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Research Article

Kinetics and Mathematical Modeling of the Drying Process of Sword Beans

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Abstract

The thin-layer drying performance of four varieties of Sword bean seeds was investigated using a laboratory drying oven at temperatures between 30°C and 40°C to identify the best mathematical model for describing their drying kinetics. The Sword bean seeds were dried over 68.04 to 171.96 minutes, with weights measured until reaching a constant value. Drying data, including moisture removal and drying rates, were analyzed as moisture ratios and fitted to six drying mathematical models. The Midilli model emerged as the most accurate for the Sword bean variety TCG-2, achieving a high correlation coefficient (R^2 = 0.9912) and a low root mean square error (RMSE = 0.0122). Effective diffusion coefficients for the four varieties ranged from 3.09×10^{-10} to 7.23×10^{-10} m^2/s. respectively This study underscores the Midilli model's suitability for predicting the drying behavior of Sword bean varieties under the tested conditions, offering a framework for optimizing drying processes in post-harvest handling. The findings provide practical insights for scaling up drying processes in agro-industrial applications, ensuring consistency and quality in large-scale production. This advancement could enhance the efficiency and sustainability of processing Sword beans and similar legumes, benefiting agro-processing industries and contributing to improved post-harvest management practices.

Keywords

Sword Bean Seeds, Mathematical Model, Drying Kinetics, Diffusion Coefficient

1. Introduction

Sword Bean (*Canvalia gladiate L.*) is an underutilized vegetable crop planted through seeds, belongs to the Fabaceae family and widely found in South and Southeast Asia. Sword bean is self-pollinated nonphoto sensitive crop and climbing in nature. Sword bean seeds are white in colour and rich in protein. Sword bean seeds are elliptical in shape with 3cm long and reddish in color. Sword bean is a warm season crop [17, 14] impervious to drought, pest and disease [26]. Sword bean needed sufficient light and temperature for its growth and has good resilience in all type of soil [19]. Sword beans contain low fat and high protein content which are used in traditional medicine [8]. Sword beans typically take 150–180 days after planting to produce mature seeds. Pods are green, firm, and of the desired size.

Seeds inside the pods are immature and tender, making them suitable for consumption as a vegetable. The pods are dry, turning brown or yellow, and have hardened.

Seeds inside the pods are fully developed, dry, and hard. After harvest, the seeds should be sun-dried further to reduce moisture content and improve storability The seeds of sword

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bean have nutritional, medicinal and antivenom properties [12]. Sword bean is a good source of antioxidant phenolics and is used for treating against coughing, lower soring and pain around kidneys [18]. This research uniquely contributes to science by expanding the understanding of drying kinetics, improving modeling techniques, and advancing sustainability. It benefits industry by optimizing post-harvest processing, enabling marketability, and supporting innovative uses of Sword beans, fostering economic and environmental advancements.

Drying is a process whereby moisture is being removal due to simultaneous heat and mass transfer [4, 13]. Mathematical modeling of drying is good for optimization of operating parameters and performance enhancements of the drying systems [1, 7]. Drying is preservation method used for agricultural products worldwide [16, 27]. Drying kinetics and mathematical modeling enhance modeling and optimization of process as well as sizing and determination of commercial application of the drying system [21, 22, 6, 32, 33]. This study aimed to evaluate drying kinetics and apply mathematical modeling to describe the drying process of four varieties of sword beans.

2. Materials and Methods

Sword beans varieties (TCG-1, TCG-2, TCG-3 TCG-4) were collected from International Institute of Tropical Agriculture [IITA] Ibadan, Oyo State, Nigeria. Sword beans were cleaned manually to remove all foreign matter such as dust, dirt, stones, chaff as well as immature or broken seeds and kept in clean nylon and labeled.

2.1. Drying Process

Drying experiments was conducted in laboratory oven by following the method of Priyadarshini *et al.,* (2013). Aluminum dish was weighed and 5 g of varieties of sword bean were put in the aluminum dish, weighed again and then placed inside oven under the time range (68.04-171.96 min) and temperatures ranges at (30 – 40ºC). emperature Uniformity of the laboratory oven used is ±1°C at 105°C The Weighing Range **is** 0.1 mg to 220 g (typical), Readability is 0.0001 g (1 mg), Repeatability is ±0.1 mg and Linearity is ±0.2 High temperatures can cause cracking, splitting, or distortion of the bean structure due to rapid moisture evaporation.mg. The dish was removed from oven at set time, allowed to cool in desiccator, weighed to determine amount of water removed. Each of dry products was stored in desiccators. Experiments were repeated thrice, and data obtained were used to calculate drying rate, moisture content and moisture ratio. Average of moisture ratio (MR) was used to draw drying curve.

