EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2026, 27(10), 258–273
https://doi.org/10.12912/27197050/226679
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Received: 2026.07.27
Accepted: 2026.08.31
Published: 2026.09.10

Comparative study of vacuum drying as an environmentally friendly technology on different types of mango: Drying kinetics, modeling, physical, and thermal properties

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ABSTRACT

The objective of this study was to identify the characteristics of mangoes during vacuum drying, including drying kinetics, modeling, physical properties, and thermal properties. Drying was performed using vacuum technology at temperatures of 40–60 °C. In addition, this study investigated the differences between mango varieties (Manalagi and Harum Manis) using a combination of pretreatments, namely blanching and soaking in an antibrowning agent. The percentage of water loss and weight reduction were 68.9–86.3% and 78.6–86.3%, respectively. The mass ratio and moisture ratio decreased as the drying process progressed. The drying rate for mangoes was 4.1–5.3 %wb/h. Moisture diffusivity ranged from 5.04×10^{-7} to 1.09×10^{-6} m²/s. Thermal properties ranged from 0.07–0.09 W/m·K (thermal conductivity) to 1495.9–1916.4 J/kg °C (specific heat). The Wang-Singh model and the Diffusion Approach emerged as the best models based on statistical analysis criteria. The Harum Manis mango variety demonstrated superior performance across all experimental parameters compared to the Manalagi variety. The practical significance of this study is to provide information on vacuum drying of mangoes to achieve optimal dry matter content, as well as modeling results to inform the future design of drying equipment.

Keywords: drying, modelling, moisture ratio, thermal properties, vacuum drying.

INTRODUCTION

Mangoes are high in fiber, carbohydrates, vitamin A, vitamin C, polyphenols, minerals, and phenolic compounds (Labaky et al., 2024; Lin et al., 2023; Saentaweesuk et al., 2026). Additionally, they offer benefits for maintaining skin health, boosting the immune system, and reducing stress (Saentaweesuk et al., 2026). The mango market size in 2026 was USD 58.4 billion, and the projected market size for 2031 is USD 70.6 billion. The growth rate from 2026 to 2031 is projected to be 3.9% CAGR (Mordor Intelligence, 2026). Mangoes have a relatively high water content of approximately 83% wb (Hawa et al., 2023). High water content correlates with increased microbiological spoilage, thereby affecting physical and chemical properties. Drying technology can extend the product's shelf life (Efendi, 2024a). Vacuum technology has a significant impact on dried products and can help maintain quality (Hawa et al., 2023; Sehrawat et al., 2018).

The drying kinetics of mangoes have been previously reported by Subbian et al. (2021) using the solar tunnel dryer method. In addition, Ampah et al. (2022) evaluated the drying kinetics and several heat and mass transfer parameters, such as drying rate and moisture diffusivity. They again reported on mathematical modeling of mangoes using a mechanical dryer with temperature variations ranging from 55–75 °C. However, comprehensive elaborations on the Wang-Singh Model, the Diffusion Approach, and the Verma Model have been reported only to an extremely limited extent in previous studies. A similar study on Totapuri mangoes by Singh et al. (2022) explored optimization to determine the best drying method, while Kalita et al. (2025) and Sharew and Woldemariam (2025) focused on identifying chemical quality and techno-economic aspects. An evaluation of the physical properties of mangoes by Caparino et al. (2012) identified several parameters describing physical changes during the drying process used to produce mango powder. The physical properties of mango milk powder were previously reported by Chauhan & Patil (2013) for the Totapari mango variety. They did not identify other physical parameters such as water loss, weight reduction, and mass ratio, which are crucial for understanding heat and mass transfer phenomena. Studies on the thermal properties of the Manalagi and Harum Manis mango varieties were extremely limited. Bon et al. (2010) reported on the determination of thermal conductivity and heat capacity in mangoes. However, they examined these thermal properties in mango pulp. A similar study was reported by Rajkumar et al. (2007) on mango pulp using the foam mat drying method.

Many researchers have examined the results of previous studies on mango drying, but information on the comparative influence of different varieties on drying behaviour is very limited. The novelty of this study is a comparative analysis of two types of mango varieties (Manalagi and Harum Manis) through a combined analysis of drying kinetics parameters (changes in moisture ratio, drying rate, and moisture diffusivity), modeling (Wang-Singh Model, Diffusion Approach, and Verma Model), physical properties (water loss, weight reduction, and mass ratio), thermal properties (thermal conductivity and specific heat capacity), and an overview of energy consumption have never been comprehensively evaluated. This combined analysis provides complete information regarding the physical and thermal characteristics of each variety related to the mass transfer of food materials.

These conditions represent a research gap in this study. The objective of this study is to compare the drying kinetics, modeling, physical, and thermal properties of Manalagi and Harum Manis mangoes at different vacuum-drying temperatures. Furthermore, energy consumption in several other drying methods, based on previous research on vacuum technology, is evaluated in this study.

MATERIALS AND METHODS

Materials and procedure

The mangoes used in this study were sourced from farmers in Pasuruan Regency, East Java, Indonesia. The physical appearance of the mango samples used in the study is shown in Figure 1. The physical characteristics of the Manalagi mango include dark green skin, more spots, and a rougher surface. The physical characteristics of the Harum Manis mango include a light green skin, fewer spots, and a smoother surface. The Manalagi and Harum Manis mangoes had Brix values of 48.8° and 36.9°, respectively. Additionally, the flesh color of the Manalagi and Harum Manis mangoes was (L*=57.03; a*=0.89; b*=53.96) and (L*=58.56; a*=2.18; b*=62.88), respectively. Furthermore, the flesh color of the Manalagi and Harum Manis mangoes was (L* = 43.40; a* = -31.95; b* = 26.26) and (L* = 58.60; a* = -35.98; b* = 31.19), respectively.

