Kinetic Analysis of Solar-Dried Mango (*Mangifera Indica L.*) Slices Via Thin-Layer Models

Egbal Elmsaad[1], Omer Elmahi[2],
Abdelnaser Omran[3], Abda Emam[4]

[1,2]Department of Agriculture Systems Engineering, Collage of Agriculture and Food Sciences, King Faisal University, Kingdom of Saudi Arabia
[1]Department of Agriculture Engineering, Faculty of Agriculture Sciences, University of Gezira, Sudan
[1]eelmsaad@kfu.edu.sa
[2]oelmunsour@kfu.edu.sa
[3]School of Applied Sciences & Engineering, Libyan Academy for Postgraduates Studies, Ajdabiya Branch, Libya
[3]naser_elamroni@yahoo.co.uk
[4]Department of Agribusiness and Consumer Sciences, College of Agricultural Science and Food, King Faisal University, Kingdom of Saudi Arabia
[4]aaeali@kfu.edu.sa

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Abstract: Drying is an important technology for preserving crops and reducing post-harvest losses. Solar dryers play a significant role in drying some vegetable and fruit crops. They are economical, technically cost-effective, and energy-saving, as they rely on sunlight for drying. This study aimed to investigate the drying kinetics of thin mango slices in a multi-mode solar dryer. The experiment was conducted on three slice thicknesses (4, 6, and 8 mm) during drying. The results showed that several thin-layer drying models were fitted to the experimental data. Based on the highest R^2 (coefficient of determination) values and the lowest χ^2 (chi-square) and RMSE (root mean square error) values, the Page model was determined to be the most appropriate for describing the drying kinetics, with R^2 value was 0.9971. The effective moisture diffusion coefficient (Deff) was calculated using Fick's second law and ranged from 3.31×10^{-10} to 9.77×10^{-10} m²/s, increasing with increasing air velocity and decreasing slice thickness. A simulation model based on Page's equation and empirical relationships for (Deff) was measured and successfully validated against experimental data, proving it to be an effective tool for predicting drying behavior and optimizing solar drying processes for mango slices.

Keywords: mango; solar drying; drying kinetics; simulation; moisture diffusivity; Page Model.

JEL Classification: Q26; Q18; Q12.

Introduction

Postharvest Technology of Horticultural Crops is a specialized field within horticulture, offered by national and international institutions to researchers and academics to address the issue of postharvest losses in fruits and vegetables (Fung *et al.* 2018). This field encompasses various disciplines focused on the handling and processing of horticultural products, including drying and wet storage techniques that reduce losses and enable reuse. Fruits and vegetables, alongside food grains, are major income sources for farmers, making postharvest losses a critical concern due to their short shelf life, high market demand, and diverse postharvest applications Cheng & Languish (2023). Harvest timing, techniques, and conditions significantly influence product quality and market price. The maturity stage at harvest affects shelf life and long-term storage potential. Optimal harvesting depends on climate, market distance, crop variety, and growing conditions. Farmers are often unaware of how their harvesting and handling practices impact the final quality of produce. Once harvested, fruits and vegetables are cut off from their nutrient supply especially water leading to visible deterioration within days of sale or storage (FAO, 2021). Solar drying is an ancient and widely used technique for drying fruits and vegetables in many parts of the world.

This method involves placing various materials on the ground or rooftops, then placing the produce to be dried on top, exposing it to direct sunlight. However, this type of drying has several drawbacks, including contamination, exposure to dust, dirt, and insects, and potential spoilage (Akpan *et al.* 2022). To address these problems, solar dryers have been developed. Their primary purpose is to provide sufficient heat for drying the produce, and they may be equipped with a collector, drying chamber, and chimney (Nnamchi *et al.* 2025). Drying is carried out using three methods: direct, indirect, and mixed, in each method, an absorber is used to capture solar energy within a solar collector (Lamrani *et al.* 2021). The absorbed radiation is then transferred to the air, facilitating its flow into the drying chamber (Ndukwu *et al.* 2023). If properly developed and executed, this method offers several advantages over traditional solar drying, including faster drying time, reduced risk of spoilage, and higher product quality (Nnamchi *et al.* 2025). However, the problem of continuous drying time arises due to intermittent solar radiation for any reason. This can be solved by using hybrid solar-powered systems that combine solar energy with non-solar heating sources, such as thermal storage materials, biomass heaters, or electric heating elements (Tyagi *et al.* 2024). This ensures energy availability and continuous drying during periods of low solar radiation. Recent studies have shown that most solar dryers are small-scale, operate using natural convection, and are designed for domestic use or for use in rural areas (Kanfa *et al.* 2020). In response to rising demand for high-quality, affordable processed foods, including fish, fruits, and vegetables, various drying technologies have emerged. These include solar-assisted dehumidification systems, solar cabinet dryers, V-groove solar collectors, indirect solar-electric hybrid dryers, indirect natural convection dryers (IDTSDs), and rack-type solar dryers for greenhouses. Among these, solar drying is considered reliable due to its low cost and environmental sustainability. Solar dryers can be constructed using locally available materials, reducing both initial and operational costs. However, current designs face challenges such as uneven drying rates, inefficiency during cloudy days, and extended drying times (Kabeel *et al.* 2021). Hybrid solar dryers have been developed to address these issues, but their high-power requirements increase operating costs. To mitigate this, phase change materials (PCMs) are used to maintain temperature at night, and vortex elements are added to the drying chamber inlet to ensure uniform airflow. Future research aims to reduce accessory components to minimize dryer weight and space, helping entrepreneurs and researchers select cost- and time-efficient drying methods (Sendhil *et al.* 2022).

