



Comprehensive Study on the Drying Kinetics and Mathematical Modelling of Black Turmeric (*Curcuma caesia*) using Different Drying Methods

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ABSTRACT

Background: BT-Black Turmeric (*Curcuma caesia*), is a medicinal plant rich in bioactive compounds. Drying extends its shelf life while preserving phytochemicals, but the method and parameters impact drying rate and quality. Optimizing drying conditions is crucial for efficient, high-quality industrial processing.

Methods: This study investigates the drying kinetics of BT slices at three thickness levels (1 mm, 2 mm and 3 mm) under different drying techniques: hot air oven drying (HAO), tray drying (TD) and vacuum drying (VD). Drying experiments were conducted at temperatures of 60°C, 70°C and 80°C to assess the influence of temperature and slice thickness on drying efficiency. The moisture ratio was modelled using nine mathematical models to determine the most suitable model for predicting drying behavior. Model performance was evaluated based on the coefficient of determination (R^2).

Result: The experimental results indicate that 1 mm slices exhibited the highest drying rate across all drying techniques and temperatures. Among the drying methods, TD was identified as the most effective at 80°C, 1 mm slices in TD demonstrated significantly reduced drying time, minimal color degradation providing an optimal balance between drying kinetics and product quality, making it the most favourable condition for large-scale processing. Furthermore, the Midilli model exhibited the best fit for describing the drying behavior of BT, achieving the highest predictive accuracy with an R^2 value of 1.000. These findings establish TD as the optimal drying conditions for industrial applications, providing a scientific framework for improving BT processing efficiency.

Key words: Black turmeric, Drying kinetics, Mathematical modelling, Midilli model, Page model, Tray dryer, Vacuum drying.

INTRODUCTION

Black turmeric (BT) (*Curcuma caesia*) is a lesser-known turmeric variety but highly valued spice, native to Southeast Asia, primarily used in traditional medicine for its numerous therapeutic properties. It belongs to the *Zingiberaceae* family and its rhizomes are particularly prized for their medicinal benefits and also in culinary applications (Fuloria *et al.*, 2022; Chauhan *et al.*, 2024). The rhizomes of BT contain various active compounds, such as curcumin, essential oils and alkaloids *etc.*, which are responsible for its medicinal effects (Kondareddy *et al.*, 2019). However, despite its promising medicinal uses, the commercialization of BT remains limited by challenges such as its post-harvest handling, preservation and drying processes. As these compounds are sensitive to temperature and time, meaning that improper drying can result in the loss of their efficacy (Manzoor *et al.*, 2019). Efficient drying of BT is vital to maintain its active constituents, flavor and overall quality during storage and transport. Therefore, the drying of BT, is a critical process in food and medicinal herb industries (Lakshmi *et al.*, 2018).

To overcome this, various drying techniques can be employed, each with its own set of advantages and challenges. For instance, in traditional method, sun drying, is a low-cost method but is highly dependent on weather conditions and can lead to inconsistent quality due to prolonged exposure to the sun (Min *et al.*, 2022). Moreover,

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in modern drying methods such as oven drying, tray drying, microwave drying, vacuum drying and freeze-drying offer greater control over other types and can preserve the medicinal properties of the plant more effectively (Adeyeye *et al.*, 2022). Oven drying provides more controlled heat, while microwave drying offers faster drying times with minimal thermal degradation (Deepak *et al.*, 2017). Tray drying offers a cost-effective and scalable drying method with uniform heat distribution, making it suitable for diverse applications (Saritha and Waghay, 2023). Vacuum drying enables efficient moisture removal at lower temperatures, minimizing thermal degradation and oxidation, thereby

preserving product quality (Krakowska-Sieprawska *et al.*, 2022). Drying can lead to undesirable quality changes, including loss of volatile compounds, degradation of active ingredients and texture changes (Chobot *et al.*, 2024). Thus, optimizing drying techniques is crucial to balance efficiency and quality. The drying kinetics of BT depend on intrinsic properties such as moisture content, texture and composition. Drying reduces moisture levels to inhibit microbial growth and enzymatic reactions, preserving the product (Sharifi-Rad *et al.*, 2020).

