

RESEARCH PAPER

Evaluation of Drying Kinetics of Mango Pulp using Vacuum and Tray Drying Approaches

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ABSTRACT

This study presents a comparative evaluation of the drying kinetics of Alphonso mango pulp (*Mangifera indica* L.) using a laboratory-scale tray dryer and vacuum dryer at 70 °C. Mango pulp layers of 2, 3, and 4 mm thickness were dried to a final moisture content of less than 8% (wb). Drying time was shorter under vacuum conditions (270, 330, and 430 minutes for 2, 3, and 4 mm, respectively) compared to tray drying (380, 440, and 520 minutes), indicating the efficiency of vacuum drying in accelerating moisture removal. In both methods, drying occurred entirely in the falling-rate period, confirming that internal diffusion governed moisture transport. Experimental moisture ratio data were fitted to five thin-layer drying models: Lewis, Page, Henderson & Pabis, Logarithmic, and Two-Term. For vacuum drying, the Page model provided the best fit ($R^2 = 0.9899-0.9974$, lowest RMSE and χ^2), whereas for tray drying, the Two-Term model showed superior performance ($R^2 = 0.999$ across all thicknesses), followed by the Logarithmic and Page models. These results demonstrate that while both drying methods effectively reduced the moisture content of mango pulp to safe storage levels, vacuum drying achieved faster drying, and tray drying was better characterized by multi-parameter models.

Keywords: Mango pulp, tray drying, drying kinetics, moisture diffusivity, Page model, quality retention

Drying is an essential preservation method commonly used in the food industry to prolong shelf life, minimize microbial activity, and enhance the nutritional concentration in fruits such as mangoes, which possess high moisture levels and are susceptible to quick spoilage. Among the various drying techniques, tray drying—a method utilizing convective hot air remains a widely used and economical option; it entails the circulation of hot air through layers of material arranged on trays, resulting in moisture removal through evaporation. However, despite its cost-effectiveness, tray drying

frequently causes unfavorable alterations in color, texture, and rehydration quality due to extended exposure to heat.

Tray drying is one of the most common drying methods in small and medium-scale food processing due to its simplicity, low capital cost, and ease of operation. However, prolonged exposure to hot air

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can cause degradation of heat-sensitive nutrients such as ascorbic acid and carotenoids. Optimizing tray drying conditions is therefore necessary to balance drying time and product quality.

In contrast, vacuum drying functions under reduced pressure, which decreases the boiling point of water and facilitates drying at lower temperatures. This process enhances moisture removal while more effectively preserving heat-sensitive bioactive compounds and reducing oxidative degradation. For example, Jaya and Das (2003) illustrated that vacuum-dried mango pulp exhibited reliable moisture diffusion modeling (R^2 values ranging from 0.98 to 0.99), and the quality of color was mainly affected by the thickness of the pulp rather than the drying temperature—with only slight color alteration occurring at approximately 72.3 °C and a thickness of 2.6 mm.

Mango (*Mangifera indica* L.) is one of the most important tropical fruits, valued for its rich flavor, high carotenoid content, and significant vitamin C levels. However, mango pulp is highly perishable due to its high moisture content (80–85% wb), making post-harvest preservation essential to reduce losses. Drying is a widely used preservation technique that reduces moisture content, thereby inhibiting microbial activity and enzymatic spoilage. The Alphonso mango frequently referred to as the “king of mangoes,” is a highly esteemed Indian variety celebrated for its rich fragrance, smooth, fiberless flesh, and a harmonious sweetness with a hint of acidity. Its distinctive flavor profile is intricately influenced by a combination of monoterpenes (notably (Z)-ocimene), along with lactones and furanones that primarily develop during the ripening process adding to its unique sensory characteristics. From a nutritional perspective, Alphonso mangoes display the typical sugar-laden composition found in ripe mangoes, where sucrose, fructose, and glucose are predominant accompanied by modest amounts of proteins, lipids, and vital micronutrients such as vitamins A and C. Moreover, enhancing its reputation, the Alphonso mango possesses a registered Geographical Indication (GI) status, which

authenticates its distinctive attributes and connection to the Ratnagiri–Konkan region of Maharashtra, acknowledged in the Indian GI registry for the years 2018–19.