The number of mangoes for each variety was determined by three mangoes (3 Manalagi mangoes and 3 Harum Manis mangoes), indicating three replications. Each replication of mangoes was harvested from different trees at the same time. Selection criteria, in addition to the physical characteristics previously described, were a mass of 250±20 g (Manalagi) and 320±20 g (Harum Manis). The mango length criteria were 9.5±1.0 cm (Manalagi) and 11.5±1.0 cm (Harum Manis). The fresh mangoes were cut into round slices with a diameter of cm and a thickness of 0.5 cm, as shown in Figure 2.

There were three stages of sample preparation: soaking in a sucrose solution, blanching, and soaking in an antibrowning agent. The mango samples were soaked in a 20% w/w sucrose solution. The mangoes were blanched at 100 °C for 10 minutes and then cooled for 5 minutes at room temperature (27–30 °C). The antibrowning agents used were citric acid (1% w/w) and calcium lactate (1% w/w). The mango samples were soaked in the antibrowning agents for 1 hour.

The mangoes were dried using a vacuum oven (Memmert VO-400, Germany) with a capacity of 49 L. The prepared mango samples were placed in the vacuum oven at an absolute pressure of 0.3 bar. Mass measurements were taken every hour for up to 15 hours of drying. The solid mass was determined to calculate the moisture content by gravimetry at 105 °C for 4 hours, as in previous studies (Efendi, 2024c; Hawa et al., 2026).

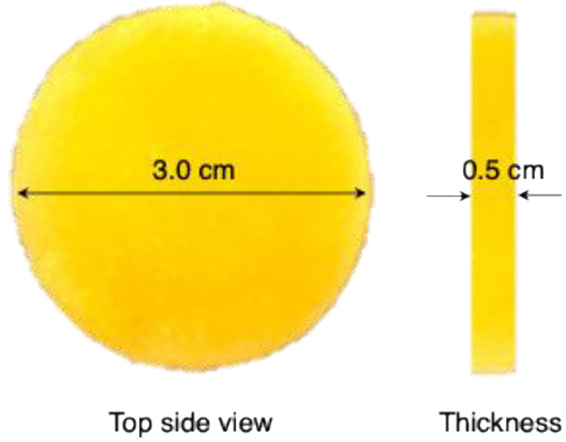

Figure 2. Dimensions of vacuum drying samples for this study

Moisture content and modeling

Determination of moisture content in mangoes during vacuum drying using the wet basis. Moisture content on a wet basis can be determined using Equation 1 as follows.

$$M = \frac{m_w - m_d}{m_w} \quad (1)$$

where: M is the moisture content (%wb), m is the mass (g), w is the total mass of solids and water in the material, and d is the mass of solids in the material.

In addition, the mass transfer process, which is influenced by temperature and drying time, can be characterized by the drying rate. The drying rate of mangoes during vacuum drying can be calculated using Equation 2 as follows.

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \quad (2)$$

where: DR is the drying rate (%wb/h), Δt is the difference in drying time (h), M_t is the moisture content at time t (%wb), and $M_{t+\Delta t}$ is the moisture content before time t (%wb).

The selected mathematical modeling equations are the Wang-Singh, Diffusion Approach, and Verma models. The modeling of mangoes in this study converts moisture content values into moisture ratios, as done in previous reports,

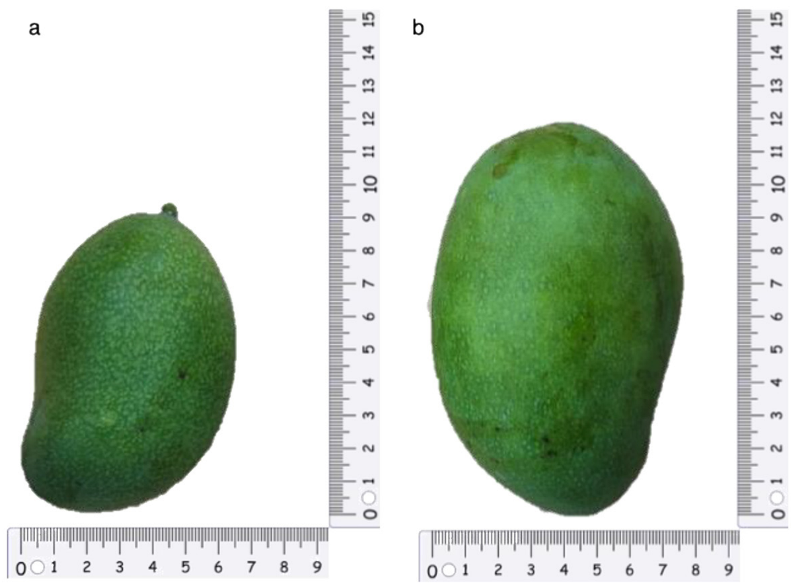

Figure 1. Fresh mango samples in this study, Manalagi (a. left) and Harum Manis (b. right)

expressed by Equation 3 as follows (Hnin et al., 2021; Thuy et al., 2025).

$$MR = \frac{M_t - M_e}{M_i - M_e} \quad (3)$$

where: M_e is the equilibrium moisture content (%wb), M_i is the moisture content of the fresh material, M_t is the moisture content at a specific time, and MR is the moisture ratio (dimensionless).

Mathematical modeling in this study in fitting the Wang-Singh, Diffusion Approach, and Verma models uses Microsoft Excel software (Microsoft Corporation, USA) (Table 1). Modeling was performed on each replication as validation data for the performance of each fitted model. However, constant data and statistical parameters were added with deviations to determine the minimum and maximum ranges for each mathematical model.

Water loss and weight reduction

An analysis of the water loss and weight reduction parameters provides an overview of mass transfer in the material during the drying process. The water loss and weight reduction parameters can be determined using Equation 4 and Equation 5 as follows (Hawa et al., 2026).

$$W_l = \frac{(w_i \times M_i) - (w_f \times M_f)}{w_i} \times 100 \quad (4)$$

$$W_r = \frac{w_i - w_f}{w_i} \times 100 \quad (5)$$

where: w_f is final weight (g), w_i is initial weight (g), M_f is final moisture content (wb), M_i is initial moisture content (wb), W_r is weight reduction (%), and W_l is water loss (%).

