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Numerical Simulation of Newton Model for Solar-Drying Characteristics of Telfairia occidentalis (Pumpkin) and Vernonia amygdalina (Bitter-leaf) using Nigerian Stored Products Research Institute Parabolic Shaped Solar Dryer

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Abstract

Green leafy vegetables (GLVs) are nutrient-rich but highly perishable, making postharvest preservation a major challenge. This study investigated the drying behavior of *Telfairia occidentalis* and *Vernonia amygdalina* in the Parabolic Shaped Solar dryer (PSSD) developed by the Nigerian Stored Products Research Institute. Sliced and unsliced samples were dried under monitored meteorological conditions, and drying rate was experimentally determined. A key novelty of this work is the transformation of the Newton drying model using Taylor's series expansion to enhance the accuracy of numerical prediction. The model's performance was also compared with the Levenberg-Marquardt iteration method. The average drying rates of *Telfairia occidentalis* (sliced and unsliced) dried in the PSSD were 0.0162 ± 0.00025 and 0.0158 ± 0.0004 kg/h; while that of the *Vernonia amygdalina* was 0.0145 ± 0.00006 and 0.0147 ± 0.00006 kg/h, respectively. The model showed excellent fitting performance with R^2 values greater than 0.9, and RMSE values tended toward zero at all conditions. These results demonstrate the potential of the Taylor's series-based numerical transformation to improve thin-layer drying modeling and simulation, and confirm the PSSD as an efficient and hygienic technology for drying GLVs under tropical conditions.

Categories: Food and Pharmaceutical Engineering, Agricultural Machinery and Automation, Bioprocess Engineering
Keywords: drying kinetics, green leafy vegetables, parabolic shaped solar dryer, solar drying, mathematical modeling

Introduction

Green leafy vegetables play a vital role in human nutrition due to their great nutritional and medicinal value. They provide several health benefits to humans when consumed [1]. These vegetables are excellent sources of essential micronutrients such as Vitamins A, C, K and folates as well as calcium, iron, and magnesium [2]. The high vitamins, dietary fiber, and mineral content of green leafy vegetables justify the need for its consumption because they are incredibly helpful in maintaining good health and preventing sickness [3]. In addition, the high dietary fiber content also aid in digestion, and helps maintain a healthy gut, thereby reducing the risk of constipation and other digestive disorder [4]. In order to retain the original constituent of the product and make it shelf-stable, it is recommended that freshly harvested green vegetables should be dried to safe moisture content of 10-12% moisture content (wet basis) [5]. Drying to this level significantly reduces water activity (below 0.6), thereby limiting microbial growth and enzymatic activities responsible for storage [6].

Properly dried leafy vegetables are far less susceptible to spoilage caused by the growth of bacteria, moulds, and insects. This is because the reduced moisture content inhibits the growth and multiplication of bacteria, moulds, and insects. The lower water activity created during drying makes the environment unsuitable for microbial proliferation, while also discouraging enzymatic reaction that lead to deterioration [7]. Additionally, the absence of excess moisture limits insect infestation during storage, thereby preserving the vegetables' nutritional quality, flavor, and shelf life. Drying of green leafy vegetables vary from plant to plant and the effect of drying depends on the initial moisture content of the vegetable [8]. Drying is a simultaneous heat and mass transfer process, which involves the use of thermal energy to reduce the moisture content available in agricultural product [9]. The study of moisture loss with respect to time requires the use of drying models. In drying kinetics, mathematical models are tools used to describe drying process. The most important feature of drying technology is process modeling, simulation for design of drying equipment, and establishment of best possible operating conditions to enhance the efficiency of drying facility [10]. Deriving solutions to model using numerical methods give excellent predicted values and results, and hence, adopting the use of numerical simulations in predicting the rate at which moisture is lost from an agricultural material is imperative [11].

There are several methods of drying that exist. The most economical is the traditional sun drying but it exposes the product to several hazards like insect infestation, rodent and bird attack, contamination, wind dispersal, aesthetic value reduction and all these can pose danger to the product quality and farmers' net profit [12]. As technology advances, solar drying technology emerges, and thus, the need for the development of other drying methods such as the solar drying technology. In addition, renewable energy sources such as solar has been discovered to be clean, environmentally friendly, and exhibit faster drying rate [13]. Apparently, change in moisture per unit time will characterize the drying behavior of green leafy vegetables to be studied since each vegetable is peculiar and will behave uniquely during drying [14].