This research paper bridges a gap through comparative evaluation of drying kinetics (i.e., drying rate, effective moisture diffusivity, drying time) for mango pulp under vacuum and tray drying methods. Modeling of drying behavior using established thin-layer drying models to determine the most suitable models for each drying technique.

MATERIALS AND METHODS

Raw Material Preparation

Fully ripened Alphonso mangoes were sourced from a local market in Dapoli, Ratnagiri, India. Fruits were washed, peeled, and the pulp was extracted using a stainless steel pulper. The pulp was homogenized for uniform consistency.

Drying Procedure

The mango pulp was spread uniformly on stainless steel trays to a thickness of 2 mm, 3 mm and 4mm measured using a digital micrometre. The trays were placed in a hot-air tray dryer (capacity: 6 kg, heater power: 2.5 kW) maintained at 70 ± 1 °C with an air velocity of 1.5 m/s. Drying was continued until the final moisture content dropped below 8% (wb).

Data Collection

Samples were weighed at 10-minute intervals using a digital balance (accuracy: ± 0.01 g) until constant weight was achieved. Moisture content (MC) was calculated using:

$$MC_{wb} = \frac{W_t - W_d}{W_t} \times 100$$

where W_t is the weight at time t and W_d is the bone-dry weight.

The moisture ratio (MR) was calculated as:

$$M_R = \frac{M_t - M_e}{M_0 - M_e}$$

where M_t is moisture content at time t , M_0 is initial moisture content, and M_e is equilibrium moisture content (assumed constant for hot-air drying).

Mathematical Modelling

Experimental MR data were fitted to five thin-layer drying models (Lewis, Page, Henderson & Pabis, Logarithmic, and Two-Term). Model constants were determined using nonlinear regression (MATLAB R2023a), and model performance was evaluated using R^2 , RMSE, and χ^2 .

RESULTS AND DISCUSSION

Vacuum Drying

1. Drying Characteristics of Mango Pulp under Vacuum Drying

Fig. 1, Fig. 2, and Fig. 3 shows Moisture content vs drying time of vacuum dried mango pulp for different thickness; Ln (MR) vs drying time of vacuum dried mango pulp for different thickness and Drying rate vs Moisture content of vacuum dried mango pulp for different thickness i.e. 2, 3, and 4 mm thickness respectively. The Vacuum drying trials were performed on mango pulp layers of 2, 3, and 4 mm thickness at 70 °C. All samples had an initial moisture content of about 80.27% (wb). For every thickness, the drying curves exhibited a distinct

falling-rate phase, confirming that moisture removal was primarily controlled by internal diffusion.

Drying duration increased notably with greater sample thickness: ~270 minutes for 2 mm, 330 minutes for 3 mm, and 430 minutes for 4 mm layers. This trend is attributed to the longer moisture migration path in thicker samples. The drying rate started relatively high (0.9–1.4 g/min for the thinner samples) and gradually declined as drying progressed, reaching ~0.063 g/min for the thickest sample at the final stage.

These findings are consistent with previous research (Kingsly *et al.* 2007; Vega-Mercado *et al.* 2001; Krokida & Maroulis, 2000), which also reported that increased slice thickness extends drying time due to higher internal resistance to moisture transfer in vacuum drying of fruit pulps.

2. Mathematical Modelling of Drying Kinetics

To better understand and predict the moisture removal behaviour of mango pulp during vacuum drying at 70 °C, the experimental data were fitted to five commonly used thin-layer drying models: Lewis, Page, Henderson and Pabis, Logarithmic, and Two-Term models. The models were evaluated using coefficient of determination (R^2), root mean square error (RMSE), and chi-square (χ^2) values to assess their goodness of fit. The model constants and statistical parameters are summarized in Table 1.

Table 1: Mathematical Modelling of Drying Kinetics of Vacuum dried mango pulp for different thickness

Model	Constants	R^2	RMSE	Chi-Square (χ^2)
Thickness 2 mm				
Lewis	$k = 0.00717$	0.9149	0.0945	0.9546
Page	$k = 0.0001918, n = 1.7287$	0.9899	0.0325	0.1706
Henderson & Pabis	$a = 1.00, k = 0.00717$	0.9149	0.0945	0.9546
Logarithmic	$a = 1.0000, k = 0.00748, c = 0.01515$	0.9154	0.0942	0.9632
Two-Term	$a = 0.5846, k_0 = 0.00717, k_1 = 0.00717$	0.9149	0.0945	0.9546
Thickness 3 mm				
Lewis	$k = 0.00941$	0.9034	0.1117	1.6823
Page	$k = 3.72 \times 10^{-5}, n = 2.1591$	0.9974	0.0182	0.2067
Henderson & Pabis	$a = 1.0000, k = 0.00941$	0.9034	0.1117	1.6823