Moisture diffusivity and activation energy

Moisture diffusivity is based on a previous study by (Hawa et al., 2026) using Fick's second law. Moisture diffusivity in mangoes is determined using Equation 6 as follows.

$$lnMR = \frac{8}{\pi^2} - \frac{\pi^2 D_{eff}}{4H^2} \quad (6)$$

The determination of moisture diffusivity can be changed to a linear one by plotting ln(MR) versus drying time to obtain the slope value of the linear equation. Moisture diffusivity from the linear equation is determined by Equation 7 as follows.

$$Slope = \frac{\pi^2 D_{eff}}{4H^2} \quad (7)$$

The mango drying process takes place by determining the minimum energy to determine the activation energy for each type of mango. The activation energy is determined from the slope of the linear equation (a plot of the 1/T curve versus ln D_{eff} at different temperatures), which is written in Equation 8 as follows (Omolola et al., 2019).

$$E_a = -slope \times R \quad (8)$$

where: D_{eff} is moisture diffusivity (m^2/s), H is material thickness (m), E_a is activation energy (J/mol), and R is the universal gas constant (kJ/mol.K)

Thermal properties

The vacuum drying phenomenon in this study refers to a previous study by Hawa et al. (2026). The evaluation of thermal properties such as thermal conductivity (k, Equation 9) and specific heat capacity (C_p, Equation 10) can be expressed as follows.

$$k = 0.05 + 0.06\left(\frac{M}{M_o}\right) \quad (9)$$

$$C_p = 1256.26\left(\frac{M}{M_o} + 0.818\right) \quad (10)$$

where: M and M_o are the moisture content at a given time (wb) and the initial moisture content (wb), respectively.

Statical analysis

For mathematical modeling of thin thin layer, the best model was selected by considering the coefficient of determination (R^2), reduced mean square of deviation (X^2), and root mean square error (RMSE). The values of the coefficient of determination (Equation 11), the reduced mean square of deviation (Equation 12), and the root mean squared error (Equation 13) can be expressed using the following equations.

Table 1. Mathematical model for drying kinetics of mango (Efendi, 2024b; Hawa et al., 2021)

Model name	Model equation
Wang-Singh	$MR = 1 + at + bt^2$
Diffusion Approach	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$
Verma	$MR = a\exp(-kt) + (1-a)\exp(-gt)$

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(\vartheta_e - \vartheta_p)^2}{\sum_{i=1}^{N}(\vartheta_e - \bar{\vartheta}_m)^2} \quad (11)$$

$$RMSE = \left[\frac{\sum_{i=1}^{N}(\vartheta_e - \vartheta_p)^2}{N}\right]^{0.5} \quad (12)$$

$$\chi^2 = \frac{\sum_{i=1}^{n}(\vartheta_e - \vartheta_p)^2}{N-p} \quad (13)$$

where: p is number of constants, N is the number of experimental data, ϑ_e is experimental data, $\bar{\vartheta}_m$ is average data, and ϑ_p is prediction data.

Data moisture ratio in mango drying and experimental temperature variations using statistical analysis such as R^2, *RMSE*, and X^2 as reported in previous studies (Efendi, 2024a; Hawa et al., 2026).

The experimental data on water loss, weight reduction, model constants, and statistical parameters were analyzed using a two-way ANOVA with a 95% confidence level. Post-hoc tests were conducted using Tukey's HSD test with a 95% confidence level and three replicates (n=3). The ANOVA analysis was performed using SPSS 24.0 software (SPSS Inc., Chicago, USA).

Experimental uncertainty analysis

Uncertainty analysis of a research parameter is very important in knowing the data range of an experiment. Determination of uncertainty can be determined by Equation 14 as belows (Efendi et al., 2024).

$$W_R = \left[\left(\frac{\partial R}{\partial x_1}w_1\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n}w_n\right)^2\right]^{\frac{1}{2}} \quad (14)$$

where: W_R is the result of measurement uncertainty, w is the uncertainty in the independent variable, and x is a function of the independent variable (Efendi et al., 2024; Hawa et al., 2021).

Uncertainty analysis for the parameters water loss, weight reduction, moisture ratio, drying rate, moisture diffusivity, thermal conductivity, and specific heat capacity, namely ±0.0400, ±0.0323, ±0.0003, ±0.0231, ±0.000, ±0.0042, and ±0.0322, respectively. From the results, the uncertainty is still below 5% and is the accepted uncertainty range (Hawa et al., 2021).

RESULTS AND DISCUSSION

Water loss and weight reduction

Table 2 presents water loss and weight reduction data for different mango varieties and vacuum drying temperatures. Water loss and weight reduction increased at temperatures between 40 °C and 50 °C, then decreased at 60 °C. Manalagi mangoes

Table 2. Water loss and weight reduction in mango during vacuum drying

Types of mango	Temperature (°C)	Water loss (%)	Weight reduction (%)
	40	78.55±2.35**	78.55±2.35**
Manalagi	50	79.93±1.96**	79.93±1.96**
	60	75.00±1.14**	84.44±0.76**
	40	86.19±0.28**	86.19±0.28**
Harum Manis	50	86.29±0.52**	86.29±0.52**
	60	68.90±3.62**	83.73±3.62**

Note: **Not significant (p>0.05) differences between type of mango and temperature. Data represents the mean (n=3) with two way ANOVA test.

tended to have higher water loss and weight reduction values than Harum Manis mangoes.

Water loss and weight reduction were nearly identical. These values essentially represent the percentage of water loss (mass transfer) during the drying process (Efendi, 2024a). Furthermore, water loss is calculated as the reduction in mass from the equilibrium moisture content. These parameters are related to changes in shrinkage. Changes in porosity and hygroscopicity also affect shrinkage, correlating with water loss and weight reduction (Tepe, 2023).

Mass ratio

Figure 3 shows the relationship between mass ratio and vacuum drying time for each temperature variation. The average mass ratio of Manalagi mango at temperatures of 40 °C, 50 °C, and 60 °C is 0.35, 0.21, and 0.15, respectively. The average mass ratio of Harum Manis mangoes at temperatures of 40 °C, 50 °C, and 60 °C is 0.32, 0.18, and 0.15, respectively. The mass ratio decreases with each drying time. In addition, the mass ratio decreases as the vacuum drying temperature increases. Manalagi mangoes tend to have a higher mass ratio than Harum Manis mangoes.

