

Drying Kinetics of Plantain (*Musa paradisiaca*) in a Parabolic-Shaped Solar Dryer Developed by the Nigerian Stored Products Research Institute

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Abstract

Drying is an essential post-harvest process for preserving plantains, reducing waste, and ensuring year-round availability. A Parabolic-Shaped Solar Dryer (PSSD) developed by the Nigerian Stored Products Research Institute offers a promising sustainable option for drying agricultural produce. This study investigated the drying kinetics of plantain (*Musa paradisiaca*) slices using the dryer under natural solar operating conditions. Experimental moisture ratio data were fitted to selected thin-layer drying models, including Midilli *et al.*, Page, Newton, Logarithmic, and Wang and Singh models, to determine the most suitable predictive model for plantain drying behavior. The Page and Midilli *et al.* models emerged as the best fit, exhibiting R^2 values of 0.999 and root mean square error values of 0.00, confirming their suitability for describing the drying characteristics of plantain. The drying process was primarily governed by the falling rate period, with moisture diffusion playing a dominant role in moisture removal. At an average temperature of 44.55 °C and relative humidity of 61.8%, the PSSD was able to reduce the plantain moisture level from 66 to 12.59% within 22 hours. The economic analysis of the PSSD operation for plantain drying showed a gross margin of ₦ 25,650, a net profit of ₦ 22,617, and a return on investment ratio of 1.20. This study provides insights into the drying behavior of plantain in a solar drying system and supports the application of thin-layer models for predicting drying kinetics under natural conditions.

Categories: Food and Pharmaceutical Engineering, Agricultural Machinery and Automation, Bioprocess Engineering

Keywords: plantain chips, drying kinetics, drying rate, modeling, moisture

Introduction

Plantain, *Musa paradisiaca*, a staple food in many tropical regions, has a high moisture content (approximately 60-65%), which predisposes it to rapid microbial spoilage after harvest. Moisture content in agricultural produce plays a crucial role in its stability, as high moisture levels in plantain promote microbial growth and biochemical reactions that lead to spoilage and deterioration. Drying, by reducing water activity, extends the shelf life of plantain, making it more suitable for storage and processing into products such as plantain flour and chips [1]. Traditional drying methods, including sun

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drying, have been widely used for plantain preservation; however, they are often associated with longer drying times, contamination, and nutrient degradation [2,3]. Therefore, improved drying technologies, such as solar drying and hot air drying, have been developed to enhance drying efficiency and maintain product quality. Parabolic solar dryers offer a more efficient alternative by concentrating solar radiation onto the drying chamber, providing consistent heating and improved drying rates [4].

Drying kinetics describes the rate at which moisture is removed from a product under controlled conditions. It involves understanding moisture diffusion, heat transfer mechanisms, and the influence of drying parameters such as temperature, relative humidity, airflow velocity, and initial moisture content. The drying process generally occurs in two phases: the constant-rate period and the falling-rate period [4]. During the constant-rate period, surface moisture evaporates rapidly under steady conditions. Once surface moisture is depleted, the drying rate decreases, and the process enters the falling-rate period, where moisture diffusion from the interior to the surface governs the drying process.

Mathematical models are often used to describe drying kinetics, including empirical, semi-theoretical, and theoretical models. The commonly applied models for plantain drying include the Page, Henderson and Pabis, and Lewis models, which help predict drying behavior and optimize drying conditions [5,6]. These models are useful for estimating drying times and understanding the moisture removal mechanism, ultimately aiding in designing more efficient drying systems. Understanding the drying kinetics of plantain is essential for optimizing drying conditions, improving energy efficiency, and maintaining product quality [6,7]. Factors such as drying temperature significantly influence drying rates and the quality of the final product [8]. Advances in drying technologies, including solar drying systems, offer promising solutions for improving plantain preservation.