Nigerian Stored Products Research Institute (NSPRI) has developed an array of solar drying technologies, and notable among them is the Parabolic Shaped Solar Dryer (PSSD). Solar drying technologies, such as the PSSD developed by NSPRI, present a sustainable and hygienic alternative to open-sun drying [15]. However, despite the increasing adoption of solar dryers, limited studies have focused on the modeling of drying kinetics for green leafy vegetables under controlled solar drying conditions. Most existing studies rely on conventional thin-layer models such as Newton, Page, Henderson, and Pabis, without exploring their mathematical transformation for improved accuracy. This gap underscores the need for advanced modeling approaches that can better simulate the drying behavior of moisture-sensitive leafy materials.

It is therefore imperative that the drying technology be evaluated using diverse agricultural crops such as the GLVs. Therefore, the present study addressed this gap by transforming the Newton's model using Taylor's series expansion to enhance numerical prediction of drying behavior. The model's performance was validated using *Telfairia occidentalis* (fluted pumpkin) and *Vernonia amygdalina* (bitter leaf). The result would produce robust and accurate data relating to the drying performance of the PSSD and quality of the dried products which would be available to help in guiding industrialists and nutritionists to provide knowledge on the drying behaviors of the leafy vegetables in order to maximize nutrient retention and possibly increase consumption of the product.

Materials And Methods

Collection of green leafy vegetables

The green leafy vegetables used in this study included *Telfairia occidentalis* (Pumpkin) and *Vernonia amygdalina* (Bitter leaf). *Telfairia occidentalis* was obtained from Alakaso village, Omi-Adio, Ido LGA, Ibadan, Oyo State, and authenticated at the Forestry Research Institute of Nigeria with batch number: 113871, while *Vernonia amygdalina* was harvested from a garden in the Elebu area, Ibadan South West LGA, Ibadan, Oyo State.

Experimental design and procedure

Representative samples were selected according to to the methods reported in the studies by authors [16,17]. Each drying experiment was conducted in triplicate to ensure reliability and reproducibility of the results. For each replicate, samples were randomly selected from a homogenized batch to minimize bias arising from initial moisture variability and leaf size distribution. The leafy vegetables (*Telfaria occidentalis* and *Vernonia amygdalina*) were prepared in two forms, sliced and unsliced, before drying. This approach was adopted to reflect common household and small-scale processing methods, where leaves are often sun-dried either whole or after slicing. The use of both forms was intended to provide a realistic context for the numerical simulation and to allow for possible variations in moisture loss due to surface area differences. However, the main emphasis of this study was on modeling the overall drying behavior using the Newton model rather than on quantifying the physical effects of slicing.

Determination of the initial moisture contents of samples was carried out by placing samples in a laboratory oven at 105°C for about 6-7 h according to the ASABE S352.1 standard [18]. Two hundred grams of the freshly harvested samples were used for each drying experiment (solar drying using NSPRI PSSD (Figure *1*) and conventionally by sun-drying (Figure *2*)). Each experiment was replicated three times according to previous studies [19-21]. Each drying experiment was monitored by weighing the samples every 30 mins for the first 3 h, then every 60 min for the next 3 h, and every 2 h until the end of drying [22,23].

The meteorological parameters that were measured included temperature and relative humidity of the drying chamber and ambient using a Temtop Datalogger [TemLog 20H (Accuracy: T - ±0.5°C; R.H. - ±3%)]. The air velocity of the drying chamber and ambient environment was measured using an air flow meter [Testo 410-1; resolution - 0.1 m/s; accuracy - ±1 m/s]. Solar radiation of the drying chamber and ambient environment was measured using a solarimeter [DT-1307 solarimeter (Resolution - 1 W/m^2; max. - 1999 w/m^2; accuracy - ±10 W/m^2)] according to previous studies [24].

