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Heat Pump Drying of Nutmeg Pericarp: Engineering Properties, Drying Kinetics, and Haghi-Angiz-II Modelling for Process Optimisation

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ABSTRACT

This study investigates the engineering properties of nutmeg pericarp and develops a mathematical model to describe its drying behavior in a heat pump dryer. Nutmeg pericarp, an underutilized part of the nutmeg fruit, is a rich source of phytochemicals but is highly perishable, necessitating immediate postharvest drying for further processing. Drying experiments were conducted at a controlled temperature of 55°C and a relative humidity of 37%. Regression modeling was used to analyze the drying kinetics, utilizing MATLAB R2020a and R Studio software. Various statistical metrics, including the coefficient of determination (R^2), adjusted R^2, and root mean square error (RMSE), were evaluated to determine the predictive accuracy of different thin-layer drying models. Among the models assessed, the Haghi and Angiz-II model best fit the experimental data, achieving the highest R^2 value of 0.999. A scatter plot comparing the experimental and predicted moisture ratios further confirmed the reliability of this model. The effective moisture diffusivity ranged from 2.1×10^{-8} to 9.08×10^{-8} m²/s. Additionally, the quality assessment indicates that heat pump drying positively influences the key quality attributes of nutmeg pericarp.

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1 Introduction

Nutmeg (*Myristica fragrans* Houtt.) is a single-seeded fleshy drupe from an evergreen tree native to the Banda Islands in the Moluccas, Indonesia (Van Gils and Cox 1994). The fruit consists of an outer fleshy pericarp, an inner kernel (nutmeg), and mace, the dried red aril encasing the kernel. The pericarp naturally splits open upon maturation, separating the seed and mace (Wallis 1985; Periasamy et al. 2016). The pericarp accounts for approximately 80-85% of the total fruit weight. Meanwhile, the nutmeg pericarp has limited uses in food products such as pickles, wines, jams, and jellies, which are commercial trades that predominantly focus on seed and aril. As a result, the pericarp is often considered agricultural waste with low economic value. However, it contains diverse, active phytochemicals, including monoterpene hydrocarbons, monoterpene acids, flavonoids, alkaloids, tannins, and aromatic ethers (Suwarda et al. 2021). Due to the perishable nature of nutmeg pericarp, immediate postharvest handling is essential to prevent spoilage and maintain quality.

Drying is a commonly used postharvest technique aimed at extending the shelf life of nutmeg pericarp by reducing biochemical, chemical, and microbiological degradation. Various drying technologies have been developed to enhance product quality and improve energy efficiency. Among these, heat pump drying is an advanced method characterized by lower energy consumption and superior retention of quality attributes. This system extracts heat from ambient air to warm the drying air (Tunckal and Doymaz 2020). It operates on a refrigeration principle, cooling and dehumidifying the air stream, condensing moisture, recovering latent heat, and recirculating the air. This approach is particularly advantageous for drying heat-sensitive materials, as it maintains low relative humidity and allows for precise control over drying conditions, thereby preserving the nutritional and sensory qualities of the final product (Patel and Kar 2012).

Extensive research has shown the effectiveness of heat pump drying for various agricultural products, demonstrating its ability to operate at lower temperatures and humidity levels while improving energy efficiency compared to conventional drying methods. However, studies focusing on nutmeg pericarp are limited, primarily due to its categorization as agricultural waste in many regions. Given its significant potential in various industries, immediate postharvest drying of nutmeg pericarp is crucial for minimizing losses. Consequently, using a heat pump drying system, the present study investigates nutmeg pericarp's engineering properties and drying characteristics. Empirical and theoretical mathematical models have also been developed and validated to characterize its drying kinetics. The findings of this research aim to optimize the heat pump drying conditions and predict the quality attributes of the final product, thereby facilitating its potential commercial utilization.

