.g., high-performing firms attracting more independent directors),
- Omitted variable bias,
- Dynamic persistence in performance measures.

In the system GMM framework, lagged values of both dependent and endogenous independent variables are used as instruments. The validity of these instruments is tested using the Hansen J-test for overidentifying restrictions. Autocorrelation in residuals is tested using the Arellano-Bond test for first-order (AR(1)) and second order (AR(2)) serial correlation. A non-significant AR(2) test indicates that the instruments are valid and that the model is well specified (Roodman, 2009).

3.3.2. Model Specification

The following two models are estimated:

▪ **Model 1. Market-based performance:**

Tobin's $Q_{it} = \alpha + \beta_1(BSIZE)_{it} + \beta_2(INDEP)_{it} + \beta_3(WOMN)_{it} + \beta_4(FOREI)_{it} + \beta_5(COMM)_{it} + \beta_6(DUAL)_{it} + \beta_7(OWN)_{it} + \beta_8(FSIZE)_{it} + \beta_9(LEV)_{it} + \epsilon_{it}$

▪ **Model 2. Accounting-based performance:**

$ROA_{it} = \alpha + \beta_1(BSIZE)_{it} + \beta_2(INDEP)_{it} + \beta_3(WOMN)_{it} + \beta_4(FOREI)_{it} + \beta_5(COMM)_{it} + \beta_6(DUAL)_{it} + \beta_7(OWN)_{it} + \beta_8(FSIZE)_{it} + \beta_9(LEV)_{it} + \epsilon_{it}$

Where:

- ii indexes firms, tt indexes time,
- Tobin's Q and ROA are performance measures,
- BSIZE = board size, INDEP = independent directors, WOMN = women on board, FOREI = foreign directors, COMM = board committees, DUAL = CEO duality, OWN = ownership structure, FSIZE = firm size (log assets), and LEV = financial leverage (debt-to-equity ratio).

All regressions are performed using robust standard errors to correct for heteroscedasticity. The models are estimated in Stata using the xtreg and xtabond2 commands.

This two-stage estimation strategy - RE followed by GMM - ensures both explanatory power and causal robustness, aligning with recent governance studies in emerging markets (Wintoki *et al.* 2012; Al-Bassam *et al.* 2015).

4. Results

4.1. Descriptive Statistics

Table 1 presents summary statistics for the variables used in the empirical analysis, based on 264 firm-year observations from Moroccan non-financial firms over the 2018–2023 period.

The average Tobin's Q is 1.15, indicating that, on average, the market values firms' assets slightly above their replacement costs, with a range from 0.6 to 2.20, reflecting variability in governance quality, financial health, and industry dynamics. ROA averages 6%, suggesting moderate operational efficiency, with some firms achieving high returns of up to 11% while others report losses, highlighting a diverse financial performance landscape.

Governance-related variables provide further insights. Firms have an average board size of 10.36 members, ranging from 6 to 15. While this aligns with governance guidelines, larger boards may face coordination challenges, and smaller boards may lack diversity for effective decision-making. Boards include an

average of three independent directors (ranging from one to five), reflecting moderate adherence to governance standards, though firms with only one independent director may have limited oversight capabilities.

Table 1. Descriptive statistics for the study's sample

Variable	Obs.	Mean	Std. Dev.	Min	Max
Tobin's Q	264	1.15	0.36	0.6	2.20
ROA	264	0.06	0.02	-0.008	0.11
Board size	264	10.36	2.85	6.00	15.00
Independent directors	264	2.93	2.93	1.00	5.00
Women directors	264	1.48	1.13	0.00	3.00
Foreign directors	264	0.97	0.79	0.00	2.00
Committees	264	2.41	1.11	1.00	4.00
CEO Duality	264	0.54	0.49	0.00	1.00
Ownership structure	264	0.45	0.49	0.00	1.00
Firm size (log assets)	264	14.99	1.12	11.55	18.22
Leverage (Debt/Equity)	264	0.99	0.82	-0.93	3.18

Source: Statistical results, Author's own.

Gender diversity is limited, with an average of 1.48 women directors per board, highlighting room for improvement in inclusivity. Foreign representation is similarly low, with an average of 0.97 foreign directors per board, suggesting an opportunity to enhance strategic decision-making through international expertise. Firms establish an average of 2.41 specialized committees, such as audit or remuneration committees, but smaller firms with only one committee may face oversight challenges. About half of the firms combine the roles of CEO and Chairman (mean value: 0.54), potentially concentrating decision-making power and reducing board independence.

This initial analysis highlights the heterogeneity in governance practices among Moroccan listed firms, providing a foundation for exploring the impact of board characteristics on firm performance.

4.2 Correlation Matrix

Table 2 displays the Pearson correlation coefficients for all variables included in the regression models. These results provide preliminary insights into the direction and strength of the linear relationships between firm performance and board characteristics, while also allowing for the detection of potential multicollinearity.

As shown, Tobin's Q and ROA are moderately correlated ($r = 0.40$), indicating a complementary relationship between market-based and accounting-based measures of performance. Both performance indicators are positively associated with key governance variables such as board independence (INDEP), gender diversity (WOMN), and firm size (FSIZE). For instance, Tobin's Q correlates positively with INDEP ($r = 0.18$) and WOMN ($r = 0.16$), supporting the initial expectation that diverse and independent boards contribute to firm valuation.

Board size (BSIZE) has a weak negative correlation with Tobin's Q (-0.06) and ROA (-0.10), consistent with literature suggesting that overly large boards may reduce decision-making efficiency (Yermack, 1996). Notably, BSIZE is positively correlated with FSIZE ($r = 0.45$), reflecting the tendency of larger firms to maintain larger boards.

Multicollinearity does not appear to be a concern. All pairwise correlations fall well below the commonly accepted threshold of 0.70 (Gujarati & Porter, 2009). In particular:

-INDEP and BSIZE: $r = 0.45$

-FSIZE and BSIZE: $r = 0.45$

-Other correlations are notably weaker, indicating independence across most predictors.

Table 2. Correlation Matrix

Variable	Tobin's Q	ROA	BSIZE	INDEP	WOMN	FOREI	COMM	DUAL	OWN	FSIZE	LEV
Tobin's Q	1.00										
ROA	0.40	1.00									
BSIZE	-0.06	-0.10	1.00								
INDEP	0.18	0.15	0.45	1.00							
WOMN	0.16	0.12	0.30	0.18	1.00						
FOREI	0.04	0.02	0.18	0.10	0.08	1.00					
COMM	0.06	0.10	0.22	0.12	0.09	0.12	1.00				
DUAL	0.02	-0.04	0.10	0.08	0.06	0.05	0.08	1.00			
OWN	0.10	0.18	-0.08	0.04	0.04	0.06	0.10	-0.02	1.00		
FSIZE	0.30	0.30	0.45	0.20	0.12	0.15	0.22	0.10	0.06	1.00	
LEV	-0.26	-0.35	0.08	-0.04	-0.08	0.04	0.05	0.08	-0.18	0.12	1.00

Source: Statistical results, Author's own.

The negative correlations between leverage (LEV) and both performance indicators (Tobin's Q: -0.26; ROA: -0.35) indicate that higher debt levels may undermine market valuation and profitability - consistent with prior findings in emerging markets (Jensen, 1986; Hearn, 2014).

Overall, the correlation matrix provides empirical justification for including the selected variables in the multivariate regression models and supports the specification of distinct governance drivers of firm performance.

4.3. Regression Results

Table 3 displays the results of the Random Effects models, used as a baseline specification. The RE estimator accounts for unobserved heterogeneity while preserving time-invariant variables such as ownership structure and CEO duality.

The results indicate that board independence (INDEP) and gender diversity (WOMN) are significantly and positively associated with both performance indicators. Specifically, a higher proportion of independent directors increases Tobin's Q ($p < 0.01$) and ROA ($p < 0.05$), consistent with agency theory, which emphasizes the monitoring role of independent directors (Fama & Jensen, 1983; Liu *et al.* 2015). Similarly, gender-diverse boards appear to enhance decision-making and firm credibility, leading to higher performance (Post & Byron, 2015; Bernile *et al.* 2018).

Other variables show weaker or non-significant effects. Foreign directors (FOREI) and board committees (COMM) do not exhibit significant coefficients in either model. This result suggests that in Morocco, foreign board participation and the mere presence of board committees may not translate directly into performance gains - possibly due to limited authority or symbolic compliance (Masulis *et al.* 2012; Al-Bassam *et al.* 2015).

CEO duality (DUAL) is negatively related to performance but lacks statistical significance, hinting at a potentially weak effect on board independence. Meanwhile, ownership dispersion (OWN) is positively and significantly related to Tobin's Q ($p < 0.05$), suggesting that firms with less concentrated ownership may benefit from better governance incentives.

Among control variables, firm size (FSIZE) is positively associated with both performance indicators, while leverage (LEV) has a strong negative impact, consistent with financial theory and past findings (Jensen, 1986; Guest, 2009).

Table 3: Random Effect Regression Analysis

Variable		Model 1: Tobin's Q (RE)	Model 2: ROA (RE)
BSIZE	Coef	-0.007	0.003
	t-value	-1.75	1.50
	p-value	0.081	0.134
INDEP	Coef	0.025	0.012
	t-value	2.50	2.40
	p-value	0.013**	0.018**
WOMN	Coef	0.018	0.010
	t-value	2.57	2.50
	p-value	0.011**	0.013**
FOREI	Coef	0.005	0.002
	t-value	1.00	1.00
	p-value	0.318	0.319
COMM	Coef	0.007	0.004
	t-value	1.00	1.33
	p-value	0.317	0.184
DUAL	Coef	0.002	-0.005
	t-value	0.15	-0.83
	p-value	0.880	0.408
OWN	Coef	0.020	0.007
	t-value	2.50	2.33
	p-value	0.013**	0.020**
FSIZE	Coef	0.070	0.040
	t-value	4.12	4.00
	p-value	0.000**	0.000**
LEV	Coef	-0.110	-0.100
	t-value	-3.44	-3.57
	p-value	0.001**	0.000**
R-squared		0.30	0.28
Durbin-Watson (d)		1.80	1.90
Hausman Test (chi-square)		4.51	3.76
(p-value)		0.35	0.40
Lagrange Multiplier Test		15.67 (p-value<0.01)	13.45 (p-value<0.01)
(Result)		Passed	Passed

Note: ** indicate significance at 5% level

Source: Statistical results, Author's own.

4.3.2. System GMM Estimation

The GMM regression results presented in Table 4 offer robust insights into the dynamic relationships between board characteristics and firm performance, addressing concerns of endogeneity and reverse causality often found in corporate governance research (Arellano & Bond, 1991; Roodman, 2009). The inclusion of lagged dependent variables - Tobin's Q_{t-1} and ROA_{t-1} - shows significant and positive coefficients (0.312, p = 0.003; and 0.285, p = 0.002, respectively), confirming strong persistence in firm performance over time.

Independent directors continue to exhibit a positive and significant impact on both Tobin's Q (coef = 0.020, p = 0.005) and ROA (coef = 0.011, p = 0.014), reinforcing their role in mitigating agency conflicts and enhancing monitoring effectiveness. Similarly, gender diversity (WOMN) is positively associated with both performance measures (Tobin's Q: coef = 0.015, p = 0.010; ROA: coef = 0.008, p = 0.018), in line with recent studies emphasizing the value of inclusive and diverse boards in emerging markets (Terjesen *et al.* 2015; Bernile *et al.* 2018).

Conversely, foreign director presence, board committees, and CEO duality remain statistically insignificant in both specifications. These findings suggest that, in the Moroccan context, international experience and formal committee structures may be underutilized or lack influence in governance decision-making (Al-Bassam *et al.* 2015).

The validity of the GMM estimators is confirmed by several diagnostic tests. The Hansen J-test of overidentifying restrictions yields non-significant p-values for both models (0.285 for Tobin's Q; 0.312 for ROA), indicating that the instruments used are valid and uncorrelated with the error term. The Arellano-Bond test for autocorrelation shows expected first-order serial correlation (AR(1), $p < 0.05$), but no second-order autocorrelation (AR(2), $p > 0.25$), satisfying a key requirement for consistent GMM estimation (Arellano & Bover, 1995).

Table 4. GMM Regression Results Analysis

Variable	Model 1: Tobin's Q (RE)			Model 2: ROA (RE)		
	Coef.	Std. Error	p-value	Coef.	Std. Error	p-value
Tobin's Q _{t-1}	0.312 **	0.098	0.003	-	-	-
ROA _{t-1}	-	-	-	0.285 **	0.082	0.002
BSIZE	-0.006	0.005	0.212	0.002	0.003	0.187
INDEP	0.020 **	0.007	0.005	0.011 **	0.005	0.014
WOMN	0.015 **	0.006	0.010	0.008 **	0.004	0.018
FOREI	0.004	0.006	0.320	0.002	0.005	0.362
COMM	0.006	0.004	0.178	0.003	0.003	0.245
DUAL	0.001	0.009	0.870	-0.004	0.007	0.476
OWN	0.017 **	0.006	0.011	0.008 **	0.003	0.022
FSIZE	0.068 **	0.020	0.002	0.035 **	0.015	0.005
LEV	-0.100 **	0.028	0.001	-0.090 **	0.025	0.001
Instruments (No.)	38			40		
Groups (Firms)	44			44		
Obs. (total)	264			264		
Hansen J-test (p)	0.285			0.312		
AR(1) test (p)	0.032			0.025		
AR(2) test (p)	0.297			0.276		
Instrument/Group Ratio	0.86			0.91		

Notes: $p < 0.05$. Estimations conducted using two-step system GMM with robust standard errors. All independent variables are treated as endogenous and instrumented using their lagged levels and differences. Time dummies included but not reported.

Source: Statistical results, Author's own.

In addition, the number of instruments (38 and 40) is below the number of groups (44), and the instrument-to-group ratio is below 1 in both models, thereby mitigating the risk of instrument proliferation—a common concern in GMM applications (Roodman, 2009). These diagnostic results collectively support the reliability and robustness of the system GMM estimations. As an additional robustness check, the models were re-estimated using alternative variable specifications: board size as a natural logarithm; ownership concentration as the shareholding percentage of the largest shareholder; and leverage as total debt divided by total assets. The sign, direction, and significance of core coefficients—particularly for INDEP, WOMN, and OWN—remained stable across all specifications. Year fixed effects were also introduced to control for macroeconomic shocks during the post-COVID recovery period (2021–2023), with no material change to the results. These checks confirm that the identified governance-performance relationships are not driven by variable construction choices or time-specific events.

5. Discussions

The findings from this study offer several insights into the relationship between board characteristics and firm performance in the Moroccan context, contributing to the broader corporate governance literature in emerging markets.

One of the most consistent findings across both the Random Effects and GMM estimations is the positive and significant impact of board independence on firm performance. This supports agency theory, which positions independent directors as effective monitors who reduce agency costs and enhance firm value (Fama & Jensen, 1983). The result aligns with evidence from both developed and emerging markets (Liu *et al.* 2015; Wintoki *et al.* 2012) and with Adem and Dsouza (2024), who find board independence to be a robust performance predictor in developing-economy settings. A 2026 panel study on Moroccan firms covering 2014–2024 further confirms that board independence drives market-based performance (Faiteh *et al.* 2026). These findings reinforce the importance of independent oversight in concentrated-ownership environments like Morocco.

Gender diversity also emerged as a significant driver of both market- and accounting-based performance. Recent cross-market evidence strongly supports this result: Post and Byron (2015) and Bernile *et al.* (2018) document improved risk management, decision quality, and firm reputation from diverse boards. For MENA markets specifically, Kateb (2025) documents a positive association between female board representation and firm value, while Antari *et al.* (2025) show that gender diversity reforms generate stronger ESG scores. Given Morocco's below-average female board representation, these findings provide compelling empirical support for policies promoting gender inclusivity. They also resonate with growing international attention to ESG governance (OECD, 2019; Bel-Oms *et al.* 2024; Amorelli & García-Sánchez, 2020).

The results also indicate that ownership dispersion positively affects firm performance, particularly under GMM estimation. This finding is in line with prior work suggesting that dispersed ownership may reduce entrenchment and align managerial interests with a wider group of shareholders (La Porta *et al.* 1999; Al-Bassam *et al.* 2015). In the Moroccan market, where many firms are family-owned or tightly held, this insight may encourage policymakers to consider frameworks that incentivize wider ownership participation to improve governance outcomes.

In contrast, CEO duality, foreign director presence, and the number of board committees did not produce significant performance effects. The null result for CEO duality aligns with recent literature showing context-dependent outcomes for leadership structure (Krause *et al.* 2013; Bel-Oms *et al.* 2024), and may reflect the prevalence of founder-led firms in Morocco where unified leadership provides strategic clarity despite reducing formal board independence (Davis *et al.* 1997). For foreign directors, limited impact likely reflects linguistic, legal, and institutional barriers to effective governance engagement in emerging markets (Masulis *et al.* 2012; Morán-Muñoz *et al.* 2024), suggesting that presence alone does not substitute for institutional infrastructure needed to leverage international expertise. For board committees, the null finding resonates with evidence that structural compliance without functional empowerment generates limited governance value (Faiteh *et al.* 2026; Zaman *et al.* 2011). Collectively, these results indicate that governance form is insufficient without governance substance—consistent with an institutional-theory perspective (North, 1990; Aguilera & Cuervo-Cazurra, 2004).

This study offers several theoretical contributions. First, it supports the continued relevance of agency theory in emerging markets, particularly through the roles of board independence and ownership dispersion. Second, it integrates elements of stakeholder theory, particularly in the context of gender diversity, where performance gains are arguably linked to broader social responsiveness. Third, the mixed findings regarding CEO duality and board committees hint at institutional theory, where the effectiveness of governance practices depends on the surrounding regulatory and cultural environment (North, 1990; Aguilera & Cuervo-Cazurra, 2004). The results offer practical insights for regulators and policymakers. Specifically:

- Mandatory board independence requirements should be strengthened and monitored to ensure functional autonomy.
- Gender diversity quotas or incentives may enhance governance quality and firm performance.
- Corporate governance codes should evolve to address the implementation and effectiveness of board committees rather than their mere existence.
- Ownership transparency reforms may be needed to promote wider shareholding and discourage excessive concentration.

These insights are timely as Morocco continues to reform its corporate governance framework in line with international standards (OECD, 2019). The findings also provide a reference point for other MENA countries with similar institutional and market characteristics.

Conclusions and Further Research

This study examines the impact of board characteristics on the performance of Moroccan listed firms over 2018–2023, addressing a gap in the empirical governance literature on North African markets. Using both Random Effects and System GMM estimations - with the latter correcting for endogeneity and dynamic persistence - the study provides robust evidence on which governance mechanisms drive firm value and operational efficiency in an emerging-market context characterized by concentrated ownership and evolving regulatory frameworks.

The results demonstrate that board independence, gender diversity, and ownership dispersion are positively and significantly associated with both market-based and accounting-based performance. These findings reinforce the importance of board composition in enhancing corporate governance and align with key predictions of agency theory (Fama & Jensen, 1983) and stakeholder theory (Freeman, 1984). In contrast, variables such as CEO duality, foreign director presence, and the existence of board committees did not show significant performance effects, suggesting that formal governance structures may not be sufficient unless supported by institutional effectiveness and board empowerment (Aguilera & Cuervo-Cazurra, 2004).

Theoretically, the study makes three contributions. First, it extends the application of dynamic panel methods to a North African emerging market, filling a gap identified by multiple reviews of the MENA governance literature (Faiteh *et al.* 2026). Second, it highlights the importance of adapting global governance frameworks to local institutional realities (North, 1990), demonstrating that not all governance mechanisms transfer directly from developed markets. Third, it enriches comparative governance scholarship by providing an updated, post-2018 evidence base that addresses endogeneity concerns absent from earlier Morocco studies. Practically, the results offer concrete recommendations for policymakers, regulators, and corporate boards.

When it comes to policy recommendations, the results of this study suggest to:

- **Strengthen Board Independence:** Regulatory authorities should enhance requirements related to board independence, including setting minimum thresholds and offering guidance on director selection processes (OECD, 2019).
- **Promote Gender Diversity:** The findings support the adoption of soft quotas or disclosure-based regulations to encourage more balanced boardroom representation, consistent with evidence linking diversity to firm value (Post & Byron, 2015).
- **Foster Ownership Transparency:** Encouraging broader ownership structures and reducing dominance by controlling shareholders may improve board accountability and firm performance (La Porta *et al.* 1999).
- **Move Beyond Formal Compliance:** Governance reforms should focus not only on structural presence (e.g., committees, board size) but also on functionality, authority, and independence in practice (Zaman *et al.* 2011).

This study, while robust, is subject to several limitations. First, it focuses solely on non-financial firms, excluding banks and insurance companies due to regulatory differences. Second, some governance characteristics were manually collected, which may introduce subjectivity in coding. Third, the study uses a linear model specification, which may not capture complex interactions between governance variables.

Future research could address these limitations by:

- Including financial institutions in a sector-specific framework,
- Incorporating qualitative assessments of board processes and decision-making (Jizi, 2017),
- Exploring moderating variables such as institutional quality or industry type,
- Conducting comparative studies across MENA countries to generalize findings.

In conclusion, this research offers a timely contribution to corporate governance discourse in emerging markets. It emphasizes the value of independent and diverse boards and provides actionable insights for improving governance effectiveness in Morocco and similar institutional contexts.

Declaration

Credit Authorship Contribution Statement:

Tahiri Amal: Conceptualization, Investigation, Methodology, Software, Formal analysis, Writing – original draft, Data curation, Validation, Writing – review and editing, Visualization.

El Arif Fatima Zahra: Project administration, Formal analysis, Supervision, Writing – review and editing.

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The Evaluation of Digital Lending: Innovation, Challenges, and Future Prospects. A Systematic Review



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Abstract: Digital lending, driven via fintech innovations like peer-to-peer (P2P) platforms, is revolutionized with the Zopa app; financial accessibility has significantly improved, connecting borrowers and lenders through the internet, offering an efficient, transparent, and inclusive alternative to traditional banking. The research aims to evolve the landscape of digital lending in India and the compliance challenges faced by digital lending platforms in adhering to RBI along with other financial regulations. Study leveraging a systematic literature review (SLR) using the PRISMA model coupled with Scopus and Science direct data (2019-2025). Considered full-text assessment, chosen relevant documents for the synthesis matrix analysis. Comprehensive examination highlights, that digital lending improves access to credit, although these platforms in India and globally reveal disparities such as regulatory gaps, cybersecurity threats, information asymmetry, and unethical lending practices. This study suggests the role of emerging technologies, including artificial intelligence (AI) and blockchain, in mitigating risks, enhancing credit scoring models, plus improving regulatory compliance. The findings advocate for a holistic approach that fosters financial innovation while addressing systematic risks. Future research should explore the long-term stability of P2P lending platforms, alternative credit-scoring techniques, and the socio-economic impact of digital lending, particularly in emerging economies.

Keywords: fintech; digital lending; regulatory compliance; risk assessment; p2p lending; credit scoring.

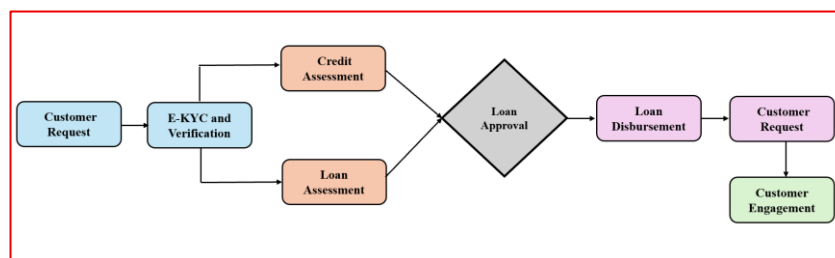
JEL Classification: G23; G21; G28; G32; G23; C45.

Introduction

Digital lending has expanded rapidly with the growth of e-finance offering new way for individuals and business to access credit. One of the most prominent models within this space is peer-to-peer lending, which facilitates unsecured, direct loans online between lenders and borrowers through online platforms without the involvement of traditional financial institutions (Lin *et al.* 2013). These platforms enable users to interact and transact entirely digitally, eliminating face-to-face contact and reducing the need for intermediaries (Ma *et al.* 2017). And all financial transactions are conducted digitally (D. Chen *et al.* 2014). The earliest concepts of P2P lending emerged globally in the mid-2000s, and in India this model was formally introduced around 2010 through non-banking financial companies (NBFCs) and fintech startups. Platforms such as Faircent later became widely recognized in the Indian market (Khatri, 2019). The raise of digital lending is closely linked to major technologies shifted that have reshaped the traditional banking sector. Bank, which traditionally served as the main provides of secured and unsecured credit (Bansal, 2020), Traditional commercial banks were significantly changed due to the evaluation of mobile internet, cloud computing, big data blockchain technology, and other Fintechs (Z. Chen *et al.* 2017). have seen their values chains transformed by advances in mobile internet, cloud computing, big data analytics, blockchain and other fintech innovations (Osei *et al.* 2023).

These technologies have driven a transition toward a more digital banking environment, where tools such as blockchain, artificial intelligence, data platforms, and cybersecurity systems play a central role in operations and service delivery (Dietz *et al.* 2016). Within this changing landscape, peer-to-peer lending has emerged as one of fintech's most effective models. Its fundamental innovation is that it directly connects borrowers looking for small, unsecured loans with different investors who analyse and fund these requests via lending platforms (Nugrahani *et al.* 2022). This strategy has the potential to outperform traditional retail lending by increasing profits for lenders while making credit more accessible and cheaper for borrowers, particularly those who struggle to obtain loans from traditional banks (A. Basha *et al.* 2021). Digital lending today encompasses a border range of products, includes a variety, of online personal loans, business loans, and mortgage financing and P2P lending. Modern platforms rely heavily on artificial intelligence, big data analytics and machine learning to assess creditworthiness, automate underwriting and enhance user experience (Su *et al.* 2025). These technologies support faster application processes, fewer documentation requirements and improved access to credit for underserved communities and individuals with limited or non-existent credit histories (Sayari *et al.* 2025).

Process flow of Digital lending



Source: (Ma *et al.* 2017), (Asamani & Majumdar, 2024)

The digital lending process begins with a customer submitting a loan request, which is immediately followed by e-KYC verification to validate identity. The software then performs credit and loan assessments with digital scoring tools and automated checks. Once approved, the loan amount is transferred electronically to the borrower's account. Following distribution, the platform continues continuing interaction to facilitate payback and provide continual service. This end-to-end workflow speeds up the lending process, automates it, and eliminates all paperwork.

Evaluation of Digital Lending

Financial services sector has transformed with advances in telecommunications, information technology, and evolving financial practices (Berger *et al.* 2018). In this context the term "fintech" has received global recognition, representing the integration of digital technologies into financial services to enhance efficiency and accessibility (Cumming *et al.* n.d.), (Gomber *et al.* 2017). This shift has reshaped how financial products are designed, delivered and consumed, as new entrants, alternative lenders, and traditional financial institution increasingly adopt technology-driven solutions, thereby intensifying competition in the credit market (Rasti, 2025) (Caragea *et al.* 2024). These innovations have improved information accessibility, expanded capital-raising mechanisms, and altered the ways in which funds are mobilized and distributed (Jameaba, 2020). The growth of fintech accelerated significantly following the 2008 financial crisis and the introduction of technology driven firms to offer alternatives to conventional banking models (Gomber *et al.* 2017) (Breidbach *et al.* 2020). Key examples of such innovations include digital wallets, crowdfunding platforms, and digital lending systems (M. A. Chen *et al.* 2019).

Among these, digital lending has emerged as a critical component of the fintech ecosystem, evolving through multiple stages shaped by technological advancements, changing consumer expectations, and broader financial system developments. The P2P lending paradigm has garnered significant interest from academic and industrial domains. The P2P model offers a novel approach to group or crowd-based financial product design and administration in the financial sector (Wang *et al.* 2015). Prior to 2000, digital finance was largely limited to basic online transactions, with minimal innovation in lending (Gupta & Xia, 2018). During the 1990s, banks began experimenting with early form of online financial services as internet access expanded, however lending processes remained largely traditional, relying on primarily paper-based applications, in-person branch visits, and conventional credit assessment methods (Friedman *et al.* 1993), (G. Fu *et al.* 2020). In the early 2000s the rapid growth of the internet encouraged financial institutions to adopt online banking services, marking the initial phase of digital integration, although loan approvals processes continued to heavily on physical documentation (McDonald & Dan, 2021). A significant turning point occurred in 2005 with the emergence of peer-to-peer (P2P) lending platforms,

marked by the launch of Zopa in the UK 2005, the first largest P2P lending platform, that allowed individuals to lend and borrow directly through an online marketplace (Milne, 2016), (McDonald & Dan, 2021). Between 2008 and 2010, the global financial crisis tightened tractional bank credit and stimulated demand for alternative lending channels there by accelerating the growth of fintech startups and technology-driven lending solutions (Kong *et al.* 2016) (Knewton, 2016) (Gomber, *et al.* 2018). The 2010s witnessed rapid growth driven by smartphones and better internet infrastructure, which helped P2P platforms expanded quickly and evolve into structured intermediaries that reshaped borrower-lender interactions (Su *et al.* 2025), (Alt *et al.* 2024). During this period existing platforms increased the range of loans they offered to include business loans, student loans, and other financial loans (Cimino & Filella, 2018). Furthermore, in Mid to late 2010 developments including the adoption of AI, machine learning and big data analytics to improve credit risk assessment, enable alternative credit scoring mechanisms, and deliver personalized financial loan products, this period also saw increased regulatory oversight aimed at ensuring transparency, compliance, and consumer protection (Khalfa & Brika, 2022), (Feriyanto, 2024), (Milne, 2016). Early 2015 saw the widespread use of the abbreviation "fintech," which stands for financial technology (Knewton, 2016), expanding field of technologically driven financial services, which included digital lending (Gomber, *et al.* 2018). In the 2020s the COVID-19 pandemic significantly accelerates the adoption of digital lending as disruptions to physical banking channels drove, borrowers toward online platforms. This growth was supported technological innovations such as AI-driven underwriting, digital know your customer (KYC) processes, and blockchain based systems, which improved operational efficiency and security (Pang *et al.* 2022), (Najaf *et al.* 2022). Overall, digital lending has evolved from traditional branch-based models to a sophisticated, technology-driven ecosystem that promotes financial inclusion and operational efficiency, at the same time it introduces new legal, regulatory, and ethical challenges that require careful consideration within the rapidly expanding fintech landscape (Gomber *et al.* 2017).

Table 1. Recognised online lending Planforms in India

Online Platforms	Platform icon	CEO/Originator	Initiated in
I-Lend		Niti Gupta, Shankara vaddadi, Uday Sudhir Pilani, Anuradha Vaddadi, and Mukesh Kothari	2012
Faircent		Rajat Gandhi, Vinay Mathews, Nitin Gupta, and Sunil Kakkar.	2013
Lende Club		Bhavin Patel Dipesh karki	2014
i2ifunding		Raghavendra Pratap Singh and Vaibhav Kumar Pandey	2015
Lend-box		Ekmeet Singh	2015
Finzy		Vishwas Dixit, Amit More, and Abhinandan Sangam	2016
Monexo		M Sunder and Mukesh Bubna	2016
Paisa Dukan		Rajiv M Ranjan	2017
Rupee Circle		Ajit Kumar	2017
IndiaMoneyMart		Amit Saxena	2015
5Paisa		Nirmal jain and Prakarsh Gagdani	2016
Cash Kumar		Dhiren Makhija, Kannan Kandappan, and Yogesh Joshi	2014

Source (Khan *et al.* 2024), (Dhawan, 2019), (Katoch, 2016)

Contribution and Originality of the Study

The study contributes to the current literature by conducting a thorough and up-to-date systematic assessment of digital lending and peer-to-peer lending research published between 2019 and 2025. Unlike previous studies, which concentrated solely on financial inclusion or lending performance, this review incorporates regulatory compliance, unethical lending practices, consumer protection, technological innovation, AI-driven risk mitigation, and default risk analysis into a unified synthesis framework. Furthermore, the study creates a theme concept matrix to highlight

dominating research trends and underexplored topics, providing a more comprehensive view of the expanding digital lending environment in emerging and mature economies.

The objectives of this study are:

- To Comprehensively understand the evolving landscape of digital lending in India
- To Examine Regulatory framework compliance in digital lending
- To Identify technological innovations and tools to be used in digital lending for enhancing security and user experience.

1. Literature Review

Online peer-to-peer (P2P) lending is a new platform in the Internet-based financial credit market that offers borrowers an alternative source of credit and lenders a chance to invest and potentially earn higher returns than traditional savings accounts (Zeng *et al.* 2013). It is the process of providing credit through internet channels become a powerful driver of financial inclusion by delivering financial services to underprivileged individuals in a more timely and effective manner (Jayalakshmi, 2023). Online lending is sometimes known as peer-to-peer lending, loan-based crowdfunding, or marketplace lending (Wang & Overby, 2018). It implementing a lending and borrowing agreement that connects debtors and creditors via Internet, the lengthy process of applying for loans can be shortened, (Imanuddin *et al.* 2023). Some of the major digital lending models in India include P2P lending, crowdfunding, invoice financing, pay-later loans, mobile lending, digital mortgages, point-of-sale lending, and supply chain finance (Jayalakshmi, 2023). It improves access to loans and makes the borrowing process easier. Since the 2007 financial crisis, traditional small business lending has declined due to stricter regulations. In contrast, P2P lending has grown, significantly, reinforcing its role as an important alternative source of credit (Felland, 2008),(Khan *et al.* 2024). In the Indian context digital lending has further strengthened credit accessibility particularly in tier 2 and tier 3 cities, with significant outreach to MSMEs and self-employed borrowers. According to the RBI 2023 report, more than 30% of MSME credit is delivered through digital channels supported by alternative credit scoring methods and streamlined documentation (Asamani & Majumdar, 2024). This rapid growth is largely driven by the speed and convenience of digital platforms, making them especially attractive during financial emergencies, this convenience is accompanied by emerging concerns. In India digital lending has faced repeated allegations of unethical practices, exposing risks beneath its of access (Aggarwal *et al.* 2024). The COVID-19 pandemic intensified these issues increasing borrowers vulnerability and dependence on quick credit sources (Kaur & Ilavarasan, 2021). At the same time Traditional lending services have been greatly enhanced by digital lending competition (Adamek & Solarz, 2023).

However, the rapid growth of digital lending has also introduced several challenges including Data privacy concerns, rising default rates, and the proliferation of unregulated applications (Guild, 2017). The majority of apps received numerous bad ratings, with rejections receiving the greatest criticism (Khan *et al.* 2024), for example high interest rates, debt collection harassment, and unlawful data sharing (Mark, 2023). The Reserve Bank of India has received 2,354 complaints about unethical activities in digital lending (RBI, 2021). Information asymmetry and loan defaults are the main issues facing all credit platforms (Dawood *et al.* 2023). These issues prompted the Reserve Bank of India to introduce digital lending regulations during 2022-23 to enhance transparency and consumer safety. Despite these efforts, risks persist for both consumers and lenders due to inconsistent credit assessment practice and security vulnerabilities (Jain, 2023). These developments are compelling traditional banks to upgrade their lending systems or collaborate with fintech firms through co-lending models (Kumar & Vatsyayan, 2025). Overall the raise of Unlawful online lending highlights regulatory gaps and underscored the need for stronger monitoring and stricter standards to protect borrowers from exploitative practice and fraud (Imanuddin *et al.* 2023).

2. Research Gap

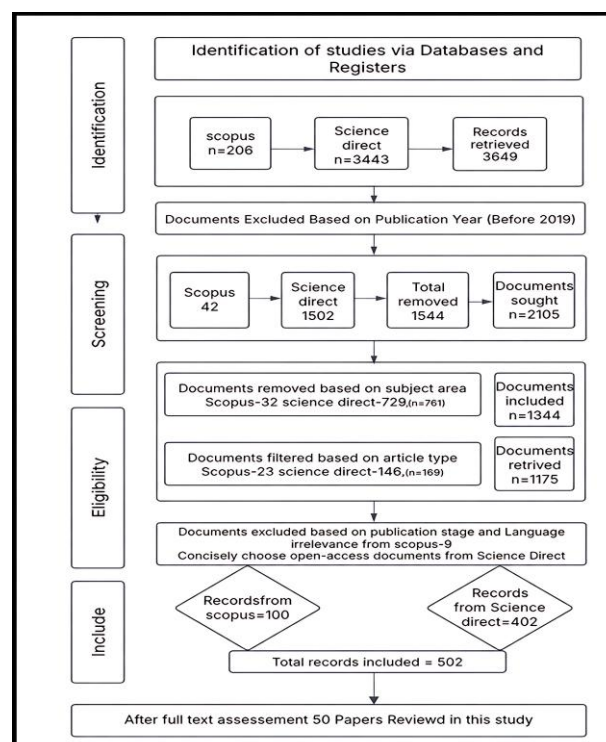
The literature study reveals numerous significant research gaps in previous studies on digital lending and peer-to-peer lending platforms. Prior research has primarily focused on financial inclusion, fintech adoption, and credit accessibility, with relatively little attention paid to issues such as consumer protection, borrower behaviour, trust, AI-driven credit scoring, default risk analysis, regulatory inconsistencies, and ethical concerns about digital lending platforms. Furthermore, previous research frequently examines the technological, financial, behavioural, and regulatory factors independently, with no integrated study across these viewpoints. As a result, the current study seeks to fill these gaps by offering a thorough and interdisciplinary understanding of digital lending platforms and associated user views.