Drying kinetics studies moisture removal rates, influenced by temperature, humidity, air velocity and material properties. Mathematical models help analyse BT's drying behavior (Keneni *et al.*, 2019), offering insights into moisture loss and quality impact (He *et al.*, 2021). Common models include the Page, Henderson and Pabis, Lewis and Newton models, each with advantages and limitations.

Therefore, this research investigates the drying kinetics of BT at different temperatures. It aims to analyze the drying process using mathematical modeling and identify the most efficient technique to minimize quality loss and drying time. The findings will support sustainable and effective drying practices in the food and herbal medicine industries.

MATERIALS AND METHODS

BT rhizomes were sourced from a local market in Chennai, Tamil Nadu, India. Mature, uniformly sized rhizomes were cleaned, sliced into (1,2,3 mm) thicknesses (verified using a calibrated vernier caliper, Absolute Digimatic CD-8'CSX) and subjected to various drying methods. Initial moisture content was determined using the AOAC (2005) hot air oven method at 105±5°C (wet basis) until a constant weight was achieved.

Different drying

The sliced rhizomes of BT were subjected to drying using hot air oven (HAO, HV-1207, Hitech Lab Solution, India), tray dryer (TD, SS Model No. HV-105, India) and vacuum dryer (VD, Hitech Equipment, India) at 70°C, 80°C and 90°C. The initial moisture content of the fresh BT rhizomes was determined using the AOAC (2005) oven-drying method at 105±5°C until a constant weight was achieved. Moisture loss during drying was monitored using an analytical balance until a stable moisture content was reached. All experiments were conducted in triplicate and product temperature was measured using a digital thermometer (Venus Calibration and Instruments, Chennai, India).

Drying kinetics

Modelling the drying characteristics of the sample is crucial for understanding the overall behavior of the drying process (Inyang *et al.*, 2018). The experimental data were represented as a plot of the dimensionless moisture ratio (MR) versus drying time (in min). The moisture ratio during the drying process was calculated using the following equation 1 (Borah *et al.*, 2015).

$$MR = \frac{M_t}{M_0} \quad \dots(1)$$

Where,

M_t , M_0 = The moisture content at any given time (g water/g dry matter), the initial moisture content (g water/g dry matter).

Drying rate

The drying rate (DR) is defined as the amount of moisture lost from the wet solid per unit of time, represented by the differential quotient $-dX/dh$, under constant drying conditions. These conditions include temperature, pressure, humidity and air velocity, which remain stable throughout the drying process.

The drying rate of the sample is calculated using the following equation 2:

$$DR = \frac{M_t + \Delta_t - M_t}{\Delta_t} \quad \dots(2)$$

Where,

$M_{t+\Delta t}$ = The moisture content at time $t+\Delta t$ (g water/g dry matter).
DR = The drying rate expressed in g water/g dry matter per minute.

Color analysis

The color analysis of different dried BT under different temperature were measured for L^* , a^* and b^* using Hunter calorimeter (Hunter Lab, ColorQuest XE, Hunter Associates Laboratory, USA).

Mathematical modelling

In order to characterize the drying process and the moisture ratio (MR) over time, mathematical modelling was done on three distinct dried BT slices using nine different models (Inyang *et al.*, 2018). These models include the Weibull model, Midilli model, Geometric model, Henderson and Pabis model, Lewis model, Page model, Logarithmic model and the Ademiluyi Modified model, as shown in Table 1.

Statistical analysis

Nonlinear regression analyses were conducted using Microsoft Excel (Version 2501, 2019) to estimate the parameter values of the model equations. The goodness of fit was assessed to evaluate the accuracy and reliability of each model in comparison to the experimental data. The following sections describe the metrics and equations used for this evaluation.

$$R^2 = 1 - \frac{\sum_{i=1}^N (M R_{pre, i} - M R_{exp, i})^2}{\sum_{i=1}^N (M R_{exp, i} - \overline{M R_{exp}})^2} \quad \dots(3)$$

RESULTS AND DISCUSSION

Drying curves

The drying kinetics of BT were analyzed to assess moisture reduction under varying conditions. Drying curves highlighted the effects of temperature (60°C, 70°C, 80°C), drying methods (HAO, TD, VD) and sample thicknesses (1-3 mm) over 0-660 min (Fig 1-3). Initially, the fresh BT rhizomes had an initial moisture content of approximately

