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Research article

Integrated drying model of lychee as a function of temperature and relative humidity

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ABSTRACT

Drying is a universal method applied for food preservation. To date, several models have been developed to evaluate drying kinetics. In this study, lychee was dried employing a hot air dryer, and the drying kinetics was evaluated by comparing the Newtonian model, Henderson and Pabis model, Page model, and Logarithmic model. However, temperature and relative humidity, the key driving forces for drying kinetics, are not considered by these models. Thus, an integrated drying model, as a function of temperature and relative humidity, was developed to predict the hot air-drying kinetics and mass transfer phenomena of lychee followed by the calibration and validation of the model with independent experimental datasets. The model validation consisted of Nash- Sutcliffe model coefficient (E), coefficient of determination (R^2) and index of agreement (d) and all of them were found close to 1 indicating perfect model fit. Besides, the developed model was applied for process optimization and scenario analysis. The drying rate constant was found as a function of temperature and relative humidity that was high at high temperature and low relative humidity. Interestingly, temperature showed a higher effect on the drying rate constant compared to relative humidity. Overall, the present study will open a new window to developing further drying model of lychee to optimize quality its quality parameters.

1. Introduction

Fruits and vegetables are highly susceptible to deterioration after post-harvest operations. Researchers, nowadays, are foraging for applying cutting-edge technologies to increase the shelf life of these fresh produces. Among all the emerging technologies, drying is predominantly used to increase shelf-life and improve product quality. Apart from food preservation, drying lessens the product weight which alleviates handling, packaging, and transportation costs [1–3]. As a result, the engineering features of drying are a crucial factor.

Although novel drying techniques such as., ultrasound-assisted drying, infrared drying, freeze drying, microwave drying, vacuum drying, refractance window dehydration, high electric field drying, and super steam drying are evolved in food industries [4,5], conventional drying like-hot air drying is still extensively preferred because of the simplicity of equipment, ease of operation, diversified form of energy utilization, mass production, and the degree of familiarity [6,7]. However, hot air drying is a complex phenomenon where simultaneous heat and mass transfer occur with or without a chemical reaction. This phenomenon might influence the overall drying process as well as food quality. Numerous drying models had been developed over time to design new drying

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systems, optimize the drying process, improve the product quality, and describe the entire drying behavior. Thus, it is salient to comprehend the fundamentals of mathematical modeling of drying kinetics, model parameters, and drying conditions [8–11].

Thin-layer drying is predominantly performed to determine the drying kinetics of fruits and vegetables, for instance, apple pomace [12], plum [13], tomato [14], carrot [15], mango [16] etc. In this drying process, the food material gets direct contact with hot air having different process conditions-time, temperature, relative humidity, and air velocity. These drying factors predominantly influence dried product quality and energy consumption [17]. Due to the presence of different drying factors, it is difficult to generalize a single drying model that can describe the drying kinetics of all fresh commodities. Thus, a key tool for characterizing the drying of certain fruits and vegetables is choosing an appropriate drying model that can evaluate all significant process parameters. Previous research [18–20] predicted the drying time of fruits and vegetables using commonly drying models including the Newtonian model, Henderson and Pabis model, Page model, and Logarithmic model; also compared here to evaluate the lychee drying kinetics. All of them used only to evaluate the kinetic rate constants without considering temperature and relative humidity as the state function - the major drawback of applying these models for the identification of real scenarios and inside mechanism of the process. Therefore, in this study, a new model was proposed with considering temperature and relative humidity as state variables. At first the Newtonian model, Henderson and Pabis model, Page model, and Logarithmic model were evaluated to find out the variation of kinetic rate constant with changing temperature and relative humidity. To overcome the limitation of the change of model kinetic parameters with temperature and relative humidity, an integrated model was developed taking lychee as a drying material. The experimental data sets were used to calibrate and validate the developed integrated model. In the end, the model was used for scenario analysis to find out the suitable process drying condition for lychee.

2. Materials and methods

2.1. Collection and preservation of food samples

Lychee (*Litchi chinensis*) was taken as the model food sample to examine the drying behavior. It is a seasonal fruit that grows during June and July. In this study, ripened lychees (China-3 variety) were collected from a local market which is very close to lychee garden in July 2018. The fleshes were cut into small pieces of approximately same size. The weight of the pieces was 7–8 g and stored them at −4 °C in plastic Ziplock bag.