The moisture removal of the samples was calculated by this equation.

$$MR = \frac{M_i - M_d}{M_i} \times 100\% \quad (1)$$

M_i is mass of sample before drying. M_d is mass of sample after drying.

Drying rate was calculated by equation 2

$$DR = \frac{M_i - M_d}{t} \quad (2)$$

M_i is referred to mass of sample before drying. M_d is mass of sample after drying, t is drying time and DR is the drying rate and its unit is kg/m^{2}s.

2.2. Mathematical Modeling

Moisture ratio [MR] and drying rate during experiments were calculated using these equations

$$Drying\ \ rate\ \ (dr); MR = \frac{M_t - M_\infty}{M_o - M_\infty} \quad (3)$$

$$\boldsymbol{RD}\ \frac{M_{t-dt} - M_t}{dt} \quad (4)$$

Where MR, Mo, M∞, Mt and M_{t+dt} are referred to moisture ratio, initial moisture content at t and moisture content at $_{t+dt}$ kg moisture/ kg dry matter respectively, t is the drying time [min]. Drying curve was fitted with Midilli, Page, Wang and sSngh, Newton, Logarithmic, Henserson and Pabis models. Analysis was performed using the Matlab software. Non-linear regression used to assess goodness of fit of six models are coefficient of determination [R^2] and root mean square error. Highest value of R^2 and lowest value of root mean square error analysis [RMSE] indicate best fitness of Model. [31]. These parameters were calculated as follows;

$$R^2 = 1 - Residualsumofsquarescorrectedtotalsquares \quad (5)$$

$$RMSE = \{1/N\sum(MRexpi - MRpre,)^2 \quad (6)$$

Where Mexp, $_I$ is experimentally observed moisture ratio, MRpre, $_I$ is ith predicted moisture ratio and N is the number constants.

2.3. Effective Moisture Diffusivity

Effective moisture diffusivity (Deff) was calculated using Fick's second equation of diffusion considering constant moisture diffusivity, infinite slab geometry and a uniform initial moisture distribution [2, 5].

$$MR = \frac{s}{r^2} \exp\left(\frac{r^2 D_{eff}}{4L^2} t\right) \quad (7)$$

MR is moisture ratio, D (m^{2}s^{-1}) is effective moisture diffusivity, L (m) is sample thickness and t is drying time (s). Equation 7 involving series of exponents can be simplified to Equation 8.

$$lnMR = \frac{\pi^2 D_{eff}}{4L^2} t + \frac{lnS}{r^2}) \quad (8)$$

Effective diffusivity (Deff) at each temperature was obtained from slope of plot of ln (MR) against time for corresponding temperature data.

3. Results and Discussion

The study on the thin-layer drying performance of four varieties of Sword bean seeds, enacted at temperatures between 30 °C and 40 °C, reveals substantial findings regarding the drying kinetics of these seeds. The drying times, studied ranging from 68.04 to 171.96 minutes, indicate that temperature plays a fundamental role in moisture removal. This integrates with existing literature, which emphasizes that higher temperatures generally lead to faster drying rates due to increased evaporation of moisture [30].

In this study, six different drying models were used to investigate the drying kinetics. The Midilli model came forth as the most suitable model for the TCG-2 variety, achieving a high correlation coefficient ($R^2 = 0.9912$) and a low root mean square error (RMSE = 0.0122). The operation of the Midilli model is in consensus with previous studies on various legumes and grains, which often find that the Midilli model effectively describes drying behavior due to its ability to account for the falling rate period of drying [29].

For example, in studies involving drying kinetics of chickpeas, coffee and lentils, similar models have been reported to provide correct representations of moisture removal dynamics [29]. The high R^2 value shows that the model's predictions are closely aligned with the observed data, affirming its applicability in the context of Sword beans.

