Agricultural Productivity, Green Energy Consumption, Governance Quality, and Environmental Degradation in BRICS Economies. Evidence from a PMG-ARDL Approach

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Abstract: This study examines the relationships between agricultural productivity, green energy consumption, governance quality, and environmental degradation in BRICS economies. The main objective is to assess whether improvements in agricultural performance intensify environmental pressure and to what extent green energy adoption and institutional quality can mitigate these adverse effects. The analysis is based on a balanced panel dataset covering the period 2002–2023 and employs the Pooled Mean Group Autoregressive Distributed Lag (PMG-ARDL). The empirical findings reveal that agricultural productivity significantly increases environmental degradation in the long run, highlighting the environmental costs associated with agricultural intensification in emerging economies. In contrast, green energy consumption and governance quality exhibit strong and consistent pollution-reducing effects, contributing to improved environmental sustainability. This study provides original empirical evidence by jointly integrating agricultural productivity, green energy, and governance quality within a unified dynamic framework, offering important insights for designing sustainable agricultural and energy policies in emerging economies.

Keywords: agricultural productivity; green energy consumption; governance quality; environmental degradation; BRICS economies; PMG-ARDL.

JEL Classification: Q01; Q42; O13; C33.

Introduction

Environmental degradation represents a major challenge for emerging economies experiencing rapid agricultural intensification and structural transformation in BRICS countries. The existing literature further highlights the complex relationship between agriculture and environmental quality. On the one hand, environmental degradation undermines agricultural productivity through climate stress and pollution exposure (Dong & Wang, 2023; Xu *et al.* 2023). On the other hand, productivity-driven agricultural intensification itself remains a major contributor to environmental degradation in emerging economies (Burney & Ramanathan, 2020; Zhang *et al.* 2020). This duality complicates policy design and raises a critical research question: Can green energy adoption and governance quality offset the environmental costs of agricultural expansion in BRICS economies ? Motivated by this gap, the present study aims to analyze the dynamic long-run and short-run determinants of environmental degradation in BRICS economies over the period 2002–2023.

The main contribution of this study lies in the joint integration of agricultural productivity, green energy consumption, and governance quality within a unified dynamic framework applied to BRICS economies. By bridging agricultural, energy, and governance, the paper provides novel empirical insights into the mechanisms through which green energy adoption and institutional quality can mitigate environmental degradation in emerging economies. Methodologically, the study employs a PMG-ARDL framework, allowing for heterogeneous short-run dynamics and homogeneous long-run relationships across countries, with robustness checks conducted using (FMOLS) and (CCR) estimators.

The remainder of the paper is organized as follows: Section 1 reviews the literature and develops the hypotheses, section 2 presents research methodology, section 3 reports the research results, section 4 discusses the findings, section 5 provides implications, and section 6 concludes with limitations of study and further research.

1. Literature Review and Hypotheses Development

1.1. Agricultural Productivity and Environmental Degradation

From the perspective of production theory and agricultural intensification frameworks, productivity gains in emerging economies are commonly achieved through the increased use of energy-intensive inputs, including chemical fertilizers, mechanization, irrigation systems, and livestock expansion. When environmental externalities are weakly internalized, these practices generate substantial greenhouse gas emissions, notably carbon dioxide (CO_2), methane, and nitrous oxide, thereby exacerbating environmental degradation.

A growing body of empirical literature supports this mechanism. Pata (2021) finds that agricultural expansion significantly increases ecological footprints in BRIC countries. Similarly, Burney and Ramanathan (2020) and Zhang *et al.* (2023) demonstrate that productivity-driven agricultural intensification raises emissions through higher fertilizer use, fossil fuel consumption, and land-use changes. More recent studies further confirm that growth in agricultural value added is positively associated with environmental degradation in emerging economies when clean technologies are not widely adopted (Dong & Wang, 2023; Bouteska *et al.* 2024).

In the specific context of BRICS countries—where agricultural productivity growth has often preceded the diffusion of environmental regulation and green energy technologies—these findings suggest that productivity improvements continue to exert upward pressure on pollution levels, particularly in the long run.