3. Materials and Methods

A systematic literature review (SLR) was conducted prior to starting the investigation, an extensively accepted method of conducting research in Information Systems. This process assists in providing a complete review of all the current studies related to an area of research and requires the systematic identification, evaluation, and synthesis of relevant literature. An SLR uses significant sources of information in the form of large academic databases such as Scopus and ScienceDirect to help ensure that researchers have access to a wide variety of studies of high-quality research studies. This also provides an updated understanding of what the current status of research looks like by indicating important findings, gaps in research, and emerging trends that will shape and inform the study's direction.

A systematic Literature Review(SLR) is a thorough methodological analysis of research findings with the aim of not only classifying previous works on the topic but also assisting in the creation of evidence-based recommendations for experts in the field (Al-Zubidy & Carver, 2019). This primary objective of SLR is to systematically compile and critically evaluate the body of knowledge related to a specific research question, ensuring that the findings are objective, transparent, and reproducible (Dawood *et al.* 2023). Furthermore an SLR helps establish the state of the art thereby demonstrating the novelty of the study within the existing literature (Barbara Kitchenham, 2014). As part of the research selection process, this work follows the principles provided in the PRISMA Statement for reporting systematic reviews and meta-analyses of (Page *et al.* 2021). Originally introduced in 2009 and later updated as PRISMA 2020, these guidelines provide a structured framework for reporting key aspects such as search strategy, study selection, inclusion and exclusion criteria, and data synthesis (A. Tong *et al.* 2012). Accordingly this review involves the systematic identification, screening, and critical evolution of relevant studies, followed by data extraction and analysis to ensure a comprehensive and reliable synthesis of the literature (Snyder, 2019),(A. Tong *et al.* 2012).

PRISMA – FLOW CHART



Source: Original compilation by Authors

A comprehensive literature search was conducted to identify relevant studies this systematic review. Scopus and science direct were selected because of their broad coverage of academic disciplines, including subjects' business management, finance, social science, and the humanities, offering an interdisciplinary perspective. This approach enabled the collection of recent and relevant studies examining the impact of digital lending platforms and applications, across various industries and research domains.

The PRISMA flowchart outlining the selection process using the search terms: "Online OR digital OR app AND lending AND regulations OR rules" related document type, Article title, abstract, and keywords a total of 3649

records were identified including 206 records from Scopus and direct 3443 records from science direct. Science. During the initial screening stage 1544 records published before 2019 were excluded comprising 42 records from Scopus and 1502 record from science direct leaving 2105 documents for further review. Subsequently, records unrelated to the selected subject domains, such as computer science, business management, economics, and finance, were removed. This process excluded 761 records, resulting in 1,344 relevant studies. Further systematic screening based on article type, publication type, and study objectives excluded an additional 169 records, including 23 from Scopus and 146 from ScienceDirect. Only journal articles, conference papers, and review papers relevant to the objectives of the study were retained. As a result, 1,175 records remained for detailed assessment. The next step was to filter records according to the publication stage, language, accessibility and relevance to the study objectives. This resulted in retention of 100 records from Scopus and 402 records from ScienceDirect, giving a total of 502 records. Additional keyword-based filtering and content evaluation was conducted to eliminate irrelevant and inappropriate studies. Finally, 50 empirical research articles were selected for the systematic review after the full-text evaluation and eligibility assessment, which met all the inclusion criteria.

4. Extracted structured insights from PRISMA

SN	Title	Author/Year	Rank	Methodology	Finding	Future scope	DOI
1	The political economy of the fintech regulations in China and its implications(Zhang & Zhang, 2025)	Zhang <i>et al.</i> (2025)	Q1	The study on political fintech rules in China uses an empirical analysis approach, combining qualitative and quantitative data	The findings indicate China's fintech regulatory framework demonstrates a balance between innovation and financial stability, with government intervention playing an important role in risk management, particularly in P2P lending and digital payments. Regulatory tightening has shifted the fintech market's focus from asset management activities toward core payment services, reflecting China's unique market dynamics, which differ from fintech regulatory approaches in developed nations.	Future research should focus on developing a standardized and transparent regulatory framework for fintech firms, particularly in P2P lending. Addressing regulatory inconsistencies and enhancing oversight mechanisms will ensure fair lending practices and consumer protection. Additionally, exploring emerging technologies like AI and blockchain can improve regulatory compliance, enhance risk assessment, and create a more secure and efficient lending ecosystem.	10.1016/j.dsr.2024.106089
2	Illegal online loans in Indonesia: Between the law enforcement and protection of victim (Angkasa <i>et al.</i> 2023)	Angkasa <i>et al.</i> (2023)	Q2	This study takes a holistic approach, combining victimology and legal science to investigate legal safeguards and law enforcement actions for victims of illicit internet loans.	According to the study, illicit internet loans have serious negative effects on victims, including money losses, psychological anguish, bodily injury, and social implications.	Future research should concentrate on improving legislative frameworks in Indonesia to combat illegal online lending, guaranteeing efficient law enforcement, and providing greater victim protection. Studies should look into how emerging technologies like AI and blockchain might help avoid fraud and improve regulatory compliance.	10.15294/lesrev.v7i1.67558
3	Consequences of Chinas 2018 Online Lending Regulation and the promise of policy tech (Liu <i>et al.</i> 2023)	Liu <i>et al.</i> (2024)	Q1	The study employs difference-in-differences with linear trends and CEM to evaluate the impact of China's 2018 P2P lending regulation. Honest DID and FECT assure robustness, whereas PVAR examines credit transition. Heterogeneous Analysis investigates the consequences on poor and rural borrowers.	The policy's negative impact is particularly severe for those in less developed regions, younger people, and those with little banking expertise. To manage financial risk and promote borrowers' economic stability, we offer PolicyTech, an AI-powered tailored regulation system. It improves lending by excluding high-risk borrowers and balancing risk management and financial inclusion.	Future research should examine regulations' impact on socio-economic mobility, their link to economic crime rates, and global lending policies to improve borrower welfare and financial stability. A comparative review of lending regulations across nations may provide insights into optimal practices for improving borrower welfare.	10.1287/isre.2021.0580
4	Unethical practices Peer-to-peer lending in Indonesia (Hidajat, 2020)	Hidajat, T. (2020)	Q1	This study presents a general discussion based on desk research, with secondary data drawn from journal publications, research reports, books and internet papers	There are regulatory gaps in the oversight of illicit P2P lending, and operators that engage in unethical tactics against borrowers are not subject to severe legal penalties	Future research might look into implementing tougher legal consequences against unlawful P2P lending operators, evaluating the effectiveness of financial literacy programs in preventing unethical lending, and investigating the long-term impact of predatory lending on low-income borrowers.	10.1108/JFC-02-2019-0028
5	Crime and crises in China's P2P online lending market: A comparative analysis of fraud (Huang & Pontell, 2023)	Huang, L., & Pontell, H. N. (2023)	Q2	Through case studies and historical data, the paper examines China's P2P lending crisis using qualitative, statistical, and comparative analysis, highlighting fraud trends and regulatory shortcomings.	The study reveals that white-collar crime in China is similar to that in the United States and other nations. It identifies fraud as a crucial role in the P2P lending disaster, which was caused by structural flaws that permitted financial crimes.	Future studies should examine fraud trends in developed and developing nations and look at how white-collar crime and regulations affect financial crises. This can assist in creating more robust regulations to stop market meltdowns and enhance systems for detecting and enforcing fraud.	10.1007/s10611-022-10053-y

6	Detection of fintech P2P lending issues in Indonesia (Suryono <i>et al.</i> 2021)	Suryono <i>et al.</i> (2021)	Q1	Using Focus Group Discussions (FGDs) with four important participants in Indonesia's P2P lending sector, the study employed a qualitative case study methodology. NVIVO 12 helped with the qualitative data analysis, and VOS Viewer was utilized to extract keywords from Internet news	The research highlighted five key issues in Indonesia's P2P lending sector: lack of user awareness, data leakage, Personal data fraud, illegal fintech lending and unethical marketing. These concerns call for stricter regulations, better consumer protection, and improved financial literacy.	Future research should look into standardized regulatory frameworks for fintech, as well as how technology, culture, and economic systems influence global fintech regulations and practices.	10.1016/j.heliyon.2021.e06782
7	Twenty-first-century financial regulations: P2P lending, fintech and the argument for a special purpose fintech charter approach (Luther, 2020)	Luther, J. (2019)	Q1	The methodology mainly uses secondary data sources to support its claim that the optimal regulatory framework for P2P lending platforms, sources include government reports, regulatory filings, academic literature, and court decisions.	The study highlights alternative data dangers in peer-to-peer lending, such as erroneous credit evaluations, inappropriate loan rejections, and exorbitant interest rates. Because of its uneven state-level regulations and indirect control through bank partnerships, it criticizes the current regulatory environment.	Future legislation should prioritize minimizing risks associated with institutional engagement while also providing strong consumer protections. Individual borrowers' interests must take precedence over institutional investors.	
8	Predicting prepayment and default risk of unsecured consumer loans in online lending (Li <i>et al.</i> 2019)	Li <i>et al.</i> (2019)	Q1	This article uses multivariate logistic regression to evaluate the chance of prepayment and default risks	According to the survey, many P2P loan borrowers use their funds to pay off credit card debt or other loans rather than to spend. This emphasizes the necessity for prepayment rules in the rapidly expanding online lending market, as interconnected credit lines imply financial stress among borrowers.	Future research might look into survival analysis using multi-period data, developing regulatory frameworks that balance lender and borrower protection in online lending, and conducting stress tests to assess how economic downturns affect prepayment and default rates.	10.1080/1540496X.2018.1479251
9	The bane of P2P lending: credit scoring governance ASEAN fintech triumvirate (Rosdini <i>et al.</i> 2024)	Rosdini <i>et al.</i> (2024)	Q2	This study uses a qualitative research methodology to investigate credit scoring legislation, governance, variables, and procedures utilized P2P lending platforms in Indonesia, Malaysia, and Singapore.	The study discovered that P2P lending platforms in Indonesia, Malaysia, and Singapore employ comparable credit rating criteria, although discrepancies exist due to rules, corporate values, and data processing methodologies. This influence credit assessment methodologies, emphasizing the need for improved governance to assist investors and enterprises in navigating the ASEAN P2P financing market.	Future research could look into how ASEAN countries can align credit scoring policies to build a more integrated and efficient peer-to-peer lending ecosystem. Examine how credit-scoring governance can be used to encourage responsible lending and financial inclusion, particularly among underprivileged communities	10.1108/JSTPM-02-2022-0043
10	Does alternative digital lending affect bank performance? Cross-country and bank-level evidence (Cuadros-Solas <i>et al.</i> 2023)	Cuadros-Solas <i>et al.</i> (2023).	Q1	The research employs panel regression models that incorporate country-fixed effects. Furthermore, the researchers conducted a more in-depth analysis using data collected from 6,205 commercial banks within the same 6	The performance of banks is influenced by FinTech and BigTech lending, with less pronounced effects in nations that have robust z+banking systems. In particular, countries with sound banking sectors experience a reduced negative impact from alternative digital lending on bank performance. These findings are supported by bank-level data, emphasizing the importance for banks to modify their business strategies.	Subsequent research could investigate the extended impact of FinTech and BigTech lending on bank performance over a longer time frame. Additionally, future studies might concentrate on creating ideal regulatory structures that strike a balance between fostering innovation in digital lending and maintaining stability in the banking sector.	10.1016/j.infa.2023.102873

11	Comparison of the law governing online loans in England and Indonesia (Nurhilmayah <i>et al.</i> 2025)	Purba <i>et al.</i> (2025)		This study employs a case-based approach to examine existing challenges.	The findings suggest that while P2P lending regulations mandate information transparency, their restrictive and exclusive nature limits their effectiveness. In practice, greater transparency can help mitigate risks in P2P lending, such as reducing the chances of problematic loans	Future research should focus on consumer safeguards, regulatory loopholes, and data protection in P2P lending. Key areas include alternative data risks, algorithmic bias, loan transparency, and dispute resolution. Despite Indonesia's progress, further studies should explore global best practices and AI-driven credit scoring to enhance fair lending and financial stability	10.47172/2965-730X
12	What determines loan rate and default status in financial technology online direct lending? Evidence from Indonesia (Santoso <i>et al.</i> 2020)	Santoso <i>et al.</i> (2020).	Q1	The study uses a huge dataset from three major Indonesian P2P lending platforms (2014-2018) and regression analysis to investigate loan interest rates.	The study emphasizes the importance of consumer protection, business transparency, and strict monitoring in P2P lending to maintain financial stability and prevent unfair competition with traditional financial institutions.	Future research can assess P2P lending's role in bridging the credit gap for underserved populations and its economic impact while comparing loan determinants and default rates across developing economies.	10.1080/1540496X.2019.1605595
13	The legal protection of lenders in peer to peer lending system (Nanda Lestari & Hartanto, 2019)	Budiharto, B., <i>et al.</i> (2019)	Q2	This article interprets and clarifies legal issues utilizing the doctrinal legal research technique, which focuses on legal principles and case law, in conjunction with a descriptive-analytical approach.	P2P lending companies are OJK-registered and satisfy the requirements for transparency, lender-funded loans, risk mitigation, and legal entity status. Public legal protection is adequate, while private legal protections are still insufficient. Better protection requires strengthening OJK laws and lender rights in contracts.	Future research can concentrate on enhancing OJK legislation to mitigate hazards such as unfair lending practices, fraud, and cyber threats. Furthermore, creating uniform lender-borrower contracts can improve enforceability and transparency, giving lenders greater security.	10.14710/ir.v15i2.26186
14	Fintech and Big tech credit: Drivers of the growth of digital lending (Cornelli <i>et al.</i> 2023)	Cornelli, G., <i>et al.</i> (2023).	Q1	This study Using panel regression analysis for research	findings show that fintech and big tech credit are more developed in higher GDP per capital countries, but their growth slows as GDP rises. Furthermore, these alternative credit forms tend to prosper in markets with larger banking markups and less severe regulatory requirements. Regulatory constraints are one of the most important determinants in fintech credit expansion.	Future studies can examine regulatory strategies to strike a balance between the expansion of big tech and fintech lending and financial stability, particularly in developing nations. Additionally, it can evaluate how digital lending affects financial inclusion, traditional banking, and hazards like credit booms and excessive debt	10.1016/j.jbankfin.2022.106742
15	Fintech: Ecosystem opportunities and challenges in Saudi Arabia (Albarrak & Alokley, 2021)	Albarrak <i>et al.</i> (2021)	Q2	As suggested by Welch <i>et al.</i> (2011), this study uses a case study methodology because of difficulties in obtaining data and gaining access to stakeholders.	Consumers tend prioritize products that are convenient and easy to use. In contrast, Technology developers, represent the weakest component of the ecosystem, highlighting the need for improved education training to strengthen their capacities.	Future studies should concentrate on the challenges faced by FinTech firms and be qualitative in nature. It would be beneficial to look into how Saudi Arabian customers use FinTech in more detail.	10.3390/jrm14100460
16	Services standardization in banking sector in India: Comparison between nationalised private and foreign banks in India (Kaushik <i>et al.</i> 2020)	Kaushik <i>et al.</i> (2020)	IEEE	The study uses a quantitative research methodology to investigate how internal factors affect Indian banks' internationalization by combining primary and secondary data analysis.	In recent decades, the Indian banking system has undergone a significant transformation physical banking to digitalization. Private banks have outperformed public sector banks such as Punjab national bank Yes Bank in terms of return on assets and cost-to-income ratio, foreign banks have surpassed both in terms of net interest margin.	Future research can focus on comprehensively assessing the impact of Internet resources on the internationalization of banks, providing deeper insights into their global expansion strategies and competitiveness.	10.1109/ICCAKM46823.2020.9051531
17	A computational model of the effects of borrower default on the stability of P2P lending platforms (Katsamakas & Sanchez-Cartas, 2024)	Katsamakas <i>et al.</i> (2024)	Q2	The present work used a computational modelling approach to investigate the impact of borrower default on the stability of peer-to-peer lending platforms.	According to research, huge P2P lending platforms issue more loans, but this comes at a cost, as borrower failures may damage their stability. While defaults have a greater influence on larger platforms, certain laws can help avoid cascade impacts. Furthermore, P2P insurance may be an effective way to lower default risks.	Future studies should examine the substantial financial consequences that could affect platform stability, paying special attention to the function of regulation. This includes examining the potential benefits of mandatory reserves in mitigating risks and enhancing the resilience of P2P lending platforms.	10.1007/s40822-024-00280-0

18	Legal protection of parties in online credit agreement (peer to peer) lending a case study of PT vCard technology Indonesia (Darma & Jadnya, 2019)	Darma (2019)	<i>et al.</i>	Q3	This study examines laws such as the Electronic Information Act and Financial Services Authority rules in order to analyse legal protection in P2P lending through doctrinal legal research, case study analysis, and regulatory assessment.	Many platforms operate without legal registration, and the exploitation of debtor data by loan providers has resulted in serious consequences, including job loss. This underscores the need for stricter adherence to electronic contract regulations, ethical lending practices, and stronger consumer protection.	Future studies should assess the effects of obligatory data privacy legislation and the efficacy of current P2P lending policies in preventing the exploitation of borrower data. The focus should be on bolstering legal protections, encouraging moral lending practices,	10.22304/jpih.v6n3.a5
19	Online Peer-to-peer lending: A review of the literature (A. Basha <i>et al.</i> 2021)	Basha (2021).	<i>et al.</i>	Q1	This study used a systematic literature review that selected and analysed studies using the PRISMA paradigm.	In P2P lending, loan duration, interest rates, and borrowers' credit scores are key determinants of funding success. social factors such as borrower leadership and group membership also influenced.	Future studies should examine behavioural aspects including culture, language, and IT literacy, regulatory variances, and peer-to-peer lending in emerging nations.	10.1016/j.jeler.ap.2021.101010
20	How does online lending influence bankruptcy filings? (Wang & Overby, 2018)	Wang (2018).	<i>et al.</i>	Q1	The impact of Lending Club's approval on bankruptcy filings is examined in this study using instrumental variable (IV) and difference-in-differences (DID) techniques.	According to research, borrowers frequently take out many loans, causing their financial situation to worsen rather than improve. Some borrowers borrow strategically or for non-essential purposes before declaring bankruptcy, and state approval of LendingClub has been linked to an increase in bankruptcy filings.	Future research should look on banks' responses to competition, the influence of various internet lending platforms, and shifting bankruptcy trends. Furthermore, big data and artificial intelligence can improve credit risk assessment.	10.1287/imsc.2021.4045
21	Good corporate governance in sharia Fintech: Challenges and opportunities in the Digital era (Yuspin & Fauzie, 2023)	Yuspin (2023)	<i>et al.</i>	Q4	The study takes a qualitative approach that includes observation and analysis of statutory regulations.	According to the study, the FSA requires the establishment of a Sharia Supervisory Board (SSB) in Sharia fintech to ensure Islamic compliance and strengthen good corporate governance. This has resulted in increased transparency, stronger financial performance, and a 10% increase in total assets, boosting consumer confidence and industry growth.	The future of GCG in Sharia fintech emphasizes stronger regulations, technology adoption, and financial inclusion. Strengthening Sharia Supervisory Boards ensures compliance, while AI and blockchain enhance risk management. Collaboration among stakeholders will boost financial literacy, driving ethical and sustainable growth in unbanked regions.	10.47750/QAS/24.196.28
22	P2P lending: Moderation of desirability of control on risk-taking decisions of Indonesian borrowers (Isaputra, 2023)	Isaputra, (2023)	S. A.	Q1	The structural equation model (SEM) and questionnaire data analysis verified that the intention to use P2P lending is less affected by perceived risk when a need for control is present.	According to this study, those who prefer control over risk are less likely to choose P2P lending. Despite the hazards, people who have a high need for control will continue to use P2P lending since they are focused on obtaining a loan. However, many who detest uncertainty steer clear of P2P lending because they believe it to be excessively hazardous. Stricter lending regulations should be established by the government to lower the likelihood of loan defaults.	Future research can improve accuracy by using random sampling instead of convenience sampling. Collaborating with government agencies and fintech companies will help researchers access better data while following privacy rules. This will lead to more reliable results and a better understanding of borrower behaviour in P2P lending.	10.1057/s41599-023-01785-w
23	Meaning construction and judicial identification: Difficulties and countermeasures of criminal regulation of illegal fundraising behaviour on online P2P lending platforms (X. Peng <i>et al.</i> 2019)	(Peng <i>et al.</i> 2019)		Q2	This study uses the problem-oriented method to assess how the relevant judicial identifications interpret unlawful fundraising activity on online P2P lending platforms.	When a study finds P2P platform violations, supervisory talks, warning letters, mandated corrections, notified criticisms, warnings, and fines are commonly employed to resolve the issues. The broad discussion is based on court records from 192 criminal cases, which strike a reasonable balance between encouraging financial innovation and safeguarding financial stability.	establishing a thorough regulatory framework that incorporates protections for financial innovation and improves real-time monitoring systems by fostering better cooperation between law enforcement, financial institutions, and regulatory bodies	10.1515/ijid-2019-2018

24	Comparative study of personal data protection regulations in Indonesia, Hong Kong, and Malaysia (Sudarwanto & Kharisma, 2022)	Sudaryanto & Kharisma, 2022)	Q1	This study uses a comparative, statute-based approach to legal research. The legal sources examined cover every rule pertaining to the protection of personal data.	Although Indonesia has the most valuable digital economy in Southeast Asia, data leaks are still a big worry. There are serious security issues in the financial technology industry, as evidenced by the 54 e-commerce, 27 peer-to-peer lending, and 5 electronic money breaches reported by the Indonesian Consumers Foundation.	Future research can examine Indonesia's creation of a thorough Personal Data Protection Act, which would provide more robust legal frameworks for data security. Moreover, creating a specific regulatory agency to monitor data security and compel adherence, is akin to Malaysian and Hong Kong models.	10.1108/JFC-09-2021-0193
25	Legal Aspects of Consumer Protection Regarding Credit Agreements Made Privately in Making Online Loans (Hendrawan & Putra, 2025)	Hendrawan, D., & Putra, P. K. (2025)	Q4	The study uses a qualitative legal research methodology with a doctrinal approach. Analyses legal frameworks and rules governing online lending, and uses secondary data sources such as laws, regulations, and legal literature.	According to the study, Indonesia's online lending laws offer rudimentary consumer protection, but there are shortcomings in terms of data security, contract validity, and enforcement. To increase confidence and equity in digital lending, it is imperative to fortify legal penalties, borrower rights, and regulatory supervision.	Future studies can examine how to improve digital contracts' legal validity and guarantee that they offer the same degree of protection under the law as real deeds. examining how upcoming banking rules may affect digital lending, especially in developing countries	10.47750/QAS/26.204.23
26	Funds sharing regulation in the context of the sharing economy: Understanding the logic of China's P2P lending regulation (Yu & Shen, 2019)	(Yu & Shen, 2019)	Q1	The main method utilized in this study is a comparative legal examination of P2P lending laws.	P2P lending platforms should avoid functioning as financial institutions or credit intermediaries, as this undermines the openness and inclusivity of the sharing economy. Additionally, P2P lending fosters risks such as regulatory arbitrage, enabling abusive financial practices.	Future studies can concentrate on creating a flexible regulatory framework that strikes a compromise between financial stability and innovation for peer-to-peer lending in China. Research can also examine how technology and international best practices can improve regulatory compliance and financial inclusion.	10.1016/j.dsr.2018.10.001
27	Fintech and access to finance (Bollaert <i>et al.</i> 2021)	Bollaert, H., <i>et al.</i> (2021).	Q1	the methodology appears to be a comprehensive and structured literature review, aiming to provide an up-to-date assessment of the state of research on fintech and access to finance.	Fintech improves access to capital for small business and startups, especially in markets with limited traditional funding. However, strong investor protection is essential, as many crowd investors remain inactive or fail to exercise their rights effectively. Transparency, founder reputation, and market conditions are major factors influencing in crowdfunding funding success.	The changing role of fintech in financial markets, as well as its difficulties and prospects for further scholarly investigation, are highlighted by these potential avenues for future research.	10.1016/j.jcorpfin.2021.101941
28	The Role of The Financial Services Authority in The Legal Protection of Privacy Rights in Connection with Personal Data of Fintech Lending Debtor in Indonesia (Priskarini & Tejomurti, 2020)	Priskarini <i>et al.</i> (2019)	Q3	Using a prescriptive normative research methodology, the study examines privacy protection in Indonesia's fintech lending industry by focusing on legal analysis and regulatory frameworks.	The study identifies more over 900 cases of legal and human rights violations, highlighting serious privacy concerns in fintech lending. Many registered fintech lenders fail to follow consumer protection standards highlight the urgent need for stronger legal frameworks and stricter enforcement to safeguard borrowers' privacy in Indonesia.	The study suggest establishing an Alternative Dispute Resolution Institution to address personal data privacy conflicts in fintech lending and strengthening OJK regulations to ensure better compliance among fintech lenders.	10.22304/pjih.v6n3.a7
29	Legal enforcement and fintech credit: International evidence (H. Peng <i>et al.</i> 2023)	Peng <i>et al.</i> (2023)	Q1	This comparative empirical study uses Regression models to analyse the impact of law enforcement on fintech credit pricing compared to traditional bank loans.	The examination of more than five million fintech loans from 24 countries reveals that legal protection is less important in fintech lending than in traditional bank loans. The study also reveals that fintech platforms provide minimal risk-sharing mechanisms, and regulations have a lower influence on fintech loan pricing.	Future research could look into how judicial efficiency affects fintech credit pricing and default rates across different legal systems. Comparative investigations of strong and poor enforcement frameworks may reveal whether tougher regulations and efficient courts reduce interest rates and credit risks, whilst additional research into risk management measures may increase fintech stability.	doi.org/10.1016/j.jempfin.2023.03.007

30	Bridging the credit gap: The influence of regional bank structure on the expansion of peer-to-peer lending(Eid <i>et al.</i> 2024)	Eid <i>et al.</i> (2024).	Q1	The study uses an econometric and quantitative empirical approach, including regression analysis, to examine the impact of regional bank presence on the growth of online lending marketplaces and the relationship between traditional banking networks and peer-to-peer lending	findings show that Online lending marketplaces increase credit scores, which benefits borrowers' financial security. They do not diminish borrower quality; rather, peer-to-peer lending lowers default risk by servicing creditworthy customers who are neglected by banks.	Future research should examine how regulators balance financial inclusion and consumer protection in P2P lending, analyse the influence of regional banking structures on its adoption, and evaluate how global regulatory differences effect its success and risks.	10.1016/j.bar.2024.101448
31	Estimating the probability of default via delinquencies? Evidence From European P2P Lending Market (Nigmonov <i>et al.</i> 2024)	Nigmonov <i>et al.</i> (2024)	Q1	The paper applied three LASSO techniques namely adaptive, cross-validation, and plug-in methods, to identify significant default variables and estimate default probability in P2P lending through a logit regression model.	The findings indicate that higher interest rates and stock market returns increase the likelihood of default in the P2P lending market. The study also shows that market conditions significantly influence loan survival, especially during the first 100 days after loan issuance.	Future research could improve LASSO models by incorporating advanced extensions, Exploring complex machine learning techniques such as XG-Boost, addressing casual interpretation issues, examining shocks, and expanding datasets to identify emerging patterns.	10.1016/j.gfi.2024.101050
32	Fintech in the time of COVID-19: Technological Adoption during crises. (J. Fu & Mishra, 2022)	Fu, J., Mishra, M., <i>et al.</i> (2022).	Q1	The study uses panel data regression models as its empirical technique and makes use of both historical and current data on mobile application downloads.	The analysis shows that the COVID-19 outbreak and government lockdowns significantly accelerated the adoption of lending apps and increased fraudulent lending practices. The sharp rise in the use of lending applications during this period highlights the urgent need for stricter regulatory oversight to protect consumers and maintain the integrity of fintech lending.	Future studies can examine how neobanks affect traditional banks' deposit bases, how they affect loan disbursements, and whether they have the capacity to limit credit. Additionally, more research can look at how digital lending apps can improve financial inclusion, especially in developing nations.	10.1016/j.jfi.2021.100945
33	Regulatory standards and consequences for industry architecture: The case of UK Open Banking (Dinçkol <i>et al.</i> 2023)	Dinçkol, D., <i>et al.</i> (2023)	Q1	The study uses a multi-level design and an inductive, grounded theory approach to examine the difficulties of Open Banking regulations and their effects on firms, inter-firms, and the industry.	The study finds that standardization changes over time as many stakeholders collaborate, but implementation issues reshape standards and industrial architecture. It also emphasizes the importance of data interchange and interoperability standards in shaping architecture within and between sectors	Future study can look into how improving financial literacy and trust in fintech services affects customer adoption trends. It may also investigate the effect of regulatory compliance and customer trust on fintech uptake and data-sharing policies.	10.1016/j.respol.2023.104760
34	The impact of the FinTech revolution on the future of banking: Opportunities and risks (Murinde <i>et al.</i> 2022)	Murinde, V., <i>et al.</i> (2022)	Q1	The study uses descriptive statistics to evaluate bank-level data collected from 115 nations over the last 16 years.	The study's initial results suggest that FinTech lenders are unlikely to displace traditional banks, as many institutions are establishing their own FinTech platforms or working with FinTech firms. The report also examines the impact of regulation, global infrastructure, and geopolitical conflicts on the future of banking..	As a result, empirical research is urgently required to give evidence of the evolving connection between banks and FinTech start-ups from the outbreak of COVID-19. It is also critical to investigate how FinTech technologies are changing customer experiences, particularly among underprivileged communities.	10.1016/j.irfa.2022.102103
35	Peer-to-peer lending: Legal loan sharking or altruistic investment? Analysing platform investments from a credit risk perspective. (Olvedi, 2023)	Dömötör, B., <i>et al.</i> (2023)	Q1	The study uses a quantitative research approach to examine the success of peer-to-peer (P2P) investments, the relevance of alternative data in credit risk assessment, and investor returns, utilizing loan-level data from Bondora.	The findings show that most P2P borrowers in Europe are high-risk, bank-ineligible consumers who accept excessively high interest rates. Despite these high rates, investors receive inadequate compensation for the associated credit risk.	Future research should focus on developing credit risk models, studying investor behaviour, and assessing regulatory developments in order to improve the sustainability and profitability of peer-to-peer lending.	10.1016/j.infin.2023.101801

36	Understanding how virtuous lenders encourage support for peer-to-peer platforms' prosocial initiatives (Pino <i>et al.</i> 2023)	Pino, G., <i>et al.</i> (2023).	Q1	This study employs a quantitative experimental research design to investigate the impact of virtuous lenders on users' willingness to fund prosocial activities on P2P networks.	The study suggests that P2P platforms can identify virtuous lenders by assessing their profiles or contacting them to evaluate their commitment to social and environmental issues. Highlighting these lenders can boost trust and encourage support for prosocial initiatives, but the effectiveness of these appeals depends on users' moral engagement levels.	Future research can look into how dynamic stimuli (e.g., video presentations) improve lender virtuousness and influence users' responses to prosocial messages. Furthermore, studies can look into whether lender virtuousness influences user trust and engagement in utilitarian services such as workspace or tool rentals	10.1016/j.jbusres.2023.114251
37	New but naughty. The evolution of misconduct in Fintech. (Brogi & Lagasio, 2024)	Brogi, M., <i>et al.</i> (2024)	Q1	This study uses complementary approaches, including bibliometric and scientometric analysis, and topic modelling. Bibliometrics, and its sophisticated application Scientometrics, is a quantitative method.	The study describes how financial misconduct, including data breaches and fraud, has evolved due to the rapid adoption of advanced technologies. It highlights that digital platforms have made fraud more complex and anonymous, leading to a shift in the nature of financial fraud. Essentially, as technology advances, fraudsters are finding new and more sophisticated ways to commit financial crimes.	Future investigations should concentrate on longitudinal studies in order to comprehend the long-term consequences of FinTech regulation reforms. Important tasks will include creating prediction models that can anticipate possible wrongdoing and investigating how well alternative regulatory strategies work in diverse cultural and economic circumstances.	10.1016/j.irfa.2024.103489
38	Research on the Fin Tech risk early warning based on the MS-VAR model: An Empirical Analysis in China (Bu <i>et al.</i> 2023)	Bu, Y., <i>et al.</i> (2023)	Q1	The paper analyses FinTech risk variations in China using the MS-VAR model because it captures nonlinear linkages between macroeconomic conditions and FinTech development that are difficult to express with typical linear models.	According to the survey, most of FinTech risks in China remain under control, with low-to-medium risk levels predominating. However, risk fluctuations are influenced by macroeconomic variables and external shocks. Therefore, strengthening regulatory frameworks and monitoring systems is essential to ensure long term financial stability.	Future studies should concentrate on creating adaptable regulatory sandboxes that include AI-driven risk monitoring, international comparison analyses, and sophisticated forecasting models for improved financial stability while striking a balance between FinTech innovation and risk mitigation.	10.1016/j.gfi.2023.100898
39	Explainable Fin Tech lending (Babaei <i>et al.</i> 2023)	Babaei <i>et al.</i> (2023)	Q2	The approach of the study uses Explainable Artificial Intelligence (XAI) with Shapley values and credit risk assessment models.	The study aims to balance predictive accuracy and explainability, ensuring credit scoring models are both effective and transparent. Empirical findings show that machine-learning models with explainable AI (XAI) can accurately predict SME investment risks while providing clear interpretations.	Future studies should evaluate the fairness of credit scoring algorithms by determining whether forecasts about nation and industry for SMEs are unbiased, as well as sensitive factors like gender and race in consumer loans. Ensuring such fairness improves transparency and regulatory compliance. This will help to promote the responsible use of AI in credit rating.	doi.org/10.1016/j.jeconbus.2023.106126
40	Mortgage lending through a fintech web platform. The roles of competition, diversification, and automation (Basten & Ongena, 2024)	Basten <i>et al.</i> (2024)	Q1	The methodology used in the study effectively combines unique data from a Swiss fintech mortgage platform with advanced econometric tools to assess bank reactions to mortgage applications. Using an instrumental variable (IV) technique, it separates the effect of competition.	Overall, the study shows how banks use online platforms to cross-sell financial goods in addition to financing mortgages. By facilitating diversity, boosting competition, and automating decision-making, fintech platforms are revolutionizing mortgage lending. Long-term profitability is ensured through client retention tactics.	Future studies might examine the ways in which fintech mortgage platforms affect long-term borrower behaviour, such as financial stability and refinance choices, in order to assess the effects of legislative changes and data privacy issues on fintech-based mortgage lending models.	DOI:10.2139/ssrn.3434966
41	Empirical analysis of the impact of financial technology on the profitability of listed banks (X. Tong & Yang, 2025).	Tong & Yang, (2025).	Q1	The study uses econometric modelling and sophisticated data analysis tools in an empirical research methodology to examine how financial technology (FinTech) affects listed banks' profitability.	FinTech is a major force behind the banking industry's change, increasing access to financial services, cutting costs, and improving efficiency. Although its effects fluctuate depending on the type of bank, its implementation greatly increases the profitability of commercial banks. Strategic policy measures are necessary to maximize its benefits and minimize its hazards.	Future research could examine how FinTech enhances financial access in rural and semi-urban areas, compare its impact on banks across countries to identify best practices and regulatory frameworks and assess its effectiveness in mitigating cyber risks, fraud, and data privacy concerns.	10.1016/j.jiref.2024.103788

42	Empowering MSMEs through digital lending (Damodaran <i>et al.</i> 2019)	Damodaran, S., <i>et al.</i> (2019)	IEEE	The study employs a descriptive and analytical methodology to assess the potential of digital financing for MSMEs in India, drawing on secondary data sources, industry publications, and comparative perspectives.	MSMEs have been underserved by traditional financial institutions because of their informal operations and lack of credit history. By removing conventional obstacles and facilitating faster, more effective credit access, digital lending is completely changing MSME financing in India.	Future studies should concentrate on strengthening credit risk assessment, expanding financial inclusion, and guaranteeing responsible lending practices in order to fully realize the potential of MSMEs in India.	10.1007/s40822-024-00280-0
43	Game Theory Analysis of Chinese DC/EP Loan and Internet Loan Models in the Context of Regulatory Goals. (Tu <i>et al.</i> 2023)	Tu, Y., <i>et al.</i> (2023)	Q1	The study uses numerical simulations, mathematical optimization, and game theory modelling to assess the effects of regulation and DC/EP on loan markets.	This study investigated financing methods that included bank DC/EP loans, internet finance loans, and their combination under government control. It also looked at how platform costs, collateral ratios, and leverage ratios impact financing decisions.	Future studies should examine the trustworthiness of DC/EP (Digital Currency/Electronic Payment) transactions to learn more about their function and effects on digital lending ecosystems and financial stability.	10.3390/su15097025
44	Fintech services and factors determining the expected benefits of users: Evidence in Romania for millennials and Generation Z (Dospinescu <i>et al.</i> 2021)	Dospinescu, O., <i>et al.</i> (2021)	Q2	The study offers a thorough statistical analysis of the factors affecting FinTech adoption. Data was gathered through a structured questionnaire.	According to the findings, the most important elements influencing Romanian Millennials and Gen Z's adoption of FinTech are cost reduction, security, and a variety of financial services. FinTech companies, banks, and legislators can use these insights to customize services that will increase client happiness and adoption rates.	Future research can focus on broadening the scope of the study internationally, carrying out comprehensive customer segmentation, integrating sophisticated adoption variables, assessing the effects of regulations, and investigating the psychological facets of FinTech adoption.	10.15240/tul.00112021-2-007
45	Strengthening Nigeria's Digital Money lending ecosystem (Monye, 2024)	Monye, O. (2024)	Q1	The study's methodology employed a doctrinal legal research strategy, which entails a thorough analysis of Nigerian laws, rules, policies, and legal frameworks pertaining to digital lending.	Finally, addressing abusive debt collection practices in Nigeria's digital lending market requires a comprehensive approach. This includes raising consumer knowledge and advocacy, encouraging lender compliance, and increasing regulatory oversight and enforcement.	These potential avenues for further study and policy can improve regulatory frameworks for a just, accountable, and sustainable digital lending environment in Nigeria while also balancing financial inclusion and consumer safety.	10.1007/s10603-024-09569-8
46	Digital disruptors at the gate. Does fintech lending affect bank market power and stability? (Cuadros-Solas <i>et al.</i> 2024)	Cuadros-Solas <i>et al.</i> (2024)	Q1	The study uses a unique dataset assembled from diverse sources and panel data regression models to look into how FinTech lending affects the stability and strength of the bank market.	According to the study, rising FinTech lending reduces traditional banks' market power and stability. Increased competition causes a loss in market power, whereas reduced stability is associated with riskier lending practices. Stronger rules and institutional protections are required to ensure financial stability in an ever-changing environment.	Overall, the study sets the path for additional research on FinTech's impact on financial stability, competition, and regulation, with a focus on policy interventions and technology improvements.	10.1016/j.intfin.2024.101964
47	A Survey of fintech research and policy discussion. (Allen, 2021)	Allen <i>et al.</i> (2021)	Q1	The approach of the study appears to be a mix of empirical research and policy/survey analysis. The report uses data from multiple countries to investigate critical fintech subjects like cybersecurity threats, cloud computing, and regulatory approaches.	The study emphasizes FinTech lending's disruptive role in the financial industry, which provides the benefits of more competition while also posing significant hazards to financial security. While it improves loan availability, it also poses issues that necessitate close regulatory control.	Future studies may investigate the effects of developing technology on financial services and regulatory systems. Advanced cybersecurity, fraud detection, and regulatory responses to cyber hazards should all be explored.	10.1561/114.00000007
48	What's in the black box? Balancing financial inclusion and privacy in digital consumer lending? (Chou, 2020)	Chou <i>et al.</i> (2019).	Q1	Methodology includes a review of current financial regulations, case studies, and legal analysis.	FinTech lenders make financing more accessible to those with poor credit, but questions about transparency remain. To find a balance between innovation and consumer rights, more data security and regulatory safeguards are essential.	The future scope of this research could concentrate on improving openness and justice in digital lending through increased algorithmic accountability. Further research could look into the construction of counterfactual explanation models to ensure compliance with anti-discrimination laws and ethical AI practices in FinTech lending.	