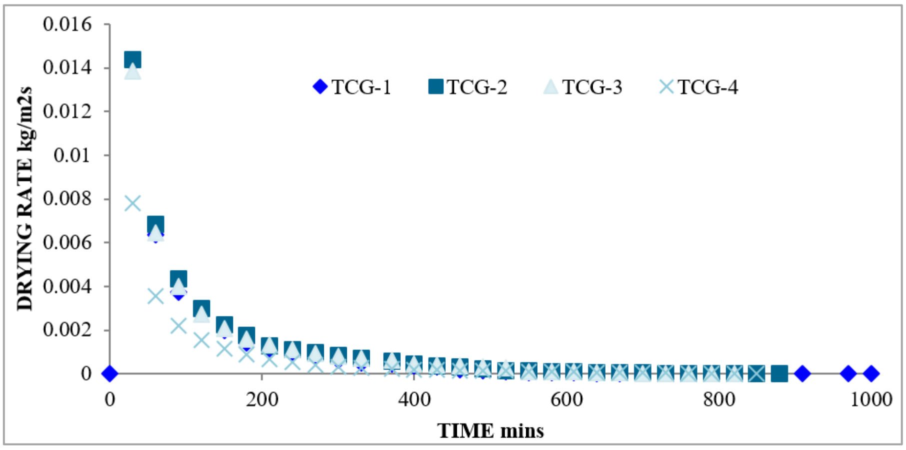


Figure 1. *Drying rate curve of Sword beans.*

3.1. Drying Rate Curve of Varieties of Sword Beans

Drying curve of sword bean seeds was shown in Figure 1. Drying rate decreases with respect to drying time parameter increases. Increase in drying rate was due to increased heat transfer potential between surrounding airs of seeds. Figure 1 showed drying rate decreases during drying process. Several other agricultural products also exhibited this behavior [24, 25, 9, 15, 16, 29].

Drying experiment occurred in falling rate period. Material surface is not imbued with water and drying rate is controlled by diffusion of moisture from inside of the seeds to the surface in falling rate period. Similar results have been demonstrated for onion slices, green beans, potato and peas, okra and carrot [10]. Researchers have suggested that when developing thin layer drying models, equilibrium moisture content of food is postulated zero [9-11, 20, 28].

The equilibrium moisture content (EMC) is calculated as the weight of water in the sample at equilibrium divided by the dry weight of the sample, multiplied by 100. Time required to reach equilibrium moisture content was attenuated by increase in drying time. TCG-1 reached equilibrium moisture content when the drying time was 940 min; at drying time of 880 min, TCG-2 reached its equilibrium moisture content. TCG-3 had its equilibrium moisture content at drying time of 820 min, TCG-4 reached equilibrium moisture content at 850 min.

As drying time increased, values of moisture content rapidly decreased. Drying curve featured falling rate period, which is in good agreement with characteristics of most agricultural products [23, 17, 2, 3]. Reason for higher moisture removal in first falling rate was because moisture percentage was higher in the samples for drying at the initial stage [3].

3.2. Modeling

Moisture ratio as a function of drying time curves were drawn in MATLAB software for four varieties of Sword beans at temperatures ranges of 30 – 40°C. Goodness of fit for a model was selected based on highest value of coefficient determination (R^2) and lowest values of RMSE. Table 1 present drying models coefficients and statistical analysis results. Result illustrated that, Midilli model showed perfect correlation with experimental drying data with R^2 of 0.9912 and RMSE 0.0122 for TCG-2.

The lowest R^2 and lowest RMSE, which was 0.9390 and 0.0204, were found in Newton model for TCG-3. Moisture ratio as function of drying time curves were drawn by Matlab by using six models for each of the varieties of Sword beans. Figure 2 showed results of performance of models simulations and that of experimental data. It could be seen that modeled moisture ratio values for six mathematical models that were used for each of varieties of Sword beans fit exactly with the experimental data for all drying time examined.

Table 1. *Statistical analysis of Mathematical model of drying for four varieties of Sword beans.*

Model	**TCG-1**		**TCG-2**		**TCG-3**		**TCG-4**	
	R^2	**RMSE**	**R^2**	**RMSE**	**R^2**	**RMSE**	**R^2**	**RMSE**
Midili	0.9887	0.0334	0.9912	0.0122	0.9840	0.0427	0.9909	0.0289
Logarithmic	0.9802	0.0436	0.9736	0.0549	0.9693	0.0584	0.9911	0.0283
Henderson and Pabis	0.9722	0.0511	0.9576	0.0688	0.9500	0.0736	0.9840	0.0376
Newton	0.9656	0.0561	0.9412	0.0801	0.9390	0.0204	0.9816	0.0398
Page	0.9872	0.0347	0.9895	0.0342	0.9791	0.0476	0.9791	0.0476
Wang and Singh	0.9777	0.0458	0.9845	0.0416	0.9835	0.0424	0.9794	0.0426