Mango (*Mangifera indica L.*) is a fruit of high nutritional and economic value. However, its seasonal nature and high perishability lead to postharvest losses estimated at 25–40% in many producing countries (FAO, 2021). Drying is one of the oldest and most effective preservation methods, reducing water activity and microbial growth while facilitating transport and storage (Chobot *et al.* 2024). Open sun drying remains common due to its low cost, but it suffers from contamination, weather unpredictability, poor product quality, and long drying durations. Solar drying using engineered dryers offers a sustainable alternative with better process control and improved product quality (Lingayat *et al.* 2020). Thin-layer drying is a fundamental concept in food engineering, assuming that the product dries as a single layer with uniform exposure to drying conditions (Popescu *et al.* 2023). Drying behavior is typically modelled using theoretical, semi-empirical, or empirical models to estimate moisture content and drying time under known temperature and humidity conditions. Numerous studies have applied thin-layer drying models to products such as potato slices, onion slices, sweet cherry, and okra (Elmsaad *et al.* 2025; Matouk *et al.* 2021; Chezanoglou *et al.* 2024; Nwakuba *et al.* 2025). Researchers have tested various models and identified those best fitting experimental data. Despite extensive literature on drying kinetics for various food products, limited research exists on modelling the solar drying of mango slices. Understanding the kinetics of this process through mathematical modelling is essential for dryer design, optimization of operating conditions, and performance prediction (Gebeyehu *et al.* 2025). While several studies have explored mango drying, comprehensive investigations combining experimental analysis of operational parameters (*e.g.*, air velocity, slice thickness) with robust simulation models are still needed. Given the climatic challenges in arid and semi-arid regions, there is a growing need to develop effective preservation techniques for seasonal fruits like mango. Solar drying is among the most sustainable and cost-effective methods, yet traditional approaches such as open sun drying often result in quality degradation and contamination. This study aims to investigate the drying kinetics of thin mango slices using controlled solar dryers, analysing the influence of operational factors such as temperature, relative humidity and slice thickness, on the drying rate. It also seeks to identify the most suitable mathematical model to describe drying behavior accurately, thereby improving dryer design and offering practical recommendations for implementation in desert environments.

The originality of this research lies in its presentation, particularly in arid and hot regions (such as the Arabian Gulf and North Africa), of previously unpublished local data, along with a hybrid solar drying system designed for this purpose (using an auxiliary fan + direct drying). This system is more suitable for the physical characteristics of mango slices in terms of their fibrous structure, thickness, and high moisture content, according to models selected based on the effective diffusion coefficient. Furthermore, the study's recommendations offer several methods and suggestions directly applicable to small-scale producers and farmers, thus bridging the gap between academic research and practical application. The study's contribution is not limited to the theoretical aspect; it also provides cost-effective and highly efficient technical solutions to a real problem faced by mango-producing regions in developing countries. This research aims to investigate the kinetics of post-harvest mango slice drying using a thin-film solar dryer and to develop an accurate mathematical model describing this process, with a focus on its practical applications.

The main objective of this study is to evaluate and study the drying characteristics of mango slices using a thin-film solar dryer, develop an accurate mathematical model, and determine the relationship between product quality and drying parameters to provide practical application recommendations, and Specific Objectives:1. To design and manufacture a hybrid solar dryer (direct drying + auxiliary fan) suitable for drying thin-film mango slices.2. To investigate the effect of slice thickness (4, 6, 8 mm) on the drying rate and total drying time.3. To measure experimental drying data such as moisture content versus time and calculate the effective moisture diffusion coefficient (D_eff) using Vic's second law.4. To test and compare three mathematical models (Lewis, Page, Henderson, and Pabis) to determine the most suitable model. The thickness of the mango slice (4, 6, 8 mm) has a significant effect on the drying rate and total drying time, with the time increasing non-linearly as the thickness increases. The drying kinetics of the mango slices can be accurately described using the Lewis or Page model, with an expected R^2 value greater than 0.995. The effective moisture diffusion coefficient (D_eff) of the mango slices ranges from 2.5×10^{-9} to 9.5×10^{-9} m^2/s and increases exponentially with increasing temperature.

1. Materials and Methods

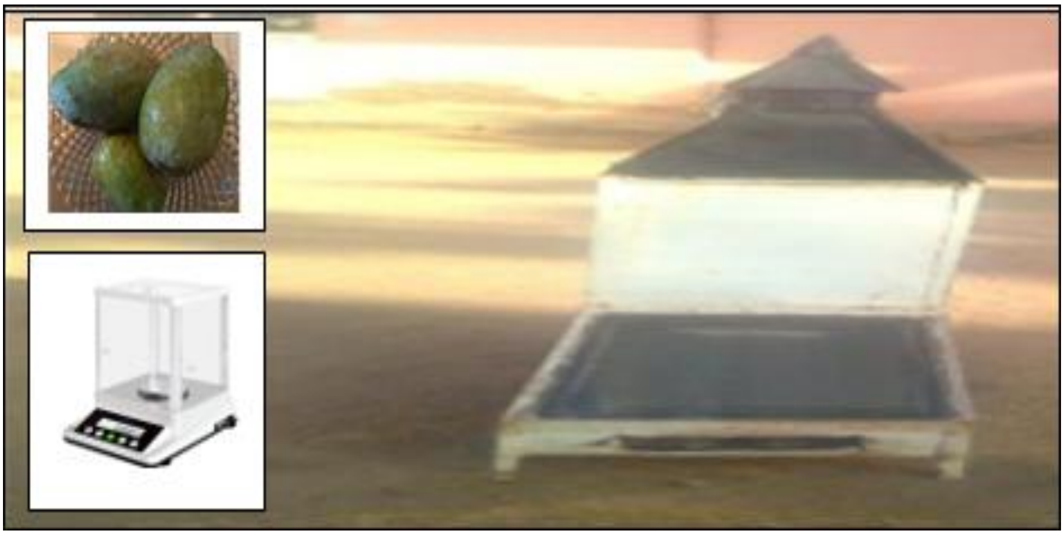
1.1 Sample Preparation

This experiment was conducted at King Faisal University, College of Agricultural and Food Sciences (latitude 26° 23' 18.56″ N, longitude 50° 11' 16.01" *E,* and an altitude of 142 m above sea level). To prepare the crop to be dried, fresh ripe mangoes (cv. Tommy Atkins) were purchased from local markets, thoroughly washed and sterilized with an aqueous solution of sodium hypochlorite at a concentration of 1 mg per litre of free chloride for 30 minutes, then rinsed with water and peeled, and cut into rectangular slices of 4- 6- and 8 mm thickness using an electric vegetable slicer to ensure uniformity. The samples were weighed at as much as 50g with the analytical balance 0.0001g Digital Lab Precision Balance Scale 0.1mg 120g 220g, at hourly intervals for the first few hours and then every 30 minutes thereafter until a constant final moisture content was achieved (approximately 10% wet basis). All experiments were performed in triplicate The initial moisture content was determined using a standard oven drying method at 105°C for 24 h until a constant value of moisture content was reached, and average values were used for calculation.