The mass ratio correlates with determining the end of drying and achieving equilibrium water content. High temperatures accelerate water movement to the surface of the material, facilitating evaporation (Hnin et al., 2021). At low temperatures, the material's water diffusivity decreases (Ayetigbo et al., 2021). This condition is related to the decrease in mass over time due to water loss. The decrease in mass ratio at the same drying time and temperature has been reported previously by (Xie et al., 2021).

Moisture ratio

Figure 4 shows the relationship between moisture ratio and vacuum drying time for different mango varieties and temperatures. Moisture ratio is a simplified value that makes it easier to compare moisture content across different materials. Moisture ratio is correlated with water content (Efendi, 2024b). The average initial water content of Manalagi and Harum Manis mangoes was 84.98% wb and 86.55% wb, respectively. The final water content of Manalagi mangoes at temperatures of 40 °C, 50 °C, and 60 °C was 27.79% wb, 18.11% wb, and 15.70% wb, respectively. The water content of Harum Manis mangoes at temperatures of 40 °C, 50 °C, and 60 °C was 25.95% wb, 19.96% wb, and 17.93% wb, respectively. The trend in water content differences is similar to that of the moisture ratio.

The MR parameter decreased over time during vacuum drying, a mass-transfer process. This condition consistently occurred in all mango samples (Manalagi and Harum Manis). Under dry conditions, the moisture content of Manalagi mangoes tended to be lower than that of Harum Manis mangoes. Topuz (2026) reported that differences in final water content in different materials were correlated with water activity. Low water content indicates low water activity and moisture ratio. Water loss from the material indicates mass transfer (Hawa et al., 2021) and changes in tissue structure (Hawa et al., 2023) are interpreted by the moisture ratio for several commodities, such

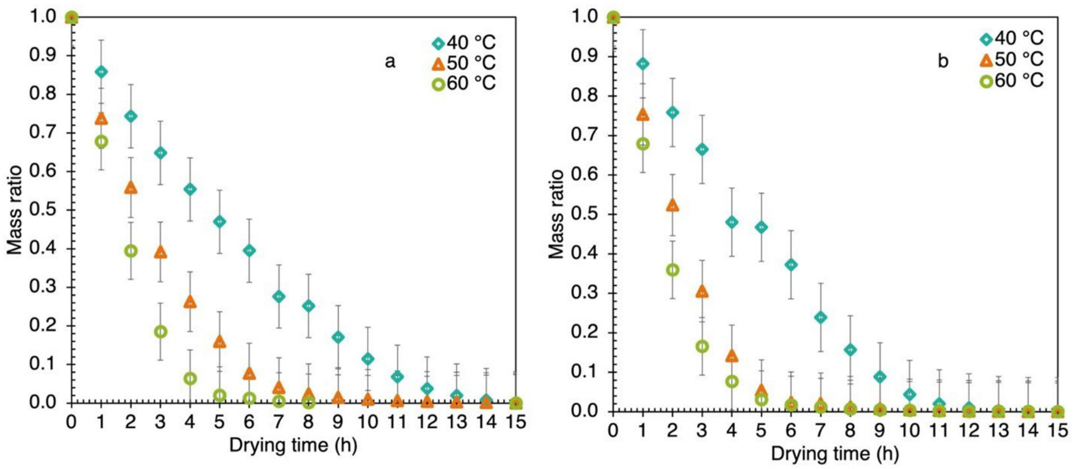

Figure 3. Mass ratio during drying time of mango: Manalagi (a), Harum Manis (b)

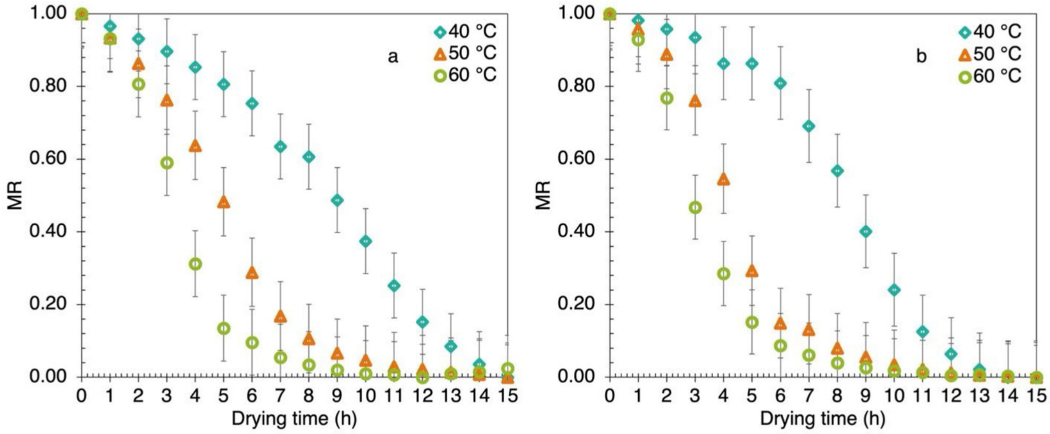

Figure 4. Moisture ratio to drying time during vacuum drying for mango, Manalagi (a) and Harum Manis (b)

as ginger (Wang et al., 2022), mango (Hawa et al., 2023), and lemon (Efendi, 2025).

Drying rate

Figure 5 shows the drying rate of mangoes at different vacuum-drying temperatures. The average drying rate for Manalagi mango at temperatures of 40 °C, 50 °C, and 60 °C is 4.13 %wb/h, 4.36 %wb/h, and 4.98 %wb/h, respectively. The average drying rate for Harum Manis mango at temperatures of 40 °C, 50 °C, and 60 °C is 4.25 %wb/h, 4.60 %wb/h, and 5.26 %wb/h, respectively.