2 Materials and Methods

2.1 Sample Preparation

Fresh nutmeg pericarp samples were obtained from a local Tavanur, Malappuram, Kerala, India farmer. The engineering properties of the mature pericarp were evaluated to understand its behavior during handling and subsequent processing. The fruit was then sliced into uniform thicknesses of 5.4 ± 0.8 mm to facilitate the drying experiments.

2.2 Engineering properties of nutmeg pericarp

2.2.1Shape and size

The shape and size of the nutmeg pericarp are characterized by sphericity, which describes how the material's shape relates to a sphere of equal volume. It is calculated using the following formula (Sahay and Singh 2009):

$$\text{Sphericity} = \frac{(\text{lbt})^{1/3}}{\text{l}} \tag{1}$$

Where l, b, and t are the nutmeg pericarp's length, width, and thickness, respectively.

2.2.2 Bulk density, True density and Porosity

The density of samples is classified into two categories: bulk density (ρ_B) and true density. Bulk density is the ratio of the sample's weight to its bulk volume. For irregular agricultural products, such as nutmeg, bulk volume is measured using the platform scale method (Sahay and Singh 2009; Murakonda et al. 2022). It is calculated as follows:

$$\text{Bulk density}, \rho_B = \frac{\text{Weight of sample, kg}}{\text{Volume of sample, m}^3} \tag{2}$$

The volume is determined by:

$$\text{Volume, m}^3 = \frac{\text{Weight of displaced water, kg}}{\text{Weight density of water, kg/m}^3} \tag{3}$$

The true density (ρ_T) of nutmeg pericarp is the ratio of the sample's weight to its true volume, excluding pore spaces. It is determined using the toluene displacement method (Kumar et al. 2022):

$$\text{True density}, \rho_T = \frac{\text{Weight of sample, kg}}{\text{True volume, m}^3} \tag{4}$$

The porosity of nutmeg pericarp is the amount of pore space present in the pericarp, expressed as follows (Kumar et al. 2022):

$$\text{Porosity} = \frac{\text{True density} - \text{Bulk density}}{\text{True density}} \tag{5}$$

2.3 Nutmeg pericarp drying analysis

The drying experiment was carried out using a heat pump dryer. 100 g of uniformly sliced samples were processed at a temperature of 55°C and a relative humidity of 37% for 6 hours. After drying, the samples were stored in polyethylene packaging in a dark environment for further analysis.

2.3.1 Moisture content

Moisture content was measured on a wet basis using an infrared moisture meter (SHI-AM Technologies, Gujarat, India).

2.3.2 Colour analysis

Color parameters (L*, a*, and b*) were measured using a Lovibond tintometer. The L* value indicates lightness on a scale from 0 to 100, the a* value ranges from green (-) to red (+), and the b* value ranges from blue (-) to yellow (+). For fresh samples, the tintometer was placed directly on the cut surface of the pericarp. For dried samples, thin slices were made and placed in a cuvette for measurement. The total color change (ΔE) was calculated using the method described by Nkhata (2020):

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \quad (6)$$

Where ΔL, Δa, and Δb represent the colour differences before and after drying

2.3.3 Antioxidant activity

The pericarp of nutmeg is rich in bioactive compounds that provide antioxidant activity, which helps to neutralize free radicals that can damage cells. The antioxidant properties were measured using the DPPH (2,2-Diphenyl-1-picrylhydrazyl) assay described by Adiletta et al. (2018). This assay was conducted on fresh and dried nutmeg samples to assess how drying affects antioxidant activity. The percentage inhibition of antioxidant activity was calculated using the following equation:

% inhibition of antioxidant activity =

$$\left(\frac{\text{Absorbance of control} - \text{Absorbance of sample}}{\text{Absorbance of control}}\right) \times 100 \quad (7)$$