1.2 Solar Drying Unit

The experiment was conducted using a mixed-mode solar dryer. It consists of three detachable components: a solar collector (air heater), a drying chamber, and an air duct and drying tray. A rectangular solar collector measuring 150 x 40 cm was used. It consists of a corrugated zinc absorber plate, painted black to increase radiation absorption. The corrugated zinc was used to increase the surface area of the absorber plate. Two 4 mm thick glass plates, each measuring 70 x 35 cm, were fixed to the overall frame of the collector and enclosed with wooden pieces to contain any thermal expansion due to heating. A type of white glass was used as a transparent cover because it is a good conductor of solar radiation. The glass also acts as a barrier between the wind and the absorber plate. The collector frame was made of 2.65 x 2.65 cm iron angles with 0.09 cm thick metal sheets at the bottom of the packaging box. 4 cm thick glass wool was used as insulation and placed between the collector and the sides of the dryer, except for the top. The front opening of the collector was rectangular, measuring 30 x 7 cm. It was oriented south-facing and angled to form an angle of 16.5° with respect to the ground, which is the latitude of the experimental site (Fig. 1). The drying chamber was used to place the product for drying. It consisted of a box with 30 x 30 cm wire mesh trays made of steel angles. The dimensions of the drying chamber were 50 cm long, 25 cm wide, and 90 cm high. The distance between the top of the drying chamber (where the mango slices were placed in a single layer on the wire mesh trays) and the ground was 120 cm. A metal plate was fixed to each side of the drying chamber. Two tray supports made of angle iron (2.65 x 2.65 cm) were installed to hold the trays. At the bottom of the drying chamber, there was a 30 x 40 cm opening to promote airflow. The top of the drying chamber was pyramid-shaped. The top was equipped with a central 25 x 40 cm opening for air to escape. The drying chamber was designed to accommodate two trays. These trays were made of wire mesh to allow hot air to circulate through the material being dried. The trays were movable for easy placement and removal within the drying chamber for loading and unloading the product. The frame of each tray was made of angle iron with dimensions of 2.55 cm x 2.55 cm and 35 cm x 25 cm, while the tray's surface area was 35 cm x 25 cm, its depth was 3 cm, and its effective area was 35 cm x 25 cm. The door was tightly sealed to prevent air leakage between the perimeter and the drying curve. The door was used for loading and unloading the trays into the drying chamber. The interior wall and floor of the chamber were lined with 4 mm thick monzonite to minimize heat loss from the drying chamber to the surrounding environment (Fig. 2). Figure 3 was drawn using GenAI after all the dimensions of the solar dryer parts used in the experiment had been entered.

Figure 1. Solar dryer with mango sample and Analytic balance

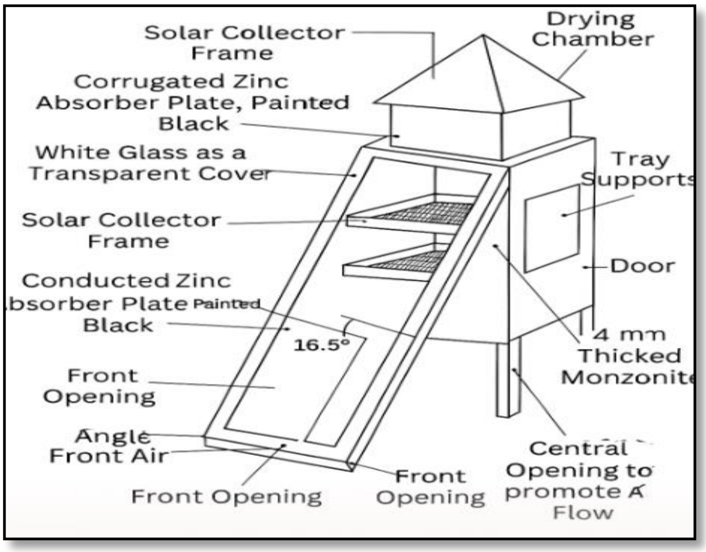


Source: The authors captured all experimental photographs during the experimental work.

Figure 2. Drying chamber with drying tray

Source: The authors captured all experimental photographs during the experimental work.

Figure 3. Mix mode solar dryer



Source: Drawing photos the authors using Figma

1.3 Measuring Instruments

The temperature and relative humidity of the air at the inlet and outlet of the drying chamber, were recorded throughout the drying period using data loggers (GSM Temperature & Humidity datalogger SMS Alarm S500EX), as well as solar radiation intensity measured by (PV204 Digital Solar Meter).