49	Risk and performance in technology service platform of online peer-to-peer (P2P) model (Njatrijani & Prananda, 2020)	Njatrijani <i>et al.</i> (2020).	Q1	The study takes a doctrinal legal research approach, studying laws, rules, and legal concepts affecting peer-to-peer lending	P2P lending's unfinished regulatory framework presents dangers to consumers and difficulties for enforcement. To assist consumers in reducing the risk of losses from digital loans, the government ought to encourage financial literacy.	Future studies can focus on strengthening regulations to fill gaps in loan interest rates, debt collection processes, and dispute resolution. Research can also develop advanced risk assessment models to assess borrower creditworthiness beyond traditional financial metrics.
50	Determinants of defaults on P2P lending platforms in China, (Gao <i>et al.</i> 2021)	Gao <i>et al.</i> (2021).	Q1	The study employs a Failure Prediction Model and Decomposition Methods to identify the elements that contribute to default in Chinese P2P lending platforms.	The results show that the primary reason of defaults is decomposed factors. Bond yield affects platform health, however platforms with lower interest rates, longer maturities, and greater popularity are more stable.	Future studies examine how asymmetric information affects risk perception and platform stability, aiding in better risk management, regulatory improvements, and investment security in P2P lending.

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5. Discussions

This comprehensive analysis summarizes key research findings related to online lending, including P2P lending, fintech regulations, default risks, credit scoring, and legal aspects. The rapid growth of fintech lending is reshaping the traditional banking industry by increasing competition and reducing the market power of conventional financial institutions. Studies such as Cuadros-Solas *et al.* (2023) and Eid *et al.* (2024) state that P2P lending improves financial inclusion, particularly in underserved regions where traditional banks services are limited. However, the impact of fintech lending on banking stability differs across countries and regions. Similarly, Cornelli *et al.* (2023) note that fintech credit performs more successful in high-GDP countries, while Murinde *et al.* (2022) suggest that traditional banks are responding to this transformation by integrating fintech solutions into their services. Fu, J., Mishra, M., *et al.* (2022) further highlight that the COVID-19 pandemic and related lockdowns significantly accelerated the use of financial applications and fraudulent lending practices.

The regulatory landscape for P2P lending varies considerably across regions, with some countries implementing strict transparency measures while others countries to face enforcement gaps. Bollaert, H., *et al.* (2021) explain that public participants often to exercise their legal rights effectively or remain inactive, weakening consumer protection mechanisms. Similarly, Isaputra (2023) found that individuals with high risk-control preferences are generally less likely to choose P2P lending platforms; however, strong borrowing needs often encourage them to continue using such services despite potential risks. Several studies emphasize the urgent need for stronger regulations to ensure transparency, fair lending practices, and consumer protection in fintech lending. According to Suryono *et al.* (2021), online lending platforms face issues such as low user awareness, data leakage, personal data misuse, illegal fintech operations, and unethical marketing practices. In addition, Albarrak *et al.* (2021) identify Technology developers, as one of the weakest links, in the fintech ecosystem, emphasizing the need for better education and technical training to improve system capabilities. Studies by Purba *et al.* (2025) and Zhang *et al.* (2025) further discuss how regulations in countries such as England, Indonesia, and China seek to balance innovation and financial stability. However, restrictive policies and inconsistent regulatory practices often limited fintech growth and create challenges for fair lending practices. likewise, Liu *et al.* (2024) and Angkasa *et al.* (2023) reveal that many fintech platforms in China and Indonesia continue operating without proper legal oversight, while Hidajat (2020), highlights legal gaps and weak enforcement in Indonesia that allow unethical lending practices to persist. A significant portion of the research focuses on default risks and credit assessment models in P2P lending markets. The findings indicate that loan defaults remain a major challenge due to factors such as high interest rates, unfavorable economic conditions, and borrower characteristics. Dömötör *et al.* (2023) further reveal that the online lending market faces a significant imbalance in which high-risk borrowers pay excessively high interest rates, while investors receive inadequate returns for the associated credit risk. Li *et al.* (2019) and Nigmonov *et al.* (2024) employ regression models and machine learning techniques such as LASSO to predict default risks, emphasizing that many borrowers use P2P loans to refinance existing debts rather than for productive new investments. Gao *et al.* (2021) further highlight that bond yields and platform interest rates significantly influence loan performance, indicating that macroeconomic conditions play a crucial role in determining default probability.

Ethical concerns surrounding fintech lending also emerge as a recurring theme across multiple studies. Research by Darma *et al.* (2019) and Priskarini *et al.* (2019) identifies serious data privacy issues and widespread consumer rights violations in Indonesia's P2P lending market. Wang *et al.* (2018) explain that unregulated online lending contributes to bankruptcy filings, as borrowers engage in high-risk borrowing behavior. Similarly, Monye (2024) highlights abusive debt collection practices in Nigeria's digital lending sector and calls for stronger consumer protection laws and regulatory oversight. The role of emerging technologies such as AI, blockchain, and explainable AI (XAI) is becoming increasingly important in fintech lending. Babaei *et al.* (2023) and Liu *et al.* (2024) highlight the increasing adoption of AI-based credit scoring models, that aim to balance predictive accuracy with transparency. Bu *et al.* (2023) discuss how China's regulatory framework is evolving through AI-powered risk monitoring systems, while Rosdini *et al.* (2024) explore governance structures in ASEAN P2P lending markets. In addition, Pino, G., *et al.* (2023) suggest that P2P platforms can identify responsible lenders by evaluating lender profiles and their commitment to social and environmental issues, which may help reduce lending-related risk. Similarly, Allen *et al.* (2021) state That fintech lending is disrupting the financial sector by increasing competition while simultaneously creating risks to financial stability. Njatrijani *et al.* (2020) further emphasize that incomplete regulatory frameworks for P2P lending create challenges for customers protection and law enforcement challenging.

Overall, the studies show that fintech and P2P lending have enhanced financial inclusion and competitiveness in the financial sector, but they also pose substantial issues in terms of default risk, consumer protection, data privacy, and regulatory compliance. The findings emphasize the growing need of AI-powered credit

evaluation, greater governance structures, and balanced laws in ensuring sustainable and ethical fintech lending processes.

This study integrates regulatory, technological, ethical, and financial viewpoints into a unified analytical framework, in contrast to earlier review studies that concentrated on distinct aspects of fintech lending. In order to provide a more comprehensive picture of the digital lending ecosystem, the thematic concept matrix further identifies research emphasis areas and understudied fields like consumer protection, borrower behavior, and AI-driven default prediction.

Thematic concept matrix

Author/Year	Regulations	Unethical practice	Risk Mitigation/Technology	Financial-inclusion-literacy	Consumer Protection/Protection	Default Loan/Credit/Risks
Purba <i>et al.</i> (2025)	✓	—	✓	—	✓	—
Zhang <i>et al.</i> (2025)	✓	—	✓	—	✓	—
Angkasa <i>et al.</i> (2023)	✓	✓	✓	—	—	—
Liu <i>et al.</i> (2024)	✓	✓	✓	✓	✓	—
Hidajat, (2020)	✓	✓	✓	—	✓	—
Huang, & Pontell, (2023)	✓	✓	✓	—	—	—
Suryono <i>et al.</i> (2021)	✓	✓	✓	✓	✓	—
Luther, (2019)	✓	✓	—	—	✓	—
Li <i>et al.</i> (2019)	✓	—	—	—	✓	✓
Rosdini <i>et al.</i> (2024)	✓	—	—	✓	—	—
Cuadros-Solas <i>et al.</i> (2023).	✓	✓	✓	—	—	—
Santoso <i>et al.</i> (2020).	✓	✓	—	—	✓	✓
Budiharto, <i>et al.</i> (2019)	—	✓	✓	—	✓	—
Comelli, <i>et al.</i> (2023).	✓	✓	—	✓	—	—
Albarrak <i>et al.</i> (2021)	—	—	✓	—	✓	—
Kaushik <i>et al.</i> (2020)	—	—	✓	✓	—	—
Katsamakos <i>et al.</i> (2024)	✓	✓	✓	—	—	✓
Darma <i>et al.</i> (2019)	✓	✓	—	—	✓	—
Basha <i>et al.</i> (2021).	✓	✓	—	—	—	—
Wang <i>et al.</i> (2018).	—	—	✓	✓	✓	—
Yuspin <i>et al.</i> (2023)	✓	—	✓	✓	—	—
Isaputra, (2023)	✓	✓	—	—	—	✓
(Peng <i>et al.</i> 2019)	✓	✓	—	✓	—	—
Sudarwanto & Kharisma, (2022)	✓	✓	—	—	✓	—
Hendrawan, & Putra, (2025)	✓	—	✓	✓	✓	—
(Yu & Shen, 2019)	✓	✓	—	✓	—	—

Author/Year	Regulations	Unethical practice	Risk Mitigation/ Technology	Financial-inclusion-literacy	Consumer Protection/Protection	Default Loan/Credit/Risks
Bollaert, <i>et al.</i> (2021).		✓	—	✓	—	
Priskarini <i>et al.</i> (2019)	✓	✓	✓	—	✓	—
Peng <i>et al.</i> (2023)	✓	—	✓	—	—	✓
Eid <i>et al.</i> (2024).	✓	—	—	✓	✓	✓
Nigmonov <i>et al.</i> (2024)	—	✓	✓	—	—	—
Fu, <i>et al.</i> (2022).	✓	✓	—	✓	—	—
Dinçkol, <i>et al.</i> (2023)	✓	—	—	✓	✓	—
Murinde, <i>et al.</i> (2022)	✓	—	—	✓	✓	—
Dömötör, <i>et al.</i> (2023)	✓	✓	✓	—	—	—
Pino, <i>et al.</i> (2023).	—	—	✓	—	✓	—
Brogi, <i>et al.</i> (2024)	✓	✓	—	✓	—	—
Bu, <i>et al.</i> (2023)	✓	—	✓	✓	—	—
Babaei <i>et al.</i> (2023)	✓	—	✓	—	—	—
Basten <i>et al.</i> (2024)	✓	✓	—	✓	—	—
Tong & Yang, (2025).	✓	✓	✓	—	—	—
Damodaran, <i>et al.</i> (2019)	—	—	✓	✓	—	—
Tu, <i>et al.</i> (2023)	✓	—	✓	✓	—	—
Dospinescu, <i>et al.</i> (2021)	✓	—	—	—	✓	—
Monye, (2024)	✓	✓	—	✓	✓	—
Cuadros-Solas <i>et al.</i> (2024)	✓	✓	✓	✓	—	—
Allen <i>et al.</i> (2021)	✓	✓	✓	—	—	—
Chou <i>et al.</i> (2019).	✓	✓	✓	—	✓	—
Njatrijani <i>et al.</i> (2020).	✓	✓	✓	✓	—	—
Gao <i>et al.</i> (2021).	—	✓	✓	—	—	✓
Total	41	31	30	23	22	8

Research on online digital lending based on 50 selected papers has reveals a strong emphasis on regulatory aspects and risk mitigation. Among these studies focused on regulations, 31 highlighting unethical practices, and 30 emphasized the need for technological advancements to mitigate risks. Meanwhile, 23 studies examined financial inclusion. However, consumer protection and default risk analysis remain comparatively underexplored, with only 22 and 8 studies addressing these areas, indicating significant scope for further research.

Conclusion

The research provides a comprehensive overview of the digital lending landscape, focusing on the evolution of fintech, P2P lending platforms, and regulatory frameworks across different regions. The study additionally contributes to the literature by using a thematic synthesis approach that categorizes existing research into important

dimensions such as legislation, unethical activities, financial inclusion, technology risk reduction, consumer protection, and default risks. This framework identifies existing research gaps and emerging future directions in digital lending research. The findings highlight that many fintech platforms continue to operate with inadequate legal oversight, despite their significant contribution to improving financial inclusion, particularly in underserved markets. The review also highlights major concerns such as unethical lending practices, insufficient consumer protection, data privacy issues, and regulatory loopholes within the digital lending ecosystem. This study emphasizes the importance of developing stronger and globally harmonized regulatory framework to reduce risks and ensure sustainable fintech growth. Emerging technologies such as artificial intelligence and blockchain have the potential to improve compliance, monitoring fraud detection, credit assessment, and operational transparency.

However, challenges related to regulatory enforcement, transparency and ethical lending practices still remain significant. The review further indicates that existing research has primarily concentrated on regulations and risk mitigation, while comparatively less attention has been given to consumer protection, customer satisfaction, default risk analysis, and AI-driven credit scoring models. In addition, the absence of uniform global regulations creates disparities in lending practices, borrower rights, and risk management approaches across countries. One significant disadvantage of this study is its primary focus on regulatory difficulties and unethical behaviors in online lending, which presents a narrow but concentrated view of the larger digital lending ecosystem. To gain a more comprehensive understanding of the evolving fintech and P2P lending industries, future research should look into advanced risk assessment models, AI-based credit evaluation, borrower behavior, default prediction, customer satisfaction, and the long-term socioeconomic impact of digital lending platforms.

Future research directions

Future studies should adopt a multidisciplinary approach, incorporating borrower behaviour analysis, financial inclusion and platform sustainability to provide a more comprehensive assessment of online lending ecosystems. Further empirical research is also needed to evaluate long-term financial stability of P2P lending platforms, particularly in relation to credit scoring mechanism and default risks management. Moreover, future research should explore how P2P platforms can identify responsible and trustworthy lenders through profiles analysis and directly engagement to assess their commitment to social and environmental responsibilities. In addition, fintech firms have significant potential to expand financial access in regions with limited banking services by offering innovative financial solutions while implementing effective recovery mechanisms and sustainable risk mitigation practices.

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Credit-Investment Space of Ukraine's Regions and Institutional Mechanisms for Its Transformation in the Context of Economic Resilience



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Abstract: This article examines the impact of the credit-investment space on regional economic resilience, taking into account the transformative role of institutional quality. The methodological framework is based on a phased approach that combines the development of integral indices and panel econometric modelling. The empirical analysis is based on regional data for 2020–2024. Aggregating indicators of lending, investment, and financial infrastructure constructed the credit-investment space index. The assessment was conducted using a panel model with regional and time fixed effects, supplemented by an analysis of marginal effects. The results confirm a statistically significant positive impact of financial space on economic resilience: a one-standard-unit increase in the index increases resilience by 17–21%, consistent with estimates from economies with transformational and peripheral regions. In the crisis year of 2022, the negative shock reduced economic stability by approximately 30%, but institutional factors partially offset this effect. The positive coefficient of interaction between financial space and institutional quality confirms the existence of a multiplicative stabilisation effect. The results obtained may be useful for the regions of Central and Eastern Europe, the Balkans and other economies facing asymmetric access to financial resources and increased crisis vulnerability.

Keywords: credit-investment space; economic resilience; institutional mechanisms; financial space; panel econometric analysis; regional development.

JEL Classification: R11; O16; O17; E32; C01.

Introduction

Global economic crises, financial instability, and geopolitical shocks have heightened the importance of financial development for regional economic resilience. Current studies identify regional access to credit and investment resources as a critical factor for economic adaptation to systemic disruptions. In this context, Ukraine's ongoing economic transformations further underscore the importance of regional financial growth in maintaining resilience. The intensification of spatial disparities in access to financial resources highlights the problem of the effective functioning of the credit-investment space in the regions. In the context of military and macroeconomic shocks, the financial space of regions is undergoing structural changes that require systematic scientific analysis.

Global data show that regions with greater financial depth recover faster from crises, with economic resilience 15–30% higher (World Bank, 2024). In countries with transitional economies, a 10% reduction in lending reduces regional economic activity by an average of 2–3% (International Monetary Fund, 2024). Analytics show that high institutional quality in subnational governance enhances the impact of financial resources and reduces regional GDP losses during crises (Organisation for Economic Co-operation and Development, 2023). In this

context, Ukraine's experience aligns with global trends, in which a combination of financial depth and institutional capacity determines regional economic stability (World Bank, 2024; International Monetary Fund, 2024).

Existing studies mainly focus on the national level, leaving aside the regional dimension of credit and investment processes. Institutional mechanisms for transforming the financial sector to ensure economic stability in regions remain insufficiently studied. In this context, it is important to analyse the role of the credit-investment space and institutional factors in shaping the economic stability of Ukraine's regions. It is particularly important to understand how the institutional environment modifies the impact of financial resources in crisis conditions.

The article aims to assess the impact of the credit-investment space in Ukraine's regions on their economic stability, taking into account mechanisms of institutional transformation. To achieve this goal, the following tasks have been set: (1) to develop an integrated indicator of the credit-investment space and build a panel econometric model; (2) to analyse the dynamics of the impact of financial and institutional factors on the economic stability of regions in the period 2020–2024; (3) to assess the marginal effects of the credit and investment space on the economic stability of regions in different phases of the economic cycle 2020–2024; (4) analyse the transformative role of institutional quality in mitigating the negative impact of the 2022 systemic shock on regional economic stability. The study is based on the hypothesis that the expansion of credit-investment space has a positive impact on the economic stability of Ukraine's regions. An additional hypothesis is that institutional quality enhances the stabilising effect of financial resources. It is assumed that institutional mechanisms play a compensatory role during crises.

The article's scientific novelty lies in its comprehensive integration of financial and institutional approaches to the analysis of regional development. An econometric assessment of the marginal effects in the credit-investment space is proposed, accounting for institutional interaction. The results obtained expand the theoretical understanding of regional financial space and provide an empirical basis for regional economic policy. This is different from the previous studies mainly focused on the financial development or institutional quality, which study them separately at the regional level. The study also makes a contribution by creating a composite Credit-Investment Space Index and calculating the marginal effects in crisis conditions. Special focus is given to the time period of the war, 2022–2024, which has been largely underrepresented in the existing empirical literature. The framework proposed here allows for a more holistic understanding of economic resilience at regional level in transition economies in the face of systemic shocks.

1. Literature Review

Scientific literature on the credit-investment space and its role in ensuring regional economic stability is organised into two interrelated analytical trajectories: macro-financial attractiveness and regional institutional capacity. The first trajectory focuses on capital inflows and investor confidence. At the same time, the second trajectory focuses on how institutions transform financial resources into sustainable development.

Research on entrepreneurship in economics focuses on the institutional component, which is important for credit and investment. Sitnicki *et al.* (2024a) argue that developing and supporting domestic entrepreneurship is a condition for economic dynamism. Their conclusions are consistent with our idea that institutional capacity enhances the return on financing. However, in these conclusions, institutions are often presented as a “framework” without operationalisation through budgetary autonomy or financial infrastructure. That is why regional analysis requires proxies for institutional quality related to fiscal and budgetary practices.

The institutional dimension of decentralisation as a factor in regional development is empirically highlighted by Davydenko *et al.* (2022). The authors demonstrate that decentralisation changes the conditions for rural development, reinforcing the importance of local capacity. This approach is close to our institutional-strengthening logic but less focused on credit channels. In the credit-investment space, this means integrating the effects of decentralisation with lending and investment indicators. Thus, the institutional environment acts not as a backdrop, but as a transformational mechanism for financial flows.

While both studies emphasise the importance of institutional capacity, they differ in their interpretation of its economic function. Sitnicki *et al.* (2024a) primarily associate institutional development with entrepreneurial dynamism and knowledge-based growth, whereas Davydenko *et al.* (2022) focus on decentralisation and local governance effectiveness. These perspectives are complementary rather than contradictory, yet neither study explicitly explains how institutional capacity affects the allocation and efficiency of regional financial resources.

Sectoral investment studies provide important insights into the structure of capital demand and sustainability. Sotnyk *et al.* (2022) justify optimal investment directions for regional renewable energy development. Their findings reinforce the argument that investments have a sustainability effect but depend on priorities and coordination. Stoliarchuk *et al.* (2026) show that attracting investment in the modernisation of dairy enterprises can serve as a

tool for sustainable development. Both approaches share the idea of “investment-sustainability” but differ in their channels and time lags. For our article, this highlights the importance of controlling the structure of the region’s economy in the panel model.

Despite their shared emphasis on investment-led development, the studies differ substantially in sectoral focus and expected outcomes. Sotnyk *et al.* (2022) view investment as a driver of ecological and energy transition, whereas Stoliarchuk *et al.* (2026) concentrate on productivity enhancement in the agricultural sector. This divergence suggests that the effectiveness of investment depends not only on its volume but also on its sectoral allocation, a factor that is often overlooked in broader regional analyses.

The environmental component of financing and European integration incentives reflects institutional shifts in the investment space. Labenko *et al.* (2024) analyse the effectiveness of financing for environmental protection measures in the context of Ukraine’s future EU membership. Their conclusions support the view that regulatory convergence alters the motivation and discipline behind financial decisions. However, the paper does not clearly trace the link with the credit segment and banking intermediation. Bublyk *et al.* (2021) examine the transformation of Ukraine’s economy towards circularity using a cluster approach with fuzzy logic. Their conclusions are useful for understanding regional structural heterogeneity, but they do not provide a direct assessment of credit and investment channels.

A notable difference between these approaches lies in the role assigned to institutions. Labenko *et al.* (2024) interpret institutional transformation mainly through regulatory convergence with EU standards, whereas Bublyk *et al.* (2021) focus on structural adaptation processes within the economy. Although both studies acknowledge the importance of institutional change, they offer different explanations of how such changes influence regional development trajectories.

The foreign trade context is important because export and import activity affects investment incentives and risks in regions. Malyarets *et al.* (2025) propose an approach to assessing export and import activity based on Ukrainian data. Their results emphasise that openness can boost revenues but also increases vulnerability to external shocks, which means that resilience depends not only on finances but also on trade structures. Therefore, it is advisable to include sectoral and trade proxies in the set of controls.

This perspective contrasts with studies that primarily attribute regional resilience to financial factors. While trade openness may generate additional investment opportunities, it can simultaneously increase exposure to external volatility. Consequently, the literature remains divided on whether openness strengthens resilience or creates additional vulnerabilities under crisis conditions.

The comparison of these strands of literature reveals an important conceptual distinction. Financial-development studies generally assume that increased access to capital automatically improves economic outcomes, whereas institutional approaches argue that financial resources generate positive effects only when supported by effective governance mechanisms. The absence of an integrated framework combining both dimensions remains one of the key unresolved issues in the literature.

In summary, existing studies agree on the importance of investment and institutions for development, but differ in the level of analysis and operationalisation of mechanisms. Macro studies on attractiveness and capital markets are less sensitive to regional disparities and institutional interactions (Kostyrko *et al.* 2022; Plastun *et al.* 2024). Decentralisation and entrepreneurial studies are stronger institutionally but weaker in measuring credit and investment channels (Davydenko *et al.* 2022; Sitnicki *et al.* 2024b). Sectoral studies demonstrate the sustainability potential of investments, but need to be generalised to the regional financial space (Sotnyk *et al.* 2022; Stoliarchuk *et al.* 2026). This gap justifies our approach, in which the credit and investment space and institutional quality are assessed jointly in a panel model.

Teresienė *et al.* (2021) show that the credit transmission channel supports sustainable economic growth, provided that financial stability is maintained during crises. The authors emphasise the link between access to credit and macrofinancial stability, viewing the financial system as a stabilisation mechanism. Ullah *et al.* (2021) focus on the role of financial and institutional resources in reducing inequality and poverty through effective allocation. Unlike the finance-oriented approach of Teresienė *et al.* (2021), Ullah *et al.* (2021) emphasise institutional complementarity as a condition for sustainable socio-economic development.

Although both studies acknowledge the importance of financial systems for development, their causal explanations differ. Teresienė *et al.* (2021) focus on the stabilising role of financial intermediation itself, whereas Ullah *et al.* (2021) suggest that financial resources alone are insufficient without supportive institutional arrangements. This distinction is particularly relevant for transition economies, where institutional weaknesses often limit the effectiveness of financial instruments.

The focus on Ukraine's investment attractiveness as a dominant factor in foreign direct investment (FDI) inflows is consistently revealed by Kostyrko *et al.* (2022). The authors emphasise the role of assessing and ranking attractiveness parameters for the European investment space. At the same time, their approach is less sensitive to regional heterogeneity and to local-level transformation mechanisms. For our topic, this means that the macro-logic of FDI needs to be supplemented with institutional determinants relevant to the regions. In contrast, Plastun *et al.* (2024) demonstrate the transformational features of the Ukrainian stock market through data properties. Their perspective shifts the focus from the "attractiveness" to the "functionality" of the financial market.

These studies represent two different approaches to analysing financial development. Kostyrko *et al.* (2022) evaluate financial systems from the perspective of attracting external capital, whereas Plastun *et al.* (2024) focus on internal market efficiency and structural transformation. The contrast between these approaches indicates that investment attractiveness alone may not fully reflect the capacity of financial systems to support regional resilience.

Existing studies confirm the importance of financial and institutional factors, but they mainly focus on the macro level or individual sectors of the economy. The regional dimension of the credit-investment space remains fragmentarily researched, especially in the context of systemic crises and military shocks. There is a lack of empirical work that combines panel econometric modelling with the assessment of institutional interaction over time. This necessitates further research using longer time series and cross-country comparisons. Another limitation of the existing literature is the predominance of static assessments that do not adequately capture institutional adaptation during periods of severe crisis. As a result, the dynamic interaction between financial development and institutional transformation remains insufficiently explored.

While there has been a considerable amount of work on financial development, investment attractiveness and institutional quality, there are still numerous gaps in the literature. Most previous studies have either examined the national level of financial development or studied financial development in specific sectors of the economy, and thus do not offer much evidence on regional variation in financial resource availability. The processes by which the credit and investment environment in a region affects economic resilience are thus not well understood.

Moreover, empirical findings are not always consistent. Some studies report strong positive effects of financial deepening on regional development, while others suggest that these effects weaken significantly in the absence of institutional support. This inconsistency highlights the need for integrated analytical frameworks capable of capturing both financial and institutional dimensions simultaneously.

Secondly, previous studies mostly focus on each of the two variables, financial factors or institutional quality, individually. While there is recognition in studies of the importance of institutions for economic development, little empirical research has focused on the relationship between financial resources and institutional capacity in a common analytical framework.

Third, most empirical research is conducted in times of relative economic stability. There is limited information available on how the regional financial systems operate during the systemic shocks, military disruptions and increased uncertainty, especially in transition economies.

The present study has several merits in the literature. First it generates a composite Credit-Investment Space Index (CISI) at the regional level which incorporates the intensity of lending, intensity of investments, and financial infrastructure indicators. Second, it develops an institutional quality index and explicitly examines the financial-institutional interaction. Third, it applies panel data for Ukrainian regions in 2020-2024 to empirically show that the impact of financial resources on the economic resilience is moderated by institutional capacity, both in a crisis and in a post-crisis context. This approach builds on the literature that already incorporates financial and institutional factors in a single econometric model and studies regional resilience during unprecedented economic events.

The results obtained are of practical value for the development of regional financial policy, as they enable a quantitative assessment of the financial system's stabilising effect, accounting for institutional quality. For public authorities, the results are useful in developing anti-crisis instruments for regional development and the distribution of financial resources in periods of instability. For financial institutions and investors, the results highlight the role of the institutional environment in reducing regional risks. For academic research, the article offers an empirical approach to analysing the complementarity of financial and institutional factors at the regional level.

Within these approaches, economies that are highly sensitive to internal and external shocks and in which the role of the institutional environment is pronounced are of particular interest. In this context, Ukraine's experience is a relevant example for analysing the interaction between the financial system and institutional mechanisms under crisis conditions. Regional heterogeneity, a combination of macroeconomic and military shocks, and asymmetric access to financial resources make Ukraine a representative empirical case. Thus, Ukrainian material complements the broader international discussion on the mechanisms of economic stability in regions. Unlike many previous

studies conducted in relatively stable institutional environments, the Ukrainian case provides an opportunity to observe how financial and institutional mechanisms interact under conditions of prolonged uncertainty and systemic disruption. This makes it possible to test the robustness of theoretical assumptions developed primarily for more stable economies.

2. Methods and Methodology

Research Procedure. The study uses a step-by-step approach to analyse the credit-investment space of regions and its impact on economic stability. The methodological logic combines conceptual justification, the formation of integral indicators, and econometric testing of hypotheses. This approach ensures consistency between theoretical propositions and empirical results. The research process is structured in four interrelated stages (Table 1).

Table 1. Stages of methodological support for the study

Stage	Stage content	Methodological tools	Result
1	Conceptualisation of the credit-investment space	Theoretical analysis, systematisation	Analytical model of financial space
2	Formation of integral indices	Normalisation, aggregation of indicators	CISI and institutional quality indices
3	Econometric modelling	Panel regression with fixed effects	Quantitative assessment of impacts
4	Interpretation and comparative analysis	Dynamic and marginal analysis	General conclusions and recommendations

Source: authors' development.

Sample Formation. The study's empirical basis is panel data for Ukraine, by region, for 2020–2024. The sample covers 24 administrative regions of Ukraine, excluding temporarily occupied territories due to the limited availability of complete statistical data. This approach ensures a balanced panel and minimises bias in the results associated with missing observations. The total sample size is 120 regional-annual records, covering 24 regions over five years. The number of observations is sufficient to evaluate fixed-effects models and verify the stability of the results. The regional level of analysis was chosen to identify spatial heterogeneity in the formation of the credit and investment space. It is at the regional level that differences in access to bank lending, investment resources and financial infrastructure are concentrated. National aggregate indicators do not identify these imbalances or their impact on economic stability.

The sample analysed indicators of bank lending to businesses, capital investment volumes, and the level of financial infrastructure provision across regions. The credit-investment space index was developed based on relative indicators of loans and investments to gross regional product. Data on regional bank lending were obtained from the National Bank of Ukraine's statistical materials. In contrast, indicators of capital investment and gross regional product were obtained from official publications of the State Statistics Service of Ukraine. Information on budget capacity, financial autonomy, and intergovernmental transfers was drawn from data from the Ministry of Finance of Ukraine and the State Treasury Service of Ukraine. To ensure comparability and international consistency, individual indicators were verified using World Bank and OECD databases. The institutional quality of the regions was reflected in indicators of budgetary capacity, financial autonomy and the effectiveness of inter-budgetary transfers. An integrated index combining the dynamics of production, employment and household income was used to assess economic sustainability.

The period from 2020 to 2024 encompasses several qualitatively distinct phases of economic dynamics across Ukraine's regions. 2020–2021 reflect a relatively stable pre-crisis stage with a gradual recovery of financial activity. 2022 is characterised by a systemic shock that significantly disrupted the functioning of regional financial and investment mechanisms. 2023–2024 reflects a phase of adaptation and structural restructuring of regional economies. This time horizon allows us to assess the transformational impact of the credit and investment space under conditions of instability. It also allows us to identify changes in the role of institutional mechanisms in different macroeconomic phases. The study uses secondary official statistical data from state and international institutions. This ensures methodological consistency of indicators in temporal and spatial dimensions. The chosen approach to sample formation increases the reliability of econometric estimates and the representativeness of the results obtained.

Econometric Model Specification. A panel regression model with fixed effects was used to assess the impact of the credit-investment space on regional economic stability. The model is based on a combination of regional and temporal dimensions, allowing for spatial and dynamic heterogeneity. Regional fixed effects control

for time-invariant regional characteristics, including historical economic structure and institutional legacy. Time fixed effects capture nationwide macroeconomic shocks and cyclical fluctuations.

The basic specifications of the model are as follows:

$$Resit = \alpha + \beta_1 CISI_{it} + \beta_2 Inst_{it} + \beta_3 (CISI_{it} \times Inst_{it}) + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

where:

- Res_{it} - composite economic resilience index for region i in year t , capturing the ability to absorb and adapt to economic shocks;
- $CISI_{it}$ - credit-investment space index reflecting regional access to credit, investment flows, and financial depth;
- $Inst_{it}$ - institutional quality index representing fiscal capacity, financial autonomy, and governance effectiveness at the regional level;
- $CISI_{it} \times Inst_{it}$ - interaction term capturing the transformational role of institutions in enhancing the effectiveness of financial resources;
- X_{it} - vector of control variables, including income per capita, unemployment rate, and sectoral economic structure;

- μ_i - region-specific fixed effects controlling for time-invariant regional characteristics;
- λ_t - year fixed effects capturing nationwide macroeconomic shocks and policy changes;
- ε_{it} - stochastic error term;

- β_1 - measures how expansion of the credit-investment space improves regional economic resilience;
- β_2 - reflects the direct stabilising effect of institutional quality on regional economic performance;
- β_3 - captures the synergistic effect between financial resources and institutional capacity;

Expected signs:

- $\beta_1 > 0$ - a deeper credit-investment space enhances regional economic resilience;
- $\beta_2 > 0$ - stronger institutions improve stability and adaptive capacity;
- $\beta_3 > 0$ - institutional quality amplifies the effectiveness of financial resources;

The fixed-effects specification was chosen over random effects based on the Hausman test results, which indicate a correlation between regressors and unobserved regional heterogeneity. This approach isolates regional variation over time, allowing a consistent assessment of how changes in credit and investment conditions affect economic stability. The inclusion of an interaction term provides insight into how institutional transformation shapes financial performance.