Despite the growing interest in solar drying technologies, there is limited information on the drying kinetics of plantain using a Parabolic-Shaped Solar Dryer (PSSD), particularly with respect to the influence of key drying parameters and the suitability of thin-layer drying models. This study, therefore, aimed to investigate the drying kinetics of plantain in the PSSD, with emphasis on the effects of operating conditions on drying behavior and the evaluation of appropriate mathematical models for describing the drying process.

Materials And Methods

Description of the dryer

The dryer was constructed within the premises of the Nigerian Stored Products Research Institute zonal office in Ibadan. It is of (6.5 m × 4.2 m × 2.5 m) size with an effective drying area of 17.85 m². It features a black tiled floor that absorbs solar heat and gradually releases it during the drying process. No additional insulation material was used in the dryer; however, the tiled floor contributes to reducing heat loss through its thermal mass. Its frame is constructed from galvanized pipes and covered with a transparent UV-stabilized transparent polyethylene sheet, measuring 6.5 m × 4.2 m, which encloses the drying chamber and facilitates heat transfer. Also, it allows solar radiation to penetrate while protecting the drying chamber. Inside the drying chamber, there are two drying racks, each with two layers, made from mild steel angle iron to provide structural support. Each rack holds seven drying trays at each layer, made of square pipes and wire mesh. The dryer is constructed with six inlet vents and two pneumatic aspirators at the top to facilitate the removal of moisture-laden air from the drying chamber during operation, thereby supporting the drying process.

Plantain preparation

A total weight of 183 kg of plantains (43 bunches) was sourced locally and peeled before being manually sliced into slices of approximately 7 mm thickness prior to drying. The total weight of 103 kg of sliced plantain was dried in the PSSD. Figure 1 shows the flowchart of the unit operations according to the procedure outlined by [6].

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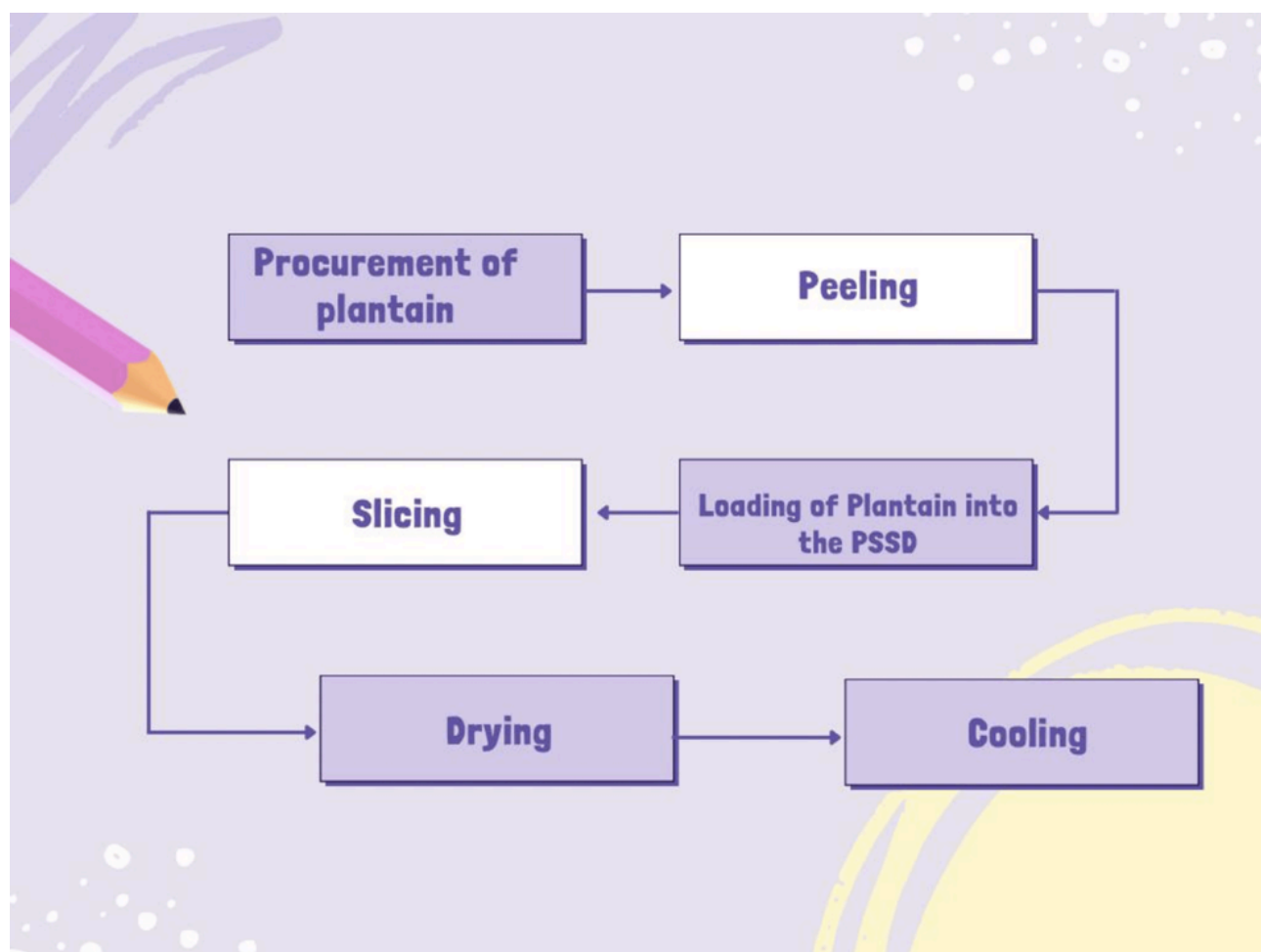