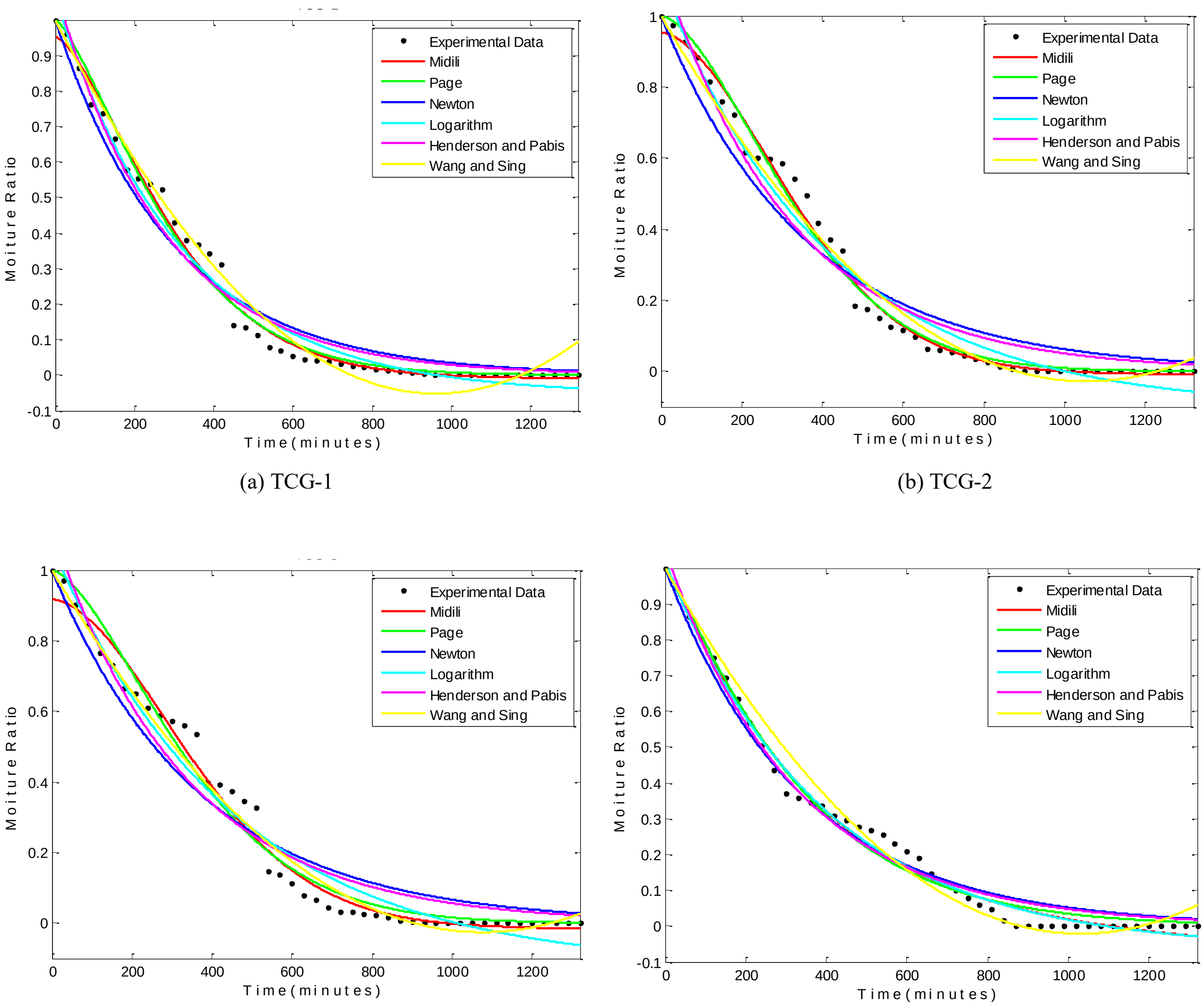
3.3. Diffusion Coefficient

Drying experimental data were also used to determine effective moisture diffusivities of four varieties of sword beans during drying in laboratory oven following method of slope. Effective moisture diffusivity (D_{eff}) demonstrated how moisture is being permeated from the seeds. Values of Deff increased with the increase of drying time. Higher drying time caused greater values of effective moisture diffusivity in seed samples used. D_{eff} values of varieties of Sword bean calculated in this study were in the range of 3.09 x10^{-10}, 6.8 x 10^{-10}, 6.84 x 10^{-10} and7.23 x 10 $^{-10}$respectively. LnDeff as a function of reciprocal of absolute temperature is plotted in Figure 3. Slope of the line is (-Ea/R) and intercept equals ln (D0 TCG1 (3.09×10^{-10} m²/s) is the smallest diffusion coefficient among the samples, showing the slowest moisture diffusion. This could be due to structural or compositional factors such as lower porosity, higher density, or stronger moisture-binding forces.