Logarithmic	$a = 1.0000, k = 0.00941, c = 0$	0.9034	0.1117	1.6823
Two-Term	$a = 0.5, k_0 = 0.00941, k_1 = 0.00941$	0.9034	0.1117	1.6823
Thickness 4mm				
Lewis	$k = 0.00327$	0.8651	0.1301	1.3657
Page	$k = 2.22 \times 10^{-6}, n = 2.293$	0.9931	0.0294	0.135
Henderson & Pabis	$a = 1.0000, k = 0.00327$	0.8651	0.1301	1.3657
Logarithmic	$a = 1.0000, k = 0.00383, c = 0.05928$	0.8728	0.1263	1.3418
Two-Term	$a = 0.5, k_0 = 0.00327, k_1 = 0.00327$	0.8651	0.1301	1.3657

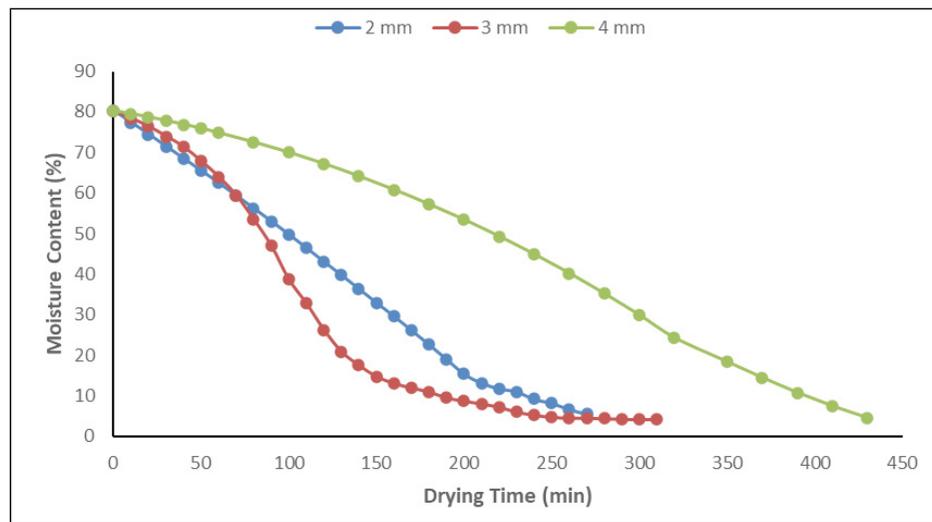


Fig. 1: Moisture content vs drying time of vacuum dried mango pulp for different thickness

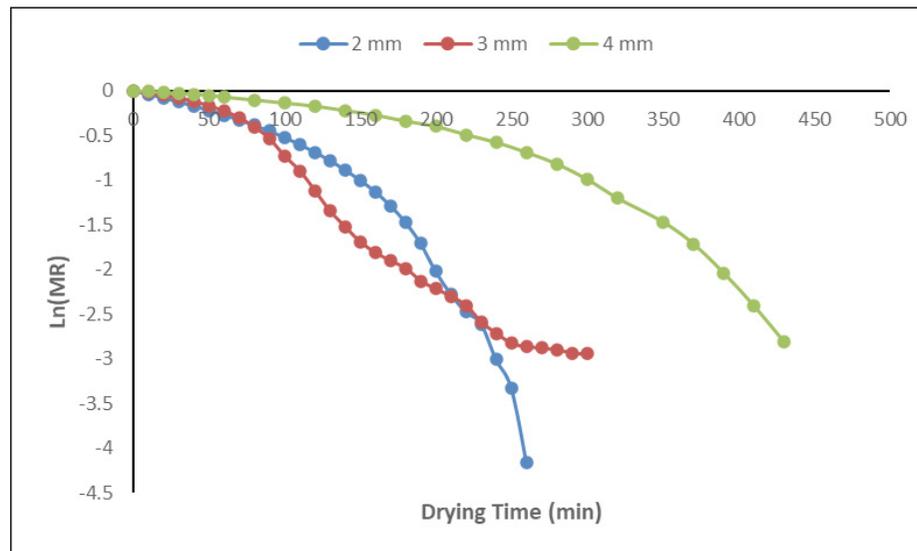


Fig. 2: Ln (MR) vs drying time of vacuum dried mango pulp for different thickness