Identification of average drying rate data shows that it increases with temperature. At a treatment temperature of 50–60 °C, the first 6–7 hours showed significant water movement during the constant and first falling rate phases. At a treatment temperature of 40 °C, after 8 hours of drying, substantial water movement was observed during the first falling-rate phase. Manalagi mangoes have a lower average drying rate than Harum Manis mangoes. The water content of fresh Manalagi mangoes is lower than that of Harum Manis mangoes. Low water content correlates with a lower average drying rate and is consistent with the drying rate determinations in this study.

Vacuum drying with temperature differences affects differences in drying rate (Hawa et al., 2023). Vacuum technology yields the best results for increasing the drying rate compared with hot-air and microwave drying (Xu et al., 2022). At high drying rates and high temperatures, the increase in drying rate was influenced by thermal penetration (Nile, 2022). Apart from that, differences in drying rate are also influenced by changes in tissue structure (Efendi, 2025). The effects of temperature and vacuum drying, with results similar to those of this study, have been reported previously for mango (Hawa et al., 2023).

Moisture diffusivity and activation energy

Moisture diffusivity in Manalagi mango at temperatures of 40 °C, 50 °C, and 60 °C were 5.04×10^{-7} m^2/s, 9.39×10^{-7} m^2/s, and 1.25×10^{-6} m^2/s, respectively. Moisture diffusivity in Harum Manis mango at temperatures of 40 °C, 50 °C, and 60 °C was 6.28×10^{-7} m^2/s, 1.09×10^{-6} m^2/s, and 1.10×10^{-6} m^2/s, respectively. Identification of moisture diffusivity data for Manalagi and Harum Manis mangoes showed a tendency to increase as vacuum drying temperature increased. A comparison of mango types showed that Harum Manis mangoes tended to have higher moisture diffusivity than Manalagi mangoes.

Moisture diffusivity was influenced by heat penetration, and differences in vacuum drying temperature and heat gradients also affect this parameter (Hawa et al. 2026). High-temperature conditions can accelerate the evaporation of water components at the internal evaporation pressure, thereby altering moisture diffusivity values during the drying process (Kamal et al., 2023). Similar research results have been previously reported for walnuts (Chen et al., 2020), sweet potatoes (Chinenye et al., 2022), and bananas (Chigbo et al., 2024). Each mango type has a different structure that influences moisture diffusivity values (Chigbo et al., 2024). Dhake et al. (2023) reported results similar to those of this study and found a linear correlation with the drying rate.

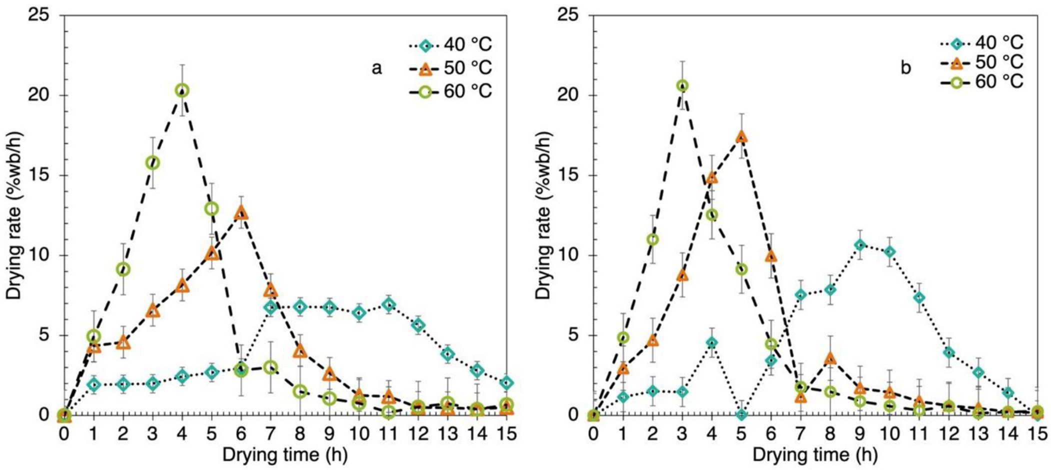

Figure 5. Drying rate of mango during vacuum drying process: Manalagi (a), Harum Manis (b)

Ampah et al. (2022) reported that the Kent, Keitt, Haden, and Palmer mango varieties had moisture diffusivities of 5.90×10^{-7}, 6.40×10^{-7}, 6.57×10^{-7}, and 7.33×10^{-7} m^2/s, respectively. Other commodities such as bilimbi (Hawa et al., 2026) had a moisture diffusivity range of 2.97–9.60×10^{-7} m^2/s. In this study, the moisture diffusivity was almost the same as that of the Kent, Keitt, Haden, and Palmer mango varieties, as well as bilimbi, which had a range of 10^{-6}–10^{-7} m^2/s. This moisture diffusivity range is common for horticultural fruit commodities. In addition, geographical differences, drying methods, and equipment configurations are factors in the differences in the range of moisture diffusivity values compared to this study.

Pretreatment using an anti-browning agent was performed on all mango samples. However, comparing the results with and without an anti-browning agent did not affect the difference in moisture diffusivity. The use of pretreatment in the drying process directly damages tissue cells, thereby accelerating mass transfer (Moreira et al., 2021). A previous study by Wang et al. (2022) on pretreated and unpretreated apples showed significant differences. They reported that unpretreated apples had stronger cell walls and a shorter drying rate. This case demonstrates that pretreatment can increase moisture diffusivity, although this was not compared in this study.

The activation energy of Manalagi and Harum Manis mangoes is 39.29 kJ/mol and 23.94 kJ/mol, respectively. The activation energy of Manalagi mango is greater than that of Harum Manis. The difference in activation energy is correlated with the average drying rate. The average drying rate of Harum Manis is greater than that of Manalagi. The increase in drying rate indicates the ease with which water can diffuse, as shown by the moisture diffusivity value of Manalagi mango, which is greater than that of Manalagi. Low activation energy describes low internal resistance, so the drying process is faster. Ampah et al. (2022) reported that the activation energy in the Haden variety of mango has a range of 19.50–25.50 kJ/mol. Forouzanfar et al. (2020) reported that the activation energy in mushrooms has a range of 16.55–19.72 kJ/mol. The activation energy in this study was greater than that in other mango varieties and different types of commodities due to differences in higher initial water content.