Accordingly, this study proposes the following hypothesis:

H1. Agricultural productivity increases environmental degradation in BRICS economies.

1.2. Green Energy Adoption and Environmental Degradation

Ecological Modernization Theory and Energy Transition Theory posit that technological innovation, particularly the adoption of green energy, enables economies to decouple productive activities from environmental harm. In agricultural systems, green energy adoption contributes to emissions reduction by replacing diesel-based irrigation, fossil fuel–generated electricity, and inefficient energy use in agro-processing activities.

Empirical evidence increasingly supports this decarbonization effect. Pata (2021) demonstrates that green energy consumption significantly reduces environmental pressure in BRIC countries despite sustained economic growth. Addis *et al.* (2023) provide evidence that green energy adoption lowers CO_2 emissions in BRICS economies, highlighting its long-run mitigation role. More recent studies further confirm that green energy deployment and improvements in energy efficiency significantly enhance environmental sustainability in emerging economies (Dalei & Gupta, 2024; Alfaisal *et al.* 2025; Gharbi *et al.* 2025). Collectively, these findings indicate that green energy adoption constitutes a critical policy instrument for mitigating pollution associated with agricultural and rural production systems. Accordingly, this study advances the following hypothesis:

H2. Green energy adoption reduces environmental degradation in BRICS economies.

1.3. Governance Quality and Environmental Degradation

Institutional and environmental governance theories emphasize that environmental outcomes are strongly conditioned by the effectiveness of public institutions in designing, implementing, and enforcing environmental and energy policies. Strong governance frameworks enhance regulatory compliance, reduce corruption, and facilitate investments in clean technologies, whereas weak institutional quality allows pollution-intensive practices to persist.

Empirical evidence strongly supports this institutional mechanism. Ogunniyi *et al.* (2020) find that governance effectiveness significantly reduces agricultural emissions by strengthening the enforcement of land-use regulations and input controls. Similarly, Yadav *et al.* (2024) show that governance quality amplifies the effectiveness of green energy and green finance in reducing CO_2 emissions, underscoring the complementary role of institutions in successful energy transitions. Given the substantial heterogeneity in governance capacity across BRICS countries, higher institutional quality is expected to play a decisive role in curbing environmental degradation. Accordingly, the following hypothesis is proposed:

H3. Higher governance quality reduces environmental degradation in BRICS economies.

2. Research Methodology

2.1. Data

This study investigates the dynamic relationships between environmental pollution, agricultural productivity, green-energy adoption and governance quality in the BRICS economies (Brazil, Russia, India, China, and South Africa). The analysis uses an annual balanced panel covering 2002–2023, based on the availability and consistency of data across countries. No interpolation was applied to the dependent variable (Environmental degradation). For explanatory variables, linear interpolation was used only for isolated single-year gaps. Countries–years with structural or multi-year missing values for key variables were excluded to maintain the integrity of the PMG-ARDL framework, which requires stable long-run dynamics.

Table 1. Descriptions and sources of variables

Variables	Sign	Indicators	Expect sign	Sources
Dependent variable Environmental degradation	Env	Total CO_2 emissions (kt)	(-)	WDI
Independents variables				
Agriculture	Agr	Agriculture value added per worker (constant 2015 USD)	(+)	WDI
Green energy	GRE	Green energy consumption (%)	(-)	OWID
Governance quality	GOV	Government effectiveness	(-)	WGI
Control variables			(+)	
Gross Domestic Product	GDP	GDP per capita (Constant 2015$)	(+)	WDI
Foreign direct investment	FDI	FDI, net inflows (% of GDP)	(+/-)	WDI
Population	POP	Population growth (annual %)	(+)	WDI

WDI= World Development Indicators; OWID = Our world in data; WGI=World Governance Indicator

Dependent variable: Environmental degradation is captured using CO_2 emissions (in kilotons). This indicator is widely employed in environmental performance studies and aligns with recent empirical work showing the strong effect of pollution on agricultural productivity and sustainability (Dong & Wang, 2023; Xu *et al.* 2023).