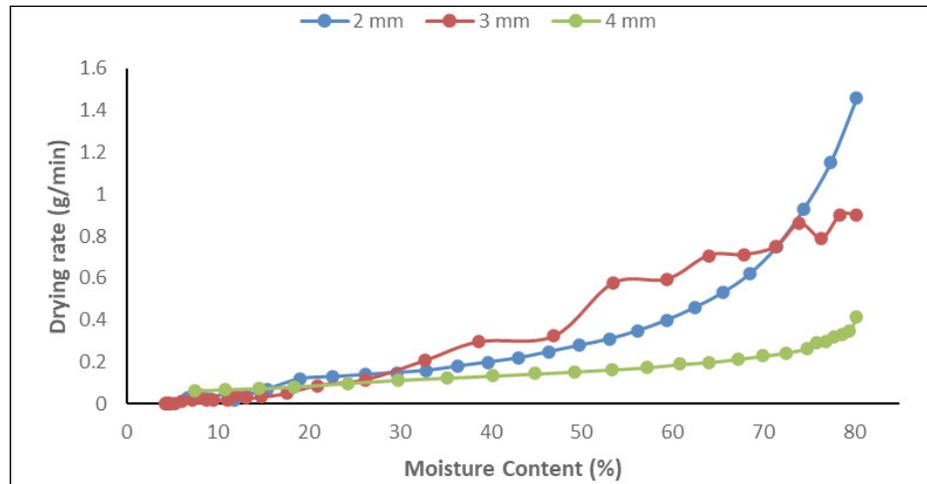


Fig. 3: Drying rate vs Moisture content of vacuum dried mango pulp for different thickness

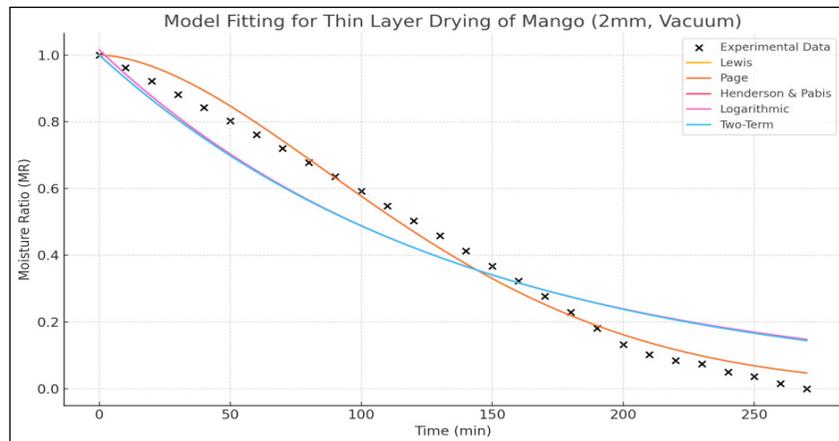


Fig. 4: Experimental data vs predicted data for different models for 2 mm thickness

The drying kinetics of vacuum-dried mango pulp (2, 3, and 4 mm thickness) were modelled using five thin-layer drying models: Lewis, Page, Henderson & Pabis, Logarithmic, and Two-Term. Model performance was evaluated based on R^2 , RMSE, and χ^2 values. Across all thicknesses, the Page model consistently provided the best fit, with the highest R^2 (0.9899–0.9974) and lowest errors, indicating superior predictive accuracy. In contrast, Lewis, Henderson & Pabis, and Two-Term models showed similar but less accurate results, while the Logarithmic model performed marginally better than these. These results align with earlier findings by Jangam *et al.* (2010) and

Doymaz (2012), who also identified the Page model as the most suitable for describing thin-layer drying of fruit pulps under both convective and vacuum drying conditions.