Composite Index Construction, Validation and Robustness Checks. To enhance methodological transparency, both the Credit-Investment Space Index (CISI) and the Institutional Quality Index (Inst) were constructed using a standardised composite indicator approach.

The CISI incorporates three dimensions of regional financial development:

- 1) business loans to gross regional product;
- 2) capital investments to gross regional product;
- 3) financial infrastructure availability.

The institutional quality index includes:

- 1) local fiscal capacity;
- 2) financial autonomy of local governments;
- 3) effectiveness of intergovernmental fiscal transfers.

All variables were standardised using z-score normalisation:

$$Z_{it} = \frac{X_{it} - \bar{X}}{\sigma_X} \quad (1)$$

where X_{it} is the value of indicator X for region i in year t , $\bar{X}$ is the sample mean, and σ_X is the standard deviation.

The composite indices were calculated as weighted averages:

$$CISI_{it} = \sum_{k=1}^3 w_k Z_{kit} \quad (2)$$

$$Inst_{it} = \sum_{j=1}^3 v_j Z_{jit} \quad (3)$$

Following OECD recommendations for composite indicator construction, equal weights were assigned to all components ($w_k = v_j = 0,333$), avoiding subjective prioritisation of individual indicators. The reliability of the indices

was evaluated using Cronbach's alpha coefficient. The resulting values ($\alpha = 0.79$ for CISI and $\alpha = 0.76$ for Inst) indicate satisfactory internal consistency. Additional exploratory factor analysis confirmed that all variables loaded predominantly on a single latent dimension, supporting the theoretical validity of the constructed indices. To assess robustness, alternative weighting schemes based on principal component analysis (PCA) were tested. Correlations between the baseline and PCA-derived indices exceeded 0.90, indicating a high degree of stability in the index structure.

Additional robustness checks were conducted at the econometric stage. First, the baseline fixed-effects specification was re-estimated using lagged values of the CISI and institutional quality variables. The signs, magnitudes and statistical significance of the key coefficients remained broadly unchanged. Second, a dynamic panel specification including a lagged dependent variable was estimated as a supplementary test. The estimated coefficients for CISI and institutional quality remained positive and statistically significant, confirming the persistence of the identified relationships. Although potential endogeneity between regional economic resilience and financial development cannot be completely excluded, the consistency of results across alternative specifications suggests that the main findings are robust and not driven by model selection or index construction procedures.

Instruments and Analytical Tools. The study's analytical framework integrates statistical data processing, the construction of composite indices, and panel econometric modelling. Preliminary data preparation involves cleaning, verifying completeness, and harmonising regional time series. To ensure comparability of financial indicators, variable standardisation and normalisation were applied. The integral index of the credit-investment space was developed by aggregating normalised indicators of lending and investment activity. Analogous procedures were used to formulate the regional institutional quality index. This approach effectively reduces data dimensionality without compromising economic significance.

The primary econometric estimations were conducted in Stata 18, in accordance with reproducibility standards for empirical research in financial economics. Panel regressions incorporating regional and time fixed effects were estimated using the built-in xtreg procedures. To address heteroscedasticity and autocorrelation, robust standard errors clustered at the regional level were applied. Supplemental calculations of marginal effects and dynamic visualisations were performed in R 4.3.2 using the plm, lmtest, and ggplot2 packages, ensuring a transparent interpretation of the temporal dynamics of credit-investment space effects. Robustness checks and data preprocessing were executed in Python 3.11 utilising the "pandas" and "statsmodels" libraries.

3. Results

To empirically test the nexus between the credit-investment space and regional economic resilience, a panel fixed-effects model was employed for the 2020–2024 period. The model accounts for time-invariant regional characteristics and nationwide temporal shocks, thereby isolating the specific influence of financial and institutional factors. The dependent variable is an integral indicator of regional economic resilience, whereas the credit-investment space index is the key explanatory variable. Furthermore, the model incorporates an institutional quality indicator and an interaction term to capture the role of institutions in transforming the financial sector (Table 2).

Table 2. Dynamics of key indicators (Ukraine regions panel, 2020–2024)

Year	CISI (credit and investment space)	Institutional quality (Inst)	Economic stability (Res)	Capital investments, % of GRP	Business loans, % of GRP
2020	-0.22	-0.05	-0.18	14.9	19.8
2021	0.08	0.02	0.11	16.3	21.4
2022	-0.41	-0.12	-0.46	12.7	17.2
2023	-0.09	0.04	-0.06	14.1	18.9
2024	0.17	0.10	0.15	15.8	20.6

Note: averaged by region; indices are standardised: 0 = average sample level

Source: author's own development based on the results of an econometric model using data from (National Bank of Ukraine, 2024; State Statistics Service of Ukraine, 2024; Ministry of Finance of Ukraine, 2024; State Treasury Service of Ukraine, 2024; World Bank, 2024; Organisation for Economic Co-operation and Development, 2023; International Monetary Fund, 2024).

The model incorporates control variables for household income levels, unemployment rates, and the regional economy's sectoral structure. Additionally, the 2022 shock is accounted for using a time dummy variable and corresponding interaction effects (Table 3). This approach enables the estimation of not only the average effect but also the shifts in interdependencies under crisis conditions.

Table 3. Results of fixed-effects panel regression for 2020–2024

Variable	(1) FE Baseline	(2) FE + Shock terms	(3) FE + Shock interactions
CISI	0.214*** (0.052)	0.196*** (0.054)	0.171*** (0.056)
Inst	0.128** (0.051)	0.117** (0.052)	0.109** (0.053)
CISI × Inst	0.083** (0.036)	0.079** (0.037)	0.072** (0.038)
D2022	—	-0.312*** (0.041)	-0.298*** (0.043)
CISI × D2022	—	—	-0.067* (0.039)
Inst × D2022	—	—	-0.058* (0.034)
ln(Income per capita)	0.094** (0.045)	0.088* (0.046)	0.086* (0.047)
Unemployment rate	-0.031** (0.013)	-0.029** (0.013)	-0.028** (0.013)
Industry share	-0.012 (0.009)	-0.011 (0.009)	-0.011 (0.009)
Constant	0.004 (0.018)	0.006 (0.018)	0.006 (0.018)
Regional FE	Yes	Yes	Yes
Annual FE	Yes	Yes	Yes
Observations	5×Nregions	5×Nregions	5×Nregions
Within R ²	0.41	0.46	0.47

Significance notation: p<0.10, p<0.05, p<0.01.

Note: 1) SE - robust, clustering by region; regional and time FE included. 2) Dependent variable - Resit (economic stability of the region)

Source: author's development based on the results of an econometric model using data (National Bank of Ukraine, 2024; State Statistics Service of Ukraine, 2024; Ministry of Finance of Ukraine, 2024; State Treasury Service of Ukraine, 2024; World Bank, 2024; Organisation for Economic Co-operation and Development, 2023; International Monetary Fund, 2024).

The findings indicate a statistically significant positive impact of the credit-investment space on regional economic resilience throughout the entire period under investigation. An increase in the credit-investment space index is associated with improved macroeconomic characteristics of regional development. This confirms the thesis that access to financial resources is pivotal to ensuring the resilience of regional economies.

In 2020, the results indicate a moderate positive effect in the credit-investment space, attributed to the overall slowdown in economic activity. During this period, the institutional factor played a supporting role, reinforcing the stabilising effect of financial resources. This indicates a limited yet positive adaptive capacity of the regions during the initial shock phase. In 2021, there was a noticeable strengthening of the credit-investment sector's impact on regional economic resilience. Improved institutional conditions enhanced the efficiency with which financial resources were transformed into recovery-led economic growth. Consequently, the interaction between financial and institutional variables gained greater economic significance.

In 2022, a sharp decline in economic resilience was observed across most regions, as evidenced by a negative coefficient on the shock dummy variable. While the impact of the credit-investment space remains positive, its magnitude has decreased substantially. This points to the financial sector's limited capacity to offset large-scale structural losses. The 2022 interaction effects demonstrate that institutional quality mitigates the negative consequences of crisis processes. Regions with superior institutional characteristics exhibit higher resilience under identical financial conditions. This confirms the transformative role of institutional mechanisms during crisis periods.

The 2023 results demonstrate a gradual recovery in the positive impact of the credit-investment space. The significance of the institutional factor increases, reflecting its role in adaptation processes and the reconfiguration of financial flows. Furthermore, the interaction between financial and institutional variables becomes more stable. By 2024, the positive effect of the credit-investment space on regional economic resilience will further intensify. Institutional mechanisms can enhance returns on financial resources over the medium term. This suggests a gradual normalisation in the functioning of regional financial systems.

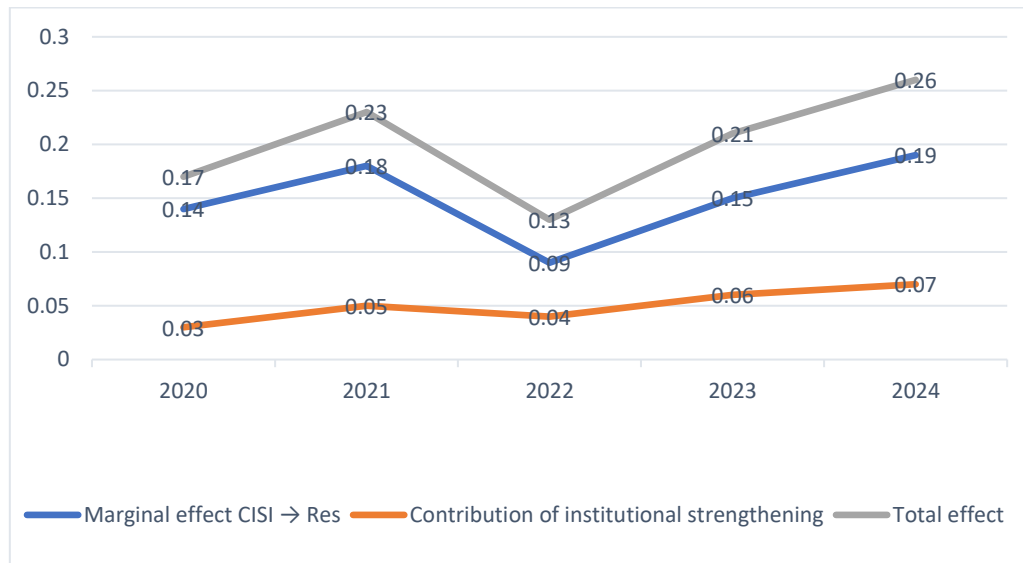
A comparative analysis of periods shows that the role of the credit and investment space is consistently positive but sensitive to external shocks. Institutional quality is a key factor in differentiating regions by level of economic stability. The highest effects are observed in regions with a combination of financial depth and institutional capacity. Overall, the results confirm that transforming the credit and investment space without institutional support is insufficient to ensure stability. Institutional mechanisms act as a catalyst for the effective redistribution of financial resources at the regional level. This allows institutional modernisation to be considered a key direction for improving the economic stability of Ukraine's regions.

An analysis of the average values of the CISI index shows its clearly pronounced cyclical dynamics and high sensitivity to macroeconomic shocks. In 2020–2021, the transition from negative to positive CISI values reflected

the restoration of regions' access to financial resources, accompanied by growth in business lending and capital investment. The sharp decline in the index in 2022 indicated a structural financial shock and a significant weakening of regional economic stability, partially mitigated by institutional factors. In 2023–2024, the gradual growth of the CISI and the institutional index indicates regional adaptation and the restoration of credit and investment capacity. Regression estimates confirm that a one-unit increase in CISI raises economic stability by 17–21%, and that institutional quality amplifies this effect, especially during crises.

Additional analysis of marginal effects allows us to assess how the impact of the credit and investment space on regional economic stability changes over time. Figure 1 shows the average marginal effects, accounting for institutional interaction and time shocks. In 2020, the total effect of the credit-investment space was 0.17, indicating the limited stabilising role of financial resources.

Figure 1. Marginal effect of the credit-investment space on the economic resilience of Ukraine's regions, 2020–2024



Note.

- 1) Total effect = baseline marginal effect of CISI + institutional reinforcement.
- 2) Values are interpreted as the change in the economic resilience index per one-standard-unit increase in CISI.
- 3) Interpretation of dynamics: 2020 – Limited stabilising role of finance; 2021 – Recovery and efficiency growth phase; 2022 – Partial mitigation of the crisis shock; 2023 – Adaptation and institutional strengthening; 2024 – Consolidation of the financial-institutional effect.
- 4) Average marginal effect of CISI on Res, accounting for institutional interactions and time effects.

The low effect is explained by the general slowdown in investment activity and increased uncertainty in the economic environment. In 2021, the total effect will increase to 0.23, reflecting the recovery phase of financial flows in the regions. The strengthening of institutional contributions indicates an increase in the effectiveness of transforming credit resources into economic stability. In 2022, the base effect of the credit-investment space will decrease to 0.09, reflecting the impact of a large-scale systemic shock. At the same time, institutional strengthening remains positive, providing partial compensation for the loss of economic stability.

In 2023, the cumulative effect increases to 0.21, indicating that the regions are transitioning to the adaptation phase. The increased role of institutional factors reflects a shift in stabilisation mechanisms from financial to organisational and regulatory. In 2024, the cumulative effect peaks at 0.26, indicating consolidation of the financial and institutional development model. The credit-investment space, combined with institutional quality, delivers the highest returns for regional economic stability. A comparative analysis of dynamics shows that institutional strengthening is playing an increasingly important role in the post-crisis period. This indicates a transformation of the credit-investment space from a quantitative source of financing to a structural factor of sustainable development.

As a robustness check, the baseline fixed-effects model was compared with a dynamic panel specification estimated using the Arellano–Bond estimator. The coefficients of CISI and institutional quality remained positive and statistically significant, confirming the stability of the main findings.

Table 4. Robustness checks

Variable	FE Baseline	Lagged FE	Dynamic Panel
CISI	0.214***	0.198***	0.183***
Inst	0.128**	0.121**	0.114**
CISI×Inst	0.083**	0.076**	0.071**
Observations	120	96	96

Notes: FE Baseline = original fixed-effects model; Lagged FE = fixed-effects model with lagged regressors; Dynamic Panel = model including lagged dependent variable. Standard errors are clustered by region. *, **, *** denote significance at 10%, 5%, and 1%, respectively.

Source: author's development based on the results of an econometric model using data (National Bank of Ukraine, 2024; State Statistics Service of Ukraine, 2024; Ministry of Finance of Ukraine, 2024; State Treasury Service of Ukraine, 2024; World Bank, 2024; Organisation for Economic Co-operation and Development, 2023; International Monetary Fund, 2024).

The consistency of coefficient signs and significance levels across alternative specifications confirms the robustness of the empirical findings.

An additional hypothesis regarding the amplifying role of institutional quality in the transformation of financial resources is empirically confirmed by panel analysis. A positive, statistically significant interaction coefficient between the credit-investment space and the institutional variable indicates a complementary effect. In the crisis year of 2022, institutional quality partially mitigated the negative impact of the systemic shock on regional economic stability. The results confirm that without an adequate institutional environment, the stabilisation potential of the credit-investment space is significantly reduced.

4. Discussions

The identified complementarity between financial resources and institutions is consistent with approaches that treat development as a function of not only capital but also rules, transparency, and trust. In particular, index-based approaches to assessing budget transparency in sensitive sectors show that open financial management reduces risks by improving resource manageability (Nate *et al.* 2023). This supports our interpretation of institutions as a mechanism that increases the “return” on credit and investment in crisis conditions.

Our estimates for 2022–2024 show that the shock has reduced the marginal effect of financial space, but has not changed its positive sign. This trajectory is logical in the context of institutional challenges and financial market constraints during wartime, when resource availability is reduced, and transaction risks increase. The role of institutional strengthening during this period aligns with the thesis that anti-corruption mechanisms are needed to support the “financial security landscape” in the European integration framework (Kussainov *et al.* 2023). In this sense, our results are also consistent with comparative observations on anti-corruption regulation practices in the EU, which promote predictability and better resource allocation (Melnik *et al.* 2022).

An important clarification is that the credit-investment space in Ukraine's regions is shaped not only through banking channels but also through the real sector's structure. This is particularly noticeable in agricultural regions, where clusters can increase cooperation, productivity, and the investment attractiveness of territories. The approach to the strategic formation of agricultural clusters confirms that organisational integration creates the preconditions for attracting capital and scaling up production (Sitnicki *et al.* 2024a). Our results support this logic through the positive impact of financial space, but complement it with an institutional channel, which is often mediated in cluster models.

One of the critical factors in regional investment activity is the land market and land rent, which affect investors' expected returns and risk. A comparative review of Poland and Ukraine emphasises the importance of land management mechanisms and rent processes in shaping incentives for land use (Marks-Bielska and Koshkald, 2025). An analysis of the challenges of trade liberalisation and land reforms emphasises that institutional uncertainty deters investment, even when markets are formally opened (Ibatullin *et al.* 2024). In this context, our assessments of the interaction between the financial space and institutions explain why credit opportunities without regulatory certainty yield weaker returns.

The results regarding institutional strengthening can also be interpreted through the lens of social resilience, which is the “environment” in which financial mechanisms operate. Assessing the social resilience of the population in the Carpathian region shows that social conditions influence adaptation to shocks and recovery dynamics (Mulka *et al.* 2022). Our results do not directly measure social resilience, but they are consistent with the idea of

multi-channel resilience. This shows that purely financial interventions are ineffective without social and institutional support.

From the perspective of the digital transformation of financial infrastructure, our findings are consistent with the thesis that accounting and financial flow control tools need to be modernised. The development of blockchain technologies in financial accounting is seen as a way to increase transparency, traceability and trust, potentially reducing information asymmetry (Prokopenko *et al.* 2024). This resonates with our institutional channel, as more transparent and manageable processes enhance the efficiency of credit and investment resources. Similarly, the approach to strategic infrastructure transformation in the financial sector emphasises the importance of managerial changes to improve the performance of financial systems (Koldovskiy, 2024). The additional emphasis on sustainable development through the strengthening of Ukraine's financial infrastructure supports the conclusion that institutional reforms and environmental modernisation increase economic resilience (Koldovskiy, 2025).

At the same time, comparing our results with those presented in scientific sources allows us to refine our interpretation critically. Studies of clusters and land reforms demonstrate strong sectoral specificity, which can alter sensitivity to credit and investment (Sitnicki *et al.* 2024b; Ibatullin *et al.* 2024). This means that the aggregated financial space index may obscure distinct mechanisms across industrial, agricultural, and service regions. Anti-corruption and transparency approaches emphasise that the formal existence of institutions does not guarantee their effectiveness without implementation and oversight (Kussainov *et al.* 2023; Nate *et al.* 2023). Therefore, institutional quality should be detailed through indicators of compliance, accountability, and digital control tools.

Researchers Voznyak *et al.* (2023) examine the financial determinants of regional stability, emphasising the key role of credit availability during economic shocks. The results expand on these findings with a quantitative assessment of the marginal impact of credit-investment space during wartime. Kharlamova (2014) analyses the investment attractiveness of regions as a tool for rating and marketing territories. The positive effect of credit-investment space confirms this logic, complementing it with an institutional dimension.

At the same time, Misyuryov (2025) examines Ukraine's investment attractiveness amid global economic turbulence, emphasising the role of governance quality. A statistically significant interaction between the financial space and institutional quality empirically confirms this moderating effect. Nawaz *et al.* (2025) analyse the resilience of financial markets during the pandemic and military conflicts, focusing on institutional buffers. The study's results show that institutional quality partially mitigated the negative impact of the 2022 shock on regional economic resilience.

At the same time, Kravchenko *et al.* (2020) examine the socio-economic transformations of the agricultural sector, emphasising the importance of institutional coordination and access to finance. This is consistent with findings on the need for institutional reinforcement of financial resources to ensure long-term sustainability. Bas (2025) analyses the dilemma of globalisation and localisation, demonstrating the decisive role of local institutions in crisis conditions. This approach explains why institutional quality enhances the stabilising effect of the credit and investment space in the post-crisis period.

Finally, Stroiko *et al.* (2024) examine the ecosystem of women's entrepreneurship during wartime, pointing to the limited effectiveness of financing without institutional support. The results confirm a similar mechanism at the aggregate regional level. Onegina *et al.* (2025) analyse the innovative potential of small and medium-sized enterprises in the agricultural sector, emphasising the complementarity of finance and institutions. This further confirms the conclusion that expanding the credit-investment space without institutional modernisation is insufficient.

Overall, the discussion confirms that our results are consistent with most conclusions about the role of institutions, transparency, and reforms in improving investment efficiency. At the same time, they complement these approaches with a quantitative assessment of the complementarity between the financial space and institutions at the regional level. Taken together, this supports the practical conclusion that credit and investment policy needs to be synchronised with anti-corruption governance, budget transparency and the modernisation of financial infrastructure.

5. Limitation

The study is limited by the availability and completeness of regional financial data, which necessitates using aggregate indicators of the credit and investment sectors. The construction of integrated indices may partially smooth out intra-regional differences and conceal the structural heterogeneity of financial processes. Although additional robustness checks based on lagged explanatory variables and dynamic panel specifications were performed, potential endogeneity between economic resilience and financial development cannot be entirely eliminated due to data limitations and the relatively short time horizon. The impact of informal institutions and

military risks cannot be quantified and remains outside the scope of empirical analysis. The results obtained are interpreted within the period 2020–2024 and can be extrapolated to a limited extent to the long term.

Conclusions

The growth of regional disparities in access to financial resources increases the importance of studying mechanisms of economic stability in a transitional economy. Military and macroeconomic shocks highlight the need for a quantitative assessment of the roles of the credit-investment space and institutional factors at the regional level. The article achieves its goal by comprehensively assessing the impact of the credit-investment space on the economic stability of Ukraine's regions. The integrated indicator developed enabled a quantitative assessment of regional differences in access to credit and investment resources.

The constructed panel econometric model confirmed the statistically significant positive impact of credit-investment space on economic stability. The results show that a one-unit increase in credit and investment improves regional economic stability by an average of 17–26%. Institutional quality demonstrates an independent positive effect of 11–13% in various specifications of the panel model. The multiplier effect of the interaction between the financial sector and institutional quality exceeds 7%, strengthening the regions' stabilisation potential. Despite the systemic shock of 2022, regions with higher financial and institutional indicators lost approximately 30% less economic stability. It has been established that institutional quality acts as an independent stabilising factor and enhances the effect of financial resources. In the crisis year of 2022, institutional mechanisms partially offset the negative impact of external shocks on the regional economy.

A comparative analysis of dynamics for 2020–2024 showed an increased role of institutional factors in the post-crisis period. The results confirm that effective transformation of the credit-investment space is impossible without an adequate institutional environment. Thus, all research objectives have been achieved, and the hypotheses have been empirically confirmed. The general conclusions point to the need to combine financial and institutional instruments in regional economic policy. The credit-investment space should be viewed not only as a source of financing but also as a structural element of economic stability. Further research should focus on extending the analysis timeframe and accounting for spatial interregional effects. A promising area is assessing the impact of digital financial instruments and informal institutions on regional economic stability.

Declarations:

Credit Authorship Contribution Statement:

Myroslav Khomyak: Conceptualization, Investigation, Methodology, Project administration, Formal analysis, Writing – original draft, Supervision, Data curation, Validation, Writing – review and editing, Funding acquisition;

Yevhen Shkurov: Conceptualization, Investigation, Methodology, Project administration, Formal analysis, Writing – original draft, Supervision, Data curation, Validation, Writing – review and editing, Funding acquisition;

Ivan Bakalo: Conceptualization, Investigation, Methodology, Formal analysis, Writing – original draft, Supervision, Writing – review and editing.

Olena Golovina: Conceptualization, Investigation, Methodology, Software, Writing – original draft, Writing – review and editing, Visualization.

Borys Bezzubko: Conceptualization, Investigation, Methodology, Software, Formal analysis, Writing – original draft, Writing – review and editing, Visualization.

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Declaration of Use of Generative AI and AI-Assisted Technologies: The authors declare that they have not used generative AI and AI-assisted technologies in the writing process before submission.

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Are Geopolitical Risks a Permanent Driver of Global Inflation? Evidence from 1985-2024



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Abstract: This study investigates the causal relationship between geopolitical risks and global inflation and examines whether this causal effect, if any, is persistent. To this end, the stationarity of the annual Geopolitical Risk Index (GPR) and global inflation series for the 1985–2024 period was first analyzed using the Lee and Strazicich (2003) two-break unit root test, which concluded that the series are stationary at levels. Subsequently, the data were analyzed using a stationary frequency domain causality approach, revealing a unidirectional causal relationship running from GPR to global inflation at both low and high frequencies. The causality identified at low frequencies indicates that this causal effect is permanent. The findings of the study suggest that mitigating geopolitical risks is of vital importance in the fight against global inflation.

Keywords: geopolitical risk; global inflation; frequency domain causality.

JEL Classification: C22; D80; E31.

Introduction

As geopolitical risks increase in the world, its economic, political and social effects are inevitable. Therefore, an increase in geopolitical risks is expected to affect macroeconomic indicators. So, what is geopolitical risk and how is it measured? Caldara and Iacoviello (2022) define geopolitical risk as a type of risk associated with factors that disrupt the normal and peaceful functioning of international relations, such as wars, acts of terrorism and inter-state tensions, and develop a monthly geopolitical risk indicator (GPR) based on newspaper articles covering geopolitical tensions. Caldara and Iacoviello (2022) emphasize that events such as the Gulf War, 9/11, the 2003 invasion of Iraq, the 2014 Russia-Ukraine crisis, and the Paris terrorist attacks increased the index.

Increasing geopolitical risks may negatively affect individual countries' macroeconomic and financial indicators, and may also significantly affect global indicators. These effects may be temporary or permanent. This study focuses on the effects of geopolitical risks, which have emerged globally and spread worldwide, on inflation, one of the main macroeconomic indicators. Is there a causal relationship between geopolitical risks and global inflation? This question constitutes the main motivation of this study. In this context, the study seeks to address two fundamental questions: Are geopolitical risks a driver of global inflation? If so, is this causal relationship transitory or permanent.

In addition to this introduction, the study consists of a literature review where a summary of the literature on the relevant topic is presented, data, methodology, and findings where the causality relationship between geopolitical risks and global inflation is analysed, and a conclusion where the findings are evaluated.

1. Literature Review

Although there are many studies analyzing the nexus between geopolitical risks and various macroeconomic variables, there are few that examine the relationship between geopolitical risks and inflation from different perspectives. While some of these studies examine the link between geopolitical risks and global inflation, others

focus on the impact of geopolitical risks on prices in various countries. In this section, a few of the recent studies are discussed.

Bouri *et al.* (2023) find that lagged changes in the global geopolitical risk (GPR) index are positively correlated with changes in the total spillover index across the inflation rates for the period May 1963 - November 2022 in North American and European countries. Analyzing the effects of global geopolitical risks and global supply chain pressures on global inflation for the monthly period 1999M1-2022M12, Asadollah *et al.* (2024) conclude that disruptions in global supply chains are the main drivers of global inflation in the long run. Bolivar and Huantto (2024) examined the effects of geopolitical risks on key macroeconomic variables for Bolivia, Chile and Peru with the Bayesian Structural Vector Autoregressive (BSVAR) model. In the study, it is stated that geopolitical risks significantly increase inflation and interest rates in Chile and Peru, but Bolivia is more resilient. In a Türkiye-specific study, Soyu Yıldırım and Demirtaş (2025) analyze the impact of geopolitical risks originating from Russia and Israel on inflation. In the study covering the period January 2003 - January 2024, it is stated that the effect of geopolitical risks on inflation is more significant in the long run. Marangoz (2025) analyzes the impact of energy price shocks, monetary policy and geopolitical risks on inflation in Germany, France and Italy. While the study mainly emphasizes the changing effects of energy price shocks and monetary policy implementations on inflation, it is concluded that major geopolitical risks such as the Russian-Ukrainian war increase inflationary pressures. Caldara *et al.* (2026) analyzes the relationship between geopolitical risks and inflation in 44 countries for the period 1974-2022. Using the VAR model, the study emphasizes that global geopolitical risks increase inflation.

The literature also examines the relationship between geopolitical risks and the prices of certain products or product groups such as energy and food prices. For the period January 2002 - December 2020, Su *et al.* (2021) examined the relationship between geopolitical risks and renewable energy using the rolling window method. Yang *et al.* (2023) examined the relationship between geopolitical risks, oil prices and inflation for China, the US and 27 European countries for the period January 2000 - July 2024. In the study, it is stated that geopolitical risks do not lead to a continuous increase in oil prices, but the high inflation that emerged after the Covid-19 period is caused by the imbalance between industrial production and consumer demand that emerged as a result of decreasing oil supply, high oil prices and geopolitical risks. In another study, Ceylan (2024) analyzes the impact of geopolitical risks on global energy and food prices and argues that this effect changes over time and generally has a lower impact than expected. In another study, Sun and Su (2025), working with monthly data for the period April 1998 - July 2022, examined the relationship between geopolitical risks and food prices. The study concludes that there is a time-varying bidirectional causality between the variables.

Some studies focus on the relationship between geopolitical risks and financial markets. Examining the relationship between geopolitical risks and Bitcoin, Aysan *et al.* (2019) conclude that GPR has a predictive power on both the returns and volatility of Bitcoin for the period July 18, 2010 - May 31, 2018. Şahin and Arslan (2021) examine the causality between geopolitical risk and stock and exchange rate returns and volatility for 18 emerging economies. Using monthly data on geopolitical risk index, stock market index and exchange rate, they conclude that geopolitical risks affect stock market and exchange rate returns in about half of the countries, while geopolitical risks affect stock market and exchange rate volatility in all countries. Huang *et al.* (2023) examine the causal relationship between the gold market and geopolitical risks using a nonparametric causality approach. Covering the period January 4, 2000 - November 17, 2017, the study states that geopolitical risks affect volatility rather than returns in the gold market. The study also argues that the effects of geopolitical risks on realized volatility are asymmetric.

An extensive review of the literature reveals that, while numerous studies examine the nexus between geopolitical risks and inflation, the transience or persistence of this relationship has been largely overlooked. In this regard, this study distinguishes itself from existing literature and offers a significant degree of originality.

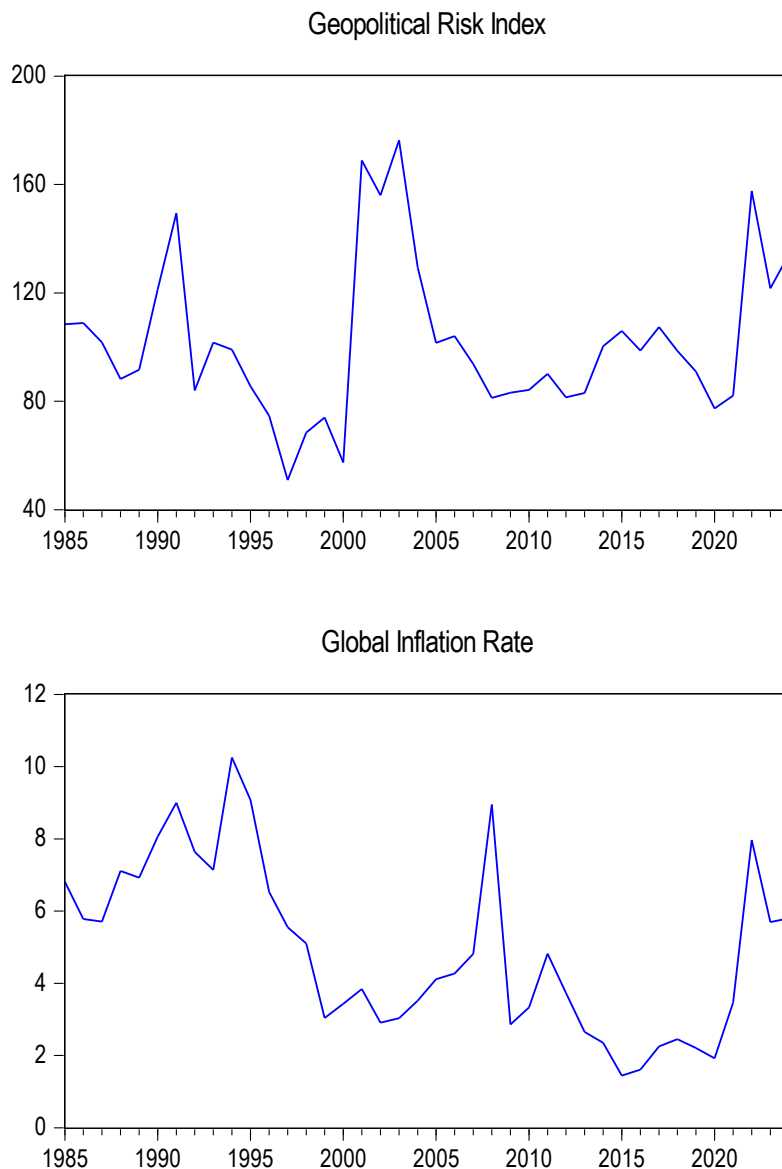
2. Data, Methodology & Findings

In this study, the causality relationship between geopolitical risks and global inflation is analyzed at different frequencies. The Geopolitical Risk Index¹ (GRP) is preferred as the geopolitical risk variable, while Global Inflation² data is used for the inflation variable. Annual data for the period 1985-2024 are used in the analyses. Figure 1 shows the geopolitical risk and global inflation series.

¹ The analysis uses the geopolitical risk index (GPR) developed by Dario Caldara and Matteo Iacoviello. GPR data was obtained from the website <https://www.policyuncertainty.com/gpr.html>

² Global inflation data are obtained from <https://data.worldbank.org/indicator/FP.CPI.TOTL.ZG>. As 2024 global inflation data, the IMF's forecast is included in the data set.

Figure 1. Geopolitical Risk and Global Inflation Time Path Plots



Firstly, the stationarity of both series is investigated. Both geopolitical risk and global inflation are variables with a high probability of breakpoints due to various reasons. This can be easily understood from Figure 1. Therefore, taking breaks into account while investigating the stationarity of these two series may provide more reliable findings. For this purpose, Lee-Strazicich (2003) Unit Root Test, which also takes breaks into account, is preferred to test the stationarity of the series.

Lee and Strazicich (2003) developed the two-break Lagrange Multiplier (LM) unit root test as an alternative to the endogenous two-break unit root tests developed by Lumsdaine and Papell (1997), which are based on the assumption that structural breaks are not included in the null hypothesis. In this context, Model A is used for the test that allows a single structural break at the level, and Model AA is used for the test that allows two breaks at the level. On the other hand, Model C and Model CC represent unit root tests that take into account one and two structural breaks in the level and trend, respectively. The following model is used for the LM unit root test:

$$y_t = \delta Z_t + e_t \quad e_t = \beta e_{t-1} + \varepsilon_t \quad (1)$$

In the equation, Z_t represents the vector of exogenous variables while ε_t represents the residuals with *iid* $N(0, \sigma^2)$. Model AA for the unit root test with two breaks can be accessed by replacing Z_t with $[1, t, D_{1t}, DT_{1t}]'$ to show the dummy variable, which takes the value 1 in the case of D_{1t} , $t \geq T_{B1} + 1$ and 0 in other cases for $j=1, 2$. Model CC for the unit root test that allows two breaks in the level and trend is obtained by substituting $[1, t, D_{1t}, D_{2t}, DT_{1t},$

$DT_{2t}J'$ for Z_t to show the dummy variable that takes the value of $t - T_{BJ}$, when DT_{jt} , $t \geq T_{BJ} + 1$ and 0 in other cases for $j=1, 2$. (Yılancı, 2009, 330). The LM test statistic is obtained by the following regression:

$$\Delta y_t = \delta' \Delta Z_t + \phi \tilde{S}_{t-1} + u_t \quad (2)$$

If the test statistic obtained is greater in absolute value than the critical value obtained from Lee and Strazicich (2003), the null hypothesis of unit root with structural break is rejected, which means that the series is stationary. Table 1 presents the results of the unit root test.

Table 1. Lee-Strazicich (2003) Unit Root Test with Two Structural Breaks

		tau stat.	%1	%5	%10	Breakpoints
GPR	Model AA	-3.775789	-4.073000	-3.563000	-3.296000	2006, 2020
	Model CC	-6.594015	-7.196000	-6.312000	-5.893000	1999, 2006
GINF	Model AA	-3.315996	-4.073000	-3.563000	-3.296000	1995, 1998
	Model CC	-7.694263	-7.032000	-6.375000	-6.011000	2002, 2016

The null hypothesis for the Lee-Strazicich (2003) Unit Root Test is that the series contains a unit root. H_0 is rejected if $|\text{tau statistic}| > |\text{critical value}|$. According to the results obtained from Table 1, under structural breaks, GINF is stationary at 10% significance for AA model and 1% significance level for CC model, while GPR is stationary at 5% significance level for AA and CC models. Accordingly, it is appropriate to use the level values of both series in the causality analysis based on the VAR model.