2.2. Drying operation

7–8 g of frozen lychee flesh was dried using a dryer (Model: VS-8111H-150) with 1 m/s air velocity maintaining constant temperature, relative humidity and same air flow direction in each experiment at thin layer drying process. The relative humidity varied from 50% to 70% and the temperature was from 40 °C to 70 °C. The weight losses were measured in every hour in dry basis and drying rates were calculated from the weight loss of the lychee sample. For each drying condition, three replications were performed to analyze the data set. The study was carried out throughout the year while ensuring similar initial condition in each experiment and no other cofactor effect the drying behavior.

2.3. Evaluation of model parameters of existing models

The Newtonian model, Henderson and Pabis model, Page model, and Logarithmic model were evolved to describe the drying behavior of lychee in this study to evaluate the model outcomes with varying temperature and relative humidity. The kinetics expressions of these models were related to the moisture ratio listed in Table 1.

2.4. Development of integrated drying model

The drying rate equation was developed based on simple mass balance considering that all the weight losses was due to water evaporation; the drying rate was proportional to the free moisture content that was defined by the difference between equilibrium moisture content and moisture content ($M_e - M$).

Table 1
Kinetic expressions of available model widely used for fruits and vegetables.

Model	Expression	Reference
Newtonian	$MR = \exp(-K\ t)$	[21]
Henderson and Pabis	$MR = a \exp(-K\ t)$	[22]
Page	$MR = a\exp(-K\ t^n)$	[23]
Logarithmic	$MR = a \exp(-K\ t) + c$	[24]

Here, MR= Moisture Ratio $= \dfrac{M - M_e}{M_0 - M_e}$ (M = Moisture content after time t; M_o = Initial moisture content; M_e = Equilibrium moisture content).

$$-\frac{dM}{dt} = K(M_e - M)$$

$$\Rightarrow \mathrm{MR} = \frac{(M - M_e)}{(M_0 - M_e)} = \exp(-Kt) \tag{1}$$

In this drying rate expression, equilibrium moisture content (M_e) and K were dependent on temperature and relative humidity. Assuming the carbs of lychee behaved as like as organic polymer, the equilibrium moisture content (M_e) was defined as a function of temperature (T), and relative humidity (h) as showed in Eq. (2) [25].

$$\mathrm{M_e} = \frac{1800}{\mathrm{W}}\left(\frac{\mathrm{kh}}{1\ -\ \mathrm{kh}} + \frac{\mathrm{k_1kh} + 2\mathrm{k_1\ k_2k^2h^2}}{1 + \mathrm{k_1kh} + \mathrm{k_1k_2k^2h^2}}\right) \tag{2}$$

where $\mathrm{M_e}$ was equilibrium moisture content (percent, dry mass basis), h was the relative humidity (fractional) and W, k, $\mathrm{k_1}$ and $\mathrm{k_2}$ were constants that were also function of temperature according to Eqs. (3)–(6) [25].

$$\mathrm{W} = \mathrm{x_o} + \mathrm{y_oT} + \mathrm{z_oT^2} \tag{3}$$

$$\mathrm{k} = \mathrm{x} + \mathrm{y\ T} - \mathrm{z\ T^2} \tag{4}$$

$$\mathrm{k_1} = \mathrm{x_1} + \mathrm{y_1T} - \mathrm{z_1T^2} \tag{5}$$

$$\mathrm{k_2} = \mathrm{x_2} + \mathrm{y_2T} - \mathrm{z_2T^2} \tag{6}$$

T was the temperature in degrees Fahrenheit.