2.3.4 Rehydration ratio

The rehydration ratio, which indicates the degree of cellular and structural disruption that occurs during the drying process, was determined by soaking 5 grams of dried nutmeg pericarp samples in 200 milliliters of distilled water until a constant weight was reached (Murali et al. 2021). The weight of the samples was recorded after 30 minutes, and the rehydration ratio was calculated using the following formula:

$$\text{Rehydration ratio} = \frac{\text{Weight of rehydarted sample}}{\text{Weight of dried sample}} \quad (8)$$

2.3.5 Shrinkage

Shrinkage is measured by the change in volume during drying, expressed as the ratio of the volume after drying to before drying (Yan et al. 2008).

$$\text{Shrinkage} = \frac{\text{Volume of sample after drying}}{\text{Volume of raw sample}} \times 100 \quad (9)$$

2.3.6 Effective moisture diffusivity

The drying of agricultural produce primarily occurs during the falling rate period, where the movement of moisture is mainly driven by internal diffusion. This process can be mathematically described using Fick's second law of unsteady state diffusion, as outlined by Zeng et al. (2024):

$$\frac{\delta M}{\delta t} = D_{eff}\, M \quad (10)$$

Nutmeg pericarp is considered an infinite slab, and Crank provided the solution to Fick's law (Crank 1975). The moisture ratio was determined by following the formula:

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp \exp\left(\frac{(2n+1)^2\pi^2 D_{eff}\, t}{4L^2}\right) \quad (11)$$

Where D_{eff} represents the effective moisture diffusivity (m^2/s), t denotes the time of drying (s), L is the half thickness of the sample (m), and n is a positive integer. The above equation is simplified for longer drying periods as follows,

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty} \exp \exp\left(\frac{-\pi^2 D_{eff}\, t}{4L^2}\right) \quad (12)$$

Taking natural logarithm, the D_{eff} is calculated as follows,

$$\ln \ln (MR) = \ln \ln \left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}\, t}{4L^2}\right) \quad (13)$$

The plot of ln MR against time (min) was developed to determine the slope. The effective moisture diffusivity coefficient D_{eff} was then calculated from the slope of the plot using the given equation,

$$D_{eff} = \frac{-\text{slope} \times 4 \times L^2}{\pi^2} \quad (14)$$

2.3.7 Mathematical modelling of drying Kinetics

To analyze the drying behavior, various mathematical models were employed to describe the drying kinetics of nutmeg pericarp. The moisture ratio concerning drying time for the experimental data of nutmeg pericarp was fitted to six thin-layer drying models: the Lewis model, Page model, Henderson and Pabis model, Wang and Singh model, Haghi and Angiz-II model, and the Logarithmic model (Haghi and Angiz 2007; Ertekin and Firat 2015). The equations for these models are provided in Table 1.

Table 1 Mathematical models used to determine the drying kinetics of nutmeg pericarp

S. No.	Name of model	Equation
1	Lewis model	MR = exp(-kt)
2	Page	MR = exp(-kt^n)
3	Henderson and Pabis	MR = aexp(-kt)
4	Wang and Singh	MR = 1+at+bt^2
5	Haghi and Angiz -II	MR = a+bt+ct^2+dt^3
6	Logarithmic	MR = aexp(-kt)+c

The goodness of fit for these models was evaluated using several metrics: the coefficient of determination (R^2), adjusted R^2, and root mean square error (RMSE). The model with the highest R^2 and adjusted R^2 values and the lowest RMSE was the best fit for the drying behavior (Murali et al. 2021). The goodness of fit of a regression model is assessed through R^2, which ranges from 0 to 1; higher values indicate a better fit (Venu et al. 2023). RMSE is a statistical measure that quantifies the difference between predicted and actual values, focusing attention on more significant errors to evaluate the accuracy of predictive models (Venu et al. 2024). For the regression analysis of non-linear equations, MATLAB R2020a and R Studio were utilized (Venu et al. 2024).

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (P_i - Q_i)^2} \quad (15)$$

Where n = Number of data points, P_i = Predicted value for the ith data point, Q_i = Actual value of the ith data point.