1.4. Drying Kinetics Analysis

Equations (1 and 2) are used to determine the initial moisture content (Mi) and calculate the moisture content at time t (Mt), respectively (Raaf *et al.* 2022). However, under equilibrium conditions, moisture is trapped due to bound water. This method has been observed in highly porous materials, as shown in studies on porous materials such as green plantain (*Musa paradisiaca L.)* peels, peeled cassava root slices, and cellulose Equation 1 can be applied under experimental conditions and is consistent with experimental drying models for plants Altgen *et al.* (2023), Equation (2) allows the moisture content (Mt) to be calculated as the ratio of the difference between the current sample weight (wt) and the final weight (wf), standardized to the initial weight (wi). The residual moisture persists under equilibrium conditions. In equations (1) and (2), wi, wf, and *wt* are, respectively, the initial weight of the sample (g), the final weight (g), and the weight of the sample at time t.

$$Mi = \frac{wi - wf}{wi} \quad (1)$$

$$Mt = \frac{Wt - Wd}{Ww} \quad (2)$$

The equilibrium moisture content (EMC) was determined for each treatment by continuing the drying process until a constant weight was recorded in successive observations of the mango slices. The moisture ratio (MR) was calculated using the following equation (Kusuma *et al.* 2024):

$$MR = \frac{Mt - Me}{Mi - Me} \quad (3)$$

where Mt, Mi, and Me represent the moisture content at time t, the initial moisture content, and the equilibrium moisture content, respectively. The equilibrium moisture content (Me) was obtained experimentally under controlled drying conditions, as reported by Noguera & Iturgaiz (2023). This process ensures accurate normalization in line with standard methods. Furthermore, for accurate data normalization, the importance of incorporating into thin-layer drying models is highlighted by (De Paula *et al.* 2020). Macedo *et al.* (2020) presented experimental methods and practices for extracting me under different drying conditions. Together, these references validate the approach used in this study and ensure consistency with established practices in thin-layer drying research. The drying rate is defined as the amount of water that can evaporate from the product over a specified period of time. The mango drying rate (DR) is calculated by dividing the time difference between the previous moisture content and time t at that moment by the time difference (Gasa *et al.* 2020).

$$Dr = \frac{Mt - Mt + \Delta t}{\Delta t} \quad (4)$$

In Equation (4), Mt+Δt is the water content at the drying time starting at time t+Δt (minutes), while Δt is the time difference (minutes).

1.5 Mathematical Models

The following assumptions were made to develop a suitable mathematical model for thin-bed drying of mango slices:
1. The temperature across all mango slices was uniform.
2. Convection was the primary cause of heat transfer.
3. Internal resistance to moisture movement was minimal.
4. Moisture was removed from the product during the period of sunlight and only in the vertical direction.
5. Liquid diffusion is the mechanism governing moisture transfer.
6. Evaporation occurred entirely on the surface of the mango slices.

Semi-theoretical models are generally derived by simplifying or modifying the general series solutions of Fick's second law and are valid within the range of temperature, relative humidity, airflow velocity, and moisture content for which they were developed (Owoh *et al.* 2025).

1.5.1 Lewis Model

This model is derived from the semi-theoretical Lewis model of thin-film drying. It is similar to Newton's law of cooling, where k is the drying constant (min $^{-1}$) and t is the drying time (min) (Ambawat *et al.* 2022)

$$MR = \exp(-k \times t) \quad (5)$$

1.5.2 Page Model

The drawbacks of the Lewis model were overcome by empirically modifying the time limit by adding non-dimensional constants (*n*), both k and *n* were related to various process variables (air drying temperature and speed, initial moisture content, etc.) and were used to study the drying behavior of corn husks (Bozkir *et al.* 2020).

$$MR = \exp(-k \times t^{n}) \quad (6)$$

1.5.3 Henderson and Pabis Model

The Henderson and Pabis model are a modification of another model using the basic Lewis model or the Page model (Kusuma *et al.* 2024). The Henderson and Pabis model are considered the first model used for kinetic drying and was used in the general solution of Fick's law (Hartati *et al.* 2018). Henderson and Pabis also modified the Lewis model by adding an empirical constant (a) to their kinetic drying model.

$$MR = a \times \exp(-k \times t) \quad (7)$$

1.5.4 Diffusivity Calculation

For thin fruit slices (treated as infinite slices), Fick's second law gives an analytical solution for the moisture content (MR) when internal diffusion controls the drying process and external resistance is negligible, this model is used when the Lewis or Page models cannot accurately represent the two drying phases (i.e., when the curve exhibits a double-slope pattern).

$$MR = a.\exp(-k.t) + (a-1).\exp(-k.b.t) \quad (8)$$

MR: Moisture Ratio the dimensionless ratio representing the remaining moisture content. a: Fraction coefficient representing the contribution of the fast-drying phase. k: Drying rate constant [s^{-1}] indicates the speed of moisture removal during drying. b: Correction factor reflecting the relative difference in the drying rate of the second phase. t: Time [s].

Relationship with effective moisture diffusivity, the model represents two simultaneous diffusion phases within the sample: The first term, a exp. (−k t) corresponds to the fast diffusion of surface moisture (near the outer surface). The second term, (1−a) exp (−k b t), represents the slow diffusion of internal moisture bound within the cellular structure. Since each exponential term can be related to Fick's second law of diffusion, each component describes a separate moisture transfer mechanism occurring during the drying process (Ma *et al.* 2022).

1.6. Statistical Analysis

The accuracy of the model fit was evaluated using the Coefficient of Determination (R^2), Chi-square (χ^2), and Root Mean Square Error (RMSE) and Average absolute difference (AAD). The model with the highest R^2 and the lowest χ^2 and RMSE values was considered to determine the best-fit model, some statistical parameters are used as follow as (Pham *et al.* 2019; Xu *et al.* 2025) reported that the parameters used in the statistical validation include the followings:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(MRexp,i - MR \quad pre,i\right)^2}{\sum_{i=1}^{N}(MRexp,i - MRave,i)^2} \tag{9}$$

$$X^2 = \frac{\sum_{i=1}^{N}(MRexp,i - MRpre,i)^2}{N} \tag{10}$$

$$SSE = 1 - \sum_{i=1}^{N}(MR\ exp,i - MRpre,i)^2 \tag{11}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(MR_{\exp,i} - Mr_{pre,i})^2}{N-n}} \tag{12}$$