FIGURE 1: Flowchart of the unit operations for production of dried plantain chips

Experimental procedure

The plantain slices, as shown in Figure 2, were weighed every 30 minutes using a digital weighing balance to monitor moisture loss, following the procedure described in [6-8]. Initial moisture content was determined by oven-drying at 105°C until a constant weight was achieved, as described in [9,10]. The total weight after drying was 39.7 kg. The ambient conditions and the drying temperature within the dryer were monitored throughout the drying process, and the results are presented in the Results and Discussion section. In addition, the temperature and relative humidity of both the drying chamber and ambient conditions were monitored using a Temtop data logger (TemLog 20H; accuracy: $\pm 0.5^{\circ}\text{C}$).

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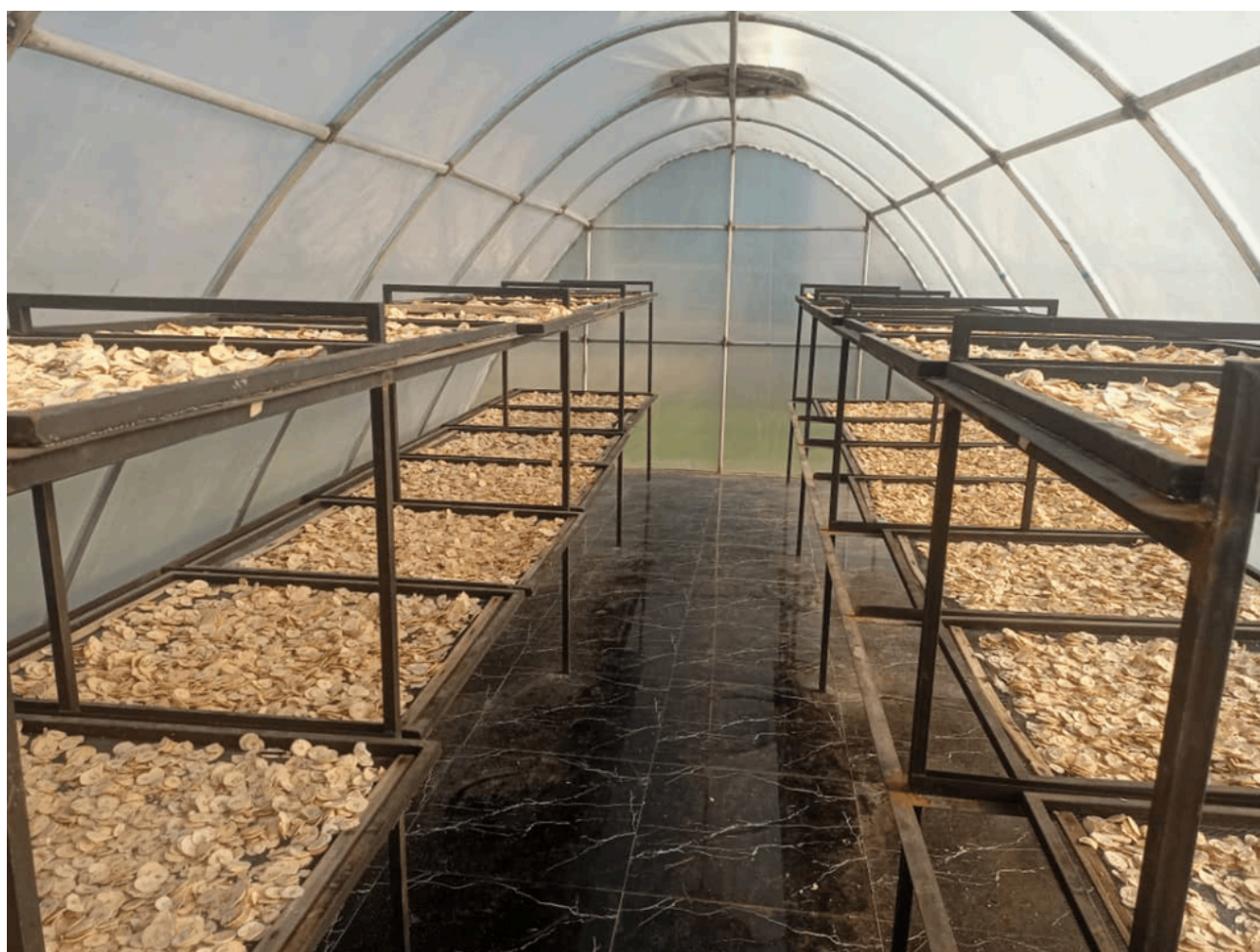


FIGURE 2: Plantain chips during drying process in the Nigerian Stored Products Research Institute Parabolic-Shaped Solar Dryer (NSPRI PSSD)

Drying rate determination

The moisture ratio (MR) of plantain slices was calculated using Equation 1, as described in [11,12]

$$MR = \frac{M^t - M^e}{M^o - M^e} \quad (1)$$

Where, MR is the Moisture ratio; M_t is the moisture content at time t (% db); M_0 is the initial moisture content (% db), M_e is the equilibrium moisture content (% db).

Drying rate was calculated using Equation 2 [13-15].

$$Dryingrate = \frac{W_t - W_{t+\Delta t}}{\Delta t} \quad (2)$$

Where: W_t is weight of the sample (kg) at time t , $W_{t+\Delta t}$ is weight of the sample at time, $\Delta + \Delta t$ and Δt is time interval (h).

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Drying kinetics and model fitting

The experimental data collected were used to generate predicted data which was fitted into the drying curve to get the best line of fit according to [16,17]. The drying models used for the fitting and predicting the rate of moisture loss from the plantain chips are presented in Table 1. The experimental moisture ratio data were fitted to five thin-layer drying models, namely Midilli et al., Page, Approximation of Diffusion, Logarithmic, and Wang and Singh, using their standard forms. The model constants (a, b, c, k, and n) were estimated through non-linear regression analysis using SPSS by minimizing the sum of squared errors between the experimental and predicted moisture ratios. Model performance was evaluated using the coefficient of determination R^2 and root mean square error (RMSE). The model with R^2 and RMSE was selected as the best-fit model following [18,19].