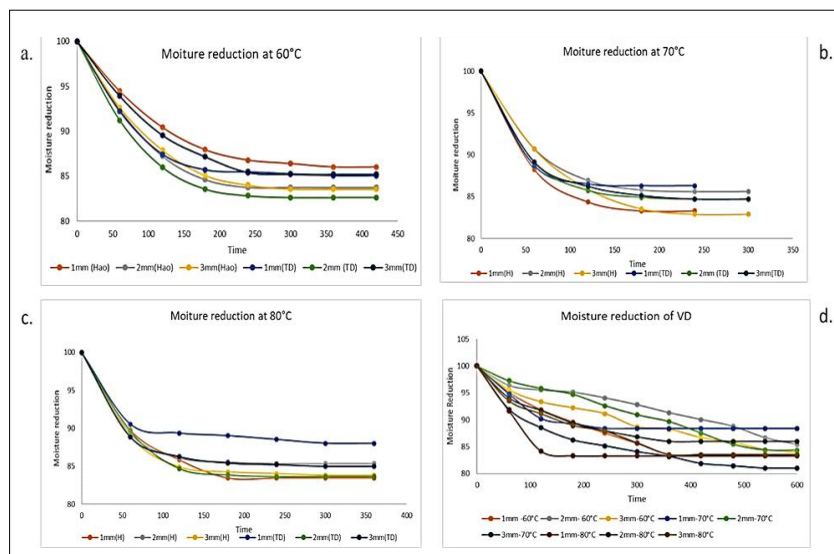


Fig 1: Graph of moisture reduction against drying time for BT slices (a) Moisture reduction at 60°C (b) Moisture reduction at 70°C (c) Moisture reduction at 80°C (d) Moisture reduction of VD.

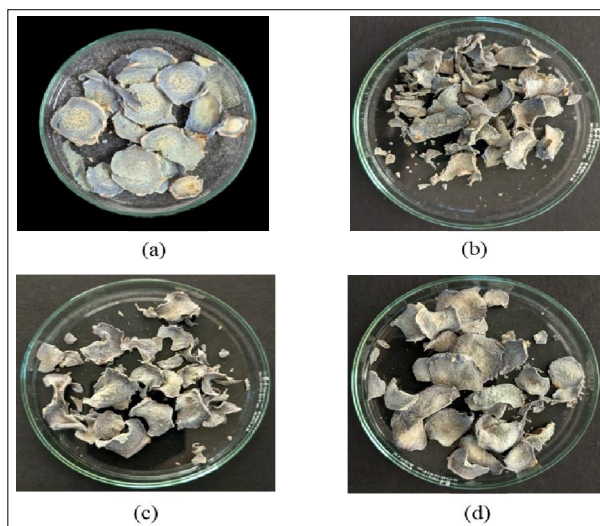


Fig 2: Image of dried BT samples (a) Fresh BT (b) HAO dried (c) TD dried (d)VD dried.

Table 1: Different modelling performed for drying kinetics.

Model name	Equation
Newton/Lewis	$MR = \exp(-kt)$
Page	$MR = \exp(-kt^n)$
Modified page	$MR = \exp[-(kt)^n]$
Henderson and pabis	$MR = a \exp(-kt)$
Logarithmic	$MR = a \exp(-kt) + c$
Weibull	$MR = \exp\left[-\left(\frac{t}{\beta}\right)^\alpha\right]$
Midilli	$MR = a \exp(-kt^n) + bt$
Geometric	$MR = a \cdot \exp(-kt)$
Ademiluyi modified	$MR = \exp\left[-\left(\frac{kt}{1 + \beta t}\right)^n\right]$