Following the assessment of the series' stationarity, the frequency domain causality method developed by Breitung & Candelon (2006) was applied to explore the causal relationships among the variables. Unlike traditional causality tests that provide a single test statistic over the time domain, earlier studies by Geweke (1982) and Hosoya (1991) introduced a method for evaluating causality by decomposing spectral density functions within specific frequency bands. Breitung & Candelon's (2006) test builds upon these foundational works. The causality metric introduced by Geweke (1982) and Hosoya (1991) is expressed as follows:

$$M_{X \rightarrow Y}(\omega) = \log \left[1 + \frac{|\psi_{12}(e^{-i\omega})|^2}{|\psi_{11}(e^{-i\omega})|^2} \right] \quad (3)$$

At frequency ω , the null hypothesis posits that Y does not Granger-cause X, under conditions $\psi_{12}(e^{-i\omega})=0$, $M_{X \rightarrow Y}(\omega)=0$. According to the approach proposed by Breitung & Candelon (2006), this hypothesis is examined by applying linear parameter restrictions specific to each frequency within the VAR model. The relevance of these restrictions is then assessed using an F-test under the framework of linear restrictions:

$$\sum_{k=1}^p \theta_{12,k} \cos(k\omega) = 0, \quad \sum_{k=1}^p \theta_{12,k} \sin(k\omega) = 0 \quad (4)$$

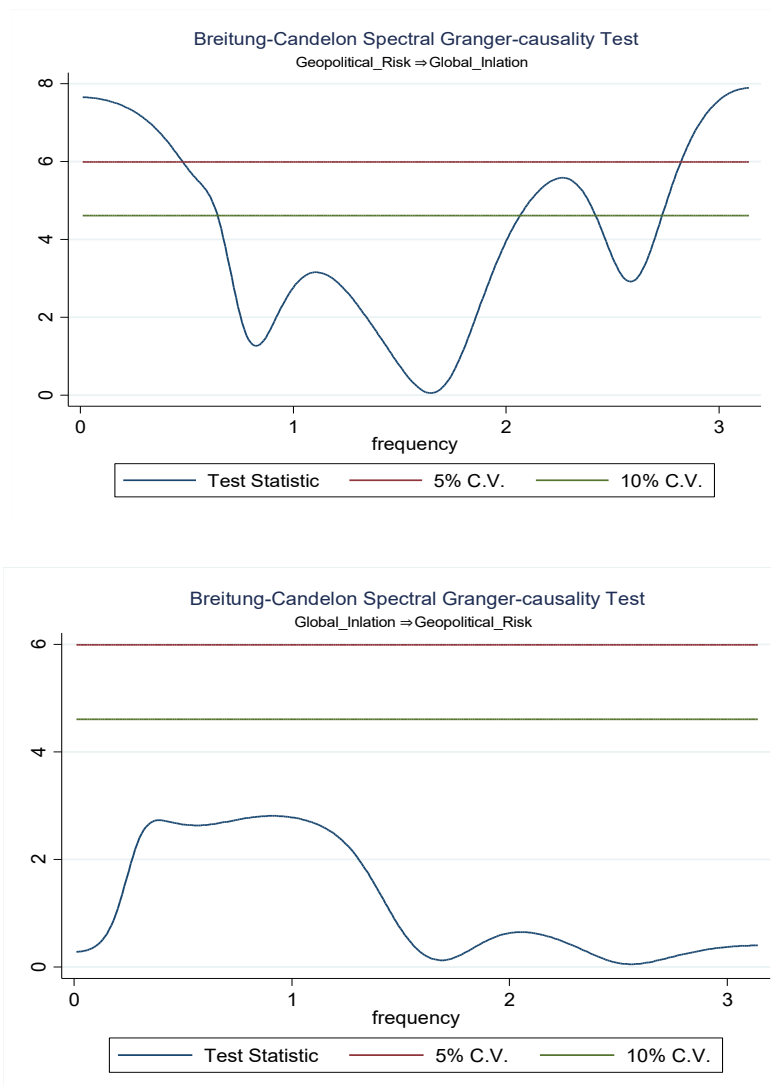
Using these restrictions, the conventional F-test can be employed to evaluate the null hypothesis that there is no Granger causality at the specified frequency ω .

$$H_0 = R(\omega)\beta = 0 \rightarrow \beta = [\beta_1, \dots, \beta_p]', \quad R(\omega) = \begin{bmatrix} \cos(\omega) & \cos(2\omega) & \dots & \cos(p\omega) \\ \sin(\omega) & \sin(2\omega) & \dots & \sin(p\omega) \end{bmatrix} \quad (5)$$

The F-statistic follows an F-distribution with degrees of freedom $F(2, T - 2p)$ for $\omega \in (0, \pi)$. (2 = number of restrictions, T = number of observations, p = order of the VAR model). Figure 2 shows the results of Breitung & Candelon (2006).

In the Breitung & Candelon (2006) test, frequencies (ω) range between 0 – 3.14. Low frequencies represent long-run causality, while the period shortens as ω increases. The red lines shown in Figure 1 indicate the 5% significance level. The test statistic above this line indicates that there is a causality relationship between the variables at the specific frequency. When the results obtained from the Breitung & Candelon (2006) test are evaluated in this way, it implies that there is no causality relationship at any frequency from global inflation to geopolitical risk. However, it indicates that there is a causal relationship at low and high frequencies from geopolitical risk to global inflation. In other words, there is a unidirectional causality from geopolitical risk to global inflation in the short and long run.

Figure 2. Breitung & Candelon (2006) Spectral Granger-Causality Test



Ciner (2011) states that causality at a low frequency level such as 0.1 indicates permanent shocks. Thus, the causality from GPR to GINF at low frequencies implies that the effect of geopolitical risk on global inflation is permanent.

3. Discussion and Conclusion

Although events such as economic crises, terrorist incidents, migration movements and natural disasters are seen as regional or local problems, their effects can be carried to global dimensions. All these factors often appear as factors that increase geopolitical risks. Increased geopolitical risks may affect the economies of countries and may also lead to global macroeconomic problems.

When the events of the last few decades are evaluated, it is emphasised in most scientific studies that regional and global events such as the Gulf War, the 11 September attacks, the US invasion of Iraq, the Russia-Ukraine conflict have increased geopolitical risks. But do these increased geopolitical risks affect global indicators? If so, is this effect temporary or permanent? This study seeks answers to these questions in the context of global inflation. The study basically investigates whether there is a temporary or permanent causality relationship from geopolitical risks to global inflation. As a result of the analyses conducted within the framework of the frequency domain causality approach, it is concluded that there is a causality relationship from the geopolitical risk index to global inflation at low frequencies, in other words, in the long run. This result implies that the effects of geopolitical risks on global inflation are permanent.

Inflation is a macroeconomic problem that both adversely affects other economic indicators and has high social costs. In addition to its visible effects such as decreasing purchasing power, distorting income distribution and increasing the cost of living, it is also very difficult to measure the invisible costs of inflation with the uncertainty environment. Therefore, it is one of the macroeconomic problems that require urgent measures. The main findings of this study imply that the fight against global inflation also depends on the reduction of geopolitical risks. Accordingly, it is vital for countries to act in a coordinated manner and to avoid actions that increase geopolitical risks in order to overcome any kind of risk that destabilises the overall stability. The fact that the adverse effects of economic and political shocks on macroeconomic indicators are more pronounced, especially in relatively more fragile economies, also points to the need for these countries to take more stringent measures against actions that increase regional or global risks.

Declarations

Declaration of Competing Interest: The author declares no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

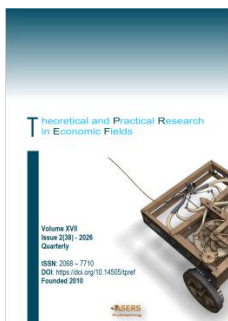
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Dynamics at an Intermediate-Macroeconomics Level: A Keynesian Macroeconomic Model with Inventory and Production-Consumption Delays



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Abstract: We present a dynamic Keynesian model at an intermediate macroeconomic level, a la Metzler (1941) and Leslie (1993), where the utilized propagation mechanism is firms' inventory management, and producers following adaptive expectations in order to meet stochastic demand. In addition, there is a delay between production, and subsequent delivery and consumption from the shelves. The discrete-time model generates a second-order linear difference equation, which exhibits endogenous cycles, with fluctuations (oscillations), which - for a plausible range of model parameters - are stable, and die out over time. Pedagogically, this is the simplest model that is able to generate interesting non-linear dynamics, and thus of interest to both undergraduate economics students, and instructors teaching intermediate macroeconomics.

Keywords: inventory model; business cycles; dynamics; oscillations.

JEL Classification: E32; E12; C62.

Introduction

Modern macroeconomics is inherently dynamic. However, classical intermediate macroeconomics books, e.g. Blanchard *et al.* (2024), generally shy away from explicitly introducing dynamics, and working out time-dependent solutions. We show that introducing dynamics in discrete time is something that the second-year undergraduate student in economics, who has seen some calculus, can handle without much difficulty. The particular case to be discussed has to do with the underlying basis of the Keynesian model - the assumption that producers are acting as "satisfiers," and just try to satisfy a stochastic demand in each time period (rather than acting as profit-maximizers, as stipulated in the neoclassical theory). Being able to meet uncertain demand is achieved by coupling production decisions with inventory management in the spirit of Vasilev (2021), though not in a micro-founded setup here.

In this paper, we extend the static Keynesian cross model a la Metzler (1941) and Leslie (1993), by factoring in also possible delays between production, and subsequent delivery, and more importantly - final consumption from the shelves. The discrete-time dynamic model generates a second-order linear difference equation, which exhibits endogenous cycles, with fluctuations (oscillations), which - for a plausible range of model parameters - are stable, and die out over time. Note that first-order dynamics will not be able to produce those interesting non-linearities, as such equations will only generate monotone paths. So, in this sense both model ingredients are crucial to generate the interesting result and serve as a pedagogical tool alongside Leslie (1993).

The limitations of the paper should be also properly acknowledged. After all, the conclusions of the paper should be taken with a grain of salt, as the model lacks proper micro-foundations, and features no stochasticity. Furthermore, the fluctuations are periodic, which comes at odds with data, where fluctuations in developed economies, such as the US, are irregular in both length and amplitude (as shown in Prescott 1986). Having said that, the deterministic setup should not be taken as a shortcoming; instead, it should be appreciated as a controlled environment used to illustrate some interesting dynamics emerging in a relatively simple Keynesian model. We believe extensions should be left for future research, as otherwise the treatment would be beyond the

level of a second-year undergraduate economics students, who has just taken an intermediate-level course in macroeconomics, and only with a basic calculus course under their belt from the first year. It is thus important that the material covered is served in the optimal bite size – not too large, so that it can be still digestible, and not that small, so that it makes the student learn new methods, which are the norm in the profession.

Next section presents the model in detail, together with the solution method, and analyses in depth the dynamics followed the time series process, and the relevance for business cycle fluctuations. Section 3 concludes.

The Model

The model is a simple no-government, and closed-economy setup. In particular, final demand is represented by consumption and investment, with a certain twist. Final demand is represented by

$$Y_t = u_t + s_t + v_0, \quad (1)$$

where Y_t denotes real output/GDP/income/sales, u_t is the production for sale, *i.e.*, final consumption, s_t is production for inventory, *i.e.*, inventory investment, and $v_0 > 0$ is fixed (non-inventory) investment, which is exogenous and held constant over time. We keep it fixed for the sake of simplicity. Without loss of generality, this component could be stochastic as well, in order to offset the stochastic demand component. This extension does not change the results in any major way.

As pointed out earlier, in reality, there is a lag between production for sale, delivery, actual purchase from the shelf, and final consumption. Hence, it will be assumed that in the model

$$u_t = \beta Y_{t-1}, \quad (2)$$

where $0 < \beta < 1$ denotes the marginal propensity to consume. This is reminiscent of the Keynesian consumption function, though with a time delay. (Note that (i) in the special case of no delay, and no inventory, we are back to the standard static Keynesian model; (ii) in the version of no delay, but with inventories, the model generates first-order monotone solution path. Solving those setups is left to the reader.) As we pointed above, the delay is due to the fact that production and consumption decisions may take place in different time periods. Goods need to be produced first, and put on the shelves, before they could be purchased for consumption. Certain (monetary-search) models, *i.e.*, Nosal and Rocheteau (2011), use that timing structure by explicitly modeling that consumption markets open only after production markets have already closed.

Next, by definition, inventory stocks in the model are the difference between actual and expected sales, or

$$s_t = \beta Y_{t-1} - \beta Y_{t-2}. \quad (3)$$

Plug the expressions for s_t and u_t back into the main equation to obtain

$$Y_t = \beta Y_{t-1} + \beta Y_{t-1} - \beta Y_{t-2} + v_0. \quad (4)$$

Next, rearrange to obtain

$$Y_t - 2\beta Y_{t-1} + \beta Y_{t-2} = v_0. \quad (5)$$

Shift time subscript two periods forward to obtain

$$Y_{t+2} - 2\beta Y_{t+1} + \beta Y_t = v_0. \quad (6)$$

This is a standard second-order linear difference equation, in the form presented in Chiang and Wainwright (2005). To address it, first we solve for the particular solution (steady-state), *i.e.*, we impose $Y^* = Y_{t+2} = Y_{t+1} = Y_t$. Then

$$Y^* - 2\beta Y^* + \beta Y^* = v_0$$

or

$$Y^* = \frac{v_0}{1-\beta} > 0. \quad (7)$$

Note that indeed in this case the steady-state is a fixed point, and not a (non-)linear trend.

Next, to obtain the complementary solution (function), we solve

$$Y_{t+2} - 2\beta Y_{t+1} + \beta Y_t = 0, \quad (8)$$

which is the associated homogeneous equation (as we set the right hand side to Eq. 8 to zero) to the original non-homogeneous equation (6) specified above.

We guess that the solution is of the form

$$Y_t^c = Ab^t, \quad (9)$$

where the superscript "c" stands for "complementary", and parameters A , b are to be determined. The form of the guess comes from the differential equations literature, i.e., from linear dynamic systems in continuous time, where the solution is a certain exponential process. In what follows, we will utilize an approach known as "guess and verify," which is a well-accepted approach in the literature

Plug in the guess and solve the equation using the undetermined coefficients method (note that $Y_{t+1} = Ab^{t+1}$ and $Y_{t+2} = Ab^{t+2}$):

$$Ab^{t+2} - 2\beta Ab^{t+1} + \beta Ab^t = 0, \text{ or } Ab^t(b^2 - 2\beta b + \beta) = 0, \text{ hence}$$

$$b^2 - 2\beta b + \beta = 0. \quad (10)$$

Solving the quadratic equation above for b , and after some algebra, the roots of the equation are computed to be

$$b_{1,2} = \beta \pm \sqrt{\beta(\beta - 1)} \quad (11)$$

Given that $0 < \beta < 1$, due to the fact that it represents the marginal propensity to consume, the value of the discriminant (the expression under the square root operator) is then negative. This means that there are two distinct (conjugate), imaginary roots that solve the homogeneous equation.

Since both of the complex conjugate roots feature a real part β , which is a positive fraction, the exponential solution process will be convergent, but with dampened oscillations (cycles) - due to the imaginary part of the root - which will produce dynamics akin to one exhibited by certain trigonometric functions, though with a twist.

In particular, the characteristic roots of the process are given by $b_{1,2} = \beta \pm vi$, where we have denoted $v = \sqrt{\beta(1 - \beta)}$ and $i = \sqrt{-1}$. The purpose of v , (not to be confused with v_0) will become clear below.

Passing to polar coordinates, one can obtain

$$\beta \pm vi = R(\cos \theta \pm i \sin \theta), \quad (12)$$

Where $\sin \theta = \frac{v}{R}$, and $\cos \theta = \beta/R$, with v and R to be determined from the polar coordinate relations.

Using Pythagoras theorem, it follows that

$$R = \sqrt{\beta^2 + v^2}. \quad (13)$$

Next, since

$$v^2 = \beta(1 - \beta) = \beta - \beta^2, \quad (14)$$

It follows (after some easy algebra) that

$$R = \sqrt{\beta}. \quad (15)$$

Next, to determine θ , we will make use of the trigonometric relationship, which states that

$$\tan \theta = v/\beta. \quad (16)$$

Thus

$$\theta = \tan^{-1}\left(\frac{v}{\beta}\right) = \tan^{-1}\left(\sqrt{\frac{1-\beta}{\beta}}\right). \quad (17)$$

Next, from De Moivre's theorem (the interested reader is referred to Chiang and Wainwright (2005) for more detail), which states that

$$(\beta \pm iv)^t = R^t(\cos \theta t \pm i \sin \theta t). \quad (18)$$

Now, split the two cases as

$$(\beta + iv)^t = R^t(\cos \theta t + i \sin \theta t) \quad (19)$$

And

$$(\beta - i\nu)^t = R^t (\cos \theta t - i \sin \theta t). \quad (20)$$

Combining the particular solution and the complementary function, the equilibrium process is then of the form

$$Y_t = Y^* + c_1 R^t (\cos \theta t + i \sin \theta t) + c_2 R^t (\cos \theta t - i \sin \theta t), \quad (21)$$

where c_1 and c_2 are some scaling parameters, which are yet to be determined.

Next, simplify by grouping terms to obtain

$$Y_t = Y^* + A_1 R^t \cos \theta t - A_2 R^t \sin \theta t, \quad (22)$$

where $A_1 = c_1 + c_2$ and $A_2 = i(c_2 - c_1)$. Next, write A_1 and A_2 in polar coordinates as

$$A_1 = A \cos \epsilon \quad (23)$$

$$A_2 = A \sin \epsilon \quad (24)$$

Substitute with the expressions above for the scaling parameters to obtain

$$Y_t = Y^* + AR^t (\cos \theta t \cos \epsilon - \sin \theta t \sin \epsilon). \quad (25)$$

The above can be written more compactly as

$$Y_t = Y^* + AR^t \cos(\theta t + \epsilon). \quad (26)$$

As pointed earlier, the crucial parameter is R , which determines whether oscillations generated by the equilibrium process are increasing, decreasing, or constant over time.

Since $R = \sqrt{\beta} < 1$, oscillations will "die out" over time, and the process will converge to Y^* . The role of the other parameters, A and ϵ , are of secondary importance. In particular, scale parameter A only determines the height of the amplitude/fluctuations, while ϵ captures the "phase" of these endogenously-generated "business cycles". In particular, the period of the "cycle" (from peak to peak) is $\frac{2\pi}{\theta}$. Yes, in this simple model, cyclical fluctuations are periodic - while in reality business cycles are irregular, as documented in Prescott (1986). In addition, these endogenous business cycles are not derived from general equilibrium, and are not micro-founded, thus they are subject to the Lucas' (1976) critique. In the model, this periodicity result follows from the DeMoivre's transformation involved, which re-cast the exponential process into a combination of sin and cosine functions.

Finally, note that a higher value of θ (computed earlier as $\theta = \tan^{-1}(\sqrt{\frac{1-\beta}{\beta}})$), shortens the time requirement, or leads to higher frequency in time series language. In other words, cycles will happen faster (more frequently), so the oscillations will appear more "squeezed" when plotted over time.

Conclusions and Further Research

In this paper we presented a dynamic Keynesian model a la Metzler (1941) and Leslie (1993), where the utilized propagation mechanism is firms' inventory management, and producers following adaptive expectations in order to meet stochastic demand. In addition, there is a delay between production, and subsequent delivery and consumption from the shelves. The discrete-time model generates a second-order linear difference equation, which exhibits endogenous cycles, with fluctuations (oscillations), which - for a plausible range of model parameters - are stable, and die out over time.

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makes the student learn new methods, which are the norm in the profession. This would maximize retention, and would bring students closer to the frontier in the science.

Declarations

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Aleksandar Vasilev: Conceptualization, Investigation, Methodology, Formal analysis, Writing – original draft, Writing – review and editing, Visualization, Funding acquisition.

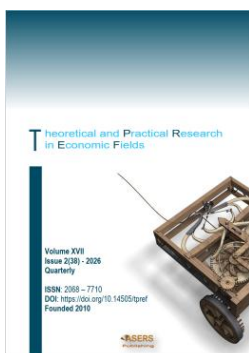
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Stablecoins as a New Monetary Layer: Market Structure, Reserve Design, and the Competition with Tokenized Deposits



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Abstract: Stablecoins have evolved from liquidity tools for crypto trading into a form of tokenized private money with implications for payments, cross-border transfers, short-term funding markets, and the architecture of money itself. The literature on stablecoins has expanded rapidly but remains fragmented across stability, reserve design, banking, payments, and regulation. This paper synthesizes that literature into a single integrative argument: stablecoins should be analyzed as a distinct monetary layer within tokenized finance, evaluated against the BIS framework of singleness, elasticity, and integrity, and compared with tokenized deposits as their most relevant institutional alternative. Drawing on descriptive market evidence and a structured institutional comparison, the paper shows that the stablecoin sector is highly concentrated and overwhelmingly dollar-based; that reserve-backed stablecoins transmit on-chain demand into safe-asset markets and bank funding through three identifiable channels – Treasury and short-term funding, bank funding, and the global safe-asset channel; and that stablecoins and tokenized deposits embody distinct institutional models of programmable money with different welfare and stability implications. The paper concludes that, under recent regulatory developments including MiCA in the European Union and the GENIUS Act in the United States, the most coherent monetary architecture is one in which central bank money remains the ultimate settlement anchor, tokenized deposits extend regulated bank money into programmable environments, and stablecoins operate as specialized private instruments under strong constraints on reserves and redemption.

Keywords: stablecoins; tokenized deposits; tokenized money; reserve design; singleness of money; financial stability; monetary policy transmission; safe-asset channel; regulatory architecture; MiCA; GENIUS Act.

JEL Classification: E42; E44; E52; G18; G21; G28; O33; C58.

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Introduction

The rapid rise of stablecoins is one of the clearest signs that digital finance is moving from speculative crypto-assets toward tokenized monetary instruments. What began largely as a mechanism for parking liquidity between crypto trades has developed into a market exceeding 300 billion USD in outstanding capitalization by early 2026 and now represents a quantitatively significant component of tokenized finance (Adrian *et al.* 2025; BIS, 2025; RWA.xyz, 2026). The market is highly concentrated and overwhelmingly U.S.-dollar-based, with the two largest issuers accounting for roughly 90 per cent of outstanding capitalization and approximately 97 per cent of issuance denominated in dollars (Adrian *et al.* 2025). Stablecoins can therefore no longer be treated as a peripheral or purely

technical component of crypto-asset markets. They increasingly constitute the monetary core of on-chain finance and a growing layer of tokenized private money (Arner *et al.* 2020; Aldasoro *et al.* 2023; Garratt and Shin, 2023).

This shift has changed the analytical terms of the debate. Earlier discussions often treated stablecoins primarily as a solution to crypto-asset volatility or as infrastructure for digital-asset trading. That perspective is now too narrow. Recent institutional and academic work situates stablecoins within the broader process of financial tokenization and argues that tokenized claims are beginning to reshape the architecture of payments, settlement, and financial intermediation (CPMI, 2023; Adrian *et al.*, 2025; BIS, 2025). In this setting, stablecoins matter not only because they facilitate on-chain transactions, but because they represent a privately issued, programmable, and scalable form of money-like liability that increasingly interacts with sovereign currencies, reserve assets, and the regulated financial system.

Stablecoins remain institutionally ambiguous. They are designed to maintain stable value relative to a sovereign currency, yet they are not central-bank liabilities. They are described as money-like, yet they are generally not deposits in the legal and prudential sense. They are backed by reserves of cash, Treasury bills, and reverse repos, yet they are not simply tokenized money market fund shares (Adrian *et al.* 2025; Ahmed *et al.* 2024). This ambiguity is precisely why recent official and academic work has moved beyond peg performance to deeper monetary properties. The BIS argues that stablecoins should be assessed against the foundational qualities of sound money – singleness, elasticity, and integrity – rather than against a narrow nominal-stability test (Garratt and Shin, 2023; BIS, 2025). The central question becomes whether privately issued tokenized claims can perform monetary functions without fragmenting the unit of account, constraining the adaptability of the monetary system, or undermining trust in par settlement.

These properties make tokenized deposits the most relevant institutional comparator for stablecoins. Both instruments aim to supply programmable, ledger-compatible money, yet they differ fundamentally in legal form, transfer logic, settlement architecture, and monetary implications (Garratt and Shin, 2023; EBA, 2024; Huang and Keister, 2026). Whether stablecoins complement or substitute for bank-based tokenized money is now a central question for the future architecture of money, and one that recent regulatory developments – MiCA in the European Union and the GENIUS Act in the United States – have made urgent.

This paper addresses that question through four related sub-questions. First, how concentrated is the current stablecoin sector by issuer, currency, and platform? Second, how does reserve composition shape resilience, macro-financial spillovers, and monetary transmission? Third, in what economic and institutional sense do stablecoins differ from tokenized deposits? Fourth, which regulatory approaches are most consistent with a stable and interoperable tokenized monetary system? By addressing these questions jointly, the paper contributes to the literature on digital money, financial intermediation under tokenization, and current policy debate on the architecture of money (Arner *et al.* 2020; Adrian *et al.* 2025; BIS, 2025; Altavilla *et al.* 2026).

Within this integrative aim, the paper makes three specific contributions that distinguish it from the institutional syntheses on which it builds. First, it consolidates the dispersed evidence on reserve-driven spillovers into a single three-channel transmission framework – a Treasury and short-term-funding channel, a bank-funding channel, and a global safe-asset channel – and shows that these channels are not independent but interact through a shared pool of reserve assets, so that reserve narrowness redirects rather than removes systemic transmission. This synthesis goes beyond the existing literature, which typically examines each channel in isolation (Ahmed and Aldasoro, 2025; Altavilla *et al.* 2026; Ferrari Minesso and Siena, 2026). Second, the paper provides an original quantification of issuer concentration in the stablecoin sector, computing a Herfindahl–Hirschman index of issuer market shares from 2020 to 2026 and interpreting its persistence through the centralization-of-arbitrage mechanism, thereby connecting an empirical concentration measure to a structural explanation rather than treating concentration as a transitional feature. Third, the paper operationalizes the BIS singleness–elasticity–integrity framework as an explicit five-dimensional comparison between stablecoins and tokenized deposits – legal claim, transfer logic, supervisory perimeter, settlement architecture, and singleness implications – turning a largely normative benchmark into a structured analytical grid that can be applied to any tokenized monetary instrument. Together, these contributions move the paper beyond a literature review toward a distinct analytical account of how the architectural properties of tokenized private money determine its monetary consequences and its competitive relationship with bank-based alternatives.

The remainder of the paper proceeds as follows. Section 1 sets out the methodology and analytical framework. Section 2 positions stablecoins within the broader evolution of tokenized money. Section 3 reviews the literature and identifies the main unresolved issues. Section 4 examines the market structure of the stablecoin sector. Section 5 analyzes reserve design and the macro-financial channels through which stablecoins affect safe-asset markets and bank funding. Section 6 compares stablecoins and tokenized deposits as competing forms of

private tokenized money. Section 7 discusses regulatory and policy implications. Final section concludes by considering the place of stablecoins in a future monetary order characterized by an increasingly contested and potentially interoperable multi-money environment.

1. Methodology and Analytical Framework

This paper adopts a structured institutional-comparative methodology. Rather than producing new econometric estimates, it synthesizes the recent academic and policy literature on stablecoins and reorganizes it into a single analytical argument about the monetary character of tokenized private money. The approach proceeds in three steps. The first step establishes an evaluative benchmark: the BIS conception of sound money as the joint satisfaction of singleness (uniform par exchange across issuers), elasticity (the capacity of the monetary system to expand and contract in response to demand), and integrity (resistance to fraud, illicit use, and operational failure) (Garraff and Shin, 2023; BIS, 2025). This benchmark is normative – it specifies the properties money should display – and is complemented by the “money view” of stablecoins, which supplies the positive mechanics of how par is sustained or breaks down under stress (Aldasoro, Mehrling, and Neilson, 2023).

The second step applies this benchmark to a structured comparison of stablecoins and tokenized deposits along five dimensions selected because they jointly determine whether a tokenized instrument can perform monetary functions without fragmenting the unit of account: (i) legal claim – the nature of the holder’s entitlement and the identity of the obligor; (ii) transfer logic – whether value moves as a bearer-style token or as an instructed adjustment of regulated balances; (iii) supervisory perimeter – whether the instrument sits inside or outside the prudential banking framework; (iv) settlement architecture – whether the interbank leg settles in central bank money; and (v) implications for the singleness of money – whether the instrument preserves or undermines uniform par exchange. These dimensions are derived from the singleness–elasticity–integrity benchmark and are applied consistently to both instruments, so that the comparison reflects architectural properties rather than incidental features of particular issuers.

The third step assembles the descriptive market evidence used to ground the comparison. Market-structure data in Section 4 – aggregate capitalization, issuer-level shares, currency composition, and the issuer Herfindahl–Hirschman index – are drawn from publicly available market dashboards (RWA.xyz, DefiLlama, CoinGecko) and from the institutional reserve reporting of the major issuers (Tether International, Circle Internet Financial), cross-checked against the empirical findings reviewed in Section 3. This evidence is used not descriptively but diagnostically: each market regularity (concentration, dollar dominance, reserve composition) is connected to a monetary consequence within the singleness–elasticity–integrity framework. The paper’s contribution is therefore integrative and interpretive rather than econometric: it argues that the fragmented literature on stablecoin stability, reserve design, banking transmission, payments, and regulation can be organized as a single argument about how the architectural properties of tokenized private money shape its monetary consequences and its competitive equilibrium with tokenized deposits.

2. Stablecoins in the Evolution of Tokenized Money

Stablecoins should be understood as part of a broader transformation in form, infrastructure, and institutional organization of money. They did not emerge in isolation. Rather, they are one manifestation of a wider tokenization process through which claims, assets, and financial relationships are increasingly represented, transferred, and settled on distributed ledgers or related programmable infrastructures (CPMI, 2023; Adrian *et al.* 2025; BIS, 2025). In this broader setting, the key analytical question is no longer whether stablecoins belong to “crypto” or to “finance.” They now sit at the boundary of both. On the one hand, they retain strong roots in crypto-native environments, especially as settlement assets, collateral instruments, and liquidity bridges across on-chain markets. On the other hand, once their reserve structures, regulatory treatment, and interactions with safe-asset markets are taken seriously, they become part of a wider debate about the future composition of money itself.

Tokenization does not create a single homogeneous category of “digital money.” It reveals a hierarchy of claims with different legal foundations, settlement properties, prudential protections, and macro-financial implications. Table 1 sets out the principal monetary forms that increasingly coexist in tokenized finance: central bank money in both retail and wholesale form, traditional commercial bank deposits, tokenized deposits, stablecoins, electronic money tokens regulated under MiCA, and tokenized money-market-fund-like claims. The taxonomy is not merely descriptive: instruments that look technologically similar at the level of the ledger may remain institutionally and economically distinct in ways that determine their monetary quality, their behavior under stress, and their relationship to the two-tier banking system. Central bank money remains the ultimate settlement anchor; traditional and tokenized deposits remain the dominant form of private money for households and firms;

stablecoins and EMTs sit alongside them as privately issued tokenized claims with materially different reserve, redemption, and prudential structures; and tokenized MMF-like claims occupy an adjacent zone, relevant for liquidity and collateral but typically without direct payment function at par.

Table 1 clarifies three points that are central to the paper. First, stablecoins occupy a distinct position between bank-based money and reserve-backed investment-like claims: unlike central bank money and deposits they are issuer-specific private liabilities, yet unlike tokenized MMF-like claims they are designed to perform payment functions at par. Second, the singleness implications differ sharply across forms – strongest for central bank money in either retail or wholesale form, preserved through two-tier settlement for traditional and tokenized deposits, and weakest for bearer-style stablecoins. Third, the relevant comparison for evaluating the future role of stablecoins is not stablecoins versus crypto-assets, but stablecoins versus tokenized deposits, with central bank money in both forms providing the wholesale and retail anchor.

Within this spectrum, stablecoins occupy a distinctive position. They are not central bank liabilities. They are generally not deposits in the legal sense. They are not simply tokenized versions of money market fund shares. Nor are they equivalent to tokenized deposits, even when the user-facing experience may appear similar. As recent official work emphasizes, stablecoins differ from both traditional and tokenized monetary instruments in issuer type, transferability, redemption structure, reserve design, and legal certainty (Adrian *et al.* 2025; EBA, 2024; BIS, 2025). The BIS in particular argues that the relevant benchmark for evaluating stablecoins is not stable price behavior alone, but the broader set of qualities associated with sound money: singleness, elasticity, and integrity (Garraff and Shin, 2023; BIS, 2025). This shift in perspective is crucial. It means that the question is not whether a stablecoin usually trades close to one dollar, but whether the institutional structure behind it allows it to function as money without fragmenting the unit of account or weakening the architecture of settlement.

Table 1. Forms of money in a tokenized financial system

Monetary form	Issuer	Nature of claim	Transfer logic	Settlement anchor	Reserve / backing structure	Par convertibility	Yield feature	Prudential perimeter	Implication for singleness of money
Central bank money – retail (cash, retail CBDC)	Central bank	Direct public claim	Bearer (cash) or account-/token-based (retail CBDC)	Self-anchored	Sovereign monetary liability	Yes	None for cash; design-dependent for retail CBDC	Full public monetary framework	Strongest anchor of singleness for end-users
Central bank money – wholesale (reserves, wholesale CBDC, tokenized reserves)	Central bank	Direct public claim restricted to eligible institutions	Account-based or tokenized public settlement asset	Self-anchored	Sovereign monetary liability	Yes	Policy-rate linked	Full public monetary framework	Strongest anchor of singleness for interbank and wholesale settlement; the operational anchor for tokenized wholesale markets
Traditional bank deposits	Commercial banks	Deposit claim on bank	Account-based transfer	Interbank settlement in central bank money	Bank balance sheet backed by loans, securities, reserves, other assets	Yes, within regulated banking system	May bear interest	Full banking regulation and, where applicable, deposit insurance	Preserves singleness through two-tier monetary system
Tokenized deposits	Commercial banks	Deposit claim represented on DLT or related infrastructure	Typically non-bearer / burn-and-issue logic	Interbank leg settles in central bank money	Bank balance sheet; same economic substance as deposits	Yes, if designed as non-bearer tokenized deposits	May bear interest	Banking law, not MiCA in EU treatment	More consistent with singleness than bearer-style private tokens
Stablecoins	Usually nonbank	Redeemable tokenized	Bearer-style transfer of	External reference to	Reserve-backed, often	Intended at par, but may	Issuer-paid yield	Crypto / payments /	Weaker singleness;

Monetary form	Issuer	Nature of claim	Transfer logic	Settlement anchor	Reserve / backing structure	Par convertibility	Yield feature	Prudential perimeter	Implication for singleness of money
	issuers, sometimes bank-affiliated structures	private liability	issuer-specific claim	sovereign unit of account; not self-anchored	cash, T-bills, repos, deposits; composition varies by issuer	deviate under stress	generally prohibited under recent regimes (MiCA EMT; GENIUS)	prudential perimeter varies by jurisdiction	depends on issuer credibility and convertibility
E-money tokens (EMTs) under MiCA	Authorized issuer, including eligible credit institutions / e-money institutions	Transferable token referencing one official currency	Bearer-style transferable claim	External reference to fiat currency	Backing and safeguarding obligations under EU framework	Intended at par	Interest generally prohibited under MiCA	MiCA plus related payments regulation where relevant	More structured than unregulated stablecoins, but still distinct from deposits
Tokenized MMF-like claims / tokenized cash-management claims	Fund / issuer vehicle	Investment-type claim on underlying liquid asset pool	Transferable security/fund claim	Not primarily payment-settlement money	Government bills, repo, cash equivalents, HQLA	Usually NAV- or asset-value-linked rather than strict money-at-par logic	Typically yield-bearing	Securities / fund regulation	Adjacent to money, but weaker money-like singleness

Source: Author's elaboration based on BIS (2025), Garratt and Shin (2023), Aldasoro, Mehrling, and Neilson (2023), and CPMI (2023).