Drying rate constant (K) also dependents on temperature and humidity. In this study relative humidity (h) was used as the state function of drying process. High relative humidity negatively affects the drying rate. According to boundary condition, the drying rate was maximum while h = 0 and rate became zero while h = 1; reasonable considered the drying rate constant as the function of (1-h) and its applicability depends on the relative humidity power coefficient (γ) as described in power-model [26] for absolute humidity. Considering relative humidity as the state function, modified power-model equation was developed for determination of drying rate constant (K) (Eq. (7)).

$$K = \varphi\ \mathrm{T}^{\alpha}\ (1\text{-h})^{\gamma} \tag{7}$$

Here,
$\varphi = \partial \mathrm{U}^{\beta}$
U = air velocity in m/s
T = temperature at F
h = relative humidity of air (fraction)
∂, α, β and γ are constants.
At constant air velocity, $\varphi = \partial \mathrm{U}^{\beta} = \mathrm{Constant}$

2.5. Sensitivity analysis, model calibration and validation

A relative sensitivity analysis of outcome variable towards kinetics parameters was performed to identify the most sensitive parameters that have significant effect on model outcome. The sensitivity analysis was evaluated by following the method described by Mozumder et al. [27] to select the model parameters that had to be estimated. The model calibration was conducted according to Mozumder et al. [27] to estimate the most sensitive parameters to determine the drying rate constant and equilibrium moisture content

Table 2
Experimental conditions for datasets that used for model calibration and validation.

Temperature (°C)	Relative humidity (%)	Applied for	
		Calibration	Validation
40	50		X
40	60	X	
40	70	X	
50	50		X
50	60		X
50	70		X
60	50	X	
60	60	X	
60	70	X	
70	50		X
70	60	X	
70	70	X	

using independent experimental datasets. The parameter estimation was conducted through the analysis of degree of freedom and development of number of independent equations from experimental datasets. With other independent data sets, the model predictions were compared to illustrate the accuracy of the model through the Nash-Sutcliffe model coefficient (E), coefficient of determination (R^2) and index of agreement (d) that determined the validation of the developed model and increased its application potentiality [28]. MATLAB version R2012b was used to perform sensitivity analysis, model calibration, validation and statistical analysis. The detailed condition of experiments to develop the datasets used for model calibration and validation were listed in Table 2.

3. Result and discussion

3.1. Experimental evaluation of lychee drying and drying rate

3.1.1. Effect of temperature on drying

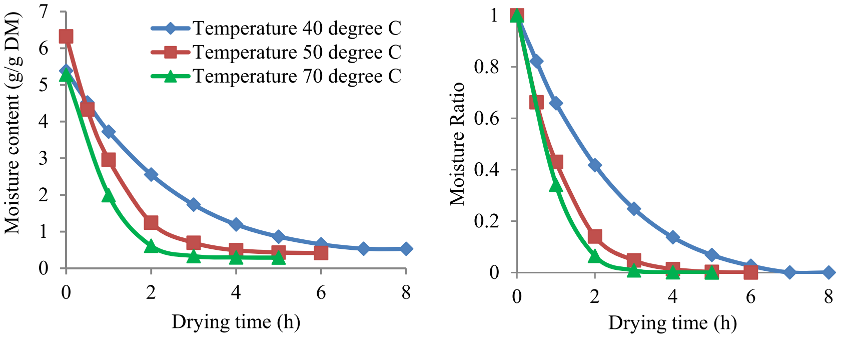
Lychee drying behavior was examined with varying temperatures of 40–70 °C and a constant 50% relative humidity summarized in Fig. 1. Fig. 1a showed the change of moisture content over time while Fig. 1b showed the moisture ratio. The drying rate was high at high temperatures and low at low temperatures, such as 66% of moisture was removed within 1 h while it was dried at 70 °C but at 40 °C it was only 35%. Drying time: the time required to reach equilibrium moisture content was reduced from 8 h to 5 h with increasing drying temperature from 40 °C to 70 °C (Fig. 1a). The rate of evaporation was increased with increasing temperature, responsible for a high drying rate at high temperatures. Improvement of drying temperature can enhance the mass transfer rate and shorten the drying time [29–32]. Vega et al. [33] found that the drying time was reduced by 9 to 6 h due to an increase in temperature from 50 to 60 °C. Decreasing the moisture ratio over time showed almost similar behavior to decreasing moisture content (Fig. 1b). The M_e was decreased from 0.53 g/g DM to 0.29 g/g DM with an increasing temperature of 40 °C to 70 °C. Saturation vapor pressure, as well as humidity ratio (g water/g dry air), was increased with increasing temperature, responsible for decreasing M_e with increasing temperature. Similar behavior was also observed for drying of other food samples such as, garlic [34], red chili [35], green bean [36], kiwis [37], pumpkin [38], figs [39], black pepper [40].