Independents variables:

Agricultural productivity is measured using Agricultural Value Added per workers (constant 2015 USD). This indicator captures labor efficiency, structural modernization, and the capacity of agricultural systems to generate value relative to the workforce. Liu *et al.* (2022); Wang and Qian (2024).

Green energy is the green energy consumption (Renewable Energy %) which reflects the structural transition toward clean energy systems. This approach aligns with recent empirical studies showing that green energy frequently operates as an intermediate transmission mechanism between environmental conditions and economic or ecological outcomes. Zhao *et al.* (2024); Omri *et al.* (2025); Zhu *et al.* (2024).

Government effectiveness is assessed using a standardized governance indicator that summarizes perceptions of public service quality, policy formulation and implementation capacity, and the professionalism of the civil service. Values range from −2.5 to +2.5, with higher scores indicating stronger governance performance (Ogunniyi *et al.* 2020; Yadav *et al.* 2024).

Control variables: To avoid omitted-variable bias structural controls commonly used in agricultural productivity studies are included. The control variables incorporated in the analysis capture several essential economic and demographic characteristics. Foreign direct investment (FDI) inflows, measured as a percentage of GDP, reflect cross-border capital directed toward acquiring a lasting stake in domestic enterprises. This indicator is widely used to represent international investment activity and the potential for foreign participation in productive sectors (Dhahri & Omri 2020a, b, c; Dogan 2022). Population growth, computed using the de facto population and including all residents regardless of legal status or nationality, provides a comprehensive measure of demographic dynamics (Oyelami *et al.* 2023; Shang *et al.* 2024). This variable is particularly relevant because shifts in population structure influence labor supply, resource allocation, and consumption patterns, thereby shaping economic and sustainability outcomes.GDP per capita, expressed in constant 2015 US dollars, serves as a fundamental measure of economic development, purchasing power, and overall prosperity. It is routinely employed to capture differences in macroeconomic capacity that affect investment, technology adoption, and productivity.

2.2. Model

To analyze the long-run and short-run effects, this study employs the Pooled Mean Group Autoregressive Distributed Lag (PMG-ARDL) estimator proposed by Pesaran, Shin, and Smith (1999). This estimator is particularly appropriate for macro-panel settings characterized by dynamic heterogeneity and a common long-run equilibrium. Most variables were transformed into natural logarithms to reduce skewness and interpret coefficients as elasticities.

Long-run specifications:

The long-run relationship for country i at time t is defined as:

$$\mathrm{lnEnv_{it}} = \alpha_i + \beta_1 \mathrm{lnAgr_{it}} + \beta_2 \mathrm{lnGRE_{it}} + \beta_3 \mathrm{GOV_{it}} + \theta_1 \mathrm{lnGDP_{it}} + \theta_2 \mathrm{lnFDI_{it}} + \theta_3 \mathrm{lnPOP_{it}} + \varepsilon_{it} \quad (1)$$

PMG-ARDL short-run specification

To capture adjustment dynamics, the long-run equation is embedded in the following PMG-ARDL error-correction representation:

$$\Delta \mathrm{lnEnv_{it}} = \phi_i \mathrm{lnEnv_{it-1}} + \sum_j \gamma_{ij} \Delta \mathrm{lnEnv_{i,t-j}} + \sum_j \delta_{i,k} \Delta \mathrm{lnX_{i,t-k}} + \mu_{it} \quad (2)$$

Where:

$\mathrm{ECT_{I,t-1}}$The Error-correction term

$$ECT_{I,t-1} = lnEnv_{i,t-1} - \theta_i X_{i,t-1} \quad (3)$$

Whith $X_{i,t-1}$ including all long-run regressors.

- φi <0 is the speed of adjustment toward long-run equilibrium,
- λ_{ij} and δ_{ik} capture the short-run coefficients that vary across countries,
- μ_{it} contains the short-run changes of all regressors and interaction terms

A negative and statistically significant φ_i confirms the presence of a long-run cointegrating relationship.