FIGURE 1: Setup of the drying experiment for Telfairia occidentalis and Vernonia amygdalina inside NSPRI PSSD

NSPRI, Nigerian Stored Products Research Institute; PSSD, Parabolic Shaped Solar dryer

FIGURE 2: Setup of the drying experiment for Telfairia occidentalis and Vernonia amygdalina for sun drying

Solar drying characteristics and selection of drying model

The Newton model (sometimes referred to as the Lewis model) was selected as the primary semi-theoretical model for fitting the thin-layer drying data. This model is founded on the analogy with Newton's law of cooling and describes the moisture ratio (MR) as an exponential decay with time, $MR = Exp(-kt)$, where k is the drying constant according to previous studies [25]. The Newton model is widely used as a simple, physically interpretable baseline in thin-layer drying studies because it requires estimation of only one parameter and effectively describes the drying behavior when the falling-rate period predominates and external mass-transfer resistance dominates (thin layers, uniform sample conditions). For this reason, it is commonly reported in reviews and comparative studies of drying models and is often employed as the starting model before testing more complex empirical or multi-term models. Hence, the Newton model, which has been used in literature for thin layer drying of agricultural crops [25,26] as is expressed in Equation (1), was used to describe the drying characteristics of *Telfairia occidentalis* and *Vernonia amygdalina*.

Newton model was solved numerically and transformed using Taylor's series to give excellent predicted values, and the results were compared with an iterative method using the Levenberg-Marquardt in SPSS software.

Numerical solution and transformation of Newton's Model using Taylor's series

Newton's model was transformed using Taylor's series according to [27]. The non-linear model of the form (Newton's model) is illustrated in Equation (1):

$$Y = Exp\left(-kt\right) = \frac{M_t - M_{eq}}{M_i - M_{eq}} = MR \quad (1)$$

Where k is the drying constant in s^{-1}, MR is Moisture Ratio, M_t is the material moisture content at time t (kg water/kg dry matter), M_{eq} is the equilibrium moisture content (kg/kg), t is the drying time(s).

Considering the function

$$Y\left(t\right) = e^{-kt}; 0 \leq t < 24 \quad (2)$$

and the initial condition

$$Y\left(0\right) = 1$$

Expanding Y(t) in a Taylor series about t = 0 gives:

$$y(tn + h) = y(tn) + hy'(tn) + h^2/2!y^n(t_n) + \ldots \quad (3)$$

Where

$$h = \frac{(t_n - t_0)}{n}$$

Equation (4) is referred to as the mesh size.

Substituting the initial condition Y(0) = 1, and the derivative from Equation (1), $Y'(t) = -Ke^{-kt}$, gives the recursive relationship:

$$y_1 = 1 - kh; y_2 = \left(1 - kh\right)^2; y_3 = \left(1 - kh\right)^3; y_n = \left(1 - kh\right)^n \quad (4)$$

where n = 1, 2,3, ..., t; k = 0, 1, 2, 3, ..., t

The expressions in Equation (4) show that, under small time-step increments $(kh \ll 1)$ the exponential decay $e^(-kt)$ can be approximated numerically by successive multiplication of the factor $(1 - kh)$, which provides a simple and stable discretized form suitable for simulation within the Euler framework.

By the explicit Euler method, the time-step *h* that satisfies the numerical stability condition for Equation (2) was determined as $h = 2^{-6}$s.

The drying rates (dr) of the samples were determined using the expression in Equation (5).

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t} \quad (5)$$

Where Δt is change in time and M_t is mass at time t.

Statistical analysis

All experiments were conducted in triplicate, and the results were expressed as mean ± standard deviation (SD). Randomization of samples prior to each drying run was carried out to minimize bias arising from variations in leaf size and initial moisture content. The data were analyzed using descriptive statistics to evaluate consistency and variability among replicates. Differences between treatments were interpreted based on observable trends and percentage variation rather than inferential statistics, since the study focused primarily on modeling and simulation validation. Statistical summaries were generated using

Microsoft Excel 2021 (Microsoft Corp., Redmond, WA, USA).

Results And Discussion

Meteorological data collected during the experimentation

Temperature Within the PSSD and Ambient Environment

An average day temperature of 34.8 ± 11.52°C was recorded in the PSSD, while 28.4 ± 4.87°C was recorded for the ambient environment. The PSSD was able to achieve a 22.3% temperature increase compared to the average reading obtained in the ambient, and similar result were reported by [24]. The temperature distributions in the PSSD relatively followed the pattern of the ambient temperature recorded during the evaluation period as shown in Figure *3a*. This further confirmed that solar radiation is the only source of heat for the dryer as designed, and that heat loss in the system is negligible, and the black body floor in the drying chamber has good capacity to effectively absorb and retain heat for subsequent use during the drying process.