The moisture ratio (MR) describes the variation in moisture content over time and is expressed as described by Murali et al. (2021):

$$\mathrm{MR} = \frac{M - M_e}{M_0 - M_e} \quad (16)$$

Where M is the moisture content at time, t and M_0 and M_e are the initial and equilibrium moisture content. The value Me is significantly smaller than Mt or M_0 during extended drying time (Tunckal 2020). Therefore, MR can be simplified to:

$$\mathrm{MR} = \frac{M}{M_0} \quad (17)$$

2.4 Statistical Analysis

The statistical analysis of the drying data offers valuable insights into moisture loss over time. The mean sample weight throughout the drying process was recorded as 31.75 g, with a standard deviation of 28.71 g, indicating significant variation in moisture content during drying. The initial weight of the pericarp was recorded at 100.6 g, which decreased progressively to a final weight of 12.4 g. The median weight was determined to be 16 g, reflecting the central tendency of the dataset. The data displayed a skewed distribution, with a rapid decrease in weight during the initial drying phase, followed by a gradual stabilization. This pattern is typical of drying kinetics, where free water evaporates quickly in the early stages, while bound moisture is removed more slowly in the later stages. This statistical evaluation enhances our understanding of drying behavior and contributes to modeling the kinetics needed to optimize drying conditions and predict equilibrium moisture content.

3 Results and Discussion

3.1 Engineering properties of nutmeg pericarp

Five nutmeg pericarp samples' shape, length, width, and thickness were analyzed. The average sphericity was found to be 0.954 ± 0.03. In a study by Yamagar and Borkar (2018), the reported average sphericity was 0.82. This observed difference may be attributed to variations in physical and geographical factors. The findings also indicated that the nutmeg pericarp's average bulk density and true density ranged from 1000 ± 0.0018 kg/m^3 to 1019 ± 0.01 kg/m^3, respectively. Additionally, the porosity was measured at 0.019 ± 0.011.

3.2 Quality characteristics of dried nutmeg pericarp

3.2.1 Colour analysis

The L* value of the dried sample (57.06±0.08) was slightly lower than that of the fresh sample (75.567±0.82), indicating a darker appearance. This darker color can be attributed to the concentration of constituents in the pericarp. Additionally, the Maillard reaction contributes to the browning, which further affects the color. Similar results were reported by Salehi and Kashaninejad (2018). The darkening observed during the drying process is associated with several factors, including pigment degradation, ascorbic acid oxidation, and non-enzymatic Maillard browning, as noted by Maskan (2001), Nadian et al. (2015), and Han and Jin (2024). In terms of color, the redness (a* value) of the pericarp significantly increased from 1.934±0.64 to 12.33±1.02, which can be attributed to pigment formation during the Maillard reaction, as reported by Tunckal and Doymaz (2020). Similarly, the yellowness (b* value) of the pericarp rose from 16.367±1.31 to 25.23±0.75, consistent with findings by Chong et al. (2013).

3.2.2 Antioxidant activity

The results showed that the antioxidant activity of the dried samples (89.72) was comparable to that of the fresh sample (89.5). This similarity indicates that the heat pump drying process effectively preserved the antioxidant properties. The slight increase in activity may be attributed to the formation of oxidized polyphenols and Maillard reaction products during the drying process (Vidinamo et al. 2022).

3.2.3 Rehydration ratio

The rehydration ratio of dried nutmeg pericarp was 2.4, indicating minimal structural damage during drying (Murali et al. 2021). This higher rehydration ratio is attributed to improved water removal from the tissues, as reported by Vadivambal and Jayas (2007).

3.2.4 Shrinkage

Shrinkage occurs when water is removed during drying, decreasing the product's volume. In this study, the sample exhibited a shrinkage of 26.2%, which indicates improved porosity and enhances its rehydration capacity (Hawlader et al. 2006). Additionally, shrinkage is affected by controlled temperature and humidity conditions. The findings suggest that effective drying was achieved without compromising the structural and nutritional quality of the product.