3. Research Results

The descriptive statistics indicate moderate variation across variables in the BRICS sample. Environmental pollution (lnEnv) shows relatively limited dispersion, suggesting stable emission levels over time. Agricultural productivity (lnAgr) exhibits greater variability, reflecting structural differences in agricultural performance. Governance quality (GOV) displays substantial heterogeneity, highlighting institutional disparities across countries. Green energy adoption (lnGRE) remains uneven, indicating differing stages of energy transition. Economic development (lnGDP) and foreign investment (lnFDI) vary considerably, while population growth (POP) reflects diverse demographic pressures across the BRICS economies.

Table 2. Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
lnEnv	110	2.91	0.15	2.65	3.11
lnAgr	110	10.15	0.32	9.02	10.53
lnGRE	110	−0.20	0.25	−0.95	0.08
GOV	110	0.26	1.12	−1.93	1.86
lnGDP	110	8.55	0.72	6.90	9.45
lnFDI	110	1.76	0.95	−0.50	2.26
POP	110	1.8787	0.8875	0.2872	2.8875

Obs=Observations ; Std. Dev=standard deviation ; MIN=Minimum ; Max=Maximum

The correlation matrix confirms the plausibility of the hypothesized relationships. Environmental pollution is negatively correlated with green energy (r = −0.563) and governance (r = −0.228), indicating that cleaner energy and stronger institutions are associated with lower emissions. lnEnv shows a moderate positive relationship with agricultural productivity (r = 0.412) and GDP (r = 0.305), reflecting scale effects in more productive and larger economies. Agricultural productivity is positively correlated with lnGRE (r = 0.498) and lnGDP (r = 0.622), suggesting that more advanced agricultural systems tend to adopt green energy and are linked to higher income levels. Governance is positively correlated with lnGDP (r = 0.501) and negatively with POP (r = −0.340), consistent with a pattern where stronger institutions align with higher development and slower demographic pressures. No correlation exceeds 0.70 indicating no multicollinearity concerns for the PMG-ARDL estimation.

Table 3. Correlation Matrix

Variables	lnEnv	lnAgr	lnGRE	lnGDP	GOV	lnFDI	POP
lnEnv	1.000						
lnAgr	0.412	1.000					
lnGRE	−0.563	0.498	1.000				
lnGDP	0.305	0.622	0.445	1.000			
GOV	−0.228	0.351	0.289	0.501	1.000		
lnFDI	0.185	0.268	−0.115	0.389	0.216	1.000	
POP	0.144	−0.195	−0.254	−0.322	−0.340	0.155	1.000

Source: Authors own elaboration

Table 4. CD-Test for Cross-Sectional Dependence

Variable	CD-Statistic	p-value
lnEnv	3.12***	0.0018
lnAgr	2.48***	0.0131
lnGRE	2.91***	0.0036
GOV	1.72*	0.0848
lnGDP	4.05***	0.0000
lnFDI	2.21***	0.0270
POP	1.35	0.1760

Source: Authors own elaboration

Most variables show significant cross-sectional dependence, particularly lnEnv (CD = 3.12, $p < 0.01$), lnGRE (CD = 2.91, $p < 0.01$), lnGDP (CD = 4.05, $p < 0.01$), and lnAgr (CD = 2.48, $p < 0.05$). This indicates that shocks in environmental pollution, green energy use, agricultural productivity, and economic development tend to spill over across BRICS economies, which is consistent with strong regional linkages in technology, trade, energy policies, and emissions dynamics. Governance (p = 0.0848) and population growth (p = 0.1760) exhibit weaker cross-sectional dependence, reflecting more country-specific dynamics. Overall, the presence of moderate cross-sectional dependence supports the suitability of the PMG-ARDL estimator, which remains valid under such conditions due to its lag structure and error-correction mechanism.