Relative Humidity Within the PSSD and Ambient Environment

The average relative humidity value recorded in the PSSD was 61.40 ± 22.70%, while 80.6 ± 23.86% was obtained in the ambient during the evaluation. There was about 23.7% reduction in the average relative humidity recorded in the dryer compared to the average value obtained in the ambient, similar result were obtained by [24]. Even though some drying sessions were conducted during cloudy and rainy periods characterized by high humidity and low temperature, the dryer was still able to bring the relative humidity in the dryer down by 23.7% because of the higher temperature recorded in the PSSD. This is one of the factors that contributed to the reduction in drying time because the air in the dryer has better potential to pick up moisture from the green leafy vegetables. The distribution pattern of the relative humidity under the two conditions is shown in Figure *3b*.

Air Velocity Within the PSSD and Ambient Environment

The average air velocity recorded in the PSSD was 0.40 ± 0.33 m/s, while 1.0 ± 0.51 m/s was recorded in the ambient. The air velocity recorded in the PSSD is an indication that the inlet vents are functional because about 40% of the air flow rate experienced in the ambient that has no restriction took place in the dryer during the evaluation, similar result were reported by [24]. This would definitely aid moisture removal from product and improve drying efficiency of the dryer. The trend of the air flow pattern is shown in Figure *3c*.

Solar Radiation Within the PSSD and Ambient Environment

The average solar radiation recorded was 115.1 W/m^2 in the PSSD, while 236.5 W/m^2 was recorded in the ambient. The result showed that the solar radiations recorded per time in the PSSD were lower than that recorded in the ambient (51.3%), similar result were obtained by [24]. Despite the lower radiation received in the PSSD, the temperature in the dryer was still higher than what was obtained in the ambient; this is an indication that the dryer has design configuration that meets the requirement of a functional solar dryer. The lower readings recorded in the PSSD was as a result of the screening effect of the covering material aimed at protecting the product from excessive solar radiation that is capable of degrading product qualities [28]. The trends of the solar radiation recorded under the two conditions are illustrated in Figure *3d*.