$$MSE = \frac{\sum_{i=1}^{N}(MR_{\exp e,i} - MR_{pre,i})^2}{N-n} \tag{13}$$

$$AAD = \frac{\sum_{i=1abs}^{N}(MR_{\exp e,i} - MR_{pred,i})}{n} \tag{14}$$

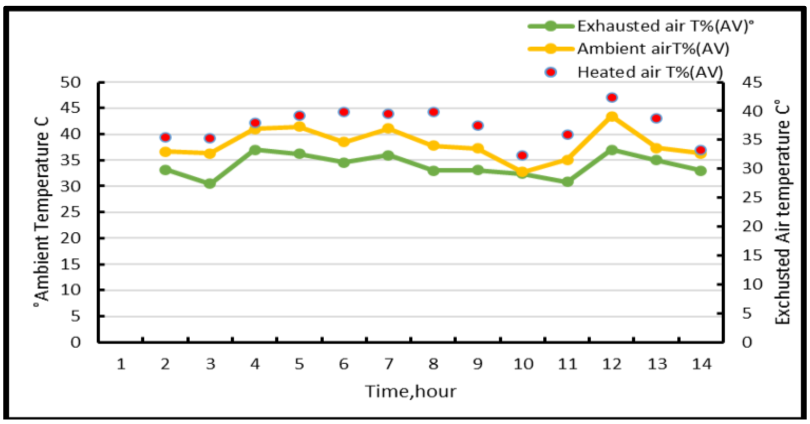
where: $MR_{exp,\ i}$ and $MR_{pre,\ i}$ are the experimental and predicted moisture ratios, respectively, N is the number of observations, and z is the number of constants in the model.

2. Results and Discussion

2.1 Drying Performance of the Solar Dryer

Figure 4 shows the temperatures of the ambient air, heated air, and exhaust air for the experimental period. It was observed that the heated air temperature increased during the afternoon and decreased during the evening over time. This is consistent with the results of (Getachew *et al.* 2024). The obtained solar collector temperatures (heated air temperatures) were higher than the ambient and exhaust air temperatures. This demonstrates the effectiveness of using the solar collector as a heat source for drying purposes.

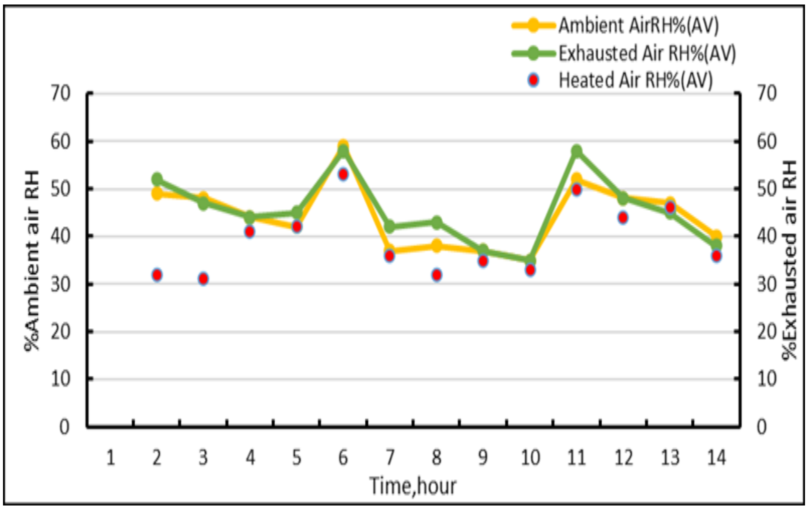
Figure 4. The temperatures of the ambient air, heated air, and exhaust air during experimental period



Source: Authors' own experimental data

Figure 5 illustrates the relationship between the relative humidity of the ambient, heated, and exhausted air inside the dryer during the drying period. Relative humidity tends in the opposite direction to temperature. The results show that the relative humidity of the heated air is lower than that of the ambient and exhausted air. When the air is heated, its relative humidity decreases, its temperature increases, and thus its ability to remove moisture from the product increases. In addition, the heated air extracts more moisture from the product than unheated air. This demonstrates that the solar dryer is a suitable device for drying applications, where the air used for drying must have a high temperature and low relative humidity (Gomez *et al.* 20 23).

Figure 5. Relative humidity of ambient, heated and exhausted air during the drying experiment



Source: Authors' own experimental data

2.2 Solar Drying Properties of Mango Slices

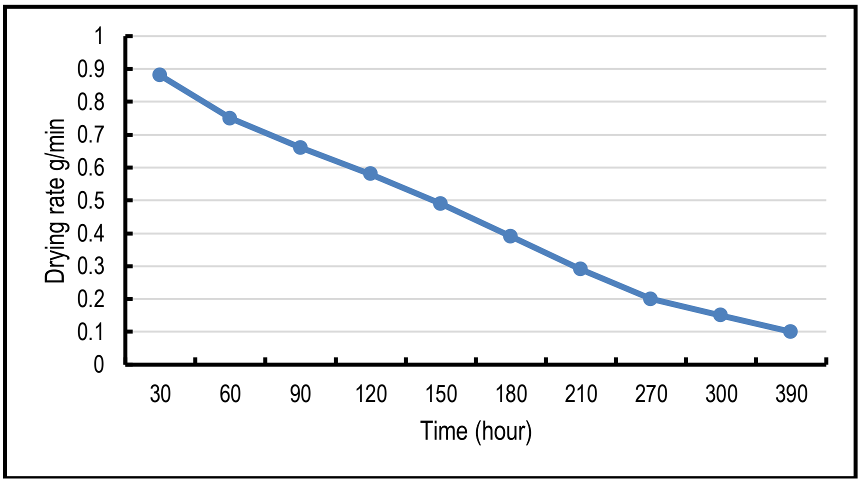
Table 1 shows the measured weight and moisture content values for both dry and wet states of mango slices. The data indicated that the mango slices were dried from an initial moisture content of approximately 80% (dry) to a final moisture content of approximately 15% (dry). The final moisture content of sun-dried mango (15%) is lower than the typical moisture content of 18% (dry) for dried fruit Therefore, the sun-dried mango slices obtained under the present conditions have acceptable moisture levels for preservation and storage according to (López *et al.* 2024). The drying process involves heat and mass transfer processes, which lead to changes in the product structure, shape, and quality (Dasore *et al.* 2020). In general, two drying periods can be observed: fast and slow drying. The fast-drying period occurs when there is a diffusion process on the outer surface of the material (Ntsowe *et al.* 2025). In this case, the water content decreases rapidly and the humidity percentage decreases rapidly because the water evaporates from the outer surface quickly. This usually occurs during the first drying period, especially in the first minutes of the drying process, as shown in Fig. 6. In the second drying period, drying slows down until the equilibrium point is reached due to the slow diffusion rate of water evaporation. This is attributed to the fact that the diffusion of liquid or vapor occurs from the inside of the material to its surface due to the difference in humidity concentration (Raaf *et al.* 2022). The slow drying period can be seen in Fig. (6), from minute 30 to end.