3.2.5 Effective moisture diffusivity

The natural logarithm of the moisture ratio, ln (MR), was plotted against drying time (min) to determine the slope. This slope was then used to calculate the effective moisture diffusivity (Figure 1). The calculation was based on Fick's second law of diffusion, which describes moisture migration during drying. The effective moisture diffusivity of nutmeg pericarp was found to be 5.5 X 10^{-8} m^2/s, and it varies with values ranging from 2.1 X 10^{-8} to 9.08 X 10^{-8} m^2/s, depending on the drying stage. The diffusivity values obtained were consistent with the typical range reported for food products, which spans from 10^{-11} to 10^{-6} (Olanipekun et al. 2014).

3.2.6 Mathematical modelling of drying

To evaluate various thin layer drying models for nutmeg pericarp, we fitted the experimentally obtained moisture ratios to six mathematical models: Lewis, Page, Henderson and Pabis, Wang and Singh, Haghi and Angiz II, and the logarithmic model. We assessed the statistical performance of each model using the values of R^2, adjusted R^2, and RMSE, as summarized in Table 2. The most suitable model was chosen based on the highest R^2, adjusted R^2 values, and the lowest RMSE. A comprehensive comparison of the statistical performance of the different moisture ratio models is presented in Figure 1.

The first three models, i.e., Lewis, Page, Henderson, and Pabis, exhibited low R^2 values of 0.28, indicating poor predictive accuracy for the drying behavior of nutmeg pericarp. In contrast, the logarithmic model showed moderate predictive performance with an R^2 value of 0.50, indicating a slight improvement. Among the six selected thin layer models, the Wang and Singh model and the Haghi and Angiz -II model displayed significantly higher R^2 values of 0.9678 and 0.998, respectively. This implies that both models could explain more than 90% of the drying data.