3.1.2. Effect of relative humidity on drying

Subsequently, the lychee was dried at different relative humidity; 50–70%, and at a constant temperature of 50 °C. The findings expressed as moisture content and moisture ratio were shown in Fig. 2. The drying rate was higher at lower relative humidity and lower at high relative humidity, such as 57% moisture was removed within 1 h at 50% relative humidity but at 70% relative humidity it was only 21%. Drying time: the time required to reach equilibrium moisture content was increased from 4 h to 6 h with increasing relative humidity from 50% to 70% (Fig. 2a) and M_e was increased from 0.42 g/g DM to 0.59 g/g DM respectively. High relative humidity reduced the driving force of evaporation which decreased the drying rate with increasing relative humidity [41]. found an almost similar result in the drying of fresh udon: M_e (dry basis) was 0.2, 0.25, and 0.3 g/g DM for 60, 70, and 80% relative humidity respectively [42]. also carried out similar type of study on onion and found the reduction of drying time by 10 h with increasing relative humidity from 10% to 80–90%, at 50 °C temperature. Moreover, the increase of relative humidity from 32 to 68% at 20 °C, the drying time increased from 1.2 h to 7.3 h for blue grass seed [43]. Acceleration of driving force for mass transfer; water from liquid phase to vapor phase was responsible to increase the drying rate at low relative humidity.

3.2. Evaluation of model parameters of existing models as a function of temperature and relative humidity

Four different models; the Newtonian model, Henderson and Pabis model, Page model, and Logarithmic model were used to describe the drying kinetics of lychee. These models were evaluated in this study to find out the effect of temperature and relative humidity on the model parameters. Table 3 shows the effect of drying conditions on these model characterization parameters.



(a) (b)

Fig. 1. Effect of temperature on lychee drying at constant relative humidity (50%) (a) moisture content and (b) moisture ration over drying period.

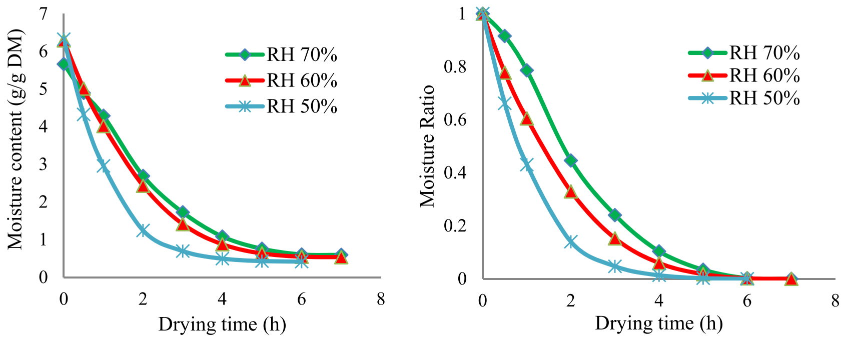


Fig. 2. Effect of relative humidity on lychee drying at fixed 50 °C temperature. (a) Moisture content and (b) moisture ratio over drying period.

3.2.1. *Newtonian model*

One of the simplest models that describe the moisture ratio over the drying time period and widely used to predict the drying behavior of foods and agricultural products is the Newtonian model (Table 1). It is also known as the Lewis model or the Exponential model, a single exponential model due to its response behavior. The only parameter that determined the drying behavior through the Newtonian model is the drying rate constant (K). It was calculated for lychee drying for every experiments with varying temperature and relative humidity (Table 3) and found K was increased with increasing temperature and decreased with increasing relative humidity. A study, conducted by Ref. [44], showed similar behavior for seaweed drying process. Applying the Newtonian model, Hossain et al. [45] concluded that drying rate constant was a function of temperature and relative humidity. Changing of drying rate constants with temperature and relative humidity made it difficult to predict the drying scenario with changing these parameters.