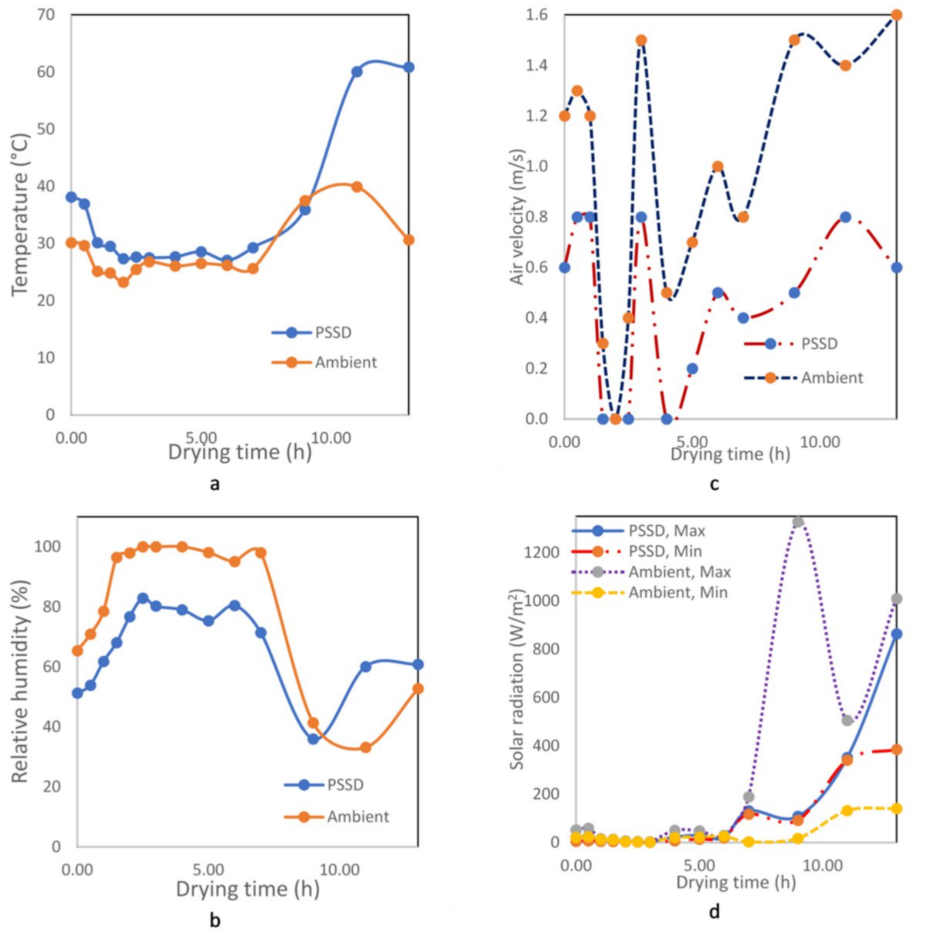

FIGURE 3: (a) Temperature distribution during drying; (b) Relative humidity distribution during drying; (c) Air velocity distribution during drying; (d) Solar radiation distribution during drying

Drying Behavior of Telfairia occidentalis and Vernonia amygdalina

The average drying rates of *Telfairia occidentalis* (sliced and unsliced) dried in the PSSD were 0.0162 ± 0.00025 and 0.0158 ± 0.0004 kg/h, while the sun drying were 0.0138 ± 0.00005 and 0.0140 ± 0.00015 kg/h, respectively. It was observed that there was no difference in the mean values of the drying rate of *Telfairia occidentalis* dried in the PSSD irrespective of the pre-drying treatment applied; likewise, the same result was also obtained in the samples sundried. However, there was a significant difference in the means of the former and latter. Higher drying rates were recorded in the PSSD, where the highest rate in the entire experiment was recorded in the sliced *Telfairia occidentalis*, which is in line with the principle of solar dryers. This result is in conformity with the findings of [29-31]. The average drying rates of *Vernonia amygdalina* (sliced and unsliced) dried in the PSSD were 0.0145 ± 0.00006 and 0.0147 ± 0.00006 kg/h, while those of the sun drying were 0.0126 ± 0.00000 and 0.0122 ± 0.00005 kg/h, respectively. It was observed that all the drying rates of *Vernonia amygdalina* were significantly different from one another; however, higher drying rates were recorded in the PSSD. In all, *Telfairia occidentalis* recorded higher drying rates regardless of the treatment. This may be due to its physiological structure. The drying rate versus time curve of the two products are shown in Figure *4*.

The results indicate that the PSSD achieved consistently higher drying rates compared to open sun drying for both *Telfairia occidentalis* and *Vernonia amygdalina*. Higher drying rates are advantageous in industrial applications because they reduce overall processing time, increase throughput, and lower the risk of microbial contamination due to shorter exposure to ambient conditions. For leafy vegetables, rapid moisture removal is particularly important for minimizing enzymatic browning and slowing biochemical deterioration. Faster drying also reduces respiration losses, thereby helping to retain chlorophyll, carotenoids, and heat-labile micronutrients. Conversely, lower drying rates observed under sun drying conditions prolong exposure to fluctuating environmental humidity and temperature, which may increase the likelihood of mold growth and nutrient degradation. The slightly higher drying rate of *Telfairia occidentalis* compared with *Vernonia amygdalina* may be attributed to differences in leaf morphology and porosity which influence moisture diffusion pathways during drying. These findings suggest that solar dryers can offer performance benefits relevant to small and medium-scale processing industries where product quality, safety, and energy efficiency are critical.

Overall, the statistical differences observed support the suitability of the PSSD as a more efficient and quality-preserving drying method for leafy vegetables in decentralized processing environments.