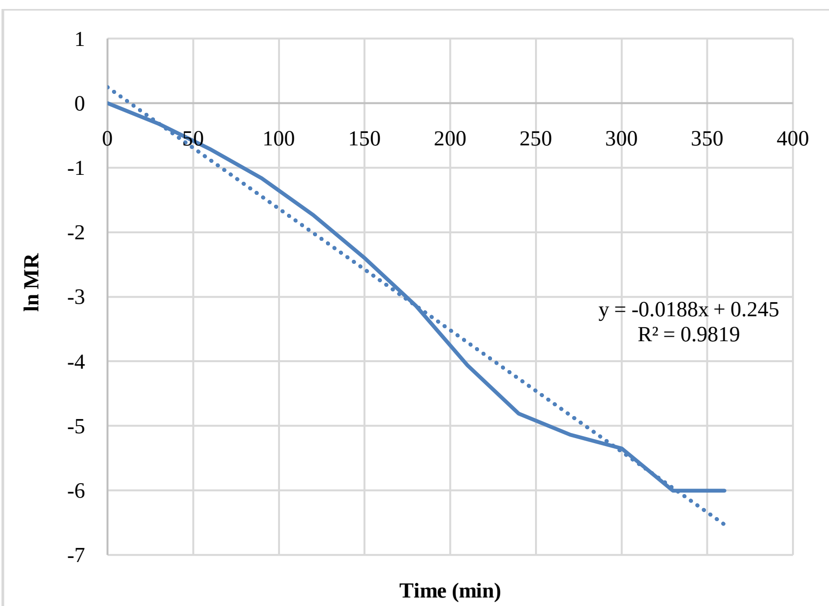

Figure 1 Plot of ln MR against drying time (min) for nutmeg pericarp drying

Table 2 Mathematical modelling of drying behaviour of nutmeg pericarp

S. No.	Name of model and equation	R^2 value	Adj. R^2 value	RMSE value	Constants
1	Lewis model MR= exp(-kt)	0.2873	0.2873	0.2741	k= 0.9706
2	Page MR= exp($-kt^n$)	0.2873	0.2225	0.2863	k = 0.9706 n = 0.9572
3	Henderson and Pabis MR= aexp(-kt)	0.2873	0.2225	0.2863	a = 1 k = 0.9706
4	Wang and Singh MR= $1+at+bt^2$	0.9678	0.9649	0.0609	a = -0.00825 b= 0.00001594
5	Haghi and Angiz -II MR = $a+bt+ct^2+dt^3$	0.9998	0.9997	0.0059	a = 1.006 b = -0.0108 c = 3.83e-05 d = -4.464e-08
6	Logarithmic MR= aexp(-kt)+c	0.5192	0.4230	0.2467	a = 0.8436 c= 0.1564 k= 0.9706

3.2.6.1 Comparative Analysis of best fitting models

To ensure a thorough comparison, we evaluated the models with higher R² values by plotting the observed and fitted values (Figure 2). Although both models demonstrated strong correlations, Figure 2(b) clearly shows that the Haghi and Angiz-II model outperformed the Wang and Singh model in accurately predicting drying behavior. The experimental data closely align with the 45° reference line, indicating a more substantial agreement between the observed and fitted moisture ratios. In contrast, the Wang and Singh model (Figure 2a) exhibits more data dispersion, signifying lower predictive accuracy. This comparison highlights the superior performance of the Haghi and Angiz-II model in effectively capturing the complexities of the drying process, demonstrating its effectiveness over the Wang and Singh model.

The analysis of moisture ratio models reveals significant differences in performance, as indicated by the R² and RMSE values. The Haghi and Angiz II model outperformed the other thin-layer models, achieving the highest R² value of 0.9998, an adjusted R² of 0.9997, and the lowest RMSE value of 0.0059. This demonstrates a robust fit of the experimental data. In contrast, the Wang and Singh model displayed an R² of 0.9678 and an RMSE of 0.0609, indicating more significant discrepancies from the actual