3.2.2. *Henderson and Pabis model*

The Henderson and Pabis model (Table 1) is derived from Fick's second law of diffusion. In this model, the model parameter a represents the shape of the materials (dimensionless) and K is the drying constant (1/s) that were estimated from the experimental datasets with varying temperature and relative humidity and shown in Table 3. Like the Newtonian model drying rate constant (K) was increased with increasing temperature and decreased with increasing relative humidity. The parameter value of a, as it is related to the shape of the materials did not have any relation with change of temperature and relative humidity (Table 3) [44]. used uniform shaped materials and found there was no effect of temperature and relative humidity on a. But [18] showed that both a and K were the function of temperature and humidity.

3.2.3. *Page model*

The Page model is an empirical modification of the Newton model aiming to shift the application potential of the model from ideal situation to real situation. The errors corresponding to the Newton model in the practical scenario were considerably reduced by the addition of a dimensionless empirical model constant (n) (Table 1) which is commonly used in semi-theoretical thin-layer models. According to the literature [1,46,47], the page model can accurately describe the drying behavior of numerous fruits and vegetables.

Page model was also evaluated in this study for the drying of lychee with variation of temperature and relative humidity. The parameter values are listed in Table 3. The rate constant (K) was increased and decreased with increasing temperature and relative humidity respectively but there was no significant effect of temperature and relative humidity on model constant n. The behavior was also confirmed by Ref. [44] through examining the effect of drying air temperature and humidity on drying kinetics of seaweed.

3.2.4. *Logarithmic model*

The logarithmic model was developed through the modification of Henderson and Pabis model; the addition of an empirical term (c) aims to overcome the limitation of Henderson and Pabis model (Table 1). The main aim was to improve application potential

Table 3
Model characterization parameters.

Temperature (°C)	Relative humidity (%)	Newtonian Model	Henderson and Pabis Model	Page Model	Logarithmic Model
40	50	$K = 0.7431$	$K = 0.8817$ a = 1.9782	$K = 0.4971$ n = 1.1501	$K = 0.3537$ a = 1.1518 $c = -1.5 \times 10^{-1}$
50		$K = 1.1107$	$K = 1.1776$ a = 1.2696	$K = 0.9074$ n = 1.1400	$K = 1.1411$ a = 1.3361 $c = 3.70 \times 10^{-3}$
70		k = 1.6152	$K = 1.7482$ a = 1.4905	$K = 1.0420$ n = 1.3746	$K = 2.0340$ a = 3.7779 $c = -8.64 \times 10^{-5}$
50	60	$K = 0.8469$	$K = 0.9581$ a = 1.6033	$K = 0.6076$ n = 1.1744	$K = 0.6404$ a = 1.3478 $c = -4.46 \times 10^{-2}$
	70	$K = 0.6014$	$K = 0.6732$ a = 1.39333	$K = 0.3442$ n = 1.4670	$K = 0.5024$ a = 1.4233 $c = -7.46 \times 10^{-2}$

through data fitting. In this model, c was the dimensionless additional empirical constant. This model gave good prediction performance for grain drying and showed the best fit in predicting the drying kinetics of stone apples [1]. However, in this study, it was found that the model parameters (K, a, c) varied with temperature and relative humidity (Table 3).

The overall analysis of these four established models revealed that the drying rate constant K in all the models depended on drying temperature and relative humidity, as it increased with the increase of temperature and decrease of relative humidity. On the other hand, the remaining model constants (n, a, c) were not followed any specific pattern like the rate constant K. Similar observation was also found by a number of researchers [44–47]. However [18], showed both a and K were function of temperature and humidity.

3.3. Integrated drying model

To determine the drying rate as a function of temperature and relative humidity, an integrated model was proposed. In this integrated model drying rate equation (Eq. 1) was developed from the mass balance of drying equation and found it was almost like the Newtonian model. The M_e and the drying rate constant were calculated using Hailwood-Horrobin equation (Eq. 2) and modified power-model equation (Eq. 7), both were a function of temperature and relative humidity.