Thermal properties

Figure 6 shows the thermal conductivity of Manalagi and Harum Manis mangoes. Manalagi and Harum Manis mangoes have similar thermal conductivity values at different drying temperatures. The average thermal conductivity at 40°C, 50 °C, and 60 °C is 0.09 W/mK, 0.08 W/mK, and 0.07 W/mK, respectively.

Figure 7 shows the specific heat capacity of Manalagi and Harum Manis mangoes. The average specific heat capacity of Manalagi mangoes at 40 °C, 50 °C, and 60 °C is 1916.4 J/kg °C, 1633.8 J/kg °C, and 1495.9 J/kg °C, respectively. The average specific heat capacity of Manalagi mango at temperatures of 40 °C, 50 °C, and 60 °C is 1866.6 J/kg °C, 1610.3 J/kg °C, and 1528.5 J/kg °C.

The k and cp values for different mango varieties and temperatures decreased as vacuum-drying duration increased. Furthermore, these parameters increased with increasing mango moisture content. These parameters also increased as temperature decreased. The trends in k and cp capacity are similar to drying kinetics. The decrease in k and cp was caused by water loss. The lost water was replaced by internal water in the material. This condition reduces the ability to transfer heat and mass, which is correlated with thermal conductivity and specific heat capacity (Efendi, 2024b). The drying kinetics observed are similar to those reported in previous studies on sweet potato (Chinenye et al., 2022) and billimbi (Hawa et al., 2026). They revealed that low moisture content increases porosity, as air supplies capillary cavities due to moisture loss. High moisture content in a material indicates an abundance of internal water (free water) and low air content, which increases thermophysical parameters. A low water fraction reduces heat conduction, and the energy required to raise the material's temperature also decreases.

Modeling

Mathematical models such as the Wang-Singh, Diffusion Approach, and Verma models were used to determine the drying kinetics of Manalagi and Harum Manis mangoes. The accuracy test of R^2, X^2, RMSE and constants of the fitted models can be seen in Table 3 and Table 4. Hawa et al. (2026) reported the determination of the best model from several models used, namely having the highest coefficient of determination, the lowest reduced mean square of deviation, and the lowest root mean squared error.

The Wang-Singh and Diffusion Approach models were the best models based on statistical analysis criteria (Figure 8). Wangh-Singh was

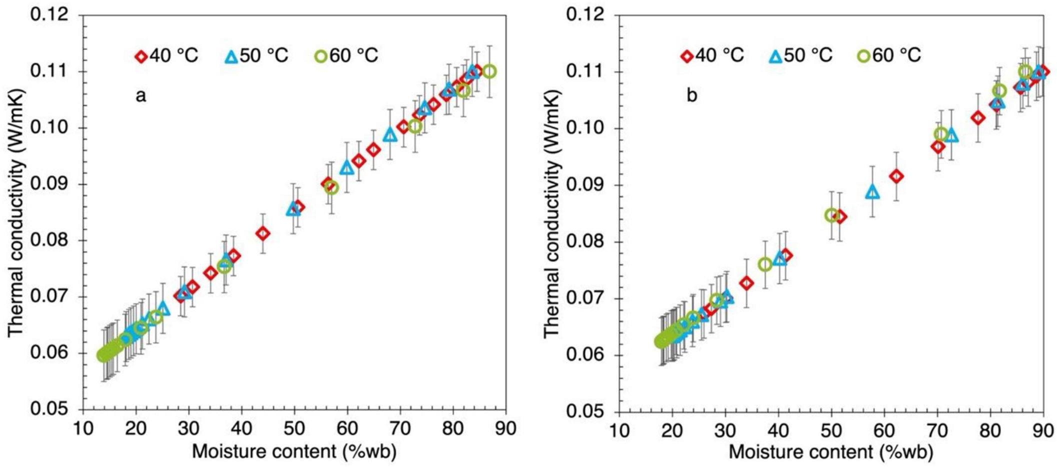

Figure 6. Thermal conductivity properties in vacuum drying of mango: Manalagi (a), Harum Manis (b)

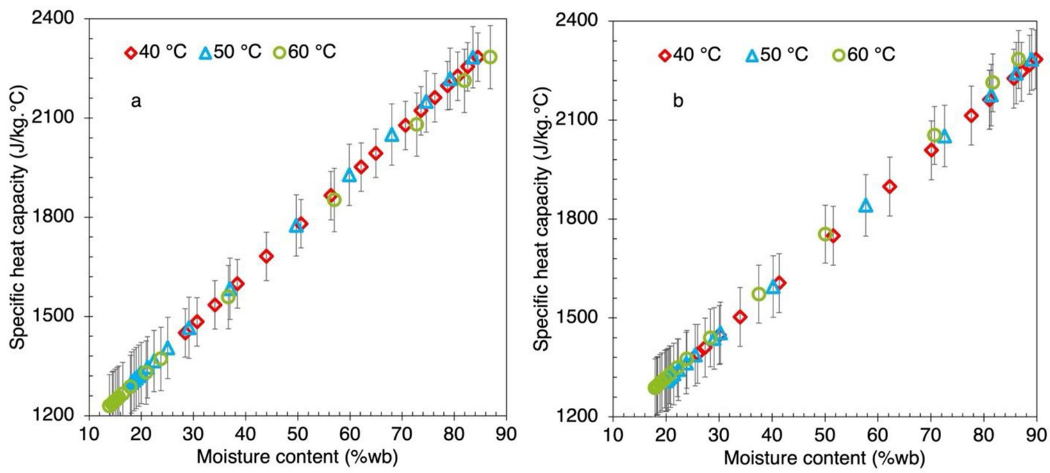

Figure 7. Specific heat capacity properties in vacuum drying of mango: Manalagi (a), Harum Manis (b)