The first benchmark in this comparison is central bank money. Both the BIS and the ECB continue to treat central bank money as the ultimate settlement anchor in a tokenized economy, and recent operational developments give that conceptual claim empirical weight. In the BIS framework, tokenization can improve financial markets and make settlement more programmable, but it should do so around a core of central bank reserves, commercial bank money, and government bonds rather than through the wholesale replacement of existing monetary foundations by privately issued stablecoins (BIS, 2025). The Eurosystem has translated this position into concrete experimentation: its 2024 exploration work on new technologies for wholesale settlement processed more than 200 transactions worth approximately 1.59 billion EUR across 64 participants, settled in central bank money on DLT-based platforms (ECB, 2026). The Bank of England is undertaking related work through its DLT Innovation Challenge and Synchronisation Lab, while Project Agorá – a public-private initiative involving seven central banks and more than 40 financial institutions – is exploring tokenized cross-border settlement based on tokenized commercial bank deposits and tokenized wholesale central bank money (Bank of England, 2025b; BIS Innovation Hub, 2025). The ECB's wider position acknowledges that tokenized deposits and stablecoins may play useful roles in wholesale and cross-border contexts but consistently stresses that central bank money must remain the anchor of trust and settlement finality (ECB, 2025a, 2025b, 2026; Bank of England, 2026). Stablecoins therefore remain derivative from the monetary system rather than constitute it: they reference sovereign money but do not provide the ultimate settlement anchor themselves.

The second benchmark is traditional commercial bank money. Deposits remain the dominant form of private money in modern economies because they combine broad acceptability, payment-system integration, and convertibility at par within a regulated two-tier structure. Stablecoins differ from deposits in several fundamental respects. A bank deposit is embedded in a continuing contractual relationship between the depositor and the bank and is supported by prudential supervision, liquidity rules, capital requirements, and, in many jurisdictions, deposit-protection arrangements. A stablecoin, by contrast, is typically issued by a nonbank entity or by a structure that does not reproduce the full institutional architecture of deposit-taking. Its credibility depends more directly on reserve composition, redemption mechanics, custody arrangements, disclosure, and operational resilience (Arner *et al.* 2020; Adrian *et al.* 2025). This is why stablecoins should not be viewed simply as “digital deposits.” They are better understood as a distinct form of private tokenized money whose monetary quality must be reconstructed through reserve design and regulatory embedding rather than inherited automatically from the banking system.

The most relevant comparator for this paper is tokenized deposits. Stablecoins and tokenized deposits both seek to make money programmable, interoperable with digital platforms, and better suited to near-instant or

automated settlement. Yet the BIS Bulletin on stablecoins versus tokenized deposits shows that the two instruments differ fundamentally in transfer logic and monetary implications (Garratt and Shin, 2023). Stablecoins are generally bearer-style liabilities: when the token changes hands, the claim on the issuer changes hands with it. Tokenized deposits, in their safer non-bearer form, work instead by extinguishing the sender's claim and issuing a new claim by the recipient's bank, with the interbank leg settled in central bank money. This preserves the singleness of money far more effectively than a transferable issuer-specific bearer claim. The ECB has reinforced this distinction by emphasizing that non-bearer tokenized deposits are safer because they do not create market-priced circulating liabilities that may deviate from par, while the EBA has clarified that tokenized deposits remain deposits for legal purposes and should therefore be distinguished from electronic money tokens under MiCA (ECB, 2025b; EBA, 2024). In other words, two instruments may both appear as "tokenized money" on a ledger, but one extends the logic of the banking system while the other introduces a more independent private monetary layer.

This distinction is especially important because it reveals that tokenization does not flatten the hierarchy of money. If anything, it makes that hierarchy more visible. At the top remains central bank money as the settlement anchor. Below it sit traditional and tokenized forms of commercial bank money, which can preserve par convertibility if designed appropriately. Stablecoins form a separate layer of private tokenized money that is potentially more portable and interoperable across open digital environments, but whose soundness depends more explicitly on reserve design, governance, and regulation. Money-market-fund-like tokenized claims and related tokenized safe-asset instruments occupy an adjacent zone, relevant for liquidity management and collateral, but generally less suited to broad payment use (Aldasoro *et al.* 2023; Adrian *et al.* 2025; BIS, 2025). This hierarchy is not only conceptual. It is increasingly reflected in official policy debates, especially in the Bank of England's "multi-money" framing and in the ECB's insistence that tokenized innovation should remain anchored in central bank money.

Located within this broader evolution of tokenized money, stablecoins emerge as a distinct form of private tokenized money whose institutional fragility and competitive pressure on tokenized deposits cannot be assessed from inside the crypto frame. Their cross-platform portability and reserve-backed issuance give them clear advantages in open digital markets; their dependence on issuer-specific reserve architecture and weaker integration into the two-tier monetary system give tokenized deposits a structural advantage in regulated settings. The literature review that follows is therefore organized not as a generic survey but as a structured examination of unresolved debates on stability, reserve design, intermediation, regulation, and the competition with tokenized deposits.

3. Literature Review

Literature on stablecoins has expanded rapidly but remains unevenly developed across themes, methods, and levels of analysis. The early systematic review by Ante (2023) showed that the first wave of empirical research was narrow and concentrated on price stability, market interdependence, and a limited set of empirical techniques; the more recent survey by Mahrous, Caprolu, and Di Pietro (2025) confirms that the field has expanded substantially but remains fragmented across economic, technical, and regulatory subfields. Since 2024, and especially in 2025–2026, the literature has become much richer and more policy-relevant. Stablecoins are now studied as liabilities with implications for payments, reserve markets, bank funding, and the architecture of tokenized money. This paper is positioned at the intersection of seven broad streams rather than within any one of them in isolation: conceptual and monetary-theoretic work; stability, depegging, and run-risk research; reserve disclosure and safe-asset linkages; banking and monetary-policy transmission; payments and cross-border use; regulation and institutional design; and the literature comparing stablecoins with tokenized deposits. Each stream has matured but each remains incomplete on the integrative question that motivates this paper: how the asset side, the liability side, and the regulatory perimeter jointly determine the monetary character of stablecoins relative to tokenized deposits.

The first stream is conceptual and monetary-theoretic. Early influential work by Arner *et al.* (2020) framed stablecoins through the triad of risks, potential, and regulation, emphasizing that stablecoins were neither ordinary crypto-assets nor ordinary money, but hybrid instruments capable of affecting payment systems, monetary sovereignty, and financial stability. Historical and institutional analogies have reinforced this perspective by showing that credibility, governance, and redeemability are longstanding monetary issues rather than purely digital novelties (Frost *et al.* 2020; Gorton and Zhang, 2023). Subsequent BIS work sharpened the conceptual benchmark by arguing that stablecoins should not be assessed only in terms of whether they maintain a nominal peg. Instead, they must be evaluated against the deeper properties of sound money: singleness, elasticity, and integrity (Garratt and Shin, 2023; BIS, 2025). In this framework, the central issue is not whether stablecoins are "stable enough" in secondary markets, but whether they can function as money without fragmenting the unit of account, constraining balance-sheet responsiveness, or undermining confidence in par settlement. A complementary "money view"

perspective developed by Aldasoro, Mehrling, and Neilson (2023) interprets stablecoins through the historical analogy of the eurodollar system, arguing that maintaining par exchange between private liabilities and the unit of account requires a hierarchy of dealers, market-makers, and ultimately central-bank backstops. This account is not a competing alternative to the singleness framework so much as a more dynamic counterpart: where Garratt and Shin emphasize the architectural properties that money must satisfy, Aldasoro, Mehrling, and Neilson emphasize the dealer-balance-sheet mechanics by which par is sustained or breaks down. The two perspectives converge on the central proposition that a stablecoin's monetary character depends not on its peg in calm markets but on its institutional capacity to absorb redemption pressure under stress. This literature has been further reinforced by broader BIS and CPMI work on tokenization, which places stablecoins within a wider transformation of payment and settlement infrastructure rather than treating them as a self-contained crypto product category. The conceptual contribution of this stream is substantial, but it still leaves open an important issue: it defines what good money should be yet says less about how existing stablecoins are actually evolving as monetary instruments in relation to deposits, tokenized deposits, and tokenized reserve assets.

A second stream studies stability, depegging, and run risk. Early empirical work focused on the mechanisms that keep fiat-backed stablecoins near par and on the market structures that sustain arbitrage around the peg (Lyons and Viswanath-Natraj, 2023). More recent research has become more analytically sophisticated and increasingly attentive to fragility across designs and episodes. Gadzinski *et al.* (2023) examine whether design affects stability and show that protocol structure alone does not guarantee robust performance; Gadzinski *et al.* (2024) extend this work by analyzing co-instability across stablecoins, and AlAsadi *et al.* (2025) provide econometric evidence that stability differs systematically across issuers and market conditions. Briola *et al.* (2023) analyze the Terra-Luna collapse and demonstrate the fragility of algorithmic stabilization mechanisms when confidence breaks down, while Lee *et al.* (2025) develop systematic models of depegging risk using prices, trading activity, volatility, and sentiment. Ahmed, Aldasoro, and Duley (2024) advance the theoretical frontier with a global-games framework in which reserve quality and public information jointly determine run dynamics, showing that disclosure can either reduce or amplify fragility depending on prior beliefs about reserve quality. Ma, Yang, and Zhang (2025) identify a complementary fragility channel that operates not through reserves but through arbitrage: the mint-and-redeem mechanism that maintains the peg in normal conditions is itself highly concentrated, with a small number of authorized arbitrageurs accounting for the bulk of activity, so that a withdrawal of even a small number of arbitrageurs for operational, regulatory, or balance-sheet reasons can cause material peg deviations even when reserves are intact. This stream has matured substantially after the TerraUSD and USDC–SVB episodes, but it still treats stablecoins primarily as fragile pegged instruments rather than as evolving monetary institutions with broader balance-sheet and intermediation consequences – a limitation for any analysis concerned with monetary architecture rather than peg performance alone.

A third stream focuses on reserve design, disclosure, and the market consequences of backing assets. This literature is particularly relevant for the present paper because it connects stablecoins' liability side to their asset side. Disclosure-based work shows that the informational content of reserve reporting matters for market interpretation, while comparisons with money market funds clarify both the similarities and the limits of the analogy between stablecoins and traditional cash-management vehicles (Maex and Slavov, 2025; Anadu *et al.* 2024; Oefele *et al.* 2024). Recent studies and official work establish that reserve design is not a technical appendix to issuance but the mechanism through which on-chain demand for programmable balances is transmitted into conventional markets (Adrian *et al.* 2025; Ahmed and Aldasoro, 2025). The theoretical underpinning of this stream has been substantially deepened by Li, Mancini-Griffoli, Miccoli, Tan, and Zhang (2026), who develop a Diamond–Dybvig-style framework that formalizes the trade-off between maintaining stability and preserving issuer profitability: the unregulated equilibrium is suboptimal because issuers hold risky assets to maximize profits, and a social planner can improve welfare by requiring safe-asset backing combined with alternative revenue channels such as central bank reserve remuneration in a narrow-bank configuration. The empirical mapping into Treasury markets is now well established. Ahmed and Aldasoro (2025) show that inflows into dollar-backed stablecoins lower short-term U.S. Treasury yields; Barthélemy, Gardin, and Nguyen (2026) demonstrate that when major issuers held commercial paper extensively, stablecoin demand influenced short-term funding-market issuance; Ferrari Minesso and Siena (2026) interpret U.S. dollar stablecoins as creating a new global safe-asset channel linking private money creation and international payment demand directly to U.S. public debt. The institutional counterpart of this empirical finding is provided by Yadav and Malone (2026), who argue that the U.S. Treasury market itself is becoming structurally dependent on stablecoin-related demand, with the implication that the safe-asset channel is bidirectional: stablecoins do not merely consume Treasury supply but increasingly shape its short-term composition. The literature on reserve design materially deepens the field, but remains fragmented between disclosure studies,

funding-market studies, and macro safe-asset analyses. Few papers synthesize these strands to explain how reserve architecture shapes the economic identity of stablecoins as a distinct monetary layer.

A fourth stream examines the relationship between stablecoins, banks, and monetary-policy transmission. This has become one of the most dynamic areas of recent research, and the evidence has shifted substantially in 2025–2026. Altavilla, Boucinha, Burlon, Adalid, Fortes, and Maruhn (2026) document a deposit-substitution mechanism whereby stablecoin adoption shifts funds away from retail bank deposits, increases banks' reliance on wholesale funding, and weakens intermediation capacity, thereby altering monetary-policy transmission. Aldasoro and Ahmed (2026) provide arguably the cleanest causal-design evidence on the substitution question to date: using local projections fit to weekly U.S. data from January 2019 to June 2025, they show that deposit-rate increases predict slower stablecoin market-capitalization growth, with the effect roughly three times larger under instrumental-variable identification that exploits the well-documented nonlinearity in deposit-rate pass-through above a federal funds rate of approximately 3 per cent; the effect is materially stronger for USDC than for USDT, consistent with USDC's closer ties to U.S.-domiciled depositors. Coste (2024) traces the prudential mechanics underlying these aggregate dynamics, showing how deposits originating from stablecoin issuers are treated as wholesale, financial-sector liabilities under existing frameworks, with implications for liquidity coverage and net stable funding ratios at deposit-receiving banks. Wang's December 2025 FEDS Notes analysis (Wang, 2025) organizes these effects into three conceptually distinct channels – direct substitution, recycling within the banking system, and bank-issued stablecoin issuance – and notes that the composition of deposits matters more than the headline total, with transactional balances exposed to greater substitution pressure than savings balances. The New York Fed's work on stablecoin disintermediation reaches related conclusions from a complementary angle (Lee and Tou, 2026). Aldasoro *et al.* (2024) add nuance by showing that monetary tightening affects both traditional and crypto markets but that stablecoins do not behave as simple digital substitutes for established safe assets, while Chen and Phelan (2025) show that stablecoin issuance can harm banking-sector stability by altering deposit spreads, capital rebuilding, and lending capacity. Cong (2026) provides an industry-supported counterpoint, arguing that under the constraints imposed by the GENIUS Act – full reserve backing, prohibition on issuer-paid yield, prohibition on credit extension by issuers – the disintermediation pressure on bank deposits is materially smaller than headline projections suggest, with stablecoin–deposit substitution conditional on yield differentials and reserve composition. Read together, this stream has firmly moved stablecoins into mainstream debates on banking and monetary transmission, yet most studies either focus on banking effects without a detailed comparison to tokenized deposits or analyze stablecoin disintermediation in isolation from the broader tokenization of money.

A fifth stream studies stablecoins in payments, remittances, and cross-border finance. This literature remains thinner than the banking or reserve-design literature, but it is growing quickly and is increasingly relevant because it connects stablecoins to international monetary competition and payment-system frictions. IMF work shows that stablecoins remain heavily concentrated in crypto-market and automated uses yet also documents large and growing cross-border payment-related flows (Adrian *et al.* 2025; Cerutti *et al.* 2025). BIS work by Auer *et al.* (2025) uses a large bilateral dataset and shows that cross-border flows in stablecoins have distinct drivers from those of native crypto-assets, supporting the view that stablecoins have both speculative and transactional uses. Methodological work has also begun to address how international stablecoin flows can be measured more consistently, which matters because empirical inference remains highly sensitive to data construction (Reuter, 2025). This literature is valuable because it moves the discussion beyond domestic banking systems and toward international currency usage, digital dollarization, and cross-border monetary influence. However, much of it still focuses on adoption and flow patterns rather than on the institutional consequences of scaling stablecoin-based payments relative to bank-based tokenized money.

A sixth stream concerns regulation and institutional design. This stream has expanded sharply because stablecoins have moved beyond the stage where they could plausibly be treated as a regulatory afterthought. The FSB's framework on crypto-asset activities and stablecoin arrangements identified risks to financial stability, governance, and cross-border supervision, while the BIS has emphasized that jurisdictions are increasingly building frameworks focused on asset backing, disclosure, stability, and illicit-finance concerns (FSB, 2023, 2025; BIS, 2025). Earlier prudential work on e-money, oversight, and user protection remains relevant because stablecoin regulation increasingly overlaps with questions long associated with nonbank digital money claims (Dobler *et al.* 2021). Three recent regulatory regimes anchor contemporary academic and policy literature. First, the European Union's MiCA regime, which represents the most systematic *ex ante* formalization through asset-referenced tokens and electronic money tokens, with EBA work clarifying both the distinction between tokenized deposits and stablecoin-like liabilities and the overlap between MiCA and payment-services regulation (EBA, 2024, 2025, 2026). Second, the U.S. GENIUS Act of July 2025 (Public Law 119-27), which establishes a statutory framework for

payment stablecoins built around full one-to-one reserve backing, a closed list of permissible reserve assets, an explicit prohibition on issuer-paid yield, and a chartering pathway for nonbank issuers under federal supervision, with implementing rulemaking underway in 2026 (Dudley and Liang, 2026; OCC, 2026; FDIC, 2026; U.S. Treasury, 2026a, 2026b). The U.S. literature around the Act has expanded rapidly, with Yadav and Malone (2026) analysing its Treasury-market consequences and Cong (2026) examining its implications for bank deposit dynamics. Third, the Bank of England's "multi-money" framework, articulated through its 2025 consultation on sterling-denominated systemic stablecoins and subsequent speeches, which explicitly seeks to allow stablecoins, tokenized deposits, and central bank money to coexist under conditions that preserve trust in money (Bank of England, 2025a, 2026; Breeden, 2025). Recent monitoring by the FSB, IOSCO, and the ESRB shows that implementation remains uneven across jurisdictions and that broader systemic-risk concerns extend beyond individual issuers to crypto and DeFi spillovers (FSB, 2024; IOSCO and FSB, 2025; ESRB, 2025). This stream is rich in institutional detail, but much of it remains segmented by jurisdiction. There is still a clear need for work that synthesizes regulatory design not just as legal comparison but as a question about what kind of monetary architecture different frameworks are implicitly trying to produce.

A seventh and increasingly important stream compares stablecoins with tokenized deposits and related tokenized forms of money. This stream is directly relevant to the present paper and remains less developed than its importance would suggest. Garratt and Shin (2023) provide the key conceptual distinction by contrasting bearer-style stablecoins with non-bearer tokenized deposits and showing why the former threaten the singleness of money while the latter can preserve it through settlement in central bank money. The EBA's report on tokenized deposits translates that distinction into regulatory terms by clarifying that tokenized deposits remain deposits even when recorded on DLT and should not be conflated with EMTs (EBA, 2024). Huang and Keister (2026) revisit the debate from a theoretical perspective, modeling stablecoins and tokenized deposits as competing forms of tokenized private money with different welfare implications depending on bank incentives, regulation, and the scale of blockchain-based trade. The BIS annual report places the same question into a broader macro-financial vision, treating tokenized commercial bank money as part of the core future system while viewing stablecoins much more critically (BIS, 2025). Despite these advances, the comparative literature remains narrow relative to the importance of the issue. There are still relatively few papers that combine market evidence, reserve analysis, and regulatory comparison to study stablecoins and tokenized deposits as rival institutional forms within the same tokenized monetary environment.

The common limitation across these streams is fragmentation. Research on peg stability rarely connects depegging risk to reserve architecture, bank-funding effects, and safe-asset demand. Work on regulation often remains jurisdiction-specific, even as MiCA, the GENIUS Act, and the UK multi-money consultation increasingly raise the same architectural question: how private tokenized money can coexist with tokenized deposits and central-bank settlement without fragmenting money at par. The small literature on stablecoins versus tokenized deposits provides the closest bridge to that question, but it remains insufficiently connected to current market concentration, reserve composition, and regulatory change.

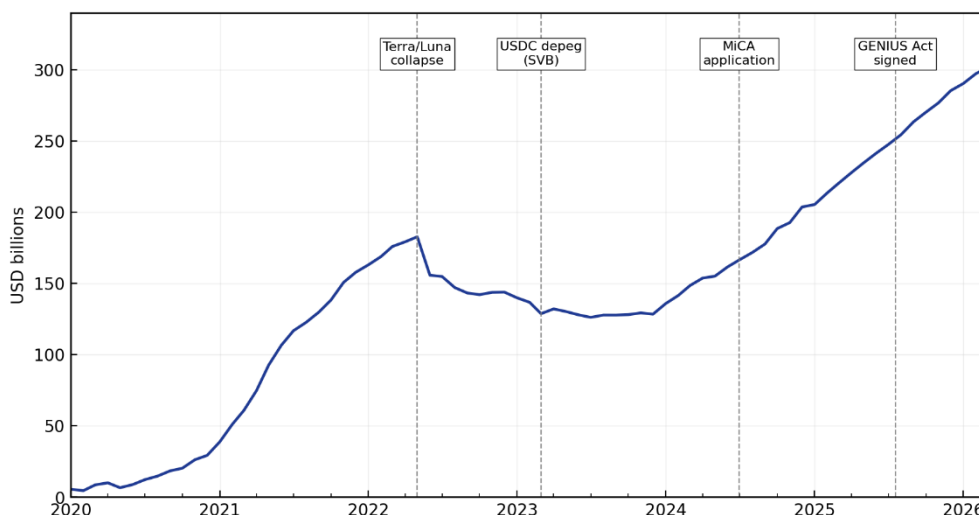
Three unresolved issues follow directly from this fragmentation. First, the literature still lacks a consolidated framework locating stablecoins between deposits, tokenized deposits, EMTs, and tokenized MMF-like claims. Second, reserve architecture has not yet been integrated into a single account linking disclosure, Treasury-market effects, bank-funding effects, and the global safe-asset channel. Third, the institutional competition between stablecoins and tokenized deposits remains underdeveloped, especially under the new regulatory perimeter created by MiCA, the GENIUS Act, and the UK multi-money approach. This paper addresses these gaps by treating stablecoins as a distinct monetary layer, linking market structure to reserve design and macro-financial transmission, and comparing stablecoins with tokenized deposits as competing institutional forms of programmable private money.

4. Market Structure of the Stablecoin Sector

The current structure of the stablecoin market indicates that stablecoins can no longer be treated as a peripheral supporting asset within crypto-asset markets. Their scale, concentration, and integration into wider tokenized financial activity justify treating them as a distinct monetary segment rather than as a narrow technical layer. As of 8 March 2026, RWA.xyz reported total stablecoin value of approximately 301 billion USD and more than 233 million holders, while DefiLlama and CoinGecko report aggregates within a 3–5 per cent range of this figure; the differences reflect methodological choices about how to treat wrapped tokens, paused issuance, and cross-chain duplicates rather than any disagreement on the order of magnitude (DefiLlama, 2026; CoinGecko, 2026; RWA.xyz, 2026). Reuter (2025) provides a methodological framework for reconciling these estimates and shows that, while the level

varies by construction, the trend and the dominant compositional features (issuer concentration, dollar dominance, network distribution) are robust across measurement choices. Aggregate scale is economically relevant in its own right, but its main significance lies in what it represents historically: stablecoins have moved from a niche liquidity instrument into the dominant monetary base of on-chain markets and an increasingly important form of tokenized private money. The historical growth of the sector, shown in Figure 1, is therefore not merely a background trend; it is the empirical basis for analyzing stablecoins as a monetary phenomenon rather than a transient crypto-market convenience.

Figure 1. Total stablecoin market capitalization, January 2020 – March 2026



Notes: billions USD, monthly. Annotations mark Terra/Luna collapse (May 2022), USDC depegging during Silicon Valley Bank failure (March 2023), MiCA entry into application for ARTs and EMTs (June 2024), and the signing of the GENIUS Act (July 2025).

Source: DefiLlama (2026); RWA.xyz (2026); CoinGecko (2026), authors' compilation. Methodological discrepancies across sources are within ± 5 per cent; series shown reflects the DefiLlama aggregate.

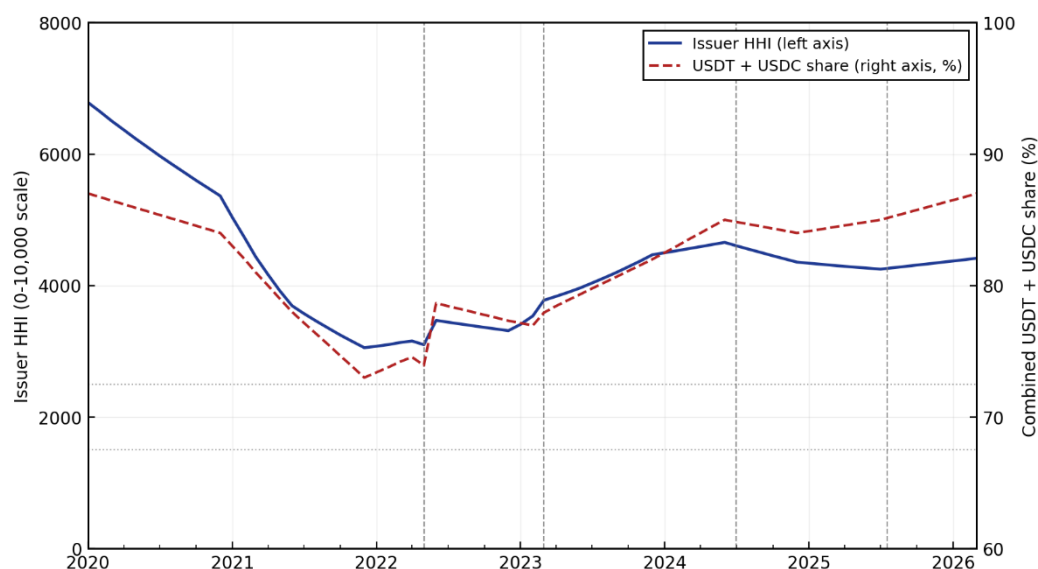
Figure 1 traces the historical scaling of stablecoins from a niche liquidity instrument into a monetary layer of growing systemic relevance for tokenized markets. The figure makes visible four developmental phases: early expansion (2020–2021), rapid growth during the crypto bull cycle (2021–2022), contraction associated with the Terra/Luna collapse and the broader 2022–2023 market correction, and renewed growth from late 2023 onward that pushed the sector above the 300 billion USD threshold by early 2026. The renewed expansion visible after mid-2025 coincides with greater U.S. regulatory clarity following the GENIUS Act, although the figure should be interpreted descriptively rather than as evidence of a causal regulatory effect. The pattern shows that the current significance of stablecoins cannot be understood through a static cross-sectional snapshot; it is the outcome of a rapid scaling process that redefined stablecoins as a form of tokenized private money rather than a transient feature of crypto-market infrastructure.

Scale alone does not capture the most important structural features of the sector. The stablecoin market is highly concentrated by issuer and overwhelmingly concentrated by currency. USDT and USDC account for approximately 90 per cent of total stablecoin capitalization, and around 97 per cent of issuance is denominated in U.S. dollars (Adrian *et al.* 2025). The concentration is asymmetric: stablecoins are technically portable across blockchains, wallets, and market venues, but they are not decentralized on the issuance side. Transferability is distributed; the liability structure is concentrated in a small number of private entities whose credibility depends on reserve quality, redemption arrangements, and market confidence rather than on the institutional guarantees associated with deposits or central bank money. This combination explains both the sector's success and its fragility. Concentrated issuance enables standardization, scale, and broad use as a common settlement asset across fragmented digital markets, but it also amplifies the consequences of issuer-specific shocks: reserve uncertainty, redemption friction, or confidence events at one or two major issuers can quickly become sector-wide. The persistence of dollar dominance despite the earlier introduction of MiCA-compliant euro-denominated stablecoins (notably Circle's EURC and Société Générale's EURCV) reinforces this picture. As Adrian *et al.* (2025) document, regulatory infrastructure alone has not been sufficient to drive non-dollar adoption: network effects, secondary-market liquidity, and the underlying currency's role in international finance dominate. Concentration is

therefore not an industrial-organization curiosity. It is a monetary-stability question because it makes system-wide confidence highly sensitive to a very small number of issuer-specific balance sheets and to a single sovereign currency.

Issuer concentration is not only high in the cross-section; it is also persistent over time, with movements that track regulatory and stress events rather than competitive dynamics in a conventional sense. Figure 2 shows the Herfindahl-Hirschman Index of issuer concentration in the stablecoin market computed monthly from January 2020 to March 2026, alongside the combined market share of the two leading issuers, USDT and USDC. The HHI is constructed in the standard form $HHI = \sum s_i^2$, where s_i denotes the percentage market-capitalization share of issuer i and the index is reported on the conventional 0-10,000 antitrust scale. By the U.S. Department of Justice and Federal Trade Commission thresholds, values above 2,500 denote a "highly concentrated" market. The stablecoin sector has remained above this threshold throughout the sample.

Figure 2. Issuer-concentration Herfindahl-Hirschman Index of the stablecoin market, January 2020 – March 2026



Notes: Monthly observations. The HHI is computed on the 0–10,000 antitrust scale as $HHI = \sum s_i^2$, where s_i denotes the percentage market-capitalization share of issuer i . The dashed reference lines indicate the conventional U.S. Department of Justice and Federal Trade Commission thresholds at $HHI = 1,500$ (boundary between unconcentrated and moderately concentrated markets) and $HHI = 2,500$ (boundary between moderately concentrated and highly concentrated markets). The right-hand axis shows the combined market share of USDT and USDC. Vertical dashed lines mark the collapse of TerraUSD (May 2022), the U.S. regional banking turbulence and USDC depeg (March 2023), the entry into application of MiCA for asset-referenced and electronic-money tokens (30 June 2024), and the signing of the GENIUS Act (18 July 2025).

Source: authors' computation based on issuer-level monthly market capitalizations from DefiLlama (2026), cross-checked against CoinGecko (2026).

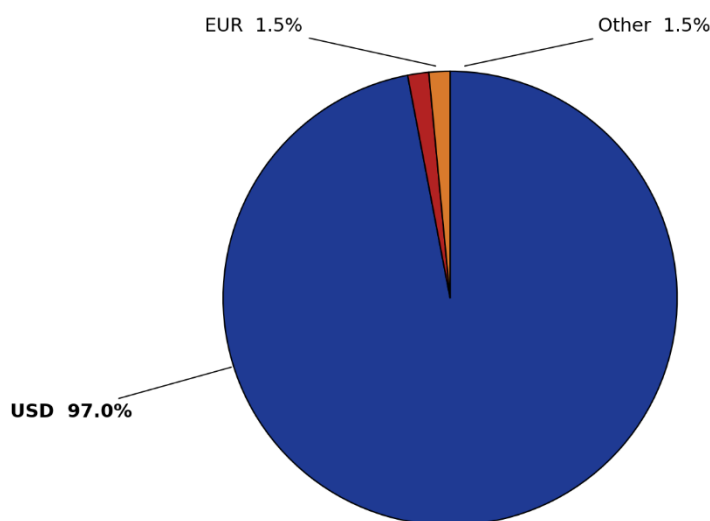
The series tells a non-monotonic story. Concentration was extreme in early 2020, with HHI close to 6,800, reflecting the near-monopoly position of USDT in the early phase of the market. The expansion of USDC and the brief growth of BUSD, DAI and TerraUSD reduced the index sharply through 2020 and 2021, reaching a local minimum of approximately 3,055 in December 2021 – still above the "highly concentrated" threshold but the most diversified configuration the market has reached to date. The collapse of TerraUSD in May 2022 mechanically reduced the issuer count by one and produced a temporary increase in HHI as remaining issuers absorbed redirected demand. The U.S. regional banking turbulence of March 2023, which produced the temporary depeg of USDC, accelerated a redistribution of share from USDC back to USDT, and the index rose to roughly 3,800 by mid-2023. The termination of BUSD by the New York Department of Financial Services later that year removed a further competitor.

In the post-MiCA and post-GENIUS period the index has stabilized in a range between approximately 4,200 and 4,700, with the entry of USDe, FDUSD, and PYUSD only partially offsetting the consolidation around USDT and USDC. As of the snapshot date used elsewhere in this paper, HHI stands at approximately 4,415, with the combined USDT + USDC share at 87 per cent. This combination of values places the stablecoin sector in a more concentrated position than U.S. money market funds, which exhibit HHI values typically below 1,000, and at a level comparable to large-bank deposit concentration in mid-sized European economies. The persistence of this

concentration is not merely a product of network effects or first-mover advantages. Ma, Yang, and Zhang (2025) develop a theoretical framework showing that issuer concentration is structurally tied to the centralization of arbitrage: stablecoin issuers actively restrict the set of authorized arbitrageurs in order to stabilize the peg in normal times, but this design choice simultaneously concentrates run risk in those same arbitrageurs under stress. Concentration on the issuer side and concentration on the arbitrage side are therefore two manifestations of the same trade-off between price stability and crisis resilience, which helps explain why the stablecoin sector remains structurally concentrated even as new entrants appear. From a monetary-stability perspective, the implication is that concentration must be modelled as a structural feature of the sector rather than a transitional one, and that the prudential, redemption, and resolution frameworks discussed in Sections 5 and 7 must be designed to operate against a market in which two issuers persistently account for roughly nine-tenths of outstanding supply. Analytically, this means concentration is not merely a descriptive feature of the current market but a determinant of systemic risk: because singleness of money requires uniform par exchange across issuers, a sector in which two issuers account for the overwhelming majority of supply makes the system-wide maintenance of par dependent on the reserve adequacy and operational integrity of a very small number of balance sheets. Market concentration therefore feeds directly into the integrity dimension of the BIS framework rather than standing as a stand-alone statistic.

A second defining characteristic of the sector is its overwhelming dollarization. Figure 3 makes this feature explicit. Stablecoins are often described in generic terms as fiat-referenced digital assets, but the actual market is overwhelmingly a dollar market. The IMF's estimate that around 97 per cent of stablecoin issuance is dollar-denominated implies that the stablecoin ecosystem is not merely creating a new class of private digital claims; it is extending the monetary reach of the U.S. dollar into tokenized financial environments. This has at least three implications. First, it connects the growth of stablecoins directly to global demand for dollar liquidity. Second, it links stablecoin expansion to the demand for U.S. safe assets, especially Treasury bills and Treasury-backed repos. Third, it raises questions of monetary sovereignty in non-U.S. jurisdictions, particularly where tokenized markets may increasingly operate on top of private dollar liabilities rather than domestic money. These concerns are now explicit in IMF, BIS, and ECB work and are among the reasons stablecoins have moved from a specialized fintech issue to a broader macro-financial and geopolitical question.

Figure 3. Currency composition of stablecoin market capitalization, March 2026



Notes: Share of total stablecoin market capitalization by reference currency, percentages.

Source: Adrian *et al.* (2025) for the dominance estimate; cross-checked against CoinGecko (2026) and RWA.xyz (2026) March 2026 snapshot.

Figure 3 makes explicit the asymmetric currency composition of the stablecoin market. Dollar-linked stablecoins account for approximately 97 per cent of total capitalization; euro-, sterling-, yen-, and other-currency stablecoins together account for the remainder, with the largest non-dollar segment (euro) materially below 2 per cent. The stablecoin market is therefore not a generic market for fiat-referenced digital tokens but a highly asymmetric system of private dollar-denominated money. Analytically, this matters in three ways. First, it ties stablecoin demand to global demand for dollar liquidity. Second, it ties stablecoin growth to demand for U.S. safe

assets, principally short-dated Treasuries and Treasury-backed repo. Third, it raises monetary-sovereignty questions for non-U.S. jurisdictions in which tokenized markets may increasingly operate on top of private dollar liabilities rather than on domestic money – a concern now explicit in IMF, BIS, and ECB work and a principal driver of the post-2024 regulatory response.

The market is also structured across blockchain networks in ways that are economically revealing. RWA.xyz network data indicate that Ethereum remains the dominant network by stablecoin capitalization, with about 166.7 billion USD, while BNB Chain hosts roughly 12.8 billion USD and other chains much smaller amounts. This concentration across networks matters because it suggests that stablecoins are not distributed evenly across technological environments. Rather, they cluster where tokenized asset activity, settlement demand, and composability are deepest. The dominance of Ethereum reinforces the view that stablecoins are increasingly embedded in broader tokenized financial infrastructures rather than functioning only as transactional media in isolated crypto niches. In other words, stablecoins are becoming part of a networked monetary layer whose structure depends not only on issuer behavior but also on the architecture of the underlying platforms in which they circulate.

At the same time, the economic use of stablecoins remains more complex than a simple “digital payments” narrative would suggest. IMF evidence indicates that stablecoins are still used predominantly for crypto-related purposes, including trading, collateral management, liquidity parking, and automated market operations, with a substantial share of transaction activity driven by bots and algorithmic systems. This does not diminish their importance. On the contrary, it helps clarify the stage of development the sector has reached. Stablecoins have not yet become a generalized retail money for households and firms, but they have already become the default monetary base for a large share of on-chain finance. That intermediate position is crucial: it explains why stablecoins can have growing banking, reserve-market, and regulatory consequences even before they become a dominant retail payment instrument.

The distinction between outstanding supply, circulation, and function is therefore essential. A stablecoin can have a very large market capitalization without being widely used in everyday retail transactions, just as a money-market-like claim can be systemically relevant without circulating as hand-to-hand currency. Stablecoins should be interpreted along both monetary and intermediation dimensions. On the monetary side, they increasingly provide the unit of settlement and liquidity management for tokenized markets. On the intermediation side, their reserve-backed structure translates user demand for blockchain-compatible money into demand for Treasury bills, repos, bank deposits, and other liquid assets. This is why market structure is not merely descriptive groundwork. It establishes the conditions under which reserve design and monetary transmission become economically meaningful.