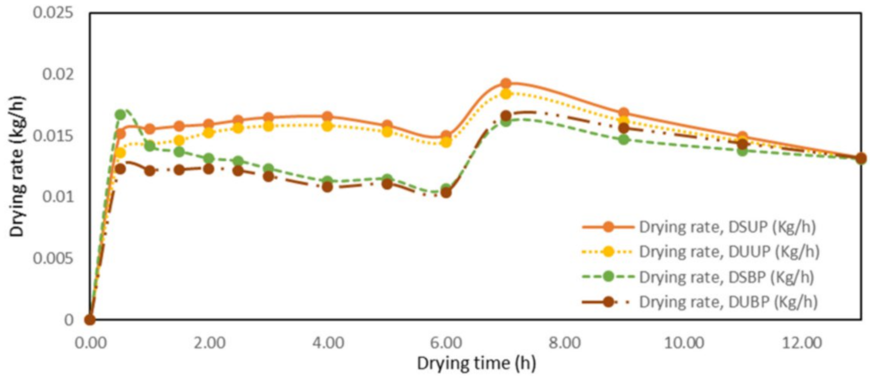

FIGURE 4: Drying rate versus time curve of Telfairia occidentalis and Vernonia amygdalina

The plotted drying rate values represent the mean of triplicate measurements, while the corresponding standard deviations are reported in the text. Error bars were not included on the plots in order to maintain clarity and avoid visual clutter, given the minimal variability observed across replicates.

Effect of Taylor's Series Transformation and Euler Discretization on Model Prediction

The transformation of Newton's model using Taylor's series and its subsequent discretization by the Euler method provided a simple yet reliable approach for predicting the variation of moisture ratio with time under solar drying conditions. The polynomial expansion $Y_n = (1 - kh)^n$ closely approximated the exponential decay behavior of the Newton model for sufficiently small step size $kh \ll 1$, confirming the numerical stability of the selected mesh size $h = 2^{-6}$ s. Simulated moisture-ratio curves followed the expected exponential trend and showed strong agreement with the experimental drying data for *Telfaria occidentalis* and *Vernonia amygdalina*, as indicated by high coefficients of determination (R^2) and low root mean square error (RMSE) values. This demonstrates that the Taylor-based transformation and Euler integration provided an accurate and computationally efficient framework for implementing the Newton model in solar drying simulations

Model Fitting of Telfairia occidentalis and Vernonia amygdalina for Newton's Models

The experimental drying data for *Telfairia occidentalis* and *Vernonia amygdalina* were evaluated using Newton's thin-layer drying model according to [32]. The model was selected as a result of its simplicity and widespread application in predicting moisture ratio in relation with drying time [33]. Across all drying conditions, the moisture ratio consistently declined as the drying time increased as shown in Figures *5*. 6, 7, and 8, and this is in line with results gotten by [34,35]. Evidently, as shown in Figures *5*-*8*, Newton's model effectively captured the exponential moisture decline during thin-layer drying of the leafy vegetables as reported by [36,37]. Furthermore, the drying process occurred mainly during the falling rate period, with no constant rate phase observed under any of the conditions. This is in agreement with result gotten by [38,39]. In addition, the statistical indicators revealed that, under all conditions the R^2 values exceeded 0.9 while the RMSE values were close to zero, confirming the model's good fit according to [40] as shown in Table *1*. This indicates that the Newton's model, when fitted using the non-linear regression approach showed excellent performance, aligning with findings previously reported by other researchers [41]. These observations are consistent with literature reports that the Newton model performs adequately in the falling-rate period, where moisture movement is largely governed by diffusion.

The difference observed in drying performance can be attributed to the combined influence of heat transfer and moisture diffusion mechanisms occurring within the product matrix. The higher drying rates recorded in the PSSD demonstrate the effect of controlled airflow and elevated temperatures, which enhance moisture diffusion from internal tissues to the product surface. This effect becomes more pronounced in sliced samples due to increased surface area and reduced diffusion pathways. Conversely, the lower drying rates under open sun conditions reflect fluctuating ambient humidity, reduced convective heat transfer, and intermittent solar intensity, all of which restrict moisture evaporative potential. This mechanistic imply that the PSSD promote more uniform gradients, resulting in shorter drying times and reduced susceptibility to microbial spoilage. Furthermore, the observed variation between the two leafy vegetables suggests that inherent leaf anatomical properties, such as thickness, stomatal distribution, and cellular water-binding capacity, play a role in determining the drying kinetics. Theses interpretations highlight the importance of product morphology and environmental control when designing drying protocols.