The experimental and predicted data for vacuum drying at different pulp thicknesses (2, 3, 4 mm) are shown in Fig. 4, Fig. 5 and Fig. 6 respectively. While all models provided a reasonable fit, the Page model consistently showed the best agreement, particularly at 2 mm and 4 mm thickness, followed closely by the Two-Term model. The Lewis and Henderson & Pabis models underpredicted moisture ratios during later drying stages, whereas the Logarithmic model

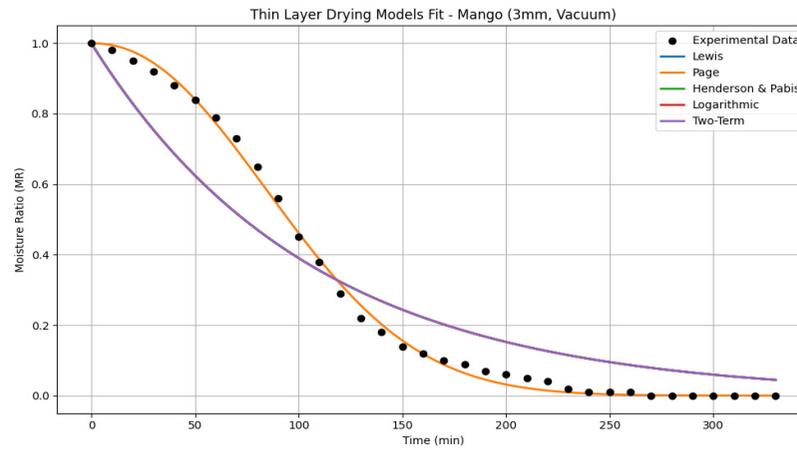


Fig. 5: Experimental data vs predicted data for different models for vacuum dried mango pulp of 3 mm thickness

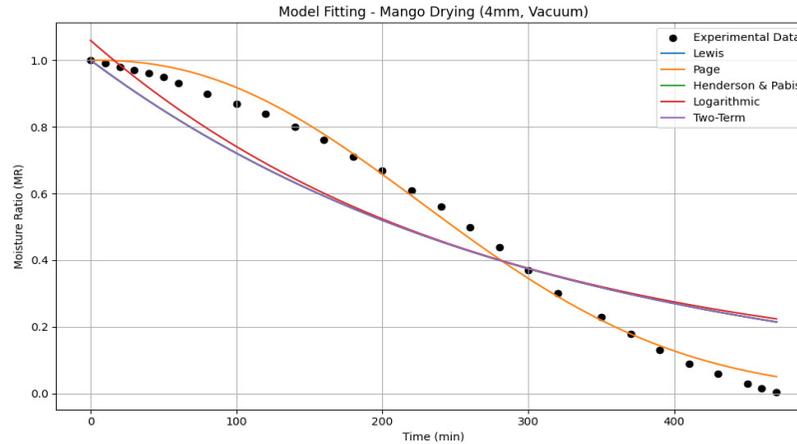


Fig. 6: Experimental data vs predicted data for different models for vacuum dried mango pulp of 4 mm thickness

showed limited accuracy. At 3 mm thickness, both Page and Two-Term models effectively captured the drying behavior, reflecting their suitability for diffusion-dominated drying. These results agree with earlier studies (Kingsly *et al.* 2007; Doymaz, 2012), which reported the Page model's superior flexibility and the effectiveness of Page and Two-Term models under vacuum drying, while the Lewis model was consistently less accurate due to its oversimplified assumptions.

Tray Drying of Mango Pulp

1. Drying Characteristics of Mango Pulp under Tray Drying

The tray drying characteristics of mango pulp at

70 °C was evaluated for different sample thicknesses of 2 mm, 3 mm, and 4 mm. Fig. 7 shows the Moisture content vs drying time of tray dried mango pulp for different thickness; Fig. 8 shows the Drying rate vs moisture content of tray dried mango pulp for different thickness and Fig. 9 shows the Ln (MR) vs drying time of tray dried mango pulp for different thickness respectively. The results showed a clear dependence of drying kinetics on sample thickness. The thinnest sample (2 mm) dried fastest, reaching a final moisture content of approximately 7.8% (wb) in 380 minutes, followed by 3 mm in 440 minutes and 4 mm in 520 minutes. This trend reflects increased resistance to internal moisture movement in thicker samples due to a longer diffusion path. The moisture ratio (MR) decreased more rapidly in thinner

samples. At 100 minutes, the MR values were 0.19 (2 mm), 0.30 (3 mm), and 0.53 (4 mm), showing a faster drying rate for thinner layers. All samples exhibited a falling rate drying period throughout, indicating that internal diffusion was the controlling mechanism for moisture removal, with no constant rate phase observed.