82.4±1.2% (wet basis). Which was taken as 100% of the original moisture level, serving as the reference point for assessing the drying behaviour. BT samples showed the most significant reduction in the first 60 min, followed by a slower phase due to the decrease in surface moisture. At 60 min, 1 mm slices exhibited moisture reduction of 95.08% (60°C) and 94.80% (70°C), similar to the findings of Akter *et al.* (2023). By 120 min, the values decreased to 91.86% (60°C) and 90.21% (70°C) and further to 89.58% and 89.28% at 180 min. By 300 min, the 3 mm samples at 70°C reached 82.90%, indicating slower drying for thicker samples. At 420 min, moisture reduction was 83.52% (1 mm, 60°C) and 83.51% (3 mm, 80°C). Final equilibrium moisture reduction levels at 660 min were 83.52% (1 mm, 60°C), 85.38% (2 mm, 60°C) and 83.51% (3 mm, 80°C). Drying followed a rapid initial loss, then a slower rate. VD ensured consistent reduction, maintaining efficiency and reaching 83.52% at 660 min for 1 mm, 60°C. TD outperformed HAO, particularly for thicker slices, aligning with Rihana *et al.* (2019), who found TD more efficient for chickpea drying. Higher temperatures (70°C, 80°C) improved drying, with 70°C slightly outperforming 60°C. These findings help optimize drying parameters to enhance efficiency and preserve BT quality.

Drying rate

The drying rate declined over time due to reduced moisture content. Thinner samples (1 mm) dried significantly faster than thicker ones (2 mm, 3 mm) across all methods (TD, HAO, VD). Higher temperatures (70°C, 80°C) improved efficiency by enhancing heat and mass transfer, while lower temperatures (60°C) prolonged drying. Thinner samples dried faster due to lower resistance to heat penetration and moisture diffusion, while thicker samples retained

more moisture and exhibited higher thermal resistance. Drying primarily occurred during the falling rate period, with an initial rapid loss followed by a slower rate. These findings emphasize the impact of sample thickness and temperature on drying efficiency. Thinner samples and higher temperatures facilitated faster drying, aligning with Abioye *et al.* (2021), who found turmeric drying times depended on specimen thickness.

Color analysis

The highest mean L^* was in BT60VD (55.40±1.06a), indicating maximum brightness, while BT80TD (44.06±0.43) showed the lowest, indicating darkness.

Intermediate L^* values were in BT70TD (50.11±0.29) and BT80HAO (50.27±1.05). For a^* , BT80HAO (0.74±0.31) was highest (red), whereas BT60TD (-1.59±0.19) and BT70VD (-1.53±0.25) were lowest (green); BT70HAO (0.34±0.32ab) was intermediate. In b^* , BT80HAO (7.83±0.21) and BT80VD (7.46±0.22ab) were highest (yellow), while BT60TD (4.13±0.34) was lowest. Intermediate b^* values in BT70VD (6.45±0.22) and BT70HAO (6.87±0.13) showed moderate yellow tones.

Mathematical modelling of drying curves

The drying kinetics of BT slices (1-3 mm) were studied at 60°C, 70°C and 80°C using hot air oven (HAO), tray (TD)

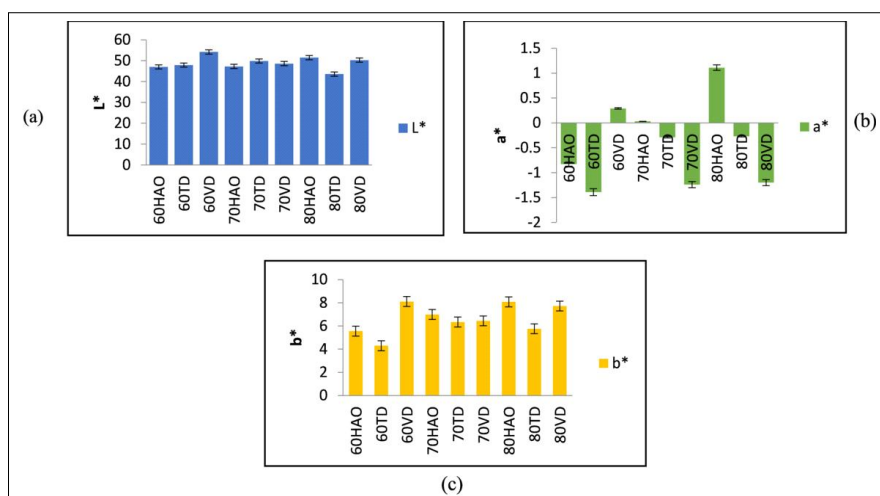


Fig 3: Colour analysis of BT at different drying conditions (a) L^* (b) a^* (c) b^* .