Moisture content is an important parameter and parameter in the drying process, as it leads to moisture removal from the product (Cheng & Langrish, 2023). The moisture content value also helps in analysing materials during the drying process, such as the drying rate, time required for water equilibration, and moisture content of the dried product. Figure 7 shows the relationship between moisture content and drying time of mango slices over two days of drying. The time required to reach a final moisture content of 15% (weight of material) is 12 hours. The figure also indicates that there is no constant-rate drying period, as the entire drying process occurs during the decreasing-rate period, confirming that diffusion is the dominant mechanism of moisture transfer. These results support the hypotheses of thin-film drying, which demonstrate that moisture removal from the product occurs only during the sunlight period and in the vertical direction. Liquid diffusion is the mechanism that regulates moisture transfer. Figure 7 shows the relationship between moisture content and drying time. It also confirms that moisture content decreases with increasing drying time. A common feature of this curve is its similarity to the typical curve for thinly packed dried fruit this result in line with (Rizki *et al.* 2025). Equation 8 explain that the two-term exponential model represents two simultaneous drying mechanisms: a fast surface diffusion and a slower internal diffusion. Each exponential term can be associated with Fick's second law, enabling the estimation of an equivalent effective moisture diffusivity as a weighted average of both phases.

Table 1. Moisture content and measured weight on wet basis and dry basis of Mango slices

Time (hr)	Weight (grams)		Moisture content
		Wet basis %	Dry basis %
9:00	4.1	80	3.2324
10:00	3.5	75	2.7145
11:00	3.3	73.4	2.5431
12:00	3	65.33	1.7776
13:00	2.9	61	1.5475
2:00	2.4	57	1.3817
15:00	2.2	48.8	1.2311
16:00	1.7	36	.0.9834
17:00	1.5	33	0.5881
9:00	1.4	25	0.3489
10:00	1.3	15	0.19448
11:00	1.3	15	0.19448
12:00	1.3	15	0.19448

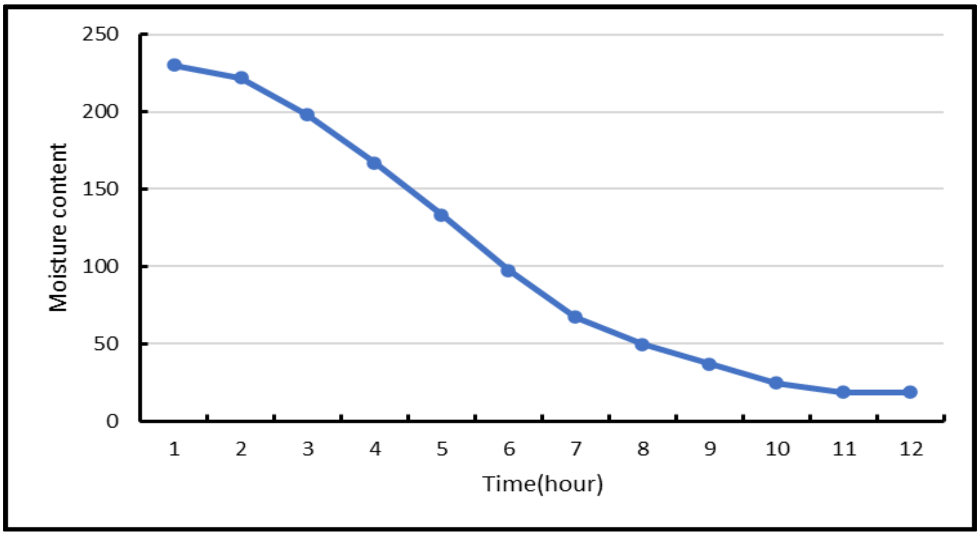
Figure 6. The relation between Drying rate and time during drying period



Source: Authors' own experimental data

Although this model provides a more detailed description of moisture transport in heterogeneous materials like mango, it is more complex and less widely used than the simpler Page model, which generally offers the best overall fit with fewer parameters. It gives a better description of moisture transport in materials with multiple porosities or layers (*e.g.*, mango, guava, potato). The effective moisture diffusion coefficient (D_{eff}) was calculated using Fick's second law and ranged from 3.31×10^{-10} to 9.77×10^{-10} m²/s, increasing with increasing air velocity and decreasing slice thickness.

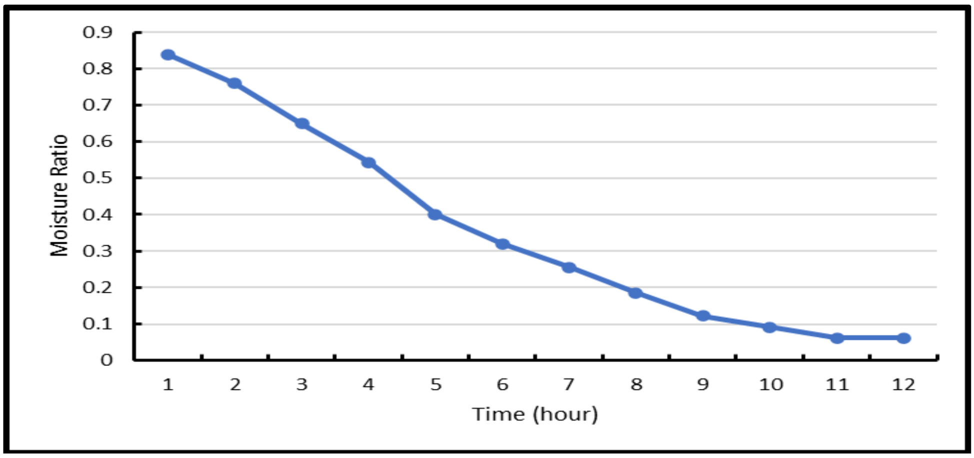
Figure 7. Variations of moisture content with drying time



Source: Authors' own experimental data

Figure 8 also shows the moisture content versus drying time. The figure shows that the moisture content gradually decreases with increasing drying time. A common feature of this curve is its similarity to the typical curve for thin-layer dried fruit.