Models	Equations	References
Midilli et al	$MR = a \exp(-kt^n) + bt$	[10]
Wang and Singh	$MR = 1 + at + bt^2$	[14]
Page	$MR = \exp(-kt^n)$	[15]
Newton Lewis	$MR = \exp(-kt)$	[18]
Approximation of diffusion	$MR = a \exp(-kt) + 1 - a \exp(-kbt)$	[19]
Logarithmic	$MR = a \exp(-kt) + c$	[19]

TABLE 1: Drying models used for the study

MR denotes the moisture ratio of plantain chips (dimensionless), t is the drying time, k represents the drying rate constant, while a, b, and c are empirical constants in the drying models.

Experimental data were fitted to commonly used thin-layer drying models, including the Newton, Henderson and Pabis, and Page models.

Economic evaluation

Return on Investment (ROI)

The measure of performance for evaluating the profitability of an investment is known as Return on Investment (ROI). The evaluation of ROI is done by dividing the benefit (return) of an investment by the cost of the investment as shown in Equation 3. The result is expressed as a percentage or a ratio.

$$ROI = \left(\frac{NetIncome}{CostofInvestment} \right) \times 100 \quad (3)$$

ROI is a tool for determining how profitable a business is. If the result of ROI is positive, it indicates that the business is profitable.

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The variables used in the ROI analysis were estimated based on experimental results and standard economic procedures. Fixed and variable costs were determined from material, fabrication, and operational expenses, while revenue was estimated from the dryer capacity and the prevailing market price of the dried product.

Depreciation was estimated using the straight-line method, assuming a constant depreciation over the useful life of the dryer. The salvage value was assumed to be negligible, and the annual depreciation cost was obtained by dividing the initial capital cost by the estimated service life of the equipment.

All cost and revenue values used in the economic analysis are presented in Nigerian Naira (₦), as the study was conducted in Nigeria and the economic data were originally obtained in local currency.