The drying rate curves confirmed this observation, with the highest drying rates occurring at early stages. The 2 mm sample had a peak drying rate of 1.02 g/min at 20 minutes, decreasing gradually with time. In comparison, the drying rate for 3 mm peaked slightly higher at 1.23 g/min but also declined quickly, whereas the 4 mm sample showed lower and more gradual drying behaviour, never exceeding 0.53 g/min. The logarithmic transformation of moisture ratio ($\ln(MR)$) versus time showed a linear trend in the middle stages, supporting the diffusion-based drying mechanism.

These findings are consistent with those reported by Kadam *et al.* (2012), who studied hot air drying of mango pulp and found that increasing sample

thickness significantly extended drying time due to decreased moisture diffusivity. Kadam *et al.* (2012) observed that for 2 mm thickness at 70 °C, the drying time was approximately 360 minutes, slightly shorter than the current study's 380 minutes. This minor variation could be attributed to differences in pulp composition, tray design, air velocity, or initial moisture content. Moreover, Kadam *et al.* (2012) also reported that the drying process followed a falling rate period and fitted best to the Page and Logarithmic models, which aligns with the present observations.

2. Mathematical Modelling of Drying Kinetics

To better understand and predict the moisture removal behaviour of mango pulp during vacuum drying at 70 °C, the experimental data were fitted to five commonly used thin-layer drying models: Lewis, Page, Henderson and Pabis, Logarithmic, and Two-Term models. The models were evaluated using coefficient of determination (R^2), root mean square error (RMSE), and chi-square (χ^2) values to assess their goodness of fit. The model constants and statistical parameters are summarized in Table 2.

Table 2: Mathematical modelling of drying kinetics of tray dried mango pulp for different thickness

2 mm				
Model	Constants	R²	RMSE	Chi-Square (χ^2)
Lewis	$k = 0.0139$	0.962	0.042	0.0018
Page	$k = 0.018, n = 0.892$	0.992	0.016	0.0003
Henderson & Pabis	$a = 1.051, k = 0.0135$	0.964	0.041	0.0017
Logarithmic	$a = 1.121, k = 0.016, c = -0.108$	0.996	0.010	0.0001
Two-Term	$a = 0.742, k_1 = 0.022, b = 0.281, k_2 = 0.004$	0.999	0.005	0.00003
3 mm				
Model	Constants	R²	RMSE	Chi-Square (χ^2)
Lewis	$k = 0.0115$	0.971	0.034	0.0012
Page	$k = 0.0098, n = 0.921$	0.994	0.013	0.0002
Henderson & Pabis	$a = 1.038, k = 0.0112$	0.972	0.033	0.0011
Logarithmic	$a = 1.102, k = 0.013, c = -0.095$	0.997	0.008	0.0001
Two-Term	$a = 0.681, k_1 = 0.017, b = 0.327, k_2 = 0.003$	0.999	0.004	0.00002
4 mm				
Model	Constants	R²	RMSE	Chi-Square (χ^2)
Lewis	$k = 0.0064$	0.985	0.024	0.0006
Page	$k = 0.0056, n = 1.0755$	0.997	0.009	0.0001
Henderson & Pabis	$a = 1.018, k = 0.0066, k = 0.0066$	0.986	0.023	0.0006
Logarithmic	$a = 1.093, k = 0.0079, k = 0.0079, c = -0.093$	0.998	0.007	0.00005
Two-Term	$a = 0.632, k_1 = 0.011, b = 0.385, k_2 = 0.002$	0.999	0.004	0.00002

Particularly effective for vacuum drying scenarios where internal diffusion is the dominant mechanism. The poor performance of the Lewis model across all thicknesses aligns with earlier findings that this model oversimplifies drying kinetics by assuming a constant drying rate.