Figure 8. Variations of moisture ratio with drying time



Source: Authors' own experimental data

Table. 2. Values of the drying constants and coefficients of three tested drying models

Models	R^2	X^2	SSE	RMSE	AAD	Models' constants & Coefficient
Lewis	0.996	0.027	0.004	0.030	0.168	K=0.2435
Page	0.997	0.087	0.003	0.001	0.029	K= 0.1401 n=1.234
Henderson & Pabis	0.995	0.031	0.019	0.003	0.146	K=0.267 a =1.2565

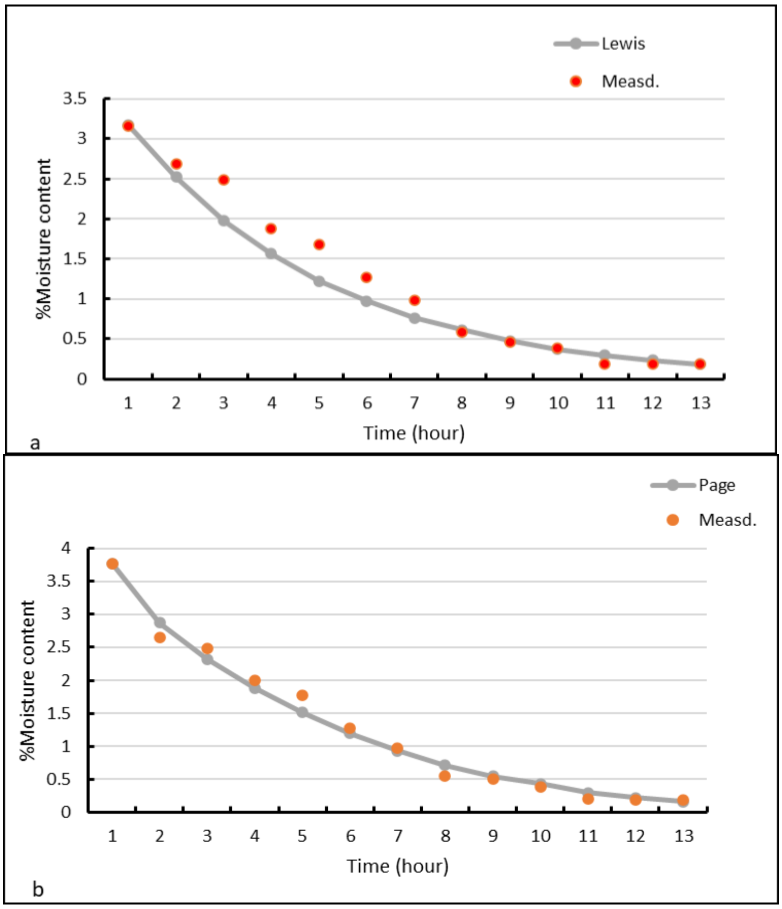
2.3 Selection of the Optimal Mathematical Model

Table (2) show the results of a linear regression analysis to fit the three tested drying models to the experimental data. This table shows the drying constants, drying coefficients, and coefficient of determination (R^2) values for the three tested drying models. The results show that the drying constant (K) is 0.2435, 0.1401, and 0.2671 for Lewis, Page, and Henderson and Pabis, respectively. The drying coefficient (n) for Page is 1.234, while the drying coefficient (a) for Henderson and Pabis is 1.2565. From the figures and table, the Page model is considered the best for representing the drying kinetics when compared to the other two models. This result is consistent with Raaf *et al.* (2022), who reached similar results in the drying of guava, according to Parmar *et al.*

(2025), the Lewis model is considered less accurate because it relies on initial drying conditions and neglects the final periods. The Henderson and Pabis model, according to Sadaka *et al.* (2022), was not suitable in his experiments on corn drying, for the first two hours of drying due to the large temperature difference between the grain and the air. Drying kinetic models are very important in determining ideal drying conditions, as they include basic criteria for design, equipment optimization, and product quality improvement (Getachew *et al.* 2025).

Figures 9 (a, b, c) show the measured and predicted moisture content (expressed as moisture content on a dry decimal basis) versus drying time. For comparison, the best kinetic drying model that could represent the drying of mango slices using a solar dryer was analysed. Five statistical error coefficients were used, and it was observed that R^2 was the highest, while the statistical values of X^2, SSE, MSE, RMSE and AAD were the smallest. However, when determining the optimal model, one basic error function is chosen for the solution, while the other error function is used as a comparator (Luke *et al.* 2021). The most important criterion is SSE, which measures the difference between the collected data and the constructed predictive model. SSE is frequently used as a research reference in determining optimal data. Ganesh *et al.* (2024) stated that a more accurate model should have a mean model error and mean absolute difference close to zero and a small standard error of estimate AAD for the best model Page model (0.0295). Therefore, it can be said that the three tested drying models adequately simulated the drying process of mango slices. However, Fig. (9) shows that the Page model is the most appropriate of the three tested drying models for simulating the drying process of mango slices. El-Mesery *et al.* (2023), obtained similar results for whole okra pods. As evident, the Page model provided the best fit to the experimental data under all conditions, registering the highest R^2 values (>0.997) and the lowest RMSE and χ^2 values. The equation 6 captures the interaction between the drying constant (k) and the dimensionless exponent (n), giving it the flexibility to accurately describe the drying curve (Kabeel *et al.* 2021).