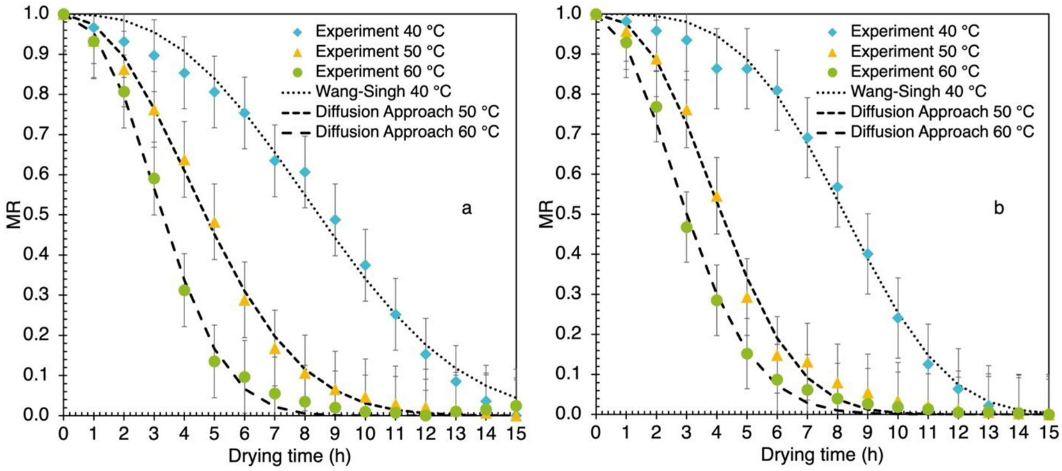

Figure 8. The performance of the Page is the best model for vacuum drying of mango: Manalagi (a), Harum Manis (b)

the best model for vacuum drying at 40 °C. The Diffusion Approach was the best model for vacuum drying at 50–60 °C. The Wang-Singh model had R^2, X^2, and RMSE ranges of 0.9506–0.9865, 0.0406–0.0007, and 0.0032–0.0879, respectively. The Diffusion Approach model has a range of R^2, X^2, RMSE of 0.9873–0.9971, 0.0004–0.0023, and 0.0184–0.0430, respectively.

The Wang-Singh model was the best model for other studies, such as mint leaves (Akpinar, 2010). Hawa et al., (2023) reported that the Wang-Singh model was the best model influenced by the sigmoid trend in drying kinetics. The Diffusion Approach model was the best model for other studies such as apricots (Zhang et al., 2016) and bananas (Kamble et al., 2022). The Diffusion Approach model can predict the preheat phase at a constant rate well. In addition, the steep first-fall rate is characteristic of the Diffusion Approach model trend, as reported in this study.

In general, the Wang-Singh and Diffusion Approach models are flexible models for predicting drying kinetics. However, accuracy, compared with other models, is also influenced by physical properties such as the drying rate, as shown in Figure 5. Based on the identification of drying rate data in this study, it shows that mango drying at 40 °C has the characteristics of a longer initial heating rate and constant rate phase that is seen up to 11 hours (Manalagi) and 9 hours (Harum Manis). These conditions make the Wang-Singh model the best model for mango drying at 40 °C. The Diffusion Approach model is the best model for mango drying at 50 °C and 60 °C for both types of mango. The Diffusion Approach model is the best model associated with a first falling rate and a second falling rate that are longer than the initial heating rate and constant rate phases during the drying process. The best modeling consistently shows the same best model at the same temperature for different types of mango. Differences in mango types do not affect the differences in the best model types, but temperature differences do affect the best model types.

Model constants, R^2, X^2, and RMSE were fitted from averaged experimental data. All deviations in model constants, R^2, X^2, and RMSE were obtained from three replications that were fitted to each replication. The constants and statistical parameters of the model show that there are significant differences ($p<0.05$) between types of mathematical models and drying temperatures

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Energy consumption overview

This section compares the energy consumption of vacuum technology with that of other drying methods, based on several previous reports by other relevant researchers. Table 5 presents information on several drying methods regarding energy consumption per kilogram of material dried. The comparative evaluation results indicate that

Table 3. Mathematical model constants for vacuum drying of mango (Manalagi)

Model	Model constant	R^2	χ^2	RMSE
Manalagi 40 °C				
Wang-Singh	a=-0.0326±0.0004; b=-0.0027±0.0003	0.9865±0.0009*	0.0007±0.0000*	0.0406±0.0002*
Diffusion approach	a=14.5270±0.2020; k=0.2454±0.0802; b=1.1024±0.0911;	0.9492±0.0089	0.0082±0.0004	0.0814±0.0011
Verma	a=-5.9371±0.1229; k=-0.0378±0.0052; g=-0.0268±0.0056	0.9847±0.0067	0.0024±0.0007	0.0440±0.0090
Manalagi 50 °C				
Wang-Singh	a=-0.1385±0.0232; b=0.0047±0.0013	0.9716±0.0920	0.0021±0.0008	0.0711±0.0049
Diffusion approach	a=20.5120±0.3202; k=0.4339±0.0872; b=1.0676±0.0882	0.9874±0.0120*	0.0023±0.0002*	0.0430±0.0048*
Verma	a=3.2192±0.0821; k=0.1404±0.0028; g=0.1205±0.0039	0.9553±0.0280	0.0125±0.0009	0.1007±0.0032
Manalagi 60 °C				
Wang-Singh	a=-0.1885±0.0009; b=0.0085±0.0004	0.9615±0.0082	0.0021±0.0003	0.0724±0.0099
Diffusion approach	a=19.6619±0.2820; k=0.6442±0.0080; b=1.0767±0.0922	0.9906±0.0091*	0.0014±0.0001*	0.0341±0.0003*
Verma	a=3.2192±0.0070; k=0.1404±0.028; g=0.1205±0.0062	0.9278±0.0622	0.0208±0.0014	0.1300±0.0093

Note: The vacuum method in the drying process reduces the pressure below atmospheric pressure, accelerating the product evaporation process (Salehi et al., 2017). The large difference between the material's internal and external pressures can influence the drying process, which occurs at low temperatures (Espinoza and Bond, 2016). Low heat loss also reduces browning (Hawa et al., 2023). This technology even achieves higher process performance than other methods (Motevali et al., 2011).

the vacuum method has a lower energy consumption range compared to microwave, convection, a combination of hot air and infrared, infrared, solar dryer, a combination of solar dryer and LPG, and open sun. The comparison with previous studies shows a correlation between energy consumption and environmental impact. Lower energy consumption for the drying process correlates with lower carbon dioxide emissions.