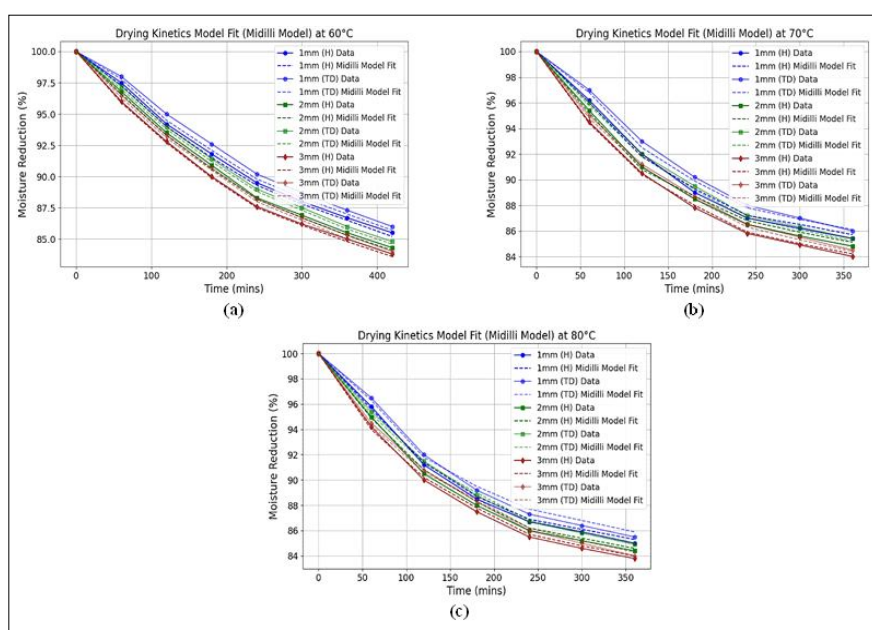


Fig 4: Comparison of experimental moisture ratio with predicted moisture ratio by models for dried BT slices at different temperature (a) 60°C (b) 70°C (c) 80°C.

Table 2: Different model constants and coefficients of BT at 60°C.

Model name	Dryer	Dataset	k	R ²
Newton/Lewis model	HAO	1 mm	0.0025	0.993
		2 mm	0.003	0.9912
		3 mm	0.003	0.9914
	TD	1 mm	0.0031	0.9933
		2 mm	0.0036	0.9904
		3 mm	0.0027	0.9935
	VD	1 mm	0	0.803
		2 mm	0	0.98
		3 mm	0	0.944
Page model	HAO	1 mm	0.0025	0.993
		2 mm	0.003	0.9912
		3 mm	0.003	0.9914
	TD	1 mm	0.0031	0.9933
		2 mm	0.0036	0.9904
		3 mm	0.0027	0.9935
	VD	1 mm	0.014	0.948
		2 mm	0	0.981
		3 mm	0.005	0.993
Logarithmic model	HAO	1 mm	5.12	0.99
		2 mm	4.89	0.98
		3 mm	4.75	0.99
	TD	1 mm	5.05	0.98
		2 mm	4.95	0.98
		3 mm	5.08	0.99
	VD	1 mm	6.12	0.968
		2 mm	235.547	0.98
		3 mm	8.681	0.991
Weibull model	HAO	1 mm	0.511	-55.257
		2 mm	0	-40.159
		3 mm	2.774	-39.792
	TD	1 mm	0	-49.859
		2 mm	0	-36.1
		3 mm	0.771	-48.239
	VD	1 mm	0	-29.315
		2 mm	0	-41.221
		3 mm	0	-35.213
Modified page model	HAO	1 mm	0.01	0.987
		2 mm	0.015	0.982
		3 mm	0.02	0.98
	TD	1 mm	0.013	0.985
		2 mm	0.016	0.983
		3 mm	0.018	0.979
	VD	1 mm	0.014	0.948
		2 mm	0	0.981
		3 mm	0.005	0.993
Midilli model	HAO	1 mm	0.02	0.988
		2 mm	0.025	0.985
		3 mm	0.018	0.992
		1 mm	0.022	0.986

Table 2: Continue...

Table 2: Continue...