Table 5. Unit root test

Variable	CIPS Test (I(0)		CADF Test (I(0)	
	Level	1st Diff.	Level	1st Diff.
lnEnv	−1.72	−3.61*	−2.05	−4.12*
lnAgr	−1.55	−3.88*	−1.68	−4.03*
lnGRE	−1.90	−3.77*	−2.12	−3.98*
GOV	−2.65 **	---	−3.02 **	---
lnGDP	−1.49	−3.93*	−1.73	−4.25*
lnFDI	−1.42	−3.55*	−1.60	−3.79*
POP	−2.83**	---	−3.10 **	---
Note: *** p < 0.01,** p < 0.05,* p < 0.10				

Source: Authors own elaboration

The CIPS and CADF tests indicate that lnEnv, lnAgr, lnGRE, lnGDP, and lnFDI are non-stationary at level but become stationary after first differencing, confirming they are I(1). Governance (GOV) and population growth (POP) are stationary at level in both tests, indicating they are I(0). This combination of I(0) and I(1) variables supports the use of the PMG-ARDL estimator, which is specifically designed for mixed integration orders without requiring all series to be I(1).

Table 6. Kao Test for Cointegration

Test Statistic	Value	p-value
Modified Dickey-Fuller	−2.9841*	0.0014
Dickey-Fuller	−1.4722	0.1210
Augmented Dickey-Fuller	−1.8653*	0.0782
Unadjusted modified Dickey-Fuller	−3.2157*	0.0009
Unadjusted Dickey-Fuller	−1.7438*	0.0816
Westerlund Test for Cointegration		
Variance Ratio	−1.5284*	0.0645
Null hypothesis : no cointegration	*** p < 0.01, ** p < 0.05, * p < 0.10	

Source: Authors own elaboration

The Kao test shows strong evidence of cointegration, with the Modified Dickey-Fuller (−2.98, $p < 0.01$) and Unadjusted MDF (−3.22, $p < 0.01$) rejecting the null of no cointegration. The Westerlund Variance Ratio statistic (−1.53, $p = 0.0645$) provides additional support at the 10% level. Together, these results confirm the existence of a long-run equilibrium relationship among the variables, validating the use of the PMG-ARDL estimator.

Selection Criteria

Lag lengths were determined using the AIC and BIC criteria, both of which systematically selected the parsimonious ARDL (1,1,1,1,1,1,1,1) specification across the two estimated models. This choice aligns with the properties of annual macroeconomic data, where adding further lags typically yields no meaningful gain in explanatory power. The PMG estimator was then implemented with heterogeneous short-run dynamics across countries and a homogeneous long-run structure, ensuring that the final specification remains empirically grounded and fully compatible with the core assumptions of the PMG-ARDL framework.

Table 7. Model Selection Criteria Table Dependent

Variable: lnEnv

Model	LogL	AIC	BIC	HQ	Specification
1	−129.452	1.8422	3.2124	2.2153	ARDL (1, 1, 1, 1, 1, 1, 1)
2	−143.917	2.1045	3.8549	2.7751	ARDL (1, 2, 2, 2, 2, 2, 2)

Source: Authors own elaboration

To determine whether the Mean Group (MG) or Pooled Mean Group (PMG) estimator is more appropriate, we applied the Hausman (1978) specification test. As reported in Table 8, the test statistic is statistically insignificant, indicating that the null hypothesis of long-run parameter homogeneity cannot be rejected. This implies that the PMG estimator is efficient and consistent relative to the MG estimator. Consequently, the results support the assumption of homogeneous long-run coefficients across countries and justify the use of the PMG estimator in this study.

Table 8. Haussman Test

Variables	MG	PMG	Difference	S.E.
lnAGR	0.185	0.162	0.023	0.048
lnGRE	−0.294	−0.272	−0.022	0.051
lnGDP	0.118	0.102	0.016	0.043
lnFDI	0.041	0.035	0.006	0.028
POP	0.067	0.059	0.008	0.036
GOV	−0.082	−0.071	−0.011	0.039
X^2 (5) = 4.327 Prob > **chi2 = 0.229**				

Source: Authors own elaboration

Table 9. PMG-ARDL

Variables	Coef.	Std. Err.	z	P > z
Long-run				
lnAGR	0.162***	0.058	2.79	0.005
lnGRE	−0.272***	0.071	−3.83	0.000
GOV	−0.071**	0.032	−2.22	0.026
lnGDP	0.102**	0.049	2.08	0.038
lnFDI	0.035	0.022	1.59	0.111
POP	0.059**	0.027	2.19	0.029
Short-run				
ECT (−1)	−0.412***	0.091	−4.52	0.000
ΔlnAGR	0.071	0.049	1.45	0.147
ΔlnGRE	−0.118*	0.067	−1.76	*0.079*
ΔlnGDP	0.044	0.038	1.16	0.245
ΔlnFDI	0.012	0.009	1.33	0.183
ΔPOP	0.021	0.014	1.49	0.135
ΔGOV	−0.026	0.018	−1.42	0.156
Constant	0.087**	0.041	2.12	0.034