3.3.1. Model calibration

Several experiments were conducted (Table 2) on lychee drying with the variation of temperature and relative humidity to find out unknown model parameter values through model calibration. According to modified power-law equation (Eq. 7) the drying rate constant was a function of temperature and relative humidity. These equations were solved through the analysis of degree of freedom and number of independent equations. By solving Eq. (7) at constant relative humidity and variable temperature, it was found that $\alpha = 2.838$ and $\varphi = 1.58825 \times 10^{-06}$, and at constant temperature and variable relative humidity, the $\gamma = 0.7181$. Using these parameter values, the drying rate constants were calculated using eq. (7) based on temperature and relative humidity.

In Hailwood-Horrobin equations (Eq. 2-6) generally used to find out the M_e as a function of temperature and relative humidity, involved several parameters. To overcome the bias error through the estimation of a large number of parameters, a relative sensitivity analysis was conducted (Table 4) and highly sensitive parameters were chosen while the relative sensitivity was higher than 4 or lower than −4. According to Table 4, W and k were found highly sensitive parameters and hence need to estimate them. W and k were related to six parameters (x_0, y_0, z_0, x, y and z) that were estimated through the analysis of degree of freedom and number of independent equations. The estimated parameters based on experimental datasets are listed in Table 5. Other six parameters ($x_1 = 6.34$, $y_1 = 7.75 \times 10^{-4}$, $z_1 = -9.35 \times 10^{-5}$, $x_2 = 1.09$, $y_2 = 2.84 \times 10^{-2}$ and $z_2 = -9.04 \times 10^{-5}$), related to k_1 and k_2 were taken from literature [25]. Using estimated parameter values, W and k would be determined as a function of temperature as per Eq. (8) and (9) and $k_1$and $k_2$were determined according to the description of [25] (Eqs. (10) and (11)).

$$W = 10.023 - 0.0613\ T + 0.0011\ T^2 \tag{8}$$

$$k = 6.5284 - 0.0005\ T - 8.0 \times 10^{-7}\ T^2 \tag{9}$$

$$k_1 = 6.34 + 7.75 \times 10^{-4}\ T - 9.35 \times 10^{-5}\ T^2 \tag{10}$$

$$k_2 = 1.09 + 2.84 \times 10^{-2}\ T - 9.04 \times 10^{-5}\ T^2 \tag{11}$$

In order to calculate equilibrium moisture content (M_e), first W, k, k_1 and k_2 were calculated based on temperature (T) using Eqs. (8)–(11) and then M_e using Eq. (2) according to relative humidity (h).

3.3.2. Model validation

The developed model was subjected to validation on different experimental datasets that differ in temperature and relative humidity (Table 2). A visual comparison of the model prediction and the experimental observations (Fig. 3) is used for validation alongside the determination of Nash-Sutcliffe model efficiency coefficient (E), coefficient of determination (R^2), index of agreement (d) for moisture content of lychee (Table 6). The value of E, R^2 and d were close to 1 in all cases ensured the validity of the model as well as the applicability of the model with changing the temperature and relative humidity.

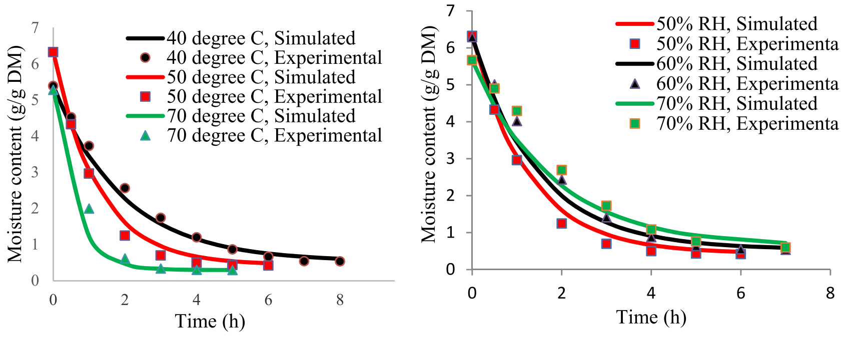
Several studies have already been conducted to find out the effect of operating parameters on drying behavior [10,24,30,48,49]. However, most of them determined the kinetic rate constant based on operating parameters without considering equilibrium moisture content as a function of temperature and relative humidity. Equilibrium moisture content is one of the prime factors to determine the

Table 4
Relative sensitivity of the parameters related to Hailwood-Horrobin equation.