Ademiluyi Modified	TD	2 mm	0.023	0.983
		3 mm	0.021	0.989
		1 mm	0.012	0.951
	VD	2 mm	0	0.98
		3 mm	0.004	0.993
		1 mm	0.01	0.987
	HAO	2 mm	0.02	0.98
		3 mm	0.03	0.975
		1 mm	0.015	0.982
Geometric	TD	2 mm	0.018	0.978
		3 mm	0.022	0.973
		1 mm	0.012	-29.663
	VD	2 mm	0.011	-41.453
		3 mm	0.01	-35.515
		1 mm	0.021	0.876
	HAO	2 mm	0.018	0.854
		3 mm	0.019	0.872
		1 mm	0.02	0.865
Henderson and Pabis	TD	2 mm	0.017	0.854
		3 mm	0.022	0.87
		1 mm	0.012	0.951
	VD	2 mm	0	0.98
		3 mm	0.004	0.993
		1 mm	0	0.798
	HAO	2 mm	0	0.709
		3 mm	0	0.753
		1 mm	0	0.669
	TD	2 mm	0	0.695
		3 mm	0	0.78
		1 mm	0	0.803
	VD	2 mm	0	0.98
		3 mm	0	0.944
		1 mm	0	

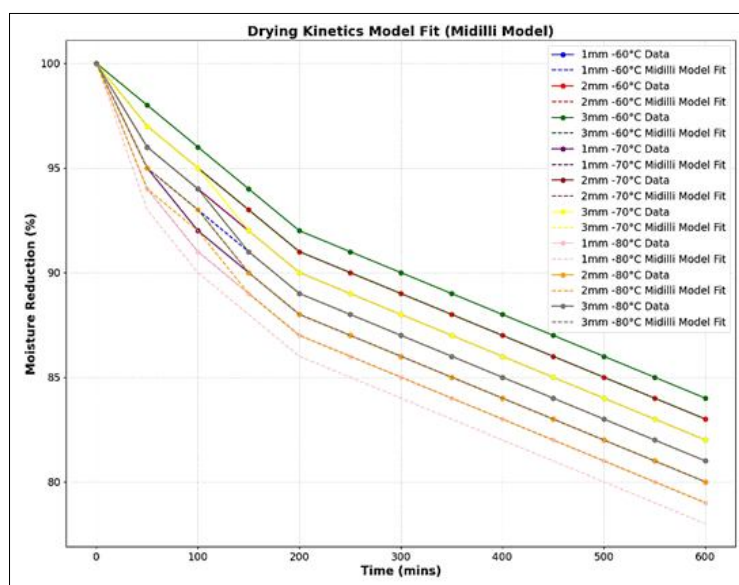
**Fig 5:** Comparison of experimental moisture ratio with predicted moisture ratio by Midilli's model for dried BT slices using VD.

Table 3: Different model constants and coefficients of BT at 70°C.

Models		Dataset	k	R ²
Newton/Lewis model	HAO	1 mm	0	0.555
		2 mm	0	0.71
		3 mm	0.001	0.802
	TD	1 mm	0	0.568
		2 mm	0.001	0.665
		3 mm	0.001	0.683
	VD	1 mm	0	0.508
		2 mm	0	0.977
		3 mm	0	0.778
Page model	HAO	1 mm	0.036	-47.773
		2 mm	0.04	-61.285
		3 mm	0.034	-43.312
	TD	1 mm	0.055	-66.129
		2 mm	0.04	-54.178
		3 mm	0.041	-55.371
	VD	1 mm	0.035	0.91
		2 mm	0.001	0.982
		3 mm	0.025	0.987
Logarithmic model	HAO	1 mm	2.15	0.954
		2 mm	3.269	0.985
		3 mm	5.385	0.987
	TD	1 mm	1.453	0.993
		2 mm	2.773	0.99
		3 mm	2.861	0.995
	VD	1 mm	2.204	0.926
		2 mm	21.505	0.984
		3 mm	5.153	0.994
Weibull model	HAO	1 mm	0	-47.775
		2 mm	0	-61.292
		3 mm	0	-43.324
	TD	1 mm	0.001	-66.129
		2 mm	0	-54.181
		3 mm	0	-55.372
	VD	1 mm	0	-68.559
		2 mm	0	-29.693
		3 mm	0	-26.945
Modified page model	HAO	1 mm	0	0.555
		2 mm	0	0.71
		3 mm	0.001	0.802
	TD	1 mm	0	0.568
		2 mm	0.001	0.665
		3 mm	0.001	0.683
	VD	1 mm	0.035	0.91
		2 mm	0.001	0.982
		3 mm	0.025	0.987
Midilli Model	HAO	1 mm	0.008	0.999
		2 mm	0.008	0.999
		3 mm	0.005	1
		1 mm	0.028	0.999

Table 3: Continue...