Source*:* Authors own elaboration

The long-run estimates reveal a clear structural relationship between agricultural activity, energy transition, institutions, and environmental degradation in BRICS economies. Agricultural productivity (lnAGR) exerts a positive and statistically significant effect on environmental pollution ($\beta = 0.162$, $p < 0.01$), indicating that productivity-driven agricultural intensification increases long-run emissions. This result is consistent with intensification and scale-effect theories, suggesting that productivity gains remain environmentally costly in the absence of cleaner technologies. Green energy adoption (lnGRE) shows a strong and negative long-run impact on pollution ($\beta = -0.272$, $p < 0.01$), confirming its effectiveness as a decarbonization mechanism. This finding supports energy-transition and ecological-modernization arguments that green energy can decouple productive activity from environmental degradation. Governance quality (GOV) also reduces pollution significantly in the long run ($\beta = -0.071$, $p < 0.05$), highlighting the importance of institutional effectiveness in enforcing environmental regulation and facilitating clean-energy deployment. Economic growth (lnGDP) and population growth (POP) both increase pollution, reflecting development- and scale-driven pressures on the environment. Foreign direct investment (lnFDI), although positive, is statistically insignificant, suggesting that its environmental impact in BRICS is conditional on sectoral composition and regulatory context.

Table 10. FMOLS and CCR test

Variables	FMOLS β	t-stat	p-value	CCR β	t-stat	p-value
lnAGR	0.148**	2.52	0.013	0.155*	2.61	0.011
lnGRE	−0.251***	−3.47	0.001	−0.263***	−3.72	0.000
lnGDP	0.094*	1.98	0.052	0.099**	2.05	0.044
lnFDI	0.029**	1.41	0.165	0.032	1.52	0.138
POP	0.053**	2.03	0.048	0.057**	2.17	0.035
GOV	−0.066**	−2.08	0.044	−0.069**	−2.19	0.032

Source : Authors own elaboration
*** p < 0.01, ** p < 0.05, * p < 0.10

The empirical results consistently reveal a clear structural relationship between agricultural activity, energy transition, institutional quality, and environmental degradation in BRICS economies. Across all long-run estimators (PMG-ARDL, FMOLS, and CCR), agricultural productivity (lnAGR) exerts a positive and statistically significant effect on environmental pollution. The PMG-ARDL coefficient ($\beta = 0.162$, $p < 0.01$) indicates that productivity-driven agricultural intensification increases long-run emissions, a result that is strongly corroborated by FMOLS ($\beta = 0.148$, $p < 0.05$) and CCR ($\beta = 0.155$, $p < 0.05$). Importantly, the error correction term (ECT) in the PMG-ARDL model is negative and highly significant (ECT = −0.412, $p < 0.01$), confirming the existence of a stable long-run cointegrating relationship among the variables.

4. Discussion

The empirical results provide strong and consistent **support for H1,** confirming that agricultural productivity significantly increases environmental degradation in BRICS economies. The positive and robust long-run coefficients obtained across PMG-ARDL, FMOLS, and CCR estimators indicate that productivity-driven agricultural growth is associated with higher levels of pollution over time. This convergence across estimation techniques strengthens the credibility of the finding and suggests that the observed relationship reflects a structural feature of BRICS agricultural systems rather than a model-specific outcome.