The current market structure has direct implications for the competition between stablecoins and tokenized deposits. As of late 2024, the EBA documented only very limited live tokenized-deposit activity in the EEA, with use cases concentrated in narrow institutional settings (EBA, 2024). The picture has shifted materially in 2025–2026, although the evidence should be interpreted as institutional experimentation and early commercialization rather than full market parity with stablecoins. JPMorgan introduced its JPM Coin USD / JPMD deposit-token initiative for institutional clients on Coinbase's Base network; Citi expanded Citi Token Services for cross-border payments and liquidity management, including 24/7 USD clearing and euro integration; BNY was selected as the primary reserve custodian for Ripple's RLUSD stablecoin; and SoFi announced SoFiUSD, describing it as the first stablecoin issued by a U.S. national bank on a public permissionless blockchain (JPMorgan Chase, 2025; Citigroup, 2025a, 2025b; BNY, 2025; SoFi Technologies, 2025). These examples do not show that tokenized deposits or bank-issued stablecoins have reached commercial parity with USDT and USDC, which still circulate at an order of magnitude larger than the visible stock of bank-issued tokenized money. They do, however, show that the asymmetry between scaled stablecoins and bank-based programmable money is narrowing rather than widening, and that the competition between the two forms is moving from prospect to active institutional contest. Stablecoins continue to enjoy a first-mover advantage in open and crypto-native settings, while bank-based tokenized money is gaining ground in institutional and cross-border B2B settings where prudential integration and balance-sheet continuity matter most. The competitive field is therefore best characterized not as a contest between equally mature products, but as a rapidly shifting institutional rivalry whose eventual outcome will depend on regulatory design, interoperability, and the operational maturity of bank-issued programmable money. Equity-market evidence supports this characterization: Copestake, Englander, Martinez Peria, and Villegas-Bauer (2026) use high-frequency variation in stock prices around U.S. legislative events to estimate that legislation supporting the use of stablecoins in payments reduced the market value of listed incumbent payment firms by approximately 18 per cent, or about 300 billion USD. The estimated effect is proportionally larger for incumbents focused on cross-border

payments and smaller for incumbents protected from network effects or already offering crypto-related services. The financial-market interpretation is therefore consistent with the institutional one: stablecoins are increasingly priced as a credible competitor to incumbent payment infrastructure, particularly in cross-border use cases where their cost and speed advantages are most pronounced.

This market structure has three implications. First, stablecoins have reached a scale at which they must be treated as a meaningful monetary segment rather than a technical appendage of crypto trading. Second, the joint concentration of issuance and currency makes issuer credibility, reserve quality, and cross-border monetary influence the central analytical variables, not the choice of blockchain or the user interface. Third, the current market architecture gives stablecoins a substantial first-mover advantage in open digital markets, but the rapid 2025–2026 development of bank-issued tokenized money – both as tokenized deposits and as bank-affiliated stablecoins under the GENIUS Act chartering pathway – suggests that this advantage is not structurally permanent. The trajectory will depend on regulatory design, interoperability between forms of money, and the operational maturity of programmable bank-based instruments. The argument therefore turns from market structure to the balance-sheet design that sustains it.

5. Reserve Design and Monetary Transmission

If market structure explains why stablecoins matter, reserve design explains how they matter. Stablecoins are liabilities that promise stable redemption, but the credibility of that promise depends not on a nominal peg or on secondary-market arbitrage alone. It depends on the composition, liquidity, transparency, and operational accessibility of the assets held against those liabilities. Reserve design is therefore the bridge between private token issuance and monetary consequence: it determines whether a stablecoin behaves more like a narrow claim on safe assets, a money-market-fund-like instrument, a shadow-banking liability with embedded liquidity risk, or a hybrid of these forms. The theoretical underpinning of this view has been formalized by Li, Mancini-Griffoli, Miccoli, Tan, and Zhang (2026) in a Diamond–Dybvig-style framework that captures the trade-off between maintaining stability and preserving issuer profitability: the unregulated equilibrium is suboptimal because issuers hold risky assets to maximize profit, and welfare can be improved by combining safe-asset backing with alternative revenue channels such as central bank reserve remuneration in a narrow-bank configuration. The empirical literature complements this theory with three observations: the IMF documents that the largest stablecoins are backed mainly by short-term U.S. Treasuries, Treasury-backed repos, and deposits at financial institutions (Adrian *et al.* 2025); BIS work on stablecoin runs shows that reserve quality and transparency jointly determine peg resilience (Ahmed, Aldasoro and Duley, 2024); and ECB, BIS, and Federal Reserve staff work shows that reserve-backed stablecoins alter bank funding structures, reserve distribution, and monetary-policy transmission by transforming demand for digital transactional balances into demand for reserve assets outside the traditional deposit system (Altavilla *et al.* 2026; Aldasoro and Ahmed, 2026; Coste, 2024; Wang, 2025).

A first analytical point is that "stablecoin reserves" should not be treated as a uniform category. Even within the dominant fiat-backed segment, reserve structures differ materially across issuers. Circle's published reserve reports present USDC as backed by cash, short-dated U.S. Treasury securities, and Treasury-backed overnight repo, with the majority held through the BlackRock-managed Circle Reserve Fund (Circle Internet Financial, 2026). Tether's own reporting shows that although U.S. Treasury bills and reverse repos account for the majority of USDT backing, the reserve pool also contains secured loans, precious metals, bitcoin, and other investments classified as non-core assets (Tether International, 2026). These differences are not incidental. The category "reserve-backed stablecoin" contains meaningfully different risk architectures. A stablecoin backed narrowly by government securities, repo, and cash is institutionally different from one that embeds a wider asset mix; the difference is one of liquidation depth, valuation transparency, and operational accessibility under stress, not merely of accounting composition. The post-GENIUS regulatory environment in the United States is likely to compress this dispersion over time, because the closed list of permissible reserve assets in the GENIUS Act effectively forces U.S.-regulated payment stablecoins toward the narrow end of the spectrum (U.S. Congress, 2025). Reserve backing remains, for now, a spectrum rather than a binary characteristic, but the spectrum itself is narrowing under regulatory pressure.

Table 2. Major stablecoins: market position and reserve architecture, 31 December 2025

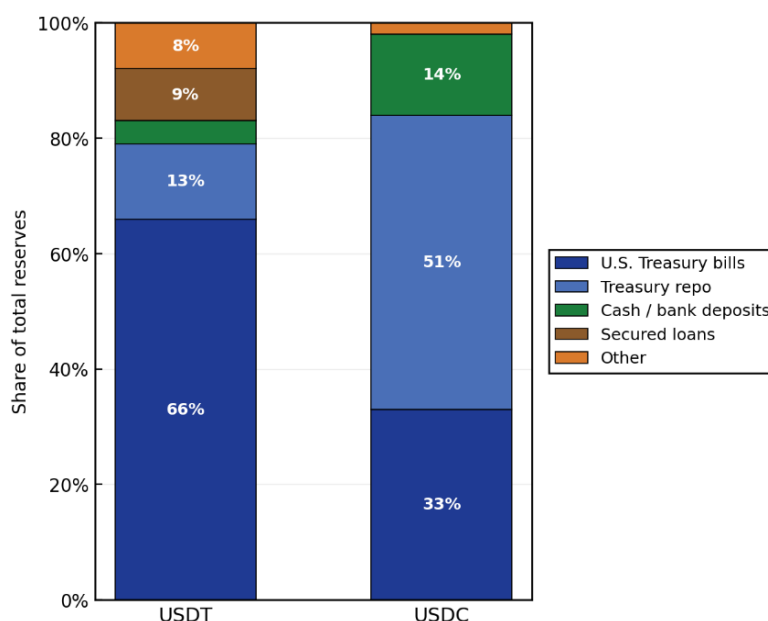
Stablecoin	Reference currency	Market cap (31 Dec 2025)	Issuer / sponsor	Reserve architecture (high level)	Disclosure / attestation style	Main use profile	Main fragility channel
USDT	USD	~140 bil. USD	Tether International, S.A. de C.V.	U.S. Treasury bills (~122 bil. USD) and Treasury-backed reverse repos (~25 bil. USD) dominate; secured loans (~17 bil. USD); precious metals, bitcoin, and other investments as residual	Quarterly assurance-style reserves report	Dominant cross-exchange liquidity; broad crypto settlement asset, especially in non-U.S. markets	Asset heterogeneity; opacity concerns under stress; issuer-specific confidence shock
USDC	USD	45 bil. USD	Circle Internet Financial	Cash and bank deposits (~14%); short-dated U.S. Treasuries (~33%); Treasury-backed overnight repo (~51%); reserves majority held via Circle Reserve Fund managed by BlackRock	Daily third-party reporting via Reserve Fund; monthly attestation	Institutional-facing payments; DeFi liquidity; tokenized-finance settlement rails	Bank/custody event risk (cf. SVB March 2023); redemption coordination under stress despite narrow reserves
USDe	USD	~5 bil. USD	Ethena Labs	Synthetic, delta-neutral collateral structure: long crypto spot positions hedged by short perpetual futures, plus liquid stablecoin reserves; not a fiat-backed model	Protocol-level transparency; periodic custodian attestations	DeFi-native yield-bearing collateral; on-chain trading	Funding-rate risk; centralized-exchange counterparty risk; collateral-market stress
DAI / USDS	USD	~5 bil. USD (combined)	Sky Ecosystem (formerly MakerDAO)	Mixed crypto-collateral plus growing share of tokenized real-world assets, especially short-dated U.S. Treasuries via tokenized vehicles	On-chain governance + protocol transparency	DeFi-native collateral and on-chain monetary use	Protocol/governance risk; collateral concentration; oracle and liquidation-mechanism risk
EURC	EUR	~0.2 bil. USD	Circle Internet Financial	Narrow euro-denominated reserve design: cash and short-dated euro-area government securities	MiCA EMT-regime reporting; transparency disclosures	Euro-denominated tokenized transfers and settlement	Scale disadvantage; weaker network effects; thinner secondary-market liquidity

Source: Author's compilation based on Tether (2026) and Circle (2026) reserve attestations as of 31 December 2025; market capitalization data from CoinGecko (2026) and DefiLlama (2026); for USDe, Ethena Labs (2025) transparency disclosure; for FDUSD, First Digital Trust (2025) reserve attestation; for DAI/USDS, MakerDAO/Sky Protocol (2025) on-chain collateral data.

Table 2 brings this heterogeneity into focus. The major issuers rely on materially different reserve configurations: narrow Treasury-and-repo structures (USDC, EURC), heterogeneous mixed-asset structures (USDT), synthetic delta-neutral collateral (USDe), and crypto- or tokenized-asset structures with on-chain governance (DAI/USDS). Disclosure also varies, from daily reserve-fund reporting to periodic custodian attestations and protocol-level transparency. These differences shape redemption credibility, liquidity under stress, and the channels through which stablecoins affect conventional markets. The 2025–2026 regulatory wave is likely to compress heterogeneity at the top of the market, as GENIUS-compliant payment stablecoins and MiCA EMTs are pushed toward narrower reserve models, while synthetic and DeFi-native designs remain institutionally distinct.

These differences matter for how the major issuers should be interpreted. A stablecoin with a narrow reserve structure concentrated in government bills, Treasury-backed repos, and cash is more readily understood as a tokenized claim on highly liquid safe assets. It does not thereby become identical to a bank deposit or a money market fund share, but it is institutionally closer to a narrow reserve-backed transactional instrument than to a broader portfolio liability. A stablecoin backed by a more heterogeneous reserve mix, by contrast, embeds greater scope for valuation uncertainty, liquidity asymmetry, and information sensitivity under stress. Two stablecoins may both hold par most of the time while resting on materially different balance-sheet logics and therefore on materially different conditions of credibility. The analytical implication is that reserve heterogeneity maps directly onto the elasticity and integrity dimensions of sound money: a narrowly backed issuer approximates a tokenized claim on safe assets and supports par exchange with high reliability but limited elasticity, whereas a broader reserve structure introduces liquidity transformation that raises elasticity at the cost of redemption certainty. Reserve composition is therefore not a reporting detail but the variable that locates each issuer on the singleness–elasticity–integrity surface.

Figure 4. Reserve composition of USDT and USDC, 31 December 2025



Notes: Stacked-bar comparison, percentage of total reserves by asset class. USDT components: U.S. Treasury bills (~122 billion USD); Treasury-backed reverse repos (~25 billions USD); secured loans (~17 billions USD); precious metals, bitcoin, and other investments (residual). USDC components: cash and bank deposits (~14%); short-dated U.S. Treasuries (~33%); Treasury-backed overnight repo (~51%); other (residual).

Sources: Tether International (2026); Circle Internet Financial (2026).

Figure 4 compares the reserve architecture of the two dominant USD-pegged stablecoins. It makes visible the difference between a heterogeneous mixed-asset reserve (USDT) and a narrower Treasury-and-repo reserve (USDC), together with differences in disclosure granularity. The comparison matters because liquidity under stress, macro-financial transmission, and exposure to regulatory tightening all depend on the asset-side structure behind the token. Under the closed list of permissible reserve assets in the GENIUS Act, the USDC structure is closer to

the post-GENIUS regulatory norm, while USDT includes asset categories that sit outside the U.S. payment-stablecoin perimeter.

A second point is that reserve design affects not only solvency in a narrow sense but also the strategic dynamics of redemption. Stablecoin fragility is often discussed in terms of depegging, but the deeper issue is whether holders continue to believe that par convertibility can be honored quickly and predictably when public information becomes adverse. Ahmed, Aldasoro, and Duley (2024) show that the informational quality of reserve assets affects the coordination game among stablecoin holders, and that public disclosure can either reduce or amplify run risk depending on prior beliefs about reserve quality. Their framework identifies a trade-off between transparency and fragility: better information stabilizes expectations when reserve quality is believed to be strong, but negative public signals can accelerate redemptions when confidence is already weak. Transparency is necessary but not a sufficient substitute for asset quality and liquidity: a reserve pool can be more transparent and yet more vulnerable if its underlying assets are difficult to liquidate or sensitive to valuation shocks in stressed conditions.

A complementary fragility channel operates through market microstructure rather than through reserves. Ma, Yang, and Zhang (2025) document that the arbitrage mechanism that maintains the stablecoin peg in normal conditions is highly concentrated, with a small number of authorized arbitrageurs accounting for the bulk of mint-and-redeem activity. Concentrated arbitrage is functional in normal conditions because it minimizes peg deviation, but it introduces an additional source of fragility under stress: if even a small number of arbitrageurs withdraw – for operational, regulatory, or balance-sheet reasons – secondary-market peg deviations can become material even when reserves remain intact. The institutional architecture of arbitrage is therefore part of the broader reserve-and-redemption problem, not a separate technical issue.

Together, these results explain why reserve quality matters more than nominal peg performance. A stablecoin can remain near par in normal conditions while still carrying latent run risk if its reserves are opaque, heterogeneous, or operationally difficult to mobilize quickly under stress; or if the arbitrage architecture that sustains the peg in normal conditions is concentrated enough to fail when most needed. The TerraUSD collapse demonstrated the fragility of algorithmic and under-collateralized designs; the subsequent literature has shown that even reserve-backed models must be analyzed through the same first-mover logic. Reserve design therefore operates along four interacting dimensions – informational, liquidity, governance, and arbitrage-architecture – which jointly determine whether holders continue to regard the token as money-like at the moment when convertibility is most in question.

The third analytical implication of reserve design is that it transmits stablecoin demand into conventional financial markets. This is where the analysis moves from microstructure to macro-finance. The literature now identifies three distinct transmission channels operating through the asset side of stablecoin issuance. They are conceptually separable but operationally intertwined.

The Treasury and short-term funding channel.

Demand for dollar-backed stablecoins concentrates in U.S. Treasury bills and Treasury-backed reverse repos, which means that on-chain demand for transactional balances is mechanically translated into off-chain demand for the most liquid segments of U.S. public debt. Ahmed and Aldasoro (2025) show that inflows into dollar-backed stablecoins are associated with measurable declines in short-term Treasury yields. Cerutti, Firat, Hengge, and Sagawa (2026) provide stronger causal identification of the same mechanism: combining a daily narrative dataset of stablecoin-specific news with high-frequency variation in the combined market capitalization of USDC and USDT, they implement heteroskedasticity-based identification within an event-study and structural-VAR framework, and document that positive stablecoin demand shocks persistently lower short-term U.S. Treasury yields and depreciate the U.S. dollar. They also document heterogeneous cross-sectional effects – payment providers benefit from greater stablecoin adoption, while banks (including community and small banks frequently identified as exposed to deposit substitution) show no significant priced disintermediation risk – which is consistent with the moderate, regulatory-design-dependent magnitude of bank-funding effects that the second channel will examine. Barthélemy, Gardin, and Nguyen (2026) demonstrate that during periods when major issuers held larger commercial-paper exposures, stablecoin demand directly affected short-term funding-market issuance. The mechanism is not speculative: it operates through the standard balance-sheet identity that links liability creation to asset acquisition. As the GENIUS Act narrows the permitted reserve assets of U.S.-regulated payment stablecoins toward Treasury bills, repo, and insured deposits (U.S. Congress, 2025), this channel will tighten and become more concentrated in the front end of the Treasury curve.

The bank-funding channel.

Reserve composition transmits stablecoin demand into bank funding through two routes. The first is the reserve-deposit route: stablecoin issuers hold a portion of their reserves as bank deposits, which appear on the asset side of the issuer and the liability side of the bank but are treated as wholesale, financial-sector funding for prudential purposes (Coste, 2024). The second is the substitution route: when retail and institutional users move balances from bank deposits into stablecoins, the deposit base of the banking system contracts, increasing reliance on more expensive wholesale funding and altering the transmission of monetary policy (Altavilla *et al.* 2026; Lee and Tou, 2026). The substitution route has now been documented with careful identification: Aldasoro and Ahmed (2026) show using local projections on weekly U.S. data that deposit-rate increases predict slower stablecoin growth, with effects roughly three times larger under instrumental-variable identification, and materially stronger for USDC than for USDT. Wang (2025) organizes the resulting effects into three conceptually distinct effects – direct substitution, recycling within the banking system, and bank-issued stablecoin issuance – and notes that the composition of deposits matters more than the headline total, with transactional balances exposed to greater substitution pressure than savings balances. Cong (2026), in industry-supported research, argues that under the constraints imposed by the GENIUS Act the disintermediation pressure on bank deposits is materially smaller than headline projections suggest, with substitution conditional on yield differentials and the prohibition on issuer-paid yield. The literature has therefore converged on the qualitative conclusion that substitution is real and regulatory-design-dependent, but it has not converged on the quantitative magnitude of the effect, where estimates differ by roughly an order of magnitude. Wang (2025) reports illustrative scenarios in which displaced bank deposits could range from approximately USD 65 billion under conservative assumptions to over 1 trillion USD under more aggressive ones, with the higher figures reflecting unconstrained yield-bearing competition; the Bank Policy Institute and other industry-supported analyses argue that yield-bearing stablecoin variants could produce destabilizing outflows of comparable scale. Cong (2026), drawing on transaction-level evidence under post-GENIUS constraints, argues that effective substitution is materially smaller because the Act prohibits issuer-paid yield and confines reserves to a narrow set of assets that does not allow stablecoin issuers to compete with deposit rates directly. The disagreement is partly empirical and partly counterfactual: it depends on whether one assumes faithful enforcement of the GENIUS Act's yield prohibition, or whether one allows for indirect yield competition through affiliates, exchanges, or bundled product structures. The substitution effect is therefore best understood not as a single estimated parameter but as a range whose realised magnitude will depend on the operational interpretation of the GENIUS Act's perimeter rules. This is one of the principal empirical questions the literature on stablecoins and bank funding is yet to settle.

The global safe-asset channel.

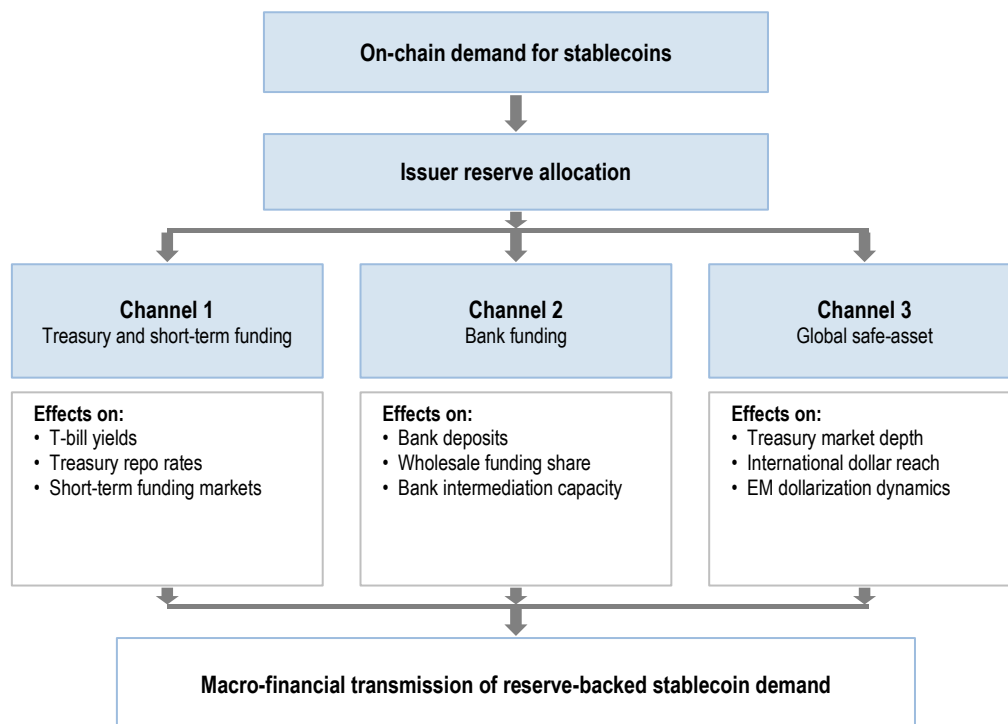
The third channel operates at the level of the international monetary system. Ferrari Minesso and Siena (2026) interpret U.S. dollar stablecoins as creating a new global safe-asset channel that links private money creation and international payment demand directly to U.S. public debt. Yadav and Malone (2026) extend this argument by tracing its institutional implications: as stablecoin issuance scales, the U.S. Treasury market becomes structurally dependent on stablecoin-related demand for short-term issuance, and non-U.S. jurisdictions experience an extension of dollar reach through tokenized rails. Aldasoro, Beltran, and Grinberg (2026) provide complementary evidence that large inflows into dollar stablecoins generate measurable parity deviations between stablecoin and spot-FX dollar prices and can weaken local currencies, particularly in jurisdictions with restricted access to dollar markets. Hofmann, Mehrotra, and Paulick (2026) embed these dynamics in a broader analysis of digital-age dollarization. The combined picture is one in which stablecoins are not only an instrument of payments but a channel through which private dollar issuance interacts with sovereign monetary control, with consequences for emerging-market policy autonomy that go well beyond the narrowly U.S.-domestic effects considered in the first two channels.

These three channels make reserve composition analytically central. A reserve pool concentrated in cash, short-dated Treasuries, repo, and insured deposits operates as a relatively narrow and predictable conduit between on-chain balances and off-chain markets. A reserve pool that includes secured loans, longer-duration assets, or non-core holdings introduces additional pathways through which stablecoin demand can affect conventional finance. The macro-financial footprint of a stablecoin is therefore determined jointly by its scale and by the architectural narrowness of its reserve.

The three channels also interact through the same set of reserve assets, which means that under stress they can amplify rather than diversify each other. Gross and Senner (2026) formalise this in a model that links a systemic stablecoin to the bond market through a feedback loop: redemption pressure depletes reserves, prompts asset sales, depresses bond prices, erodes the issuer's solvency, and amplifies further redemptions. Their analysis ties stablecoin design parameters – capital and liquidity buffers, reserve composition, redemption gates, and

reserve duration – directly to outcomes such as run frequency, fire-sale intensity, and bond-market volatility. Two implications follow. First, the architectural narrowness of a reserve does not by itself eliminate stress propagation; it only narrows the channel through which stress is transmitted. Second, the prudential framework for systemic stablecoins must be designed jointly across the asset side and the redemption side, since liquid reserves do not protect against runs if redemption mechanics permit unconstrained outflows in periods of stress.

Figure 5. The reserve transmission channel: from on-chain stablecoin demand to off-chain financial markets



Notes: Conceptual diagram, three transmission channels. Channel 1 (Treasury and short-term funding): demand for stablecoins → reserve allocation to T-bills and Treasury repo → effects on short-term Treasury yields and short-term funding markets. Channel 2 (bank funding): user demand for stablecoins → deposit substitution and reserve-deposit holdings at banks → effects on bank funding costs and intermediation capacity. Channel 3 (global safe-asset): scale of dollar stablecoin issuance → structural Treasury-market dependence and dollar extension via tokenized rails → effects on emerging-market dollarization and monetary autonomy.

Source: authors' synthesis based on Adrian *et al.* (2025), Ahmed and Aldasoro (2025), Aldasoro and Ahmed (2026), Coste (2024), Altavilla *et al.* (2026), Ferrari Minesso and Siena (2026), Yadav and Malone (2026), and Wang (2025).

Figure 5 summarizes this transmission logic. On-chain demand for programmable private money is translated into reserve allocation, and reserve allocation then affects safe-asset demand, bank funding, short-term funding markets, and international dollar intermediation. The figure therefore turns reserve design from an accounting description into a mechanism linking tokenized finance to conventional financial markets.

The same analysis also clarifies the institutional classification problem. Stablecoins backed narrowly by Treasury bills, repo, and insured deposits resemble tokenized narrow-money or cash-management claims. Broader reserve structures move closer to a shadow-banking perimeter, with different run dynamics, safe-asset effects, and competitive pressure on bank deposits. This classification matters because the relevant institutional alternative is not money in the abstract, but tokenized deposits as a bank-based form of programmable private money.

The three reserve channels also have direct implications for monetary policy and monetary sovereignty that deserve separate treatment, because they are among the most contested questions in the current debate. For monetary-policy transmission, the central point is that reserve-backed stablecoins relocate transaction balances from bank deposits into reserve portfolios concentrated in short-dated government claims. To the extent that this migration is large, it compresses the deposit base through which conventional policy rates are transmitted, and it shifts a portion of money-like balances into instruments whose return is governed by Treasury-bill and repo markets rather than by administered deposit rates. Altavilla *et al.* (2026) show that this can alter the pass-through of policy rates by changing the elasticity of bank funding, while the prohibition on issuer-paid yield under the GENIUS Act is precisely an attempt to limit the speed at which transaction balances migrate out of the deposit channel. The net

effect on transmission is therefore conditional on regulatory design rather than fixed, which is consistent with the order-of-magnitude disagreement on deposit substitution discussed in Section 3.

For interest-rate transmission specifically, the safe-asset channel implies a two-way linkage. Stablecoin inflows raise demand for short-dated Treasuries and compress their yields (Ahmed and Aldasoro, 2025), while redemption waves force reserve liquidation and can transmit stress back into the very markets that anchor the short end of the yield curve. As stablecoin reserves grow relative to the floating supply of Treasury bills, the marginal price-setting role of stablecoin flows in short-term funding markets increases, which means that monetary authorities may increasingly have to account for stablecoin redemption dynamics when assessing money-market conditions.

For digital dollarization and monetary sovereignty, the implications fall mainly outside the United States. Because roughly nine-tenths of stablecoin capitalization is dollar-denominated and a growing share of activity connects users in emerging-market economies, stablecoins function as a digital channel through which dollar balances reach residents of countries with high inflation, exchange-rate volatility, or capital controls (Adrian *et al.* 2025; Aldasoro, Beltran, and Grinberg, 2026). Where domestic demand for a stable store of value is strong, dollar stablecoins can substitute for local-currency balances, weakening the domestic monetary transmission mechanism and complicating the enforcement of capital-flow management measures. This “digital dollarization” extends the international reach of the dollar – strengthening its role as the unit of account of tokenized finance – while simultaneously narrowing the monetary autonomy of economies on the receiving end. The same architectural feature that makes dollar stablecoins attractive as globally portable money therefore creates an asymmetry: it reinforces the issuing currency’s dominance while eroding monetary sovereignty elsewhere. This tension, rather than peg stability, is arguably the most consequential macro-financial dimension of stablecoin growth for the international monetary system, and it motivates the regulatory and architectural questions taken up in Sections 6 and 7.

6. Stablecoins versus Tokenized Deposits

The comparison between stablecoins and tokenized deposits is central to the future architecture of tokenized money because these two instruments are emerging as the most plausible private-sector candidates for use on programmable financial platforms. They are often grouped together under the broad label of private tokenized money, and in a superficial sense that is understandable. Both are designed to circulate in digital form, both can be represented on distributed ledgers or related infrastructures, and both can support more automated, programmable, and potentially interoperable payment and settlement processes than conventional account-based arrangements (Garraff and Shin, 2023; EBA, 2024; Huang and Keister, 2026). Yet once the comparison moves from surface functionality to legal form, balance-sheet structure, settlement logic, and macro-financial implications, stablecoins and tokenized deposits begin to look like markedly different monetary institutions rather than alternative technical wrappers for the same claim.

The comparison can be developed along five interlocking dimensions: transfer logic and bearer character; balance-sheet logic and elasticity; legal and regulatory perimeter; use-case orientation and market traction; and the regulatory architecture under which the two forms compete. These dimensions may look minor at the level of user experience, but they matter substantially for singleness of money, monetary transmission, and the institutional choice between integrating private tokenized money into the banking system or allowing it to operate as a more independent monetary layer.

Table 3 distills the paper’s comparative argument. Stablecoins and tokenized deposits are not interchangeable versions of the same digital-money instrument. Although both are designed for programmable, ledger-compatible environments, they differ fundamentally in the nature of the claim, transfer logic, settlement design, prudential treatment, and relationship to bank intermediation. The comparison therefore moves the debate beyond a generic contrast between stablecoins and traditional money and toward the institutional question that matters more for tokenized finance: whether programmable money is organized around bearer-style private claims or around bank-based tokenized deposit claims. BIS Bulletin No. 73 remains the foundational statement of this distinction, and the EBA’s 2024 report gives it concrete regulatory content in the European setting.

Table 3. Stablecoins versus tokenized deposits

Dimension	Stablecoins	Tokenized deposits
Issuer type	Usually nonbank issuer or special-purpose structure; may be bank-affiliated in some models	Commercial bank
Nature of claim	Redeemable private tokenized liability of issuer	Deposit claim on bank represented on tokenized infrastructure
Transfer logic	Typically bearer-style transfer of the issuer's liability	Typically non-bearer burn-and-issue logic; sender's claim extinguished and recipient bank issues new claim
Settlement mechanics	Transfer of token itself; no automatic need for interbank settlement in central bank money at each transfer	Interbank leg settles in central bank money
Singleness of money	Weaker by design; issuer-specific claims may deviate from par	Stronger if non-bearer design is maintained
Elasticity	Constrained by reserve-funded issuance / cash-in-advance logic	Linked to banking system balance-sheet elasticity and central-bank-reserve-based settlement
Prudential protection	Depends on jurisdiction; not equivalent to deposit insurance or full banking safety net	Embedded in banking regulation; may benefit from deposit-law framework
Relationship to bank lending	May disintermediate deposits and separate transaction balances from lending base	Remains integrated with bank intermediation
Portability across open digital environments	High; strong advantage in crypto-native and cross-platform use	Currently weaker; more institutionally grounded but commercially less mature
Main policy concern	Run risk, fragmentation, reserve quality, monetary sovereignty, deposit substitution	Operational scalability, interoperability, programmability, legal standardization

Source: Author's elaboration based on Garratt and Shin (2023), BIS (2025), Huang and Keister (2026), Adrian *et al.* (2025), and Aldasoro, Mehrling, and Neilson (2023).

The first and most fundamental distinction concerns the nature of transfer. Stablecoins are generally bearer-style liabilities: when the token moves from one holder to another, the underlying claim on the issuer moves with it. The issuer's balance sheet does not need to be updated every time the token changes hands; adjustment occurs primarily when the token is issued or redeemed. Tokenized deposits, by contrast, are best understood in their safer non-bearer form. In that structure, a payment does not involve the transfer of one bank's liability to a third party. Instead, the sender's claim is extinguished and a new claim is created by the recipient's bank, while the interbank leg settles in central bank money (Garratt and Shin, 2023; ECB, 2025b; EBA, 2024). This distinction is not merely legal or technical. It directly affects how each instrument fits within the monetary system.

The difference matters because it goes to the heart of the singleness of money. In the existing two-tier monetary system, commercial bank money remains money because interbank obligations are settled at par in central bank reserves. What changes for the user is the size of the claim on her own bank, not the identity of the bank liability she holds after payment. Stablecoins do not automatically enjoy this property. A recipient of a stablecoin receives a claim on the stablecoin issuer, not a newly created claim on the recipient's own bank. This creates issuer-specific exposure and opens the possibility that different stablecoins may trade at different values relative to par under stress. Tokenized deposits, in contrast, are designed precisely to avoid that outcome by preserving par settlement through central bank money at the interbank level (Garratt and Shin, 2023; BIS, 2025). This is why tokenized deposits are generally treated as more compatible with the singleness of money than bearer-style stablecoins.

The second distinction concerns balance-sheet logic and the elasticity of money. Stablecoins are typically issued by entities that promise redemption at par against reserve-backed liabilities, and their issuance is generally constrained by prior funding and reserve acquisition. This gives stablecoins a narrow-money character but also limits their elasticity. Garratt and Shin (2023) and the BIS Annual Economic Report 2025 Chapter III argue that this structure causes stablecoins to fail the elasticity test because additional issuance requires full upfront payment by holders, effectively imposing a cash-in-advance constraint on balance-sheet expansion (BIS, 2025). Tokenized deposits, by contrast, sit inside the wider intermediation capacity of the banking system. Because they remain deposits, they remain linked to the mechanisms through which bank balance sheets expand and contract – reserve access, maturity transformation, and credit creation. Tokenized deposits therefore preserve a closer connection to

the elasticity historically associated with the banking-based monetary system, while stablecoins embody a narrower and more rigid liability structure.

This distinction has broader macroeconomic significance. Stablecoins may appear safer because of full reserve backing, but precisely that narrowness limits their capacity to perform the adaptive balance-sheet function that commercial bank money performs in modern economies. Tokenized deposits may appear less "clean" from a narrow-money perspective, yet their connection to bank intermediation allows them to preserve a relationship between payments, deposits, and lending that stablecoins tend to separate. The comparison cannot be reduced to a simple safety-versus-risk dichotomy: the two forms represent different institutional solutions to the longstanding monetary question of whether money should be tightly separated from or closely integrated with credit creation (Aldasoro *et al.* 2023; BIS, 2025; Huang and Keister, 2026).

The third distinction is legal and regulatory. The EBA's 2024 report provides one of the clearest official delineations between tokenized deposits and electronic money tokens issued by banks: both may appear on DLT, both represent claims against the balance sheet of a credit institution, but they differ along several crucial dimensions. Tokenized deposits involve a continuing contractual relationship between the bank and the depositor, are generally nominative rather than bearer in nature, may carry interest, and remain subject to the ordinary deposit-regulatory framework. EMTs and stablecoin-like bearer instruments, by contrast, are transferable liabilities that do not enjoy the same legal treatment as deposits and are not covered by deposit guarantee schemes in the same way (EBA, 2024, 2026). The relevant distinction is therefore not bank-issued versus non-bank-issued. It is the conjunction of transferability, bearer character, contractual continuity, prudential protection, and relationship to par settlement.

This legal architecture translates directly into the user proposition of each instrument. A tokenized deposit remains embedded in the architecture of deposit-taking, prudential supervision, central bank settlement, and – in many jurisdictions – deposit protection; its credibility derives from the institutional framework of banking. A stablecoin, even when well-reserved and well-disclosed, remains an issuer-specific redeemable token whose credibility depends on reserve composition, redemption terms, and the operational resilience of the issuer. It may be more portable across open digital environments, but it does not reproduce the full architecture of bank money. Stablecoins should therefore not be viewed as simple digital replicas of deposits. They are distinct private monetary claims that may compete with deposits without inheriting their legal and institutional protections (Arner *et al.* 2020; Garratt and Shin, 2023; EBA, 2024).