Figure 9 (a, b, c). Measured and simulated moisture contents by Lewis, Page and Henderson and Pabis models



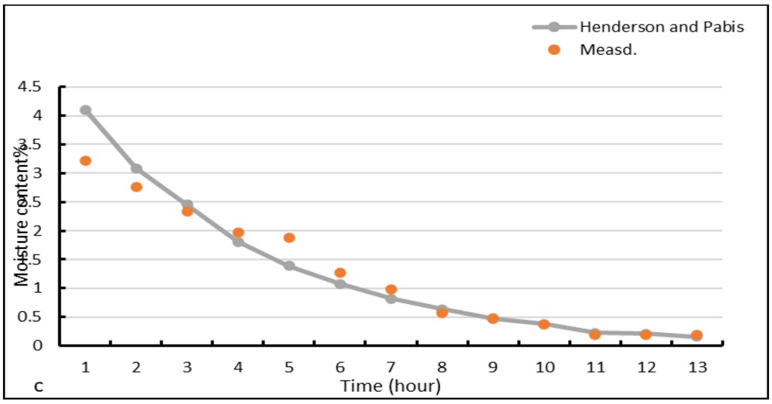


Table 3. Two-sample T-Test of the sample means of experimental and simulated moisture contents by the three tested drying models

Model name	95% confidence interval for $\mu_1 = \mu_2$	$\mu_1 = \mu_2$ vs $\mu_1 \neq \mu_2$			
		t_0	t_1	*P*	*d.f.*
Lewis	(-0.664, 0.952)	0.38	2.057	0.561	22
Page	(-0.833, 0.863)	0.03	2.067	0.981	22
Henderson & Pabis	(-0.952, 0.890)	-0.07	2.073	0.952	22

(expressed as moisture content on dry basis, decimal)

Table 3 shows a t-test to determine whether there is a difference in the sample means for the experimental and predicted moisture content for determining the moisture content of mango slices (expressed as moisture content on a dry decimal basis). From this table, it is concluded that the null hypothesis (H_0: $\mu_1 = \mu_2$) is true, i.e., $t_0 \leq t_1$, for the three tested drying models. There is insufficient evidence to reject the null hypothesis. In other words, based on the current data, there is no difference between the two methods with regard to determining the moisture content of mango slices. This confirms that the three tested drying models are successful in simulating the thin-layer drying process of mango slices (Mbaye *et al.* 2026).

Where: μ_1: population mean of the measured moisture content, decimal (d.b.). μ_2: population mean of the predicted moisture content, decimal (d.b.).t_o: calculated value of the test statistic (calculated t).t_1: tabulated value of the upper α/2 percentage point of the t-distribution (tabulated t). P: probability or percent risk of being wrong if the null hypothesis (H_o) is rejected. df: degrees of freedom.

The thin-layer drying models - Lewis, Page, Henderson and Pabis, and Logarithmic - are empirical or semi-theoretical equations that describe the drying behavior of agricultural materials. All these models are linked to Fick's second law of diffusion, which governs moisture transfer inside the material. The Lewis model assumes a simple exponential decay of moisture ratio, corresponding directly to a constant effective moisture diffusivity. The Henderson and Pabis model introduces a shape factor to better represent the initial drying phase. The Page model, a modified form of Lewis, adds an exponent n to time, allowing flexible curvature and thus fitting experimental data more accurately, particularly when the drying rate decreases non-linearly. Therefore, the Page model generally provides the best correlation (highest R^2) and yields more realistic estimates of effective moisture diffusivity, especially for fruits like guava with non-uniform internal structure and varying porosity (Nnamchi *et al.* 2025; Khaled *et al.* 2024).

2.4 Analysis of the Method of Drying Mangoes with a Solar Dryer

Various drying techniques are used in various studies, including oven drying, sun drying, and freeze drying. Each has distinct advantages and disadvantages in preserving the essential properties of the product. Therefore, choosing the appropriate drying method has a significant impact on product quality, the retention of bioactive compounds, and its energy efficiency. Some drying methods increase or increase the temperature, which affects product quality and the preservation of other properties. Sun drying is an ideal, cost-effective, and environmentally friendly alternative. However, there are some challenges regarding process control and drying efficiency. Although it preserves some bioactive compounds, such as beta-carotene, studies indicate that the degradation of essential oils occurs due to prolonged exposure to ultraviolet radiation (Khaled *et al.* 2024). Solar drying, while energy efficient can be affected by climatic conditions because it relies on the sun for drying, requiring longer drying periods (Nnamchi *et al.* 2025). Based on the results of previous studies, solar drying remains a viable option in resource-limited environments, but precautions must be taken to prevent microbial contamination and degradation caused by ultraviolet radiation (Shrivastava & Gaur, 2026).

Conclusions and Further Research

This study demonstrated the characterization of the drying kinetics of mango slices using a solar dryer using a thin-layer method. Different thin-layer models were compared to determine the most appropriate mathematical representation of the drying process. Among the evaluated models (Lewis, Page, and Henderson & Pabis), the Page model showed the best fit with the highest correlation coefficient (R2 = 0.997) and the lowest error values, demonstrating its accuracy in predicting drying behavior. Furthermore, the designed dryer heated the drying air satisfactorily, which is optimal for drying mango slices. Furthermore, all mango slices were dried within the falling rate period, with diffusion being the dominant mechanism of moisture transport. Mathematical modelling can be used as a practical tool in simulating the drying of agricultural products. Using a solar dryer is less expensive and energy-intensive, making crop processing easier and reducing waste during the drying process. It is also a small-scale investment project that allows entrepreneurs and small farmers to increase their income. For future work, it is recommended to study the effect of air temperature more discretely, analyse the quality attributes (such as colour and vitamin C content) of the dried product, and integrate the model with IoT and learning machine and into a user-friendly interface to facilitate its use by engineers and farmers.

Declarations

Credit Authorship Contribution Statement:

Egbal Elmsaad: Writing, Original draft.
Omer Elmahi: Methodology, Supervision
Abdelnaser Omran: Editing, Plagiarism
Abda Emam: Supervision

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Declaration of Use of Generative AI and AI-Aided Technologies: The authors declare that they did not use generative artificial intelligence.

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