Sample ID	Estimated parameters and statistical criteria	Newton
DSUP	n	0.152
	RMSE	0.0891
	R^2	0.9586
DUUP	n	0.144
	RMSE	0.0832
	R^2	0.9643
DSBP	n	0.119
	RMSE	0.1003
	R^2	0.9279
DUBP	n	0.120
	RMSE	0.1140
	R^2	0.9200

TABLE 1: Estimated parameters and statistical criteria for solar drying of Telfairia occidentalis and Vernonia amygdalina in the PSSD

DSUP: Dried sliced ugu (Telfairia occidentalis); DUUP: Dried unsliced ugu (Telfairia occidentalis); DSBP: Dried sliced bitter leaf (Vernonia amygdalina); and DUBP: Dried unsliced bitter leaf (Vernonia amygdalina). PSSD, Parabolic Shaped Solar dryer

Limitation and future work

This study was limited to a single environmental setting and crop type, restricting broader applicability. Future studies should examine performance across different climates and seasons, evaluate additional agricultural products, and compare drying kinetics using more advanced thin-layer models. Incorporating sensor-based monitoring, evaluating dryer durability, and conducting economic analysis will further strengthen practical relevance.

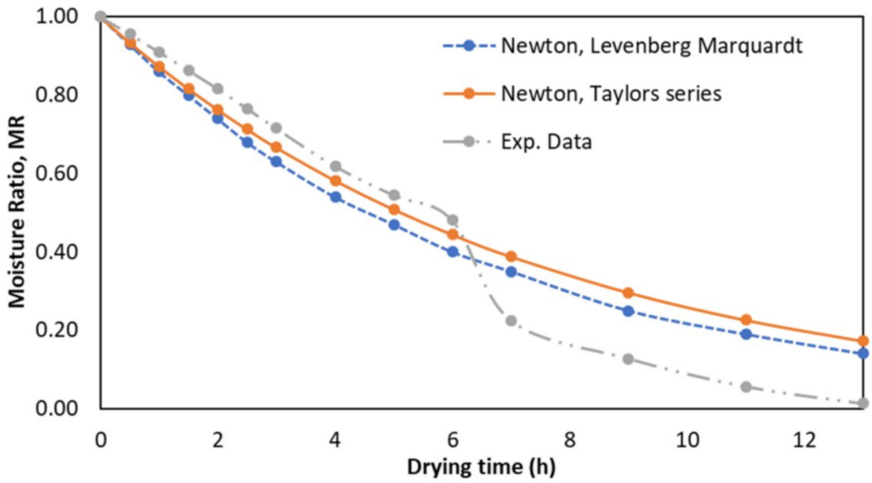

FIGURE 5: Drying model fittings for sliced Telfairia occidentalis

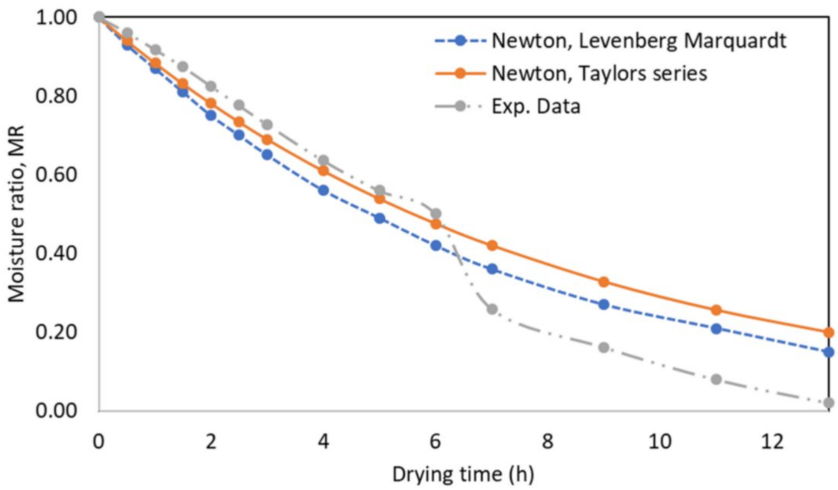

FIGURE 6: Drying model fittings for unsliced Telfairia occidentalis

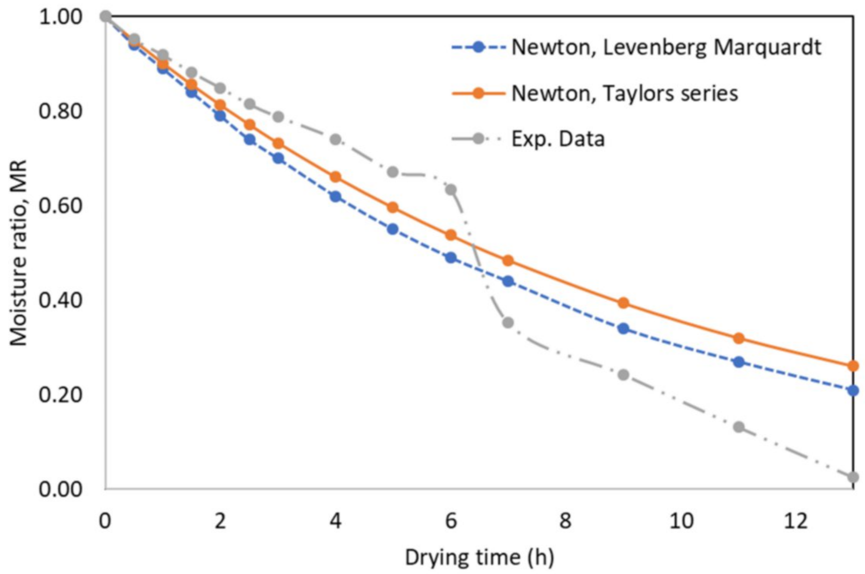

FIGURE 7: Drying model fittings for sliced Vernonia amygdalina

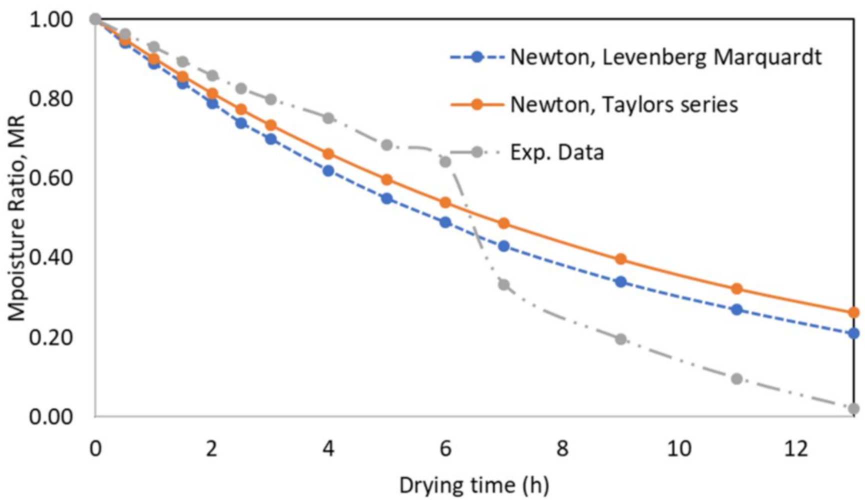

FIGURE 8: Drying model fittings for unsliced Vernonia amygdalina

Conclusions

The study demonstrated that the NSPRI PSSD effectively improved drying conditions for leafy vegetables by increasing drying chamber temperature and reducing relative humidity compared to ambient conditions. The drying of *Telfairia occidentalis* and *Vernonia amygdalina* occurred predominantly in the falling-rate period, indicating moisture migration governed by internal diffusion. Higher drying rates recorded in the PSSD relative to open sun drying confirm its efficiency for reducing moisture content and shortening drying time.

The Newton thin-layer drying model, transformed using the Taylor's series numerical approach, provided good agreement with the experimental data, demonstrating the potential of numerical methods for predicting solar drying behavior of leafy vegetables. This modeling approach supports better dryer design optimization and process control.

The findings highlight the applicability of the PSSD for smallholder farmers and rural processors, where improved drying technologies can contribute to reduced postharvest losses, enhanced product quality, and improved food security. For industrial adoption, the system offers a low energy, environmentally friendly alternative for large-scale dehydration of perishable leafy crops.

Future work should focus on integrating nutritional quality assessments, exploring performance under diverse climatic conditions, scaling design parameters for industrial capacities, and comparing model performance with more advanced thin-layer models such as Page and Midilli.

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

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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