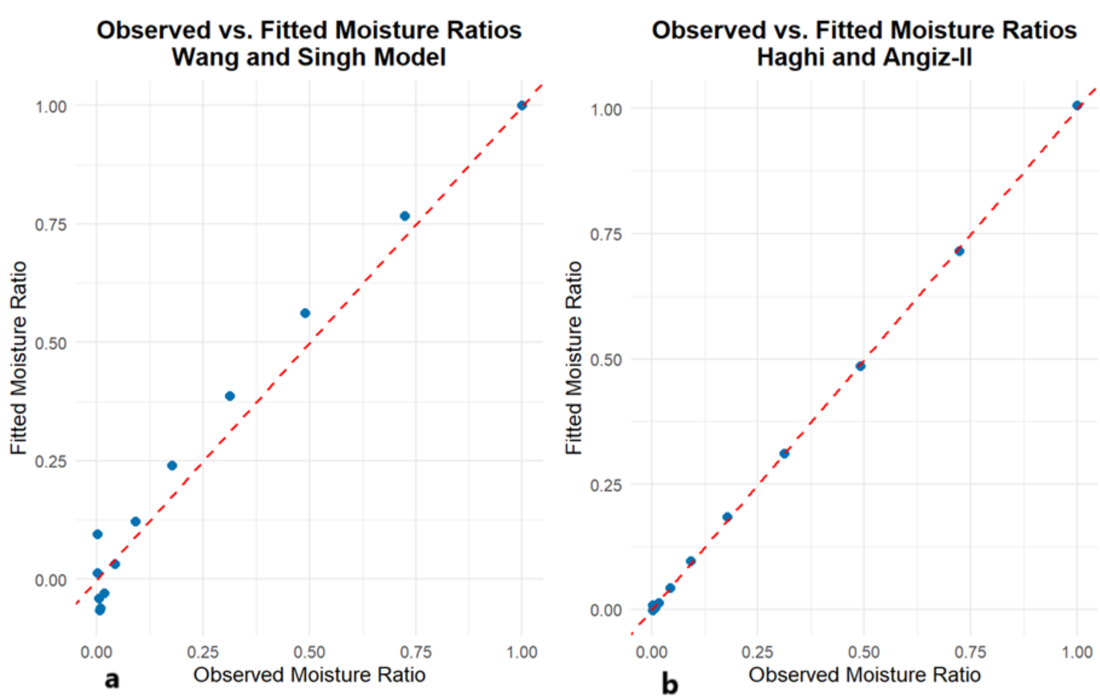

Figure 2 Plot of observed against fitted moisture ratio values of nutmeg pericarp: (a) Wang and Singh model, (b) Haghi and Angiz-II model

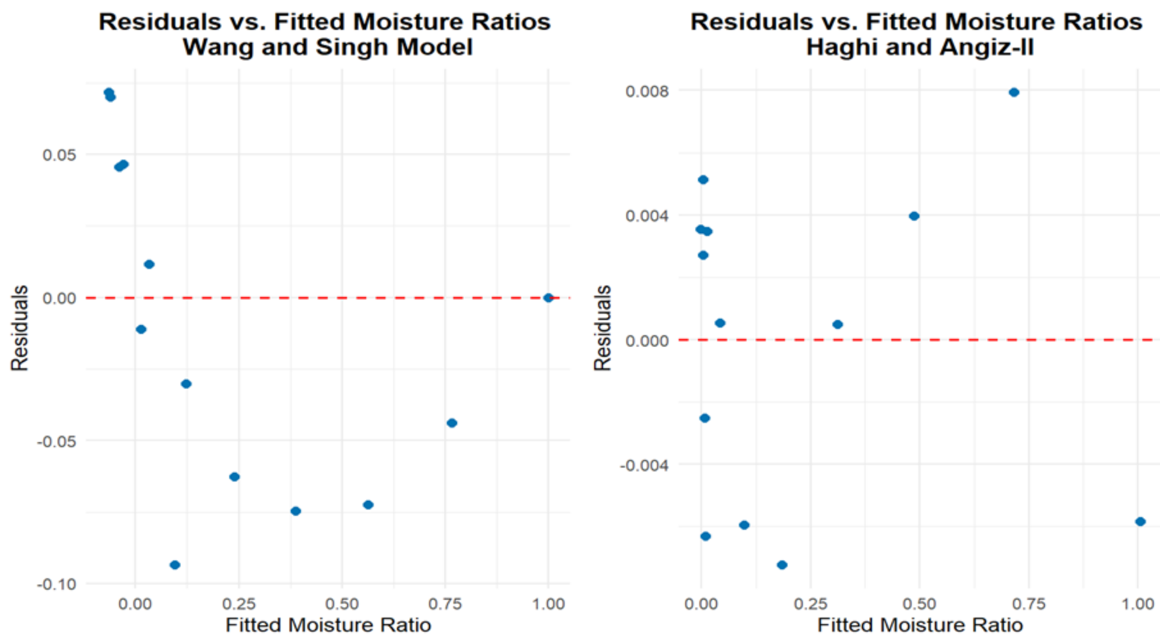

Figure 3 Plot of residuals against fitted moisture ratio values of nutmeg pericarp: (a) Wang and Singh model, (b) Haghi and Angiz-II model

moisture ratios. The observed versus fitted plot further supports these findings, showing that the data points for the Haghi and Angiz II model cluster closely around the reference line, illustrating its accuracy. These statistical results suggest that the Haghi and Angiz II model is the most reliable and suitable for accurately predicting the drying behavior of nutmeg pericarp. Additionally, the residuals against the fitted plot, as shown in Figure 3, reveal a more random distribution for the Haghi and Angiz II models, indicating minimal bias. In contrast, the Wang and Singh model exhibits a noticeable pattern in the residuals, which points to potential predictive shortcomings.