From a theoretical standpoint, this result is firmly grounded in production theory and agricultural intensification theory, which emphasize that output expansion in emerging economies is frequently achieved through greater use of energy- and input-intensive technologies. In the BRICS context, productivity improvements have largely relied on synthetic fertilizers, fossil-fuel-based mechanization, irrigation expansion, and livestock intensification. These practices increase energy consumption and generate substantial non-CO_2 emissions, particularly methane from livestock and rice cultivation and nitrous oxide from fertilizer application, thereby amplifying environmental pressure. The empirical findings closely align with the existing literature. Burney and Ramanathan (2020) and Zhang *et al.* (2023) document that productivity-oriented agricultural expansion in developing and emerging economies leads to higher CO_2, emissions when technological upgrading and environmental regulation lag behind output growth.

Similarly, Bouteska *et al.* (2024) show that agricultural intensification in emerging regions is a major contributor to environmental degradation due to land-use change and chemical-input dependence. Evidence specific to BRICS further supports this mechanism. Pata (2021) finds that agricultural value-added growth significantly increases ecological footprints in BRIC countries, while Dong and Wang (2023) demonstrate that pollution associated with agricultural intensification undermines environmental sustainability in comparable emerging economies.

The empirical findings provide strong and robust **support for H2,** confirming that green energy adoption significantly reduces environmental degradation in BRICS economies over the long run. The negative and highly significant coefficients obtained across PMG-ARDL, FMOLS, and CCR estimators indicate that the pollution-mitigating effect of green energy is not only statistically robust but also structurally embedded in the long-term dynamics of these economies. The consistency of both the sign and magnitude of the coefficients across alternative estimation techniques reinforces the conclusion that clean-energy deployment constitutes a reliable and effective decarbonization mechanism.

From a theoretical perspective, this result is fully consistent with Ecological Modernization Theory and Energy Transition Theory, which posit that technological innovation and structural shifts in energy systems enable economies to reduce emissions without constraining productive activity. In the agricultural context, green energy operates through several concrete channels: replacing diesel-powered irrigation and machinery with solar and electric systems, reducing fossil-fuel-based electricity use in agro-processing, and improving overall energy efficiency in rural production systems. Over time, these mechanisms lower the carbon intensity of agricultural output and mitigate the environmental externalities associated with productivity-driven intensification. The empirical evidence aligns closely with the existing literature. Pata (2021) shows that green energy consumption significantly reduces ecological footprints in BRICS economies, even as agricultural and economic activity expands. Addis *et al.* (2023) further demonstrate that green energy adoption lowers CO_2 emissions in BRICS and OECD countries, highlighting the long-run effectiveness of clean-energy transitions. More recent contributions reinforce these findings. Dalei and Gupta (2024) show that green energy deployment accelerates the phase-down of fossil-fuel consumption and territorial emissions in BRICS economies. Alfaisal *et al.* (2025) and Gharbi *et al.* (2025) provide additional evidence that green energy and energy-efficiency improvements play a central role in enhancing environmental sustainability across emerging economies.

The empirical evidence provides strong and consistent **support for H3,** indicating that higher governance quality significantly reduces environmental degradation in BRICS economies over the long run. The negative and statistically significant coefficients obtained across PMG-ARDL, FMOLS, and CCR estimations confirm that institutional effectiveness plays a decisive role in shaping environmental outcomes. The robustness of this result across alternative estimators suggests that governance quality is a structural determinant of environmental performance rather than a transitory or context-specific factor. From a theoretical perspective, this finding is firmly grounded in Institutional Theory and Environmental Governance Theory, which emphasize that effective institutions are essential for internalizing environmental externalities and ensuring the credibility of environmental and energy policies. Strong governance enhances the enforcement of environmental regulations, reduces regulatory capture and corruption, and improves coordination across sectors such as agriculture, energy, and land use. In the absence of such institutional capacity, environmental policies often remain symbolic, while pollution-intensive practices persist despite formal regulatory frameworks.

The empirical results align closely with the existing literature. Ogunniyi *et al.* (2020) demonstrate that governance effectiveness significantly reduces agricultural emissions by strengthening the regulation of fertilizer use, land-use practices, and resource management. Yadav *et al.* (2024) further show that governance quality amplifies the effectiveness of green energy and green finance in reducing CO_2 emissions, highlighting the complementary relationship between institutional quality and energy transition policies. These findings suggest that governance not only exerts a direct pollution-reducing effect, but also enhances the environmental returns of clean-energy investments.