Results

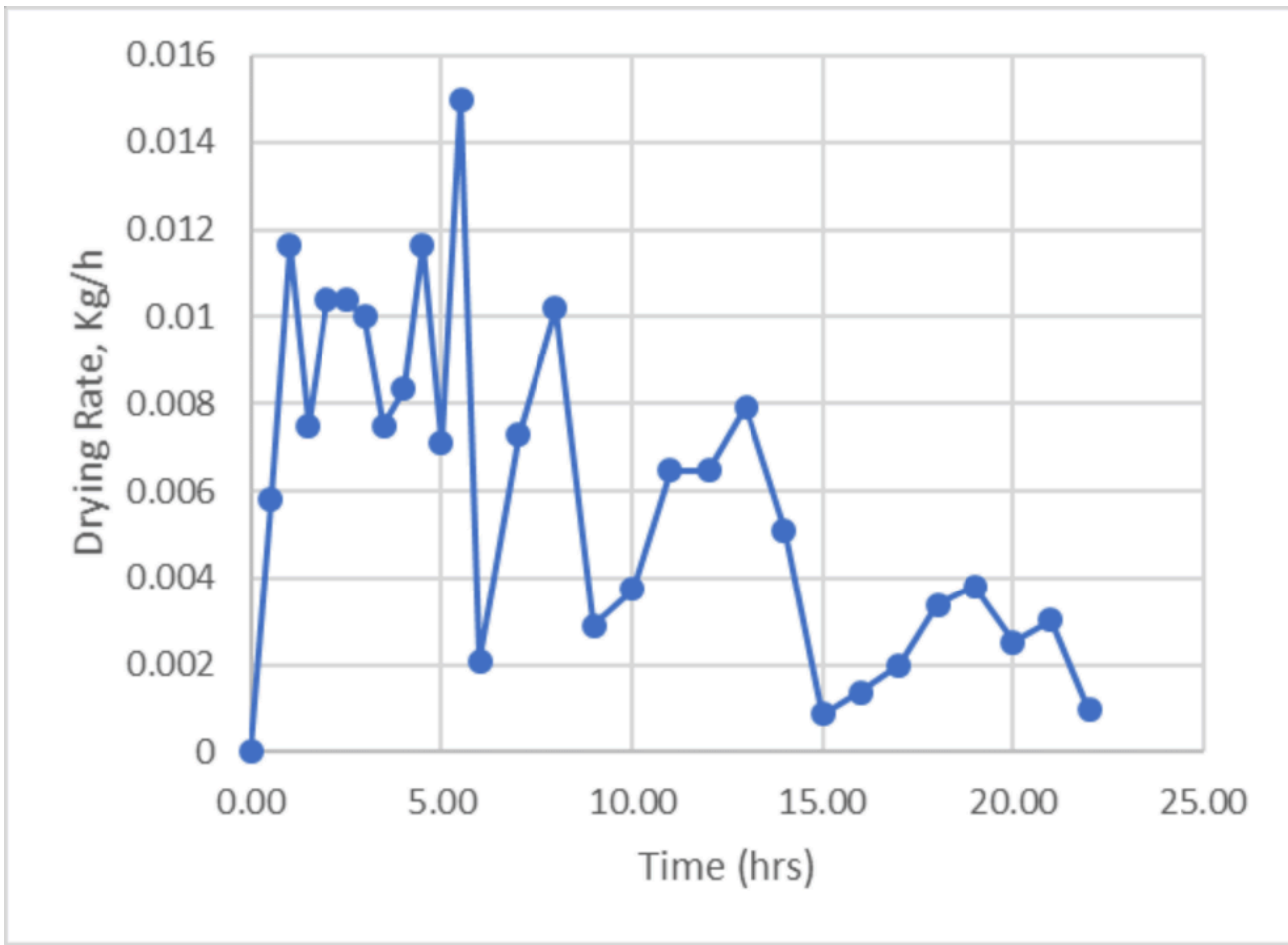


FIGURE 3: Graph of drying rate against drying time

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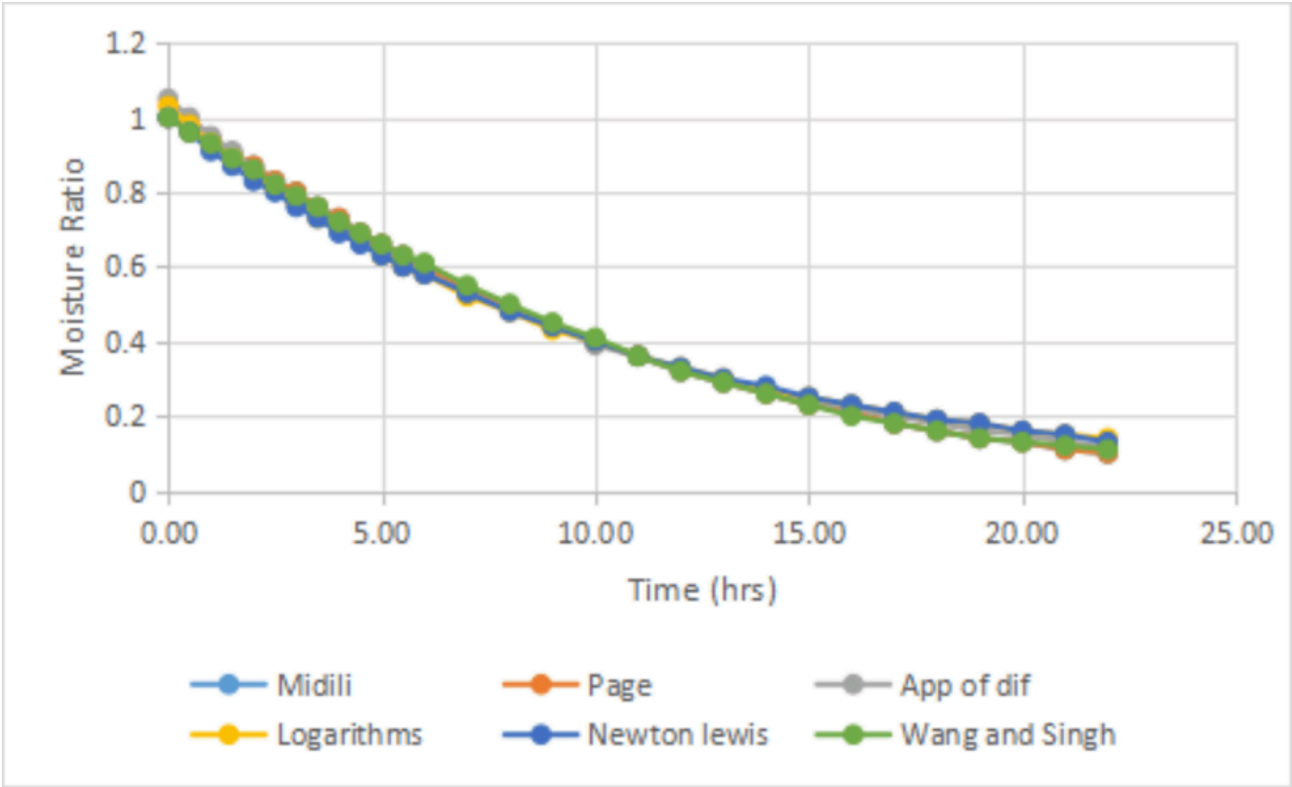


FIGURE 4: Graph of predicted data of all models against time

Models	Parameter (k)	Parameter (n)	Parameter (a)	Parameter (b)	Parameter (c)	RMSE	R ²
Midili et al	0.066	1.139	1.004	0		0.00012	0.999
Page	1.002	1.157				0.00011	0.999
Approximation of diffusion	0.98	0.10	-0.024	1.2		0.00034	0.995
Logarithmic	0.100		1.1		0.028	0.00891	0.992
Newton Lewis	0.10		1.10		0.028	0.00923	0.991
Wang and Singh			-0.75	0.002		0.00063	0.998

TABLE 2: Distribution of mathematical models showing performance for plantain

RMSE, root mean square error

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Revenue	Amount (Naira)
Proceeds from sales of plantain flour	198,500
Total Revenue (TR)	198,500
Variable Cost (VC)	
Cost of plantain bunches	150,000
Transportation	12,000
Labor	5,000
Cost of packaging materials	5,850
Total Variable Costs (TVC)	172,850
Fixed Costs (FC)	
Depreciated cost of PSSD	2,778
Depreciated cost of milling machine	120
Depreciated cost of measuring scale	21
Depreciated cost of sealing machine	19
Depreciated cost of utensils (bowls, knives and slicers)	95
Total Fixed Costs (TFC)	3,033
Total Costs (TC = TVC + TFC)	175,883
Gross Margin (TR-TVC)	25,650
Net Profit (TR-TC)	22,617
Return on Investment (TR/TVC)	1.20

TABLE 3: Result of the return on investment analysis

Note: Currency is in Naira.

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Discussion

Drying behavior of the plantain chips

Figure 3 shows the graph of drying rate versus time, and results indicate that drying occurred predominantly in the falling rate period. This suggests that internal moisture diffusion was the dominant mechanism governing moisture movement during drying. Similar observations have been reported by [20] who investigated the drying patterns of fresh and osmotically pretreated cooking banana and plantain slices. Their report indicated that drying occurred in the falling rate period, emphasizing the role of internal moisture diffusion. Also, according to [21], microwave drying kinetics of Mabonde banana variety was used to describe moisture migration using Fick's diffusion model, with drying taking place largely in the falling rate period.