Table 3: Continue...

Ademiluyi Modified model	TD	2 mm	0.014	0.999
		3 mm	0.016	1
		1 mm	0.035	0.911
	VD	2 mm	0.001	0.983
		3 mm	0.023	0.988
		1 mm	0.008	0.999
	HAO	2 mm	0.008	0.999
		3 mm	0.005	1
		1 mm	0.028	0.999
Geometric model	TD	2 mm	0.014	0.999
		3 mm	0.016	1
		1 mm	0.013	-68.545
	VD	2 mm	0.015	-29.942
		3 mm	0.017	-27.214
		1 mm	0	0.555
	HAO	2 mm	0	0.71
		3 mm	0.001	0.802
		1 mm	0	0.568
	TD	2 mm	0.001	0.665
		3 mm	0.001	0.683
		1 mm	0.035	0.911
	VD	2 mm	0.001	0.983
		3 mm	0.023	0.988
		1 mm	0	0.555
Henderson/Pabis model	HAO	2 mm	0	0.71
		3 mm	0.001	0.802
		1 mm	0	0.568
	TD	2 mm	0.001	0.665
		3 mm	0.001	0.683
		1 mm	0	0.508
	VD	2 mm	0	0.977
		3 mm	0	0.778

and vacuum drying (VD). Nine models were evaluated (Table 2-4) and (Fig 4-5). At 60°C, the Logarithmic model performed well ($R^2 \approx 0.99$), while the Weibull model showed poor performance with negative R^2 . The Modified Page and Midilli models had moderate fits ($R^2 > 0.98$). The Newton/Lewis and Page models performed best (R^2 0.9904-0.9935). Nukulwar and Tungikar (2021) similarly reported the Page model as the best fit (R^2 0.99) for turmeric drying.

At 70°C, the Newton/Lewis model had moderate predictive capability (R^2 0.508-0.977). Doymaz *et al.* (2011) found the Page model best fit (R^2 0.99) for sweet cherry drying at 70°C. VD samples, especially 2 mm, showed good fits, but 1 mm samples had high variability. The Weibull model showed stable performance for VD, the Modified Page model improved upon the standard Page model for TD and the Midilli model was the most accurate with high R^2 values.

At 80°C, the Newton/Lewis model performed well (R^2 0.555-0.918), best for 2 mm VD but weaker for 1 mm VD.

Komonsing *et al.* (2022) identified the Midilli and Kucuk models as best fits (R^2 0.99) for turmeric drying at 80°C. Bhogesara *et al.* (2024) found the Midilli model optimal for fenugreek leaves dried with a solar dryer. The Page model excelled for HAO and TD (R^2 0.908-0.993), peaking at 2 mm HAO but lower for VD. The Logarithmic model was consistent (R^2 0.907-0.99), highest for 1 mm HAO, lowest for 1 mm VD. The Weibull model was unreliable, with good fits for HAO/TD (R^2 0.91-0.95) but negative R^2 for VD. The Modified Page model had moderate accuracy (R^2 0.481-0.984), best for 2 mm VD but inconsistent elsewhere. The Ademiluyi Modified model performed well for HAO/TD (R^2 0.908-0.993) but failed for VD. The Geometric model performed poorly, except moderate fits for VD (R^2 0.898-0.984). The Henderson and Pabis model had moderate accuracy (R^2 0.431-0.918), best for 2 mm VD but inconsistent otherwise. Overall, the Midilli model outperformed others, aligning with Siqueira *et al.* (2024), which highlighted its superior predictive accuracy for turmeric and similar species.

Table 4: Different Model constants and coefficients of BT at 80°C.