TCG2 (6.80×10^{-10} m²/s) has a significantly higher diffusion coefficient than TCG1, TCG2 shows about a 2.2-fold increase in the rate of moisture movement. This suggests that TCG2 may have structural or compositional properties favoring easier moisture migration, such as higher porosity or a more open microstructure. TCG3's diffusion coefficient is very close to TCG2, with only a marginal difference (0.04×10^{-10} m²/s). This similarity suggests that TCG2 and TCG3 likely share comparable physical and chemical characteristics affecting moisture transport. TCG4 (7.23×10^{-10} m²/s) has the highest diffusion coefficient, indicating the most efficient moisture migration among the samples. Its diffusion coefficient is about 2.3 times that of TCG1, suggesting significantly less resistance to moisture movement, which is due to structural factors like higher porosity, better connectivity of microchannels, or weaker moisture-binding forces.

4. Conclusion

All the models used in this research work effectively captured the drying kinetics of Sword beans at temperatures ranging from 30°C to 40 °C. Among the mathematical models, the Midilli model stood out as the most accurate showing superior fit parameters with a correlation coefficient (R^2) of 0.9912 and a root mean square error (RMSE) of 0.0122. The model could be used to predict drying times and moisture content at various temperatures within the studied range.



(a) TCG-1 (b) TCG-2

(c) TCG-3 (d) TCG-4

Figure 2. *Comparison between Experimental and Simulation results of six Mathematical model of varieties of Sword beans.*

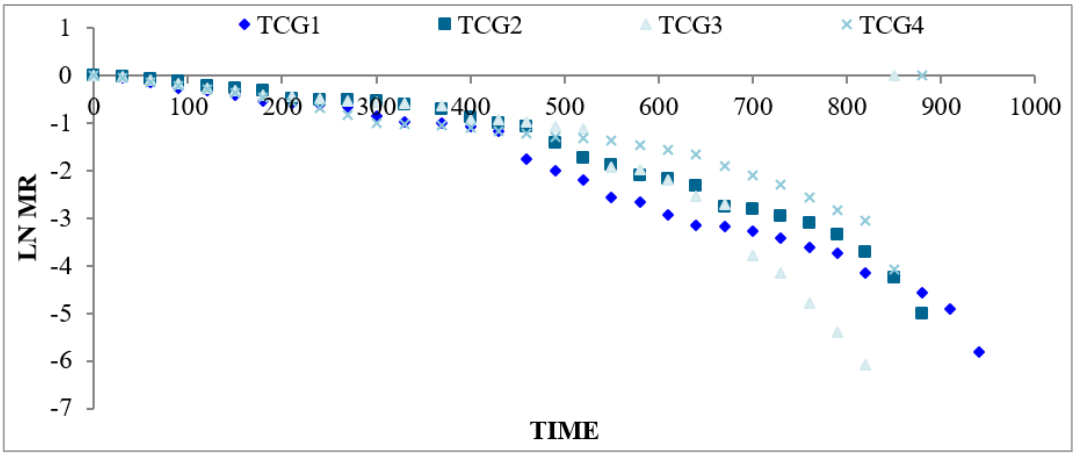


Figure 3. *Linear relationship between Ln (MR) and drying time of four varieties of Sword beans.*

Midilli model could be used to identify the ideal temperature and drying time combination that minimizes energy use while achieving desired moisture content. Leveraging the Midilli model to optimize the design and operation of drying equipment. Investigate the applicability of the Midilli model to other legumes or crops with similar drying behaviors. The limitations of this research work include Complexity of Drying Mechanisms, Experimental Limitations and Limitations of Empirical Models In the future research these limitations can be overcome by using advanced modeling techniques such as multi-physics simulations or hybrid models combining empirical and theoretical approaches to better represent complex interactions, Calibrating and validating equipment regularly, use standardized procedures, and perform multiple replicates to minimize experimental errors and Complementing empirical models with mechanistic models that account for physical and thermodynamic principles to enhance prediction accuracy.

Author Contributions

Esther Awotona is the sole author. The author read and approved the final manuscript.

Data Availability Statement

The data supporting the outcome of this research work has been reported in this manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

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Biography

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Research Field

Esther Awotona: Dehydration of Agricultural produce, Hydration of Agricultural produce, Wastewater treatment, Coagulation-flocculation process, Mathematical Modelling and Separation Process