Temperature (°C)	Relative humidity (%)	W	k	k_1	k_2
40	50	4.76	−4.42	−0.51	−0.79
50	50	4.77	−4.47	−0.52	−0.79
60	50	4.72	−4.55	−0.55	−0.81
70	50	4.76	−4.67	−0.59	−0.83
50	60	4.79	−5.41	−0.37	−0.65
50	70	4.70	−7.08	−0.26	−0.51

Table 5
Estimated parameters related to Hailwood-Horrobin equations (Eq. 3,4).

Parameters related to W	Estimated value	Parameters related to k	Estimated value
x_0	10.023	x	6.5284
y_0	−0.0613	y	−0.0005
z_0	0.0011	z	8.0×10^{-7}



(a) (b)

Fig. 3. Model validation through the determination of moisture content (dry basis) of lychee over drying period. Comparison between the simulation outcome and experimental observations with (a) varying temperature at a constant relative humidity (50%) and (b) varying relative humidity (RH) and at a constant temperature (50 °C).

drying rate as well as overall drying behavior. The function of equilibrium moisture content was calculated in this model through Hailwood-Horrobin equations. According to this model, the M_e depends on relative humidity and drying air temperature.

The drying rate constant (*K*) is the most important characteristic within the drying model, from which the process efficiency as well as application suitability would be determined. The rate constant depends on several process variables, mainly temperature and humidity. In this study, *K* was determined based on drying temperature and relative humidity using modified power-model and described the lychee drying process perfectly. However, in this study laboratory scale dryer (Model: VS-8111H-150) was used which had a better control of temperature and humidity. For an industrial scale drying equipment where a small variation of temperature and humidity would be observed, the model needs to adopt with the uncertainty of these parameter values for that equipment.

3.4. Evaluation of drying rate constant using integrated drying model

The validated model was applied to evaluate the drying rate constant with altering temperature and relative humidity. The model was simulated with varying temperatures from 0 to 100 °C and relative humidity from 0 to 80%. The simulation outcome, shown in Fig. 4, indicated the effect of the drying rate constant as the function of air temperature and relative humidity. In all cases, the estimated α, φ, and γ were used, indicating that the numerical values of the drying rate constant would be applicable for lychee drying and for a similar type of drying apparatus used in this study. It was revealed that the drying rate constant was increased exponentially with increasing temperature and decreasing relative humidity. Such as the drying rate constant was increased by 9 times (from 0.34/h to 2.8/h) with increasing temperature from 30 °C to 81 °C but decreasing relative humidity from 80% to 37.7% increased the rate constant by 2 times. Most of the literature working on the determination of drying rate got a similar approach [23,39,41,50,51]. The drying rate constant was found to be 1.83/h for lychee drying at 60 °C and 10% relative humidity, and [44] found the rate constant 2.37/h for the same condition but for seaweed drying.

In a drying operation, heat must be applied to raise the temperature of the incoming air, warm up the material being handled, heat up and evaporate the water from the material, and hence increase the drying rate. Least drying-air humidity accelerates the drying

Table 6
Nash-Sutcliffe model efficiency coefficient (***E***), coefficient of determination (R^2), index of agreement (*d*) for moisture content of lychee for proposed model using estimated parameter values.

Temperature (°C)	Relative humidity (%)	*E*	R^2	*d*
40	50	0.99	0.99	0.99
50		0.99	0.99	0.99
70		0.97	0.97	0.99
50	60	0.98	0.99	0.99
	70	0.96	0.97	0.99