Models		Datasets	k	R ²
Newton/Lewis model	HAO	1 mm	0	0.555
		2 mm	0	0.71
		3 mm	0.001	0.802
	TD	1 mm	0	0.568
		2 mm	0.001	0.665
		3 mm	0.001	0.683
	VD	1 mm	0	0.431
		2 mm	0	0.918
		3 mm	0	0.786
Page model	HAO	1 mm	0.025	0.991
		2 mm	0.044	0.993
		3 mm	0.08	0.908
	TD	1 mm	0.035	0.966
		2 mm	0.06	0.95
		3 mm	0.064	0.992
	VD	1 mm	0.067	0.897
		2 mm	0.008	0.984
		3 mm	0.018	0.963
Logarithmic model	HAO	1 mm	2.5	0.99
		2 mm	2.7	0.98
		3 mm	2.9	0.97
	TD	1 mm	2.6	0.98
		2 mm	2.55	0.97
		3 mm	2.8	0.97
	VD	1 mm	2.522	0.907
		2 mm	8.853	0.983
		3 mm	5.245	0.975
Weibull model	HAO	1 mm	160	0.95
		2 mm	170	0.94
		3 mm	160	0.92
	TD	1 mm	180	0.93
		2 mm	180	0.94
		3 mm	160	0.91
	VD	1 mm	0	-33.288
		2 mm	0	-24.269
		3 mm	0	-32.147
Modified page model	HAO	1 mm	1313.554	0.83
		2 mm	1940.266	0.714
		3 mm	2788.387	0.481
	TD	1 mm	2934.589	0.706
		2 mm	2442.443	0.572
		3 mm	2673.305	0.59
	VD	1 mm	0.067	0.897
		2 mm	0.008	0.984
		3 mm	0.018	0.963
Ademiluyi modified model	HAO	1 mm	0.025	0.991
		2 mm	0.044	0.993
		3 mm	0.08	0.908
		1 mm	0.035	0.966

Table 4: Continue...

Table 4: Continue...

Geometric model	TD	2 mm	0.06	0.95
		3 mm	0.064	0.992
		1 mm	0.014	-33.285
	VD	2 mm	0.016	-24.494
		3 mm	0.018	-32.474
		1 mm	64.913	-51.2
	HAO	2 mm	32.936	-55.103
		3 mm	0.082	-48.897
		1 mm	46.802	-74.555
	TD	2 mm	17.868	-45.232
		3 mm	30.463	-54.685
		1 mm	0.067	0.898
Henderson/Pabis model	VD	2 mm	0.007	0.984
		3 mm	0.016	0.964
		1 mm	0.001	0.83
	HAO	2 mm	0.001	0.714
		3 mm	0	0.481
		1 mm	0	0.706
	TD	2 mm	0	0.572
		3 mm	0	0.59
		1 mm	0	0.431
	VD	2 mm	0	0.918
		3 mm	0	0.786

CONCLUSION

This study presents a comprehensive analysis of the drying kinetics of black turmeric (BT) subjected to three different drying methods such as hot air oven (HAO), tray dryer (TD) and vacuum dryer (VD) under varying temperatures (60°C, 70°C and 80°C) and slice thicknesses (1 mm, 2 mm and 3 mm). The drying process exhibited an initial phase of rapid moisture removal followed by a gradual decrease as equilibrium moisture content was approached. Among the investigated methods, tray drying (TD) demonstrated the highest drying efficiency, reducing the moisture content from $82.4 \pm 1.2\%$ to approximately 8.5% (wet basis) within 420 min at 80°C for 1 mm slices, whereas HAO and VD required longer durations to achieve similar reductions. This superior performance of TD can be attributed to its uniform air circulation and effective heat transfer, which facilitated faster and more consistent drying, especially for thinner slices. Furthermore, the Midilli model provided the most accurate prediction of drying behaviour, consistently yielding the highest coefficients of determination ($R^2 \approx 0.99-1.00$) across all conditions, confirming its robustness in describing BT drying kinetics. Sample thickness was found to significantly influence drying rates, the thinner slices dried faster due to enhanced heat and mass transfer, while thicker slices exhibited slower drying because of increased internal resistance. Overall, this research establishes TD as the most effective and scalable

drying method for BT processing and validates the Midilli model as a reliable predictive tool. These findings provide a scientific basis for optimizing drying parameters in industrial applications to improve energy efficiency and product quality in the food and herbal industries.

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Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Informed consent

This study does not involve any animal experiments and no ethical approval for animal procedures is required.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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