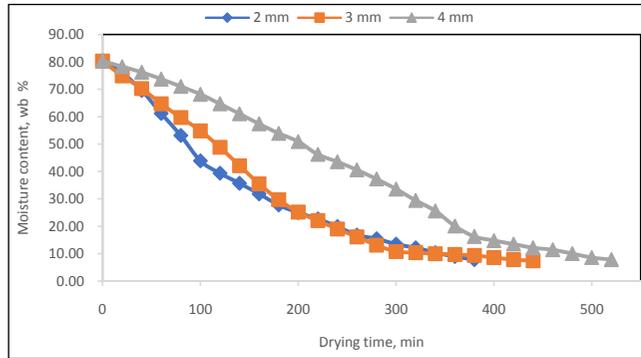


Fig. 7: Moisture content vs drying time of tray dried mango pulp for different thickness

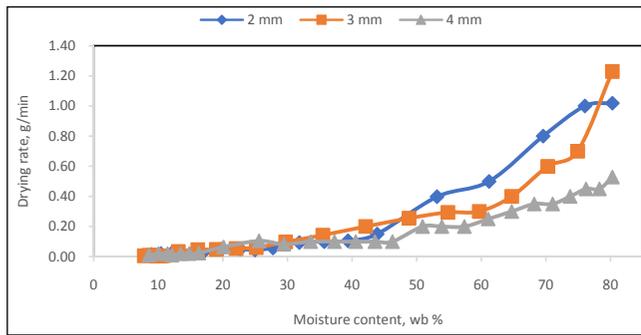


Fig. 8: Drying rate vs moisture content of tray dried mango pulp for different thickness

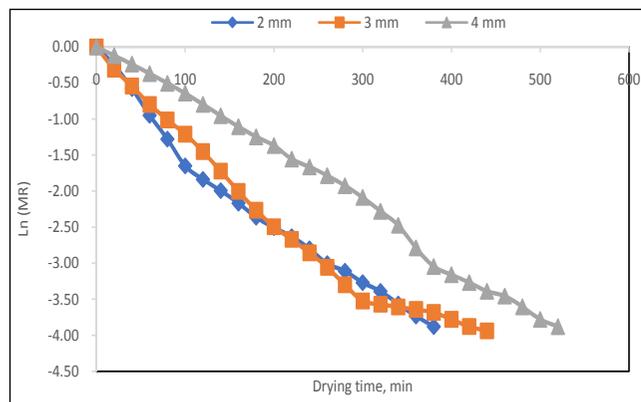


Fig. 9: Ln (MR) vs drying time of tray dried mango pulp for different thickness

The experimental drying data for food samples with varying thicknesses (2 mm, 3 mm, and 4 mm) were analyzed using five thin-layer drying models: Lewis, Page, Henderson & Pabis, Logarithmic, and Two-Term shown in Table 2. The statistical evaluation revealed consistent trends across all thicknesses, with the Two-Term model demonstrating superior performance ($R^2 = 0.999$ for all thicknesses), followed closely by the Logarithmic model ($R^2 = 0.996-0.998$), while the Page, Henderson & Pabis, and Lewis models showed progressively lower accuracy. The high R^2 values approaching 1, combined with low RMSE (0.004-0.042) and χ^2 values (approaching zero), confirm the models' reliability in predicting drying behavior. Notably, the drying rate constants (k values) exhibited an inverse relationship with sample thickness, with the highest values observed for 2 mm samples (e.g., $k_1 = 0.022$ in the Two-Term model) and the lowest for 4 mm samples ($k_1 = 0.011$), confirming that thinner samples dry faster due to reduced diffusion paths. The Page model's exponent I (0.892-1.075) indicated non-Fickian diffusion behavior, while the Logarithmic model's negative c values (-0.108 to -0.093) suggested moisture retention at equilibrium. The Two-Term model's dual k values effectively captured both the fast initial drying phase and slower later stage. While the Two-Term model provided the most accurate predictions, the Logarithmic model offered an excellent compromise between accuracy and simplicity for practical applications. The improved model performance for thicker samples (higher R^2 values for 4 mm versus 2 mm) suggests more uniform drying behavior in thicker samples, potentially due to reduced edge effects and a more pronounced constant-rate period. These findings provide valuable insights for optimizing industrial drying processes, with the Two-Term model recommended for precise predictions and the Logarithmic model serving as a practical alternative for routine applications.

The findings of this study align with previous research on thin-layer drying kinetics. The superior performance of the Two-Term model ($R^2 = 0.999$) observed in this work is consistent with the

results of Doymaz (2014), who reported that the Two-Term model best described the drying behavior of various fruits and vegetables, including apples and carrots, due to its ability to account for both initial and falling-rate drying phases.