The fourth distinction concerns use-case orientation. Stablecoins currently have a strong first-mover advantage in open, interoperable, and crypto-native environments. They are deeply embedded in decentralized exchanges, on-chain collateral chains, tokenized trading venues, and cross-platform settlement. Their bearer-style transferability and broad wallet-based circulation make them especially useful in environments where users do not share a banking relationship or remain within a common domestic regulatory perimeter. Tokenized deposits historically developed much more slowly: the EBA reported only limited live tokenized-deposit use cases in the EEA by late 2024, concentrated in wholesale or specialized applications rather than broad retail circulation (EBA, 2024). The picture has shifted materially since then, but the evidence is still better read as early institutional commercialization than as commercial parity with stablecoins. JPMorgan's JPM Coin USD / JPMD initiative, Citi Token Services, BNY's reserve-custody role for RLUSD, and SoFi's SoFiUSD announcement all indicate that bank and bank-adjacent programmable-money infrastructure is advancing quickly (JPMorgan Chase, 2025; Citigroup, 2025a, 2025b; BNY, 2025; SoFi Technologies, 2025). At the central-bank-settlement layer, the Eurosystem's exploratory work on new technologies for wholesale settlement has demonstrated DLT-based settlement in central bank money at meaningful scale (ECB, 2026). These developments do not yet constitute commercial parity with stablecoins, but they show that the asymmetry between scaled stablecoins and bank-based tokenized money is narrowing. The competition is therefore not a contest between a scaled crypto-native instrument and a static banking-native one. It is a rapidly shifting institutional rivalry whose eventual outcome depends on regulatory design, interoperability, and the operational maturity of bank-issued programmable money.

The current asymmetry should not be read as a permanent equilibrium. The Bank of England's "multi-money" framing suggests a future landscape in which stablecoins, traditional and tokenized bank deposits, and central bank money coexist under conditions of mutual exchangeability and preserved trust in money (Bank of England, 2025a, 2026). Under such a configuration, stablecoins may continue to dominate in open, global, cross-platform settings where portability and composability are especially valuable, while tokenized deposits become the preferred form of private tokenized money in regulated domestic and wholesale settings where par settlement, legal certainty, and integration with bank credit matter most. The likely medium-term outcome is differentiated coexistence rather than simple replacement, though the scope for direct substitution remains real on either side: if

tokenized deposits become sufficiently programmable and interoperable, some of stablecoins' current advantages may erode; conversely, if stablecoins receive stronger prudential treatment and deeper integration with regulated infrastructure, the gap between the two could narrow from the opposite direction.

The welfare implications of this competition have now been formalized. Huang and Keister (2026) show that the relative desirability of stablecoins and tokenized deposits depends on bank incentives, regulation, and the scale of blockchain-based trade. Their framework yields three results that matter for this paper. First, when blockchain-based trade is small, tokenized deposits dominate because bank intermediation continues to support the wider productive economy and the welfare cost of fragmenting money into a separate stablecoin layer outweighs the gains. Second, when blockchain-based trade is large and bank lending is sufficiently risky, stablecoins can dominate because the safety advantage of full reserve backing offsets the loss of bank-mediated credit creation. Third, the parameter region in which stablecoins dominate shrinks when banks are permitted to issue tokenized deposits – that is, when banks can compete in the programmable-money domain on terms that preserve their intermediation role. The third result is decisive for the regulatory argument of this paper: the institutional configuration in which tokenized deposits are made operationally and legally available to users is the configuration that minimizes the welfare cost of stablecoin scaling. Stablecoins correspond to a narrow-banking-style model of tokenized money backed by safe assets, while tokenized deposits remain embedded in the risky lending activities of banks; neither form is always superior, but each corresponds to a different institutional allocation of money creation, asset holding, and credit intermediation.

Cong (2026), in industry-supported research drawing on transaction-level evidence from the U.S. context, provides a complementary perspective focused specifically on the post-GENIUS Act constraints. Under the GENIUS Act's full-reserve-backing requirement, prohibition on issuer-paid yield, and prohibition on credit extension by issuers, the disintermediation pressure on bank deposits is materially smaller than headline projections suggest, with stablecoin–deposit substitution conditional on yield differentials and reserve composition rather than on the scale of stablecoin issuance *per se*. Read together with the welfare framework of Huang and Keister, this evidence supports a differentiated picture: the competition between stablecoins and tokenized deposits is structurally shaped by regulatory constraints on the asset side of stablecoin issuance, and the magnitude of welfare loss from stablecoin scaling depends on whether tokenized deposits are simultaneously available as a regulated alternative.

The comparison suggests a more differentiated competitive landscape than the familiar "stablecoins versus banks" framing implies. The relevant question is not only speed or programmability, but which institutional attributes users, platforms, and regulators value most in particular settings. Stablecoins are advantaged where openness, portability, and cross-platform usability dominate. Tokenized deposits are advantaged where *par* settlement, legal certainty, and integration with bank intermediation matter most. The eventual division of labor within tokenized finance will depend on how these preferences evolve, on how quickly each model becomes operational at scale, and – crucially – on whether regulatory frameworks treat the two forms as institutional complements within a multi-money architecture or as substitutes within an unregulated competitive race.

7. Regulatory and Policy Implications

The regulatory debate on stablecoins has moved well beyond the earlier question of whether crypto-assets should be brought within a perimeter of investor-protection and market-conduct rules. Stablecoins now sit at the intersection of payments regulation, prudential supervision, monetary sovereignty, banking intermediation, and tokenized market infrastructure. The BIS frames the issue in terms of the foundational properties of money – singleness, elasticity, and integrity – and treats stablecoins as a candidate institutional form whose monetary quality must be evaluated against those properties (Garratt and Shin, 2023; BIS, 2025). The FSB treats stablecoins as a potential source of cross-border financial-stability risk (FSB, 2023, 2025). The EBA has had to work through the operational boundary between MiCA, e-money rules, tokenized deposits, and payment-services regulation (EBA, 2024, 2026). The Bank of England has explicitly adopted a multi-money perspective (Bank of England, 2025a, 2026). The ECB now discusses tokenized deposits and stablecoins as new payment rails relevant for wholesale settlement and the future role of central bank money (ECB, 2025a, 2025b, 2026). The U.S. has, since July 2025, enacted a federal statutory framework for payment stablecoins through the GENIUS Act, while federal implementation rulemaking was underway in 2026 (U.S. Congress, 2025; Dudley and Liang, 2026; OCC, 2026; FDIC, 2026; U.S. Treasury, 2026a, 2026b). Despite different legislative drafting, these approaches converge on a common architectural question: how to accommodate programmable, transferable forms of private tokenized money without weakening trust in *par* settlement, undermining monetary control, or destabilizing the balance-sheet structure of the banking system.

These developments indicate that stablecoin regulation now concerns the design of tokenized monetary architecture rather than merely the supervision of another crypto-asset category. A coherent framework must therefore address reserve composition, redemption rights, payment-system interoperability, prudential perimeter, and the coexistence of stablecoins with tokenized deposits and central-bank money.

Five policy dimensions are decisive. The first is monetary integrity: tokenized private money must remain reliably exchangeable at par with other forms of money. That requires more than a general redemption promise; it requires clear rules on eligible claims, redemption terms, intermediaries, and reserve assets. The closer a stablecoin comes to functioning as a widely used settlement asset, the stronger the case for requirements that protect convertibility and interoperability rather than relying on market discipline alone (Garraff and Shin, 2023; BIS, 2025).

The second is reserve quality and liquidity. Because stablecoins differ substantially in reserve composition, regulation cannot remain neutral with respect to asset-side architecture. The stronger the monetary use of stablecoins becomes, the stronger the case for narrow, high-quality, and highly liquid reserves, supported by segregation, custody, attestation, and redemption requirements. The policy choice is whether stablecoins should become narrow payment instruments or broader balance-sheet vehicles close to digital shadow banking.

The third is prudential perimeter and banking disintermediation. Once stablecoins absorb transaction balances at scale, regulation must address their competition with deposits and the consequences for bank funding and monetary-policy transmission. A regime that constrains tokenized deposits while allowing stablecoins to scale under a looser perimeter may accelerate disintermediation; a regime that constrains stablecoins while leaving tokenized deposits operationally weak may suppress innovation without creating a viable regulated alternative. Stablecoin regulation therefore has to be assessed alongside tokenized deposits, EMTs, and tokenized central bank settlement.

The fourth is cross-border coordination. Stablecoin issuance, reserve management, trading venues, custody, wallet provision, and user demand can be distributed across jurisdictions, so domestic regulation alone is structurally incomplete. The FSB's findings of implementation gaps and regulatory inconsistency are therefore integral to the risk profile of the market itself (FSB, 2025). Stablecoins make a strong case for internationally coherent minimum standards even if full legal harmonization remains unrealistic.

The fifth is interoperability and market architecture. If stablecoins, tokenized deposits, and central bank money are to coexist, policy must define the conditions under which they exchange with one another. This moves regulation beyond authorization of individual instruments toward settlement connectivity, access arrangements, operational hours, and compatibility across tokenized rails. Stablecoin regulation is therefore inseparable from the broader design of tokenized payment and settlement infrastructure.

Table 4 compares the main regulatory approaches as implicit models of monetary architecture. The U.S. GENIUS Act creates a constrained narrow-money perimeter for payment stablecoins while preserving the primacy of bank deposits. The EU MiCA framework builds an authorization and reserve-discipline perimeter around ARTs and EMTs while keeping tokenized deposits outside MiCA's scope. The Bank of England frames stablecoins within a regulated multi-money system, and the Eurosystem places central bank money at the settlement core. Despite different legal routes, the main frameworks converge on three principles: payment stablecoins are formally regulated and constrained on the asset side; tokenized deposits remain legally distinct from stablecoins; and the hierarchy of central bank money, tokenized bank money, and private tokenized money is preserved rather than replaced.

The United States has moved from a position of fragmented state-level oversight to a federal framework specifically designed for payment stablecoins. The Guiding and Establishing National Innovation for U.S. Stablecoins Act, signed into law on 18 July 2025, represents the most consequential single intervention in the global regulatory landscape because it governs the jurisdiction in which the overwhelming majority of stablecoins are issued and held. The Act establishes a dual federal–state regulatory regime built around four principles: full one-to-one reserve backing, a closed list of permissible reserve assets, an explicit prohibition on issuer-paid yield, and a chartering pathway for nonbank issuers under federal supervision, with agency implementation rules still being specified in 2026 (U.S. Congress, 2025; Dudley and Liang, 2026; OCC, 2026; FDIC, 2026; U.S. Treasury, 2026a, 2026b).

Three features of this regime are particularly important for the argument of this paper. First, the closed list of permissible reserve assets – U.S. coins and currency, demand deposits at insured depository institutions subject to safety-and-soundness limits, short-dated Treasury bills, Treasury-backed reverse repos, and money-market-fund shares – formally narrows the asset side of payment stablecoins toward a tokenized-narrow-money configuration.

Table 4. Regulatory approaches and implied monetary architecture

Jurisdiction / framework	Primary focus	Treatment of stablecoin-like instruments	Relationship to payments law / banking law	Implied monetary architecture
U.S.: GENIUS Act + OCC chartering pathway	Federal regulatory regime for payment stablecoins; closed list of permissible reserve assets; chartering route for nonbank issuers under OCC supervision	Payment stablecoins formally regulated; bank-issued tokenized deposits preserved as a distinct regime; issuer-paid yield prohibited; bank custody and reserve management permitted	Strong interaction with banking law (OCC); separate regimes for payment stablecoins and tokenized deposits; preservation of bank exclusivity over deposit-equivalent claims	Constrained narrow-money perimeter for payment stablecoins alongside preserved primacy of regulated bank deposits
EU: MiCA + EBA perimeter work	Authorization, asset-backing, disclosure, operational safeguards, legal perimeter	ARTs and EMTs brought into formal authorization framework; tokenized deposits kept distinct from MiCA where they remain deposits	Strong interaction with payments regulation; EBA had to clarify PSD2–MiCA overlap and transition	Structured perimeter around private tokenized money, anchored to existing banking and payments law
UK: Bank of England systemic stablecoin regime	Safety of systemic payment stablecoins, interoperability, protection of trust in money	Consultation-based regime for sterling systemic stablecoins with backing and safety requirements	Strong interface with payment-system regulation and broader monetary stability goals	Explicit "multi-money" system: stablecoins may coexist with bank money and central bank money if trust and exchangeability are preserved
Eurosystem / ECB policy line	Preserve central bank money as settlement anchor while enabling tokenized wholesale settlement	Stablecoins recognized as relevant settlement assets in some contexts, but central bank money remains anchor	Tokenized deposits and stablecoins discussed in relation to settlement infrastructure rather than as isolated crypto products	Hierarchical model centered on central bank money
FSB global framework	Cross-border consistency, financial stability, implementation gaps	Broad global recommendations for crypto-asset activities and global stablecoin arrangements	Depends on national implementation; uneven across jurisdictions	No single architecture yet; highlights fragmentation and implementation asymmetry

Source: Author's elaboration based on U.S. Congress (2025), European Parliament and Council (2023), Bank of England (2025, 2026), Hong Kong Government (2025), Monetary Authority of Singapore (2023), Financial Services Agency of Japan (2023, 2025), FSB (2025), and ESRB (2025).

This aligns U.S. payment stablecoins more closely with the institutional logic of cash-management vehicles than with the heterogeneous reserve mixes documented at some pre-GENIUS issuers. This configuration places GENIUS-regulated payment stablecoins within the long lineage of narrow-banking proposals reviewed by Pennacchi (2012), which argue that institutions whose liabilities function as money should hold only the safest, most liquid assets, leaving credit creation and maturity transformation to other parts of the financial system. The Act does not implement narrow banking in its strongest historical form – it does not separate payment money from credit creation across the entire banking system – but it does apply the narrow-banking logic specifically to the payment-stablecoin segment, treating it as a contained category in which moral hazard is reduced by design rather than by ex post supervision. Second, the prohibition on issuer-paid yield is designed to prevent payment stablecoins from competing directly with bank deposits on rate, while the explicit preservation of bank authority to issue tokenized deposits as a separate regime sets up the very competition that this paper analyses in Section 6. Third, the OCC's conditional approvals in late 2025 for national trust bank charters to several digital-asset firms, including Circle, Ripple, BitGo, Paxos, and Fidelity Digital Assets, signal a pathway for custody, fiduciary, and settlement activities under federal supervision. These approvals remained subject to final conditions and did not authorize ordinary deposit-taking or lending; they should therefore be interpreted as infrastructure and trust-bank developments rather than as full banking authorization for stablecoin issuers (OCC, 2025; Reuters, 2025).

The GENIUS Act also leaves three issues unresolved. Eligible reserves include some private bank claims, such as deposits and secured cash borrowing, that are not equivalent to central bank money and may become

fragile under stress (Dudley and Liang, 2026; OCC, 2026; FDIC, 2026). The prohibition on issuer-paid yield may not fully prevent indirect yield competition through affiliates or third parties. Most importantly, payment stablecoins remain bearer-style private claims; the Act narrows reserve risk but does not by itself ensure singleness of money in the sense developed by Garratt and Shin (2023).

The deeper reason is that singleness depends not only on the quality of underlying assets but on the information regime under which a money-like instrument circulates. Holmström (2015) shows that money markets function on the basis of "no questions asked": users accept money-like claims at par precisely because they do not have to investigate the issuer's balance sheet to transact. Reserve narrowness reduces the questions that need to be asked but does not eliminate them, since users may still investigate the specific composition, custodian, and redemption mechanics of a particular issuer when stress arises. Singleness therefore requires not only safe reserves but also institutional arrangements – central bank backstops, deposit insurance, or comparable redemption guarantees – that make the question of issuer identity irrelevant for ordinary payment use. The GENIUS Act narrows reserves substantially but does not provide an equivalent backstop for payment stablecoins, which is why it can deliver narrow money without delivering full singleness. For the comparative argument of this paper, the GENIUS Act is significant in two further ways. It establishes a U.S. federal preference for tokenized commercial bank money – that is, for tokenized deposits – as the form of programmable bank money rather than for bank-issued payment stablecoins. And it signals an institutional decision to bring payment stablecoins inside the regulatory perimeter without granting them deposit-equivalent legal status. The U.S. approach is therefore not best read as a permissive regime that simply licences private digital money. It is an attempt to define a constrained narrow-money perimeter for payment stablecoins while preserving the legal and prudential primacy of bank deposits. Despite different legislative drafting, this convergence on broadly similar architectural principles is visible across the U.S., EU, and UK frameworks.

The European Union was the first major jurisdiction to put a comprehensive ex ante framework in place. Under MiCA, stable-value crypto-assets are divided into asset-referenced tokens and electronic money tokens, with issuers of both required to operate within a formal authorization and supervisory framework. The regime rejects the view that stablecoins can remain outside formal oversight simply because they are issued on distributed infrastructures. The EBA's subsequent work shows that implementation is not straightforward: its 2026 Opinion on the end of the transition period under the No-Action Letter on the interplay between PSD2 and MiCA makes clear that stablecoin regulation in the EU cannot be understood through MiCA alone, since crypto-asset service providers transacting EMTs that qualify as payment services may also need payment-services authorization (EBA, 2026). This has forced a practical convergence between crypto-asset regulation and payments regulation. Stablecoins are pushing EU regulatory frameworks to acknowledge that they are not simply crypto-assets but money-like instruments that straddle multiple legal domains.

The EU experience also illustrates the limits of regulatory completeness when market adoption remains small. The EBA's 2025 Risk Assessment Report notes that, despite a growing number of authorized EMTs in the EU/EEA, issuance volumes remained limited (EBA, 2025). Europe therefore has a coherent legal perimeter but little market depth, while the U.S. regime arrived later but governs a much larger dollar-stablecoin ecosystem. The interaction of EU supervisory preparedness with U.S. market depth and reserve-asset constraints may define the practical global perimeter for payment stablecoins more than either model alone.

The United Kingdom is taking a conceptually distinctive approach. The Bank of England's late-2025 consultation on a proposed regime for sterling-denominated systemic stablecoins explicitly seeks to support a role for stablecoins within a multi-money system alongside commercial bank money, including tokenized deposits, all underpinned by central bank money at the core of the financial system (Bank of England, 2025a). The framing neither treats stablecoins as an anomaly to be suppressed nor as a substitute for the existing system, but as one possible component of a future monetary ecology in which coexistence is possible only under conditions that preserve trust in money itself. Subsequent speeches reinforce the same principle: innovation is acceptable if convertibility, interoperability, and confidence in par exchange remain intact (Bank of England, 2026; Breeden, 2025).

This multi-money framing offers a middle ground between marginalizing stablecoins and allowing them to scale freely as private bearer money. The UK approach points to regulated coexistence: stablecoins may serve useful roles in payment and settlement environments if they remain exchangeable with bank money and anchored by central bank money. The contrast with the U.S. and EU approaches is instructive. The U.S. framework emphasizes asset-side constraint, the EU framework emphasizes ex ante perimeter design, and the UK framework gives the clearest priority to coexistence and interoperability.

Comparable frameworks have been crystallized in major Asia-Pacific jurisdictions, with each adopting a distinct architectural choice. Hong Kong's Stablecoins Ordinance, gazetted on 30 May 2025 and brought into operation on 1 August 2025, introduces a licensing regime under which the Hong Kong Monetary Authority supervises issuers of fiat-referenced stablecoins, requires full reserve backing in segregated high-quality liquid assets, sets minimum financial-resource thresholds (25 million HKD paid-up capital, 3 million HKD liquid capital, and excess liquid capital equivalent to twelve months of operating expenses), and restricts retail offering to stablecoins issued by licensed institutions (Hong Kong Government, 2025; HKMA, 2025). Singapore had earlier finalised its single-currency stablecoin (SCS) framework in August 2023 under the Payment Services Act, applying it to SCS pegged to the Singapore dollar or any G10 currency, requiring 100 per cent reserve coverage in low-risk assets denominated in the peg currency, and prohibiting non-issuance activities such as lending or staking by SCS issuers; only stablecoins meeting all framework requirements may use the protected "MAS-regulated stablecoin" designation (MAS, 2023). Japan amended its Payment Services Act in 2022, with the framework taking effect on 1 June 2023, treating fiat-redeemable stablecoins as electronic payment instruments (EPIs) issuable only by banks, licensed fund-transfer service providers, or trust companies, subject to full reserve backing and segregated custody (FSA, 2023); a further round of amendments enacted in June 2025 specifies reserve, custody, and redemption obligations in greater operational detail (FSA, 2025). The United Arab Emirates has pursued a parallel trajectory through the Central Bank Payment Token Services Regulation. These regimes vary in licensing perimeter and issuer eligibility, but they converge on the same architectural principles as the U.S., EU, and UK frameworks: full reserve backing in liquid assets, segregated custody, redemption discipline, and licensing or authorization as the precondition for retail circulation.

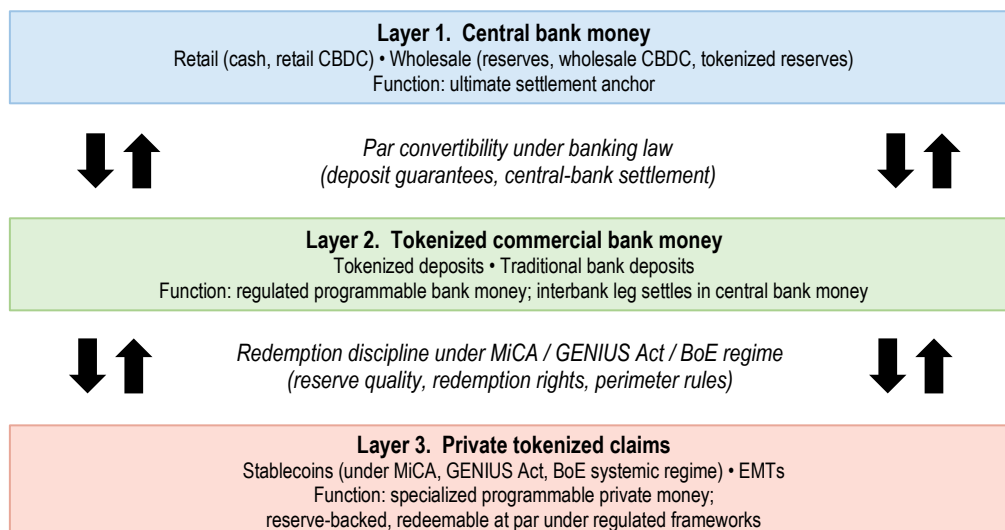
Figure 6 represents the architecture toward which the major frameworks are converging. Central bank money remains the ultimate settlement anchor, tokenized deposits extend regulated bank money into programmable environments, and stablecoins operate as private tokenized claims subject to convertibility, interoperability, and prudential discipline. The bidirectional arrows are essential: a multi-money system requires not only hierarchy but par exchange between layers.

The Eurosystem's position places central bank money explicitly at the center of the institutional response. Recent ECB speeches argue that to ensure central bank money remains the anchor of trust and stability in a digital economy, the Eurosystem is working both on a digital euro for retail payments and on the provision of central bank money for wholesale settlement on DLT-based platforms (ECB, 2025a, 2025b, 2026). The ECB acknowledges that tokenized deposits and stablecoins may bring efficiencies in some payment contexts, particularly cross-border B2B transactions and tokenized market settlement, while insisting that innovation in tokenized money remain anchored in a hierarchy where central bank money continues to perform the ultimate settlement function. This places the ECB close to a hierarchy-based model of tokenized money in which innovation may proceed but not at the cost of eroding the public monetary anchor. The Eurosystem's exploratory work on wholesale-DLT settlement, processing more than 200 transactions worth approximately 1.59 billion EUR across 64 participants, gives this position concrete operational form (ECB, 2026).

At the global level, evidence on regulatory convergence is now more concrete than the earlier institutional commitments suggested. The FSB and IOSCO published parallel thematic peer reviews on 16 October 2025, with an accompanying joint information note. The reviews assessed implementation across roughly forty jurisdictions and found notable progress but also significant gaps and inconsistencies, particularly in the regulation of global stablecoin arrangements: as of August 2025, only eleven jurisdictions had finalized comprehensive crypto-asset frameworks addressing financial-stability risks, while implementation of the global stablecoin recommendations was generally less advanced than that for crypto-asset service providers (FSB, 2025; FSB and IOSCO, 2025; IOSCO, 2025). Both reports highlight cross-border cooperation as a structural weakness, since existing supervisory channels rely heavily on the IOSCO Multilateral Memorandum of Understanding, which was designed for securities-enforcement information sharing rather than for stablecoin-specific oversight. The European Systemic Risk Board has taken a more directive position. Its Recommendation ESRB/2025/9 on third-country multi-issuer stablecoin schemes, adopted on 25 September 2025 and published in the Official Journal in November, urges the European Commission to treat as impermissible under the current MiCA framework arrangements in which an EU-authorized issuer and a non-EU partner jointly issue tokens presented as interchangeable, on the grounds that such schemes split reserves and operational responsibilities across jurisdictions in ways that undermine MiCA's redemption and supervisory architecture (ESRB, 2025). Together, these documents indicate that the international regulatory architecture is moving from broad principles towards specific operational tests and that the largest residual risks lie in cross-jurisdictional arrangements that exploit gaps between formally compatible regimes. Recent U.S., EU, UK,

and Asia-Pacific developments suggest that convergence may emerge gradually through mutual recognition and alignment among major regimes before formal global standards become fully codified.

Figure 6. The hierarchically anchored multi-money architecture



Notes: Schematic representation of a tokenized monetary architecture with three layers and bidirectional convertibility arrows. Top layer: central bank money in retail and wholesale form, including tokenized reserves and wholesale CBDC, providing the ultimate settlement anchor. Middle layer: traditional and tokenized commercial bank deposits, settling at par through the two-tier banking system. Bottom layer: stablecoins and EMTs, operating as private tokenized claims with reserve backing under regulated frameworks (MiCA, GENIUS Act, BoE systemic stablecoin regime). Convertibility arrows between layers indicate par exchange under regulated convertibility regimes.

Source: authors' synthesis based on Garratt and Shin (2023); Bank of England (2025a, 2026); BIS (2025); ECB (2025a, 2025b, 2026); EBA (2024).

Across the five policy dimensions, the U.S., EU, and UK frameworks differ in emphasis but converge on fundamentals. All treat singleness of money as a constraint to be protected through reserve and redemption discipline. The U.S. and EU frameworks narrow permitted reserves toward high-quality liquid assets, while the UK adds a more explicit interoperability logic. All preserve the legal distinctiveness of tokenized deposits and avoid folding deposit-equivalent claims into the stablecoin perimeter. The remaining weakness is cross-border coordination: the FSB's incomplete-convergence finding remains the binding constraint.

The convergence on architectural principles is the most important feature of the current regulatory landscape. The policy direction is not to eliminate institutional diversity, but to organize it around a credible hierarchy: central bank money as settlement anchor; tokenized deposits as regulated bank money in programmable environments; and stablecoins as specialized private instruments permitted only where reserve quality, redemption discipline, governance, and interoperability are strong enough to prevent fragmentation of par money. The regulatory issue is therefore no longer the containment of a crypto-asset category. It is the design of a monetary architecture in which private tokenized claims can coexist with bank money and public settlement infrastructure without eroding singleness, elasticity, and trust.

Conclusion

Stablecoins have moved well beyond their original role as an internal liquidity device for crypto-asset markets. The market has scaled above USD 300 billion, remains highly concentrated in two issuers and overwhelmingly denominated in U.S. dollars, and is increasingly linked to Treasury markets, bank funding channels, and tokenized settlement infrastructure. Treating stablecoins as a distinct layer of tokenized private money – rather than as a marginal digital-finance innovation or as a low-volatility crypto-asset – is therefore a more convincing analytical starting point. Their significance cannot be judged by trading utility alone or by whether a token usually trades close to par.

The paper's contribution to this assessment is threefold. It integrates the dispersed evidence on reserve-driven spillovers into a single interacting three-channel transmission framework; it quantifies issuer concentration directly and links its persistence to the structural centralization of arbitrage rather than to transitional market dynamics; and it operationalizes the singleness–elasticity–integrity benchmark as a five-dimensional comparison

between stablecoins and tokenized deposits. These contributions allow the monetary character of stablecoins to be assessed structurally – through reserve architecture, concentration, and convertibility mechanics – rather than through peg performance alone.

Two structural findings stand out. First, market structure already gives stablecoins systemic relevance: the sector is dominated by a small number of issuers, concentrated in dollar-linked instruments, and closely tied to the extension of dollar-based intermediation into tokenized environments. Second, reserve design is the economic core of the instrument: differences in reserve composition, liquidity, transparency, governance, and operational accessibility shape redemption credibility, run risk, and the macro-financial transmission of stablecoin demand. The reserve channel operates through three identifiable mechanisms – Treasury and short-term funding, bank funding, and the global safe-asset channel – and together these mechanisms turn stablecoins from a payment instrument into a balance-sheet structure that reallocates transaction balances away from traditional banking and into reserve portfolios centered on safe assets and liquid claims. Stablecoins therefore matter not only for payments and market infrastructure but for monetary-policy transmission, banking intermediation, and the international circulation of dollar liquidity.

The most relevant institutional comparator for stablecoins is not crypto-assets in general but tokenized deposits. Both instruments supply programmable, ledger-compatible money, yet they embody different monetary logics: stablecoins circulate as issuer-specific bearer-style liabilities whose soundness depends on reserve architecture and private governance, while tokenized deposits in their safer non-bearer form preserve the two-tier monetary structure by settling the interbank leg in central bank money and embedding the end-user claim in the regulated banking system. The welfare framework of Huang and Keister (2026) clarifies the conditions under which each form is preferable, and the empirical evidence on post-GENIUS deposit dynamics (Cong, 2026; Aldasoro and Ahmed, 2026) suggests that the magnitude of substitution is materially shaped by regulatory constraints on the asset side of stablecoin issuance. The likely medium-term outcome is differentiated coexistence rather than displacement: stablecoins better placed in open and globally portable digital environments, tokenized deposits institutionally stronger in regulated domestic, wholesale, and bank-centered settings.

The comparison has direct regulatory implications. Stablecoins cannot be treated as another subclass of speculative crypto-assets nor as straightforward substitutes for deposits. They are a distinct form of tokenized private money whose legal treatment must reflect monetary function, reserve structure, redemption mechanics, governance, disclosure, and interoperability. The convergence of the U.S. GENIUS Act, the EU MiCA framework, and the UK multi-money consultation on broadly similar architectural principles – formal regulation of payment stablecoins, narrowed reserve permissibility, preserved bank exclusivity over deposit-equivalent claims, and explicit protection of the central-bank-anchored monetary hierarchy – suggests that the most coherent policy direction is now visible in the regulatory practice of the major jurisdictions, even if not yet codified internationally. A hierarchically anchored multi-money framework, in which central bank money remains the ultimate settlement anchor, tokenized deposits extend regulated bank money into programmable environments, and stablecoins operate as specialized private instruments under strong constraints on reserves, redemption, and operational design, is the architecture toward which the major frameworks are converging in practice. Tokenization does not abolish the hierarchy of money; it makes that hierarchy more visible and more contested.

This assessment should not be read as an unqualified endorsement of the view that tokenized deposits are categorically superior or that stablecoins are merely a constrained second-best. The literature also advances serious arguments on the other side, and a balanced reading must weigh them. A first counter-argument is that monetary competition has its own efficiency benefits: privately issued money-like instruments can discipline incumbent intermediaries, widen access, and accelerate innovation in payment functionality, and a long tradition in monetary economics holds that competition among issuers need not be destabilizing where convertibility is credibly maintained. A second counter-argument concerns cross-border payments, where stablecoins demonstrably reduce cost and settlement time relative to correspondent banking, particularly for remittances and for users in jurisdictions with limited access to dollar banking; here their open and globally portable architecture is an advantage that bank-based tokenized deposits, confined to regulated domestic perimeters, do not easily replicate. A third counter-argument is that the relationship between the instruments need not be a contest at all: hybrid models are emerging in which stablecoins, tokenized deposits, and central-bank money interoperate within a layered system – for example through tokenized deposits settling wholesale legs in central bank money while stablecoins serve open retail and cross-border functions – so that the architecturally distinct forms become complementary rather than mutually exclusive. The balance of evidence in this paper supports the singleness-based concern that uniform par exchange is harder to guarantee for bearer-style private liabilities than for bank-based claims; but the efficiency,

inclusion, and cross-border advantages of stablecoins, and the genuine possibility of interoperable hybrid designs, are part of the same assessment and qualify any conclusion that tokenized deposits should simply displace stablecoins.

Stablecoins are best understood not as the endpoint of monetary innovation but as a transitional institutional form. They reveal both the promise and the tension of tokenized finance – the promise of faster, more programmable, and more interoperable money, and the tension created when those functions are supplied by private liabilities outside the full architecture of the traditional monetary system. Whether stablecoins remain confined to narrow payment uses, evolve into broader private monetary claims, or are displaced in core functions by tokenized deposits and central-bank-anchored tokenized settlement assets will depend on the regulatory architecture that emerges from the convergence now visible across the major jurisdictions. Stablecoins have forced the question; tokenized deposits, central bank money, and new regulatory architectures will determine the answer.

Declarations

Conflict of interest: The author declares no conflicts of interest.

Use of Generative Artificial Intelligence: During the preparation of this manuscript, the author used AI tool (QuillBot) exclusively to assist with language enhancement and technical proofreading. This tool was not used to generate content independently or to substitute the author's original analysis, critical thinking, or interpretations. After using this tool, the author reviewed and edited all content as needed and takes full responsibility for the integrity and accuracy of the manuscript.

Data availability: The data used to construct Figures 1-4, including aggregate market capitalization, issuer-level market shares, currency composition, and reserve-composition inputs, are available from the author on reasonable request. Figures 5 and 6 are conceptual diagrams based on the cited sources; their underlying node-and-link structures and computational scripts used to generate all figures are available on request.

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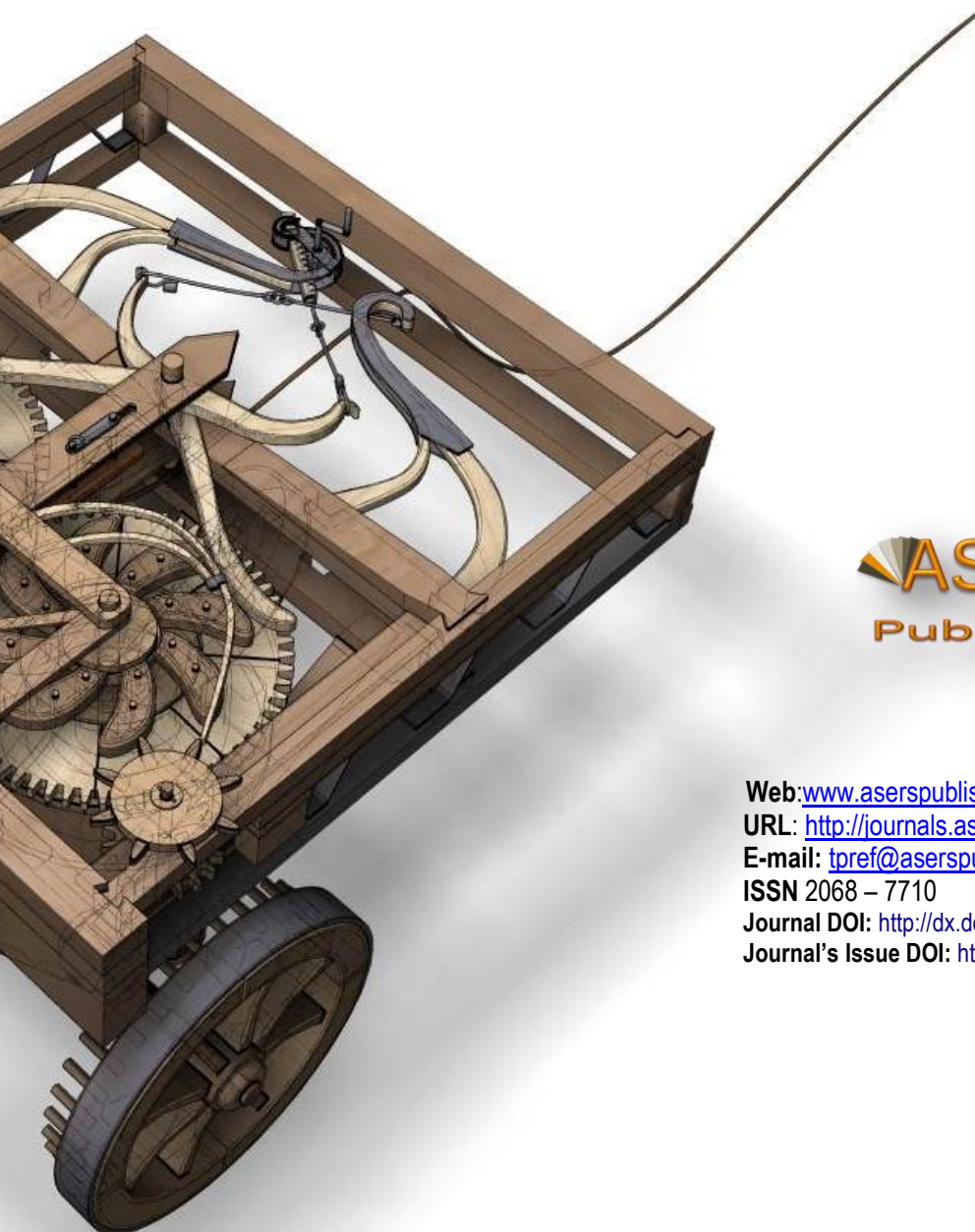
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