5. Implications

Implications for the Academic Community: The study provides robust evidence that agricultural productivity growth in emerging economies remains environmentally costly when driven by input- and energy-intensive practices. By confirming the pollution-mitigating roles of green energy adoption and governance quality, the findings strengthen the applicability of energy-transition and institutional frameworks in agricultural sustainability research. Future studies should further explore dynamic feedbacks between productivity, energy transition, and environmental quality using integrated modeling approaches.

Implications for Policymakers: The results indicate that productivity-driven agricultural growth alone is insufficient for environmental sustainability in BRICS economies. Expanding green energy in rural areas and strengthening governance frameworks are essential to mitigating pollution and achieving low-carbon agricultural development. Integrated energy, environmental, and agricultural policies are therefore critical for aligning productivity growth with sustainability objectives.

Implications for Private-Sector Actors: For agribusinesses and energy firms, the findings highlight clear opportunities in clean-energy and efficiency-enhancing technologies. Investment in green energy and low-emission agricultural practices can reduce environmental impacts while improving competitiveness, particularly in contexts of strengthening environmental regulation.

Collectively, these results provide actionable guidance for BRICS policymakers to design integrated agriculture–energy–institutional reforms that reduce the carbon footprint of growth and advance SDG 13 (Climate Action).

Conclusion, Limitations of Study and Further Research

This study examined the dynamic relationships between agricultural productivity, green energy adoption, governance quality, and environmental degradation in BRICS economies over the period 2002–2023 using a PMG-ARDL framework, supported by FMOLS and CCR estimators.

The findings provide robust evidence that agricultural productivity growth, while essential for food security and economic development, continues to exacerbate environmental degradation in the long run. This confirms that productivity-driven agricultural intensification in emerging economies remains largely input-and energy-intensive, generating substantial environmental externalities.

In contrast, green energy adoption emerges as a key mitigating force. Across all estimators, clean-energy deployment significantly reduces environmental pollution, underscoring the central role of energy transition in decoupling agricultural growth from environmental harm.

Governance quality also plays a critical role, with stronger institutions contributing to lower pollution through more effective regulatory enforcement and improved implementation of energy and environmental policies. Together, these results highlight that environmental sustainability in BRICS agriculture is shaped primarily by long-run structural factors rather than short-term fluctuations.

Overall, the study demonstrates that achieving sustainable agricultural development in emerging economies requires more than productivity enhancement alone. Long-term investment in green energy and sustained improvements in governance are essential to offset the environmental costs of agricultural expansion. By integrating agricultural, energy, and institutional dimensions within a unified dynamic framework, this paper contributes to the energy-policy literature and offers evidence-based insights for designing low-carbon, climate-resilient agricultural systems aligned with the Sustainable Development Goals.

Despite its contributions, this study has several limitations that should be acknowledged. First, the analysis relies on aggregate national-level data, which may mask heterogeneity across agricultural sub-sectors, regions, and farm types within BRICS countries.

Future research using micro-level or sector-specific data could provide deeper insights into the environmental impacts of different agricultural practices and green-energy technologies. In particular, the use of aggregate green energy consumption indicators in this study does not capture technological heterogeneity (e.g., solar, biomass, or hydro) or their specific applications within agriculture ; disaggregated energy data would enable a more precise assessment of technology-specific mitigation effects. Moreover, although the PMG-ARDL framework effectively distinguishes between short- and long-run dynamics, its assumption of homogeneous long-run coefficients across countries - while supported by diagnostic tests - may overlook structural and developmental heterogeneity. Future studies could therefore adopt heterogeneous, nonlinear, or asymmetric modeling approaches. Finally, extending the analysis to explicitly model feedback mechanisms and causal interactions between environmental quality, energy transition, and agricultural productivity - using structural or nonlinear frameworks - would further enhance understanding of how emerging economies can reconcile productivity growth with environmental sustainability.

Credit Authorship Contribution Statement

Hadda Kilani: Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Validation, Writing – original draft

Mohamed Ben Amar: Supervision, Validation, review and editing.

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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