Plantain has a drying rate of 0.006054073 kg/h at an average temperature of 44.55°C and average relative humidity of 61.8% and it was dried to a moisture content of 12.59% within 22 hours. This finding is consistent with the previous studies [22,23]. For instance, the research by [22] investigated the effect of pretreatments on the drying characteristics of plantain and reported that higher drying temperatures significantly reduced drying time, while thinner slices dried faster than thicker ones. However, unlike those studies that independently varied drying temperature and slice thickness, the present study evaluates drying kinetics and model fitting under the natural operating conditions of Parabolic Shaped Solar Dryer. Therefore, observed differences in drying behavior are attributed to the combined effects of dryer operating conditions rather than isolated effects of individual variables.

Model fitting

Figure 4 shows the graph of moisture ratio against drying time for both experimental and predicted data for all models. Table 2 shows the result for all drying parameters of all the models shown in Table 1 which is the estimation of the model's parameters. Also, the result of the statistical tool (R^2 and RMSE) used to determine the best model for the prediction of the drying kinetics of Plantain using NSPRI PSSD is shown in Table 2. The Page model and Midili et al provided the best fit for the experimental data, with the highest value of R^2 (>0.98) and lowest value of RMSE (<0.05) which tends towards zero for all drying conditions. This result aligns with findings from earlier studies on agricultural produce from other researchers in the literature [24-26].

Therefore, the mathematical equation for Page and Midili et al models for the drying of plantain are as follows:

For Midili et al model

$$MR = 1.004 \exp(-0.066t^{1.139}) \quad (4)$$

For Page model

$$MR = \exp(-1.002t^{1.157}) \quad (5)$$

Economic evaluation of NSPRI PSSD

Table 3 reveals the cost incurred in the processing of plantain flour, the revenue (income) as well as the profit accruable to plantain flour processing using NSPRI PSSD. The result shows that the total revenue (TR) generated was N198,500 while the total cost (TC) was N175,883. The gross margin obtained was N25,650, with a net profit of N22,617 and a return on investment ratio of 1.20, indicating that every N1.00 (One Naira) invested by plantain flour processors using NSPRI PSSD gives a return of N0.20k. This implies that plantain flour processing with NSPRI PSSD is economically viable.

Conclusions

This study confirms that the NSPRI PSSD is a viable and sustainable technology for drying plantain slices under practical operating conditions. The drying process primarily occurred in the falling rate period, indicating that moisture diffusion was the dominant mechanism governing moisture removal.

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Plantain slices of uniform thickness (7 mm) were successfully dried to a final moisture content of 12.59% within 22 hours under natural solar drying conditions. The observed drying behavior reflects the influence of drying temperature within the drying chamber as governed by ambient environmental conditions.

Mathematical modeling of the drying process showed that the Page and Midilli et al. models best represented the drying kinetics, with high accuracy in predicting moisture reduction over time. The high coefficient of determination ($R^2 = 0.999$) and low RMSE (0.00001) values confirm their suitability for describing drying behavior. These models can be applied in future studies for predicting drying characteristics under similar conditions.

This drying performance is comparable to values reported in the literature for solar and other drying methods, indicating its effectiveness as a viable drying option. In addition, the use of solar energy offers potential advantages such as reduced energy cost and minimized contamination risk compared to conventional drying techniques.

Despite the promising results, some limitations remain. The drying behavior observed is based on specific operating conditions, and further studies are needed to investigate the drying kinetics of plantain under varying drying conditions to improve model applicability and prediction accuracy. Future research may also explore hybrid drying technologies that combine solar energy with auxiliary heating to enhance drying performance.

Overall, the findings of this study support the application of NSPRI PSSD for plantain preservation, contributing to improved post-harvest management in tropical regions.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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Disclosures

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