3.2.6.2 Time-moisture ratio relationship and model equation

Figure 4 shows a time versus moisture ratio plot featuring model curves. This reinforces the conclusion that the Haghi and Angiz II

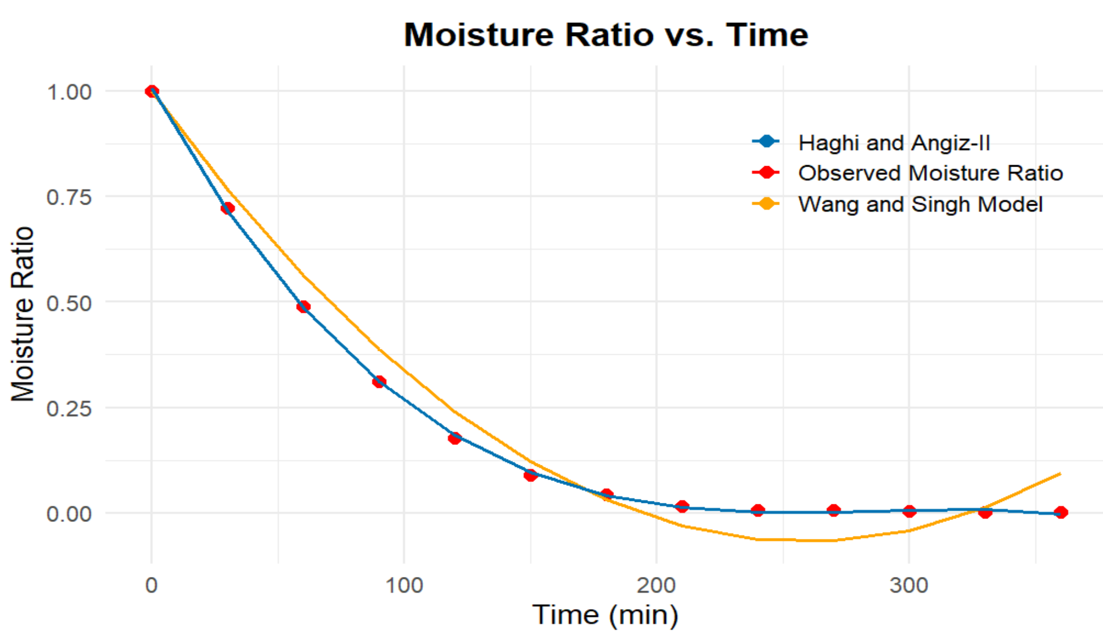

Figure 4 Plot of moisture ratio versus time of nutmeg pericarp using Observed values, Wang and Singh, Haghi and Angiz-II model

model effectively captures the dynamics of the drying process. In contrast, the Wang and Singh model does not perform as well, which justifies the preference for the former in practical applications.

The mathematical equation can express the Haghi and Angiz II model:

$$MR = 1.006 - 0.0108\,t + 3.83 \times 10^{-5} t^2 - 4.464 \times 10^{-4} t^3 \quad (18)$$

This equation underpins the model's high R^2 and low RMSE values, reinforcing its effectiveness in capturing the complexities of the drying process.

Conclusion

The study thoroughly examined the engineering properties, drying kinetics, and quality attributes of nutmeg pericarp dried using a heat pump dryer. The drying process was carried out at a consistent temperature of 55°C and a relative humidity of 37%, which reduced the moisture content from 87% (wet basis) to 3.3% (wet basis) within 6 hours. Mathematical modeling of the drying behavior indicated that the Haghi and Angiz-II models provided the most accurate predictions, demonstrating superior performance in illustrating the moisture removal kinetics of nutmeg pericarp slices. Additionally, the quality analysis showed that heat pump drying significantly improved the key quality parameters of the dried product. Overall, the findings confirm that the heat pump dryer performed exceptionally well in drying nutmeg pericarp while effectively preserving the quality of the dried product.

Conflict of Interest

The authors declare no conflict of interest.

Ethical Clearance

Not application on this study.

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