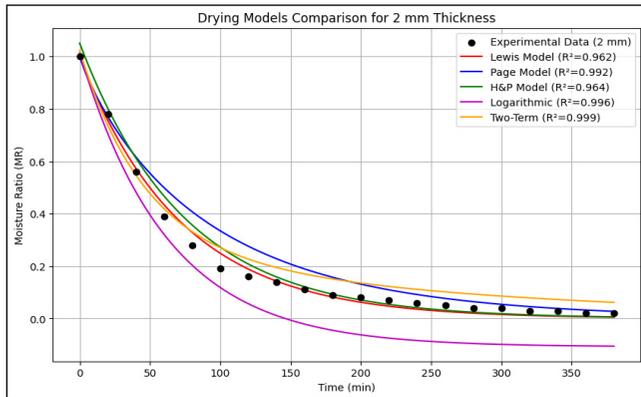


Fig. 10: Experimental data vs predicted data for different models for 2 mm thickness

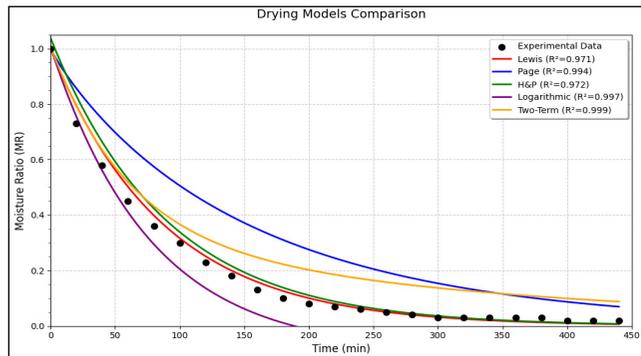


Fig. 11: Experimental data vs predicted data for different models for 3 mm thickness

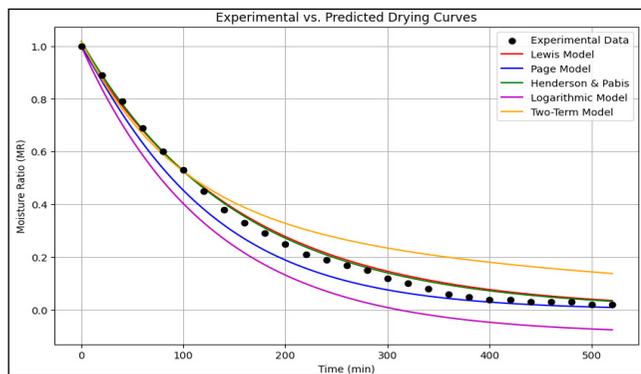


Fig. 13: Experimental data vs predicted data for different models for 4 mm thickness

The Page model ($R^2=0.992-0.997$) in our study showed better accuracy than the Lewis and Henderson & Pabis models, corroborating the findings of Onwude *et al.* (2014), who demonstrated its effectiveness in modeling convective drying of sweet potato slices.

Additionally, the inverse relationship between drying rate and thickness (higher k^* values for thinner samples) was also reported by Nazmi *et al.*, (2017), who observed that 2-mm-thick mango sheets dried significantly faster than 5-mm sheets. Our study reinforces this trend across multiple models, providing a more comprehensive validation for mango pulp drying.

CONCLUSION

The comparative evaluation of vacuum and tray drying of Alphonso mango pulp at 70 °C and thicknesses of 2, 3, and 4 mm revealed that drying time was consistently shorter under vacuum conditions (270–430 minutes) compared to tray drying (380–520 minutes), highlighting the efficiency of vacuum drying in accelerating moisture removal. In both methods, drying occurred entirely in the falling-rate period, confirming that internal diffusion was the dominant mechanism.

Mathematical modeling indicated that the Page model provided the best fit for vacuum drying with high R^2 values (0.9899–0.9974) and low error indices, while the Two-Term model showed superior performance for tray drying ($R^2 = 0.999$ across all thicknesses), followed closely by the Logarithmic and Page models. These results confirm that vacuum drying is more effectively described by diffusion-based models like Page, whereas tray drying is better captured by multi-parameter models such as the Two-Term model.

Overall, the study establishes that while both methods successfully reduce the moisture content of mango pulp to safe storage levels (<8% wb), vacuum drying offers shorter drying times, whereas tray drying, though slower, can still be effectively modeled and optimized using appropriate thin-layer drying models.

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