Limitations and prospects

This study has limitations in using two types of mango (Manalagi and Harum Manis) and three vacuum drying temperatures (40–60 °C). In addition, the vacuum pressure was limited to 0.3 bar in all treatments. This study primarily identifies the characteristics of vacuum drying at each temperature increase in determining the optimum temperature. This optimum temperature can be used as a basis for future research using different vacuum pressures to produce good-quality dried mangoes supported by drying characteristics. In the future, the results of this study have good prospects in the food industry. Semi-dried mango with the addition of sucrose is a promising downstream product and a favorite food of the general public by maintaining the contents of the mango. However, before achieving this promising prospect, studies related to optimizing vacuum pressure and the physical thickness of mangoes are urgently needed. The right thickness can provide the desired texture. Vacuum pressure optimization correlates with low energy consumption. However, drying mangoes in semi-dry downstream products is very promising in the future for improving the economy and health food products.

CONCLUSIONS

A study of the drying kinetics, modeling, and physical and thermal properties of Manalagi and

Table 4. Mathematical model constants for vacuum drying of mango (Harum Manis)

Model	Model constant	R^2	χ^2	RMSE
Harum manis 40 °C				
Wang-Singh	a=-0.0322±0.0002; b=-0.0030±0.0001	0.9506±0.0002*	0.0032±0.0001*	0.0879±0.0012*
Diffusion approach	a=57.9959±0.4833; k=0.2869±0.0932; b=1.0276±0.0211	0.9349±0.0109	0.0135±0.0043	0.1049±0.0181
Verma	a=-8.8159±0.0821; k=-0.0368±0.0082; g=-0.0289±0.0091	0.9478±0.2911	0.0104±0.0010	0.0921±0.0082
Harum Manis 50 °C				
Wang-Singh	a=-0.1568±0.0110; b=0.0060±0.0010	0.9612±0.0924	0.0029±0.0008	0.0837±0.0233
Diffusion approach	a=86.1820±0.0251; k=0.5311±0.0063; b=1.0172±0.0015	0.9873±0.0009*	0.0022±0.0000*	0.0425±0.0003*
Verma	a=-9.6291±0.1180; k=0.0843±0.0042; g=0.0926±0.0035	0.9436±0.0244	0.0113±0.0033	0.0960±0.0036
Harum Manis 60 °C				
Wang-Singh	a=-0.1913±0.0680; b=0.0087±0.0027	0.9603±0.0190	0.0019±0.0008	0.0685±0.0082
Diffusion approach	a=93.9266±0.0092; k=0.6900±0.0220; b=1.0145±0.0081	0.9971±0.0082*	0.0004±0.0000*	0.0184±0.0008*
Verma	a=-9.7466±0.082; k=0.1550±0.0921; g=0.1642±0.0188	0.9633±0.0390	0.0063±0.0016	0.0713±0.0022

Note: This energy consumption comparison reports the results of previous research, where the experimental conditions differed from those in this study. Several factors influence energy consumption, including temperature, food variety, mass flow rate, sample shape, sample collection location, drying equipment configuration, and research location. These conditions significantly influence energy consumption. However, there provides information on the relative energy consumption performance of various drying methods to guide future drying method selection for specific materials.

Table 5. Comparison of energy consumption in various drying methods

No.	Method	Material	Energy consumption (kWh/kg)	References
1.	Vacuum	Camellia oleifera seeds	1.51–5.17	(Zhang et al., 2023)
2.	Vacuum	$LiFePO_4$ battery powder	1.27–3.30	(Zhao et al., 2018)
3.	Microwave	Mushroom	2.51–6.00	(Motevali et al., 2011)
4.	Microwave	Camellia oleifera seeds	2.34–4.03	(Zhang et al., 2023)
5.	Convective	Orange	19.93–91.00	(Alibas and Yilmaz, 2022)
6.	Hot air-infrared	Mushroom	28.35–43.92	(Motevali et al., 2011)
7.	Infrared	Mushroom	50.84–93.45	(Motevali et al., 2011)
8.	Solar dryer	Potato	12.37	(Abdelkader et al., 2024)
9.	Solar - LPG	Clam	4.73	(Delfiya et al., 2024)
10.	Open sun	Clam	4.11	(Delfiya et al., 2024)

Harum Manis mangoes at different vacuum-drying temperatures has been successfully conducted. The objectives of this study are described as follows.

- Manalagi mangoes tended to have higher water loss and weight-reduction values than Harum Manis mangoes.
- The longer the vacuum drying time and temperature, the lower the moisture ratio and mass ratio.
- The average drying rate parameter increases with increasing vacuum drying temperature.
- Moisture diffusivity in Manalagi and Harum Manis mangoes tended to increase with

increasing vacuum drying temperature. Furthermore, Harum Manis mangoes tended to have higher moisture diffusivity compared to Manalagi mangoes.

- The k and cp values increased with increasing water content, depending on the mango type and vacuum drying temperature.
- Based on the accuracy test (R^2, X^2, and RMSE), the Wang-Singh and Diffusion Approach models were the best.

The practical significance of this study is to provide information on vacuum drying of mangoes to achieve optimal dry matter content, as well as modeling results to inform the future design of drying equipment. In addition, the identification of drying characteristic data and mathematical and thermophysical models used to characterize differences in mangoes can be used as a reference in the control system of modern drying equipment to produce mangoes of the quality demanded by the market.

Acknowledgements

This research was funded by the Ministry of Higher Education, Science, and Technology of the Republic of Indonesia (Kemendiktisaintek) under the Beginner Lecturer Research Grant (Penelitian Dosen Pemula/PDP) 2026 funding scheme (Contract No. 287/C3/DT.05.00/PL-BARU/2026).

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