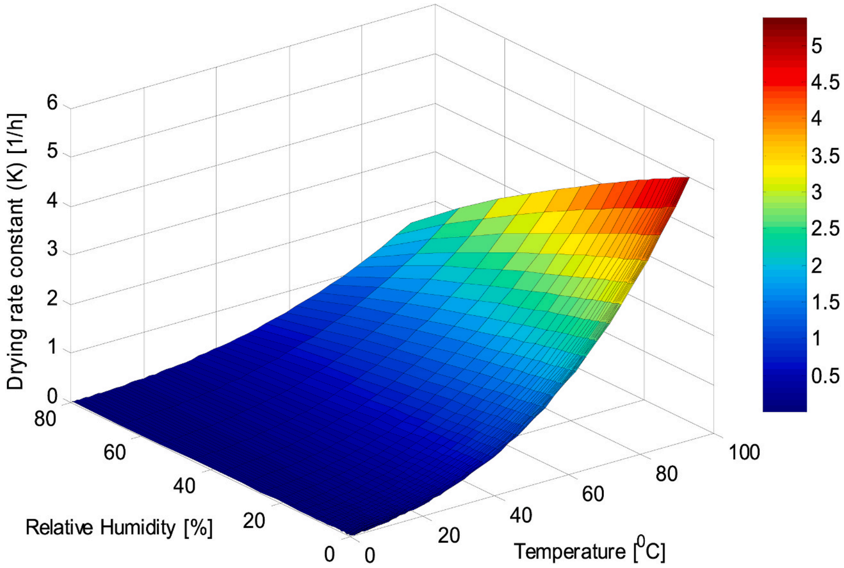


Fig. 4. Lychee drying rate constant with varying temperature and relative humidity.

rates: at a constant dry-bulb temperature, any increase in humidity reduces its capacity for holding additional water vapor, the rate of evaporation, and the drying rate. The severity of these negative impacts decreases at temperature rises, but they are most noticeable at low air temperatures and when the moisture content is close to saturation.

3.5. Evaluation of drying period using integrated drying model

Simulations were conducted to determine the M_e and drying period with the variation of temperature and relative humidity. The M_e was increased with increasing relative humidity and decreased with increasing temperature (Fig. 5a). Such as increasing relative humidity from 40% to 60% at 30 °C, equilibrium moisture content was increased from 33.2 % (dry basis) to 78.8 % (dry basis) but at 50 °C it was increased from 23.3 % (dry basis) to 54.3 % (dry basis). Overall, a 20% increase in relative humidity increased 2.35-fold of equilibrium moisture content. At a constant temperature, decreasing relative humidity decreased the equilibrium moisture; increased the drying rate. Increasing temperature from 40 °C to 75 °C at 50% relative humidity, the M_e was decreased from 52.2% to 26.5%.

The drying rate constant was increased with decreasing the relative humidity. The combination of the amount of water evaporated and the drying rate, the drying period of lychee drying was decreased with decreasing relative humidity. The drying time decreased from 52 h to 11 h by decreasing the relative humidity from 90% to 40% at a temperature of 40 °C. The relative humidity, below 40%, did not have a significant effect on the drying period (Fig. 5b) [44,50]. found a decrease in drying time below 40% relative humidity using vegetables and seaweed respectively in a low temperature and humidity chamber. The air velocity was the reason that was constant in this study was the cause of faster drying at constant relative humidity [52,53]. Increasing temperature decreased the M_e as well as increased the drying rate, the overall effect was decreased of drying time (Fig. 5c). As the ambient temperature of Bangladesh was around 30 °C, the drying rate is very low below 30 °C and it would take a very long time that might not be feasible an economic and food quality point of view.

A study was conducted to dry riesling, cab franc, and concord at different temperature and constant humidity, where decreasing equilibrium moisture content and drying time was found with increasing operation temperature [54]. A similar observation was also found by a number of literatures [41,52,53,55].

4. Conclusion

Increasing drying temperature increased the drying rate constant and decreased the equilibrium moisture content enhancing the overall drying rate. Relative humidity decreased the drying rate by decreasing the drying rate constantly.

A drying model was developed that was integrated with the determination of drying rate constant and equilibrium moisture content as a function of temperature and relative humidity. The developed model was calibrated and validated with independent experimental datasets that differ in temperature and relative humidity. Both drying rate constant and equilibrium moisture content were dependent on temperature and relative humidity.

Overall, a 20% increase in relative humidity increased 2.35-fold of equilibrium moisture content but increasing temperature from 40 °C to 75 °C decreased the equilibrium moisture content of lychee by 2-fold. Decreasing relative humidity from 90% to 40%, decreased the drying time by 4.65–5.83 times lower and increasing temperature from 40 °C to 80 °C decreased the drying time by 4.42 times lower. Toward this end, the suitable way to gain desired moisture content in a shorter period is to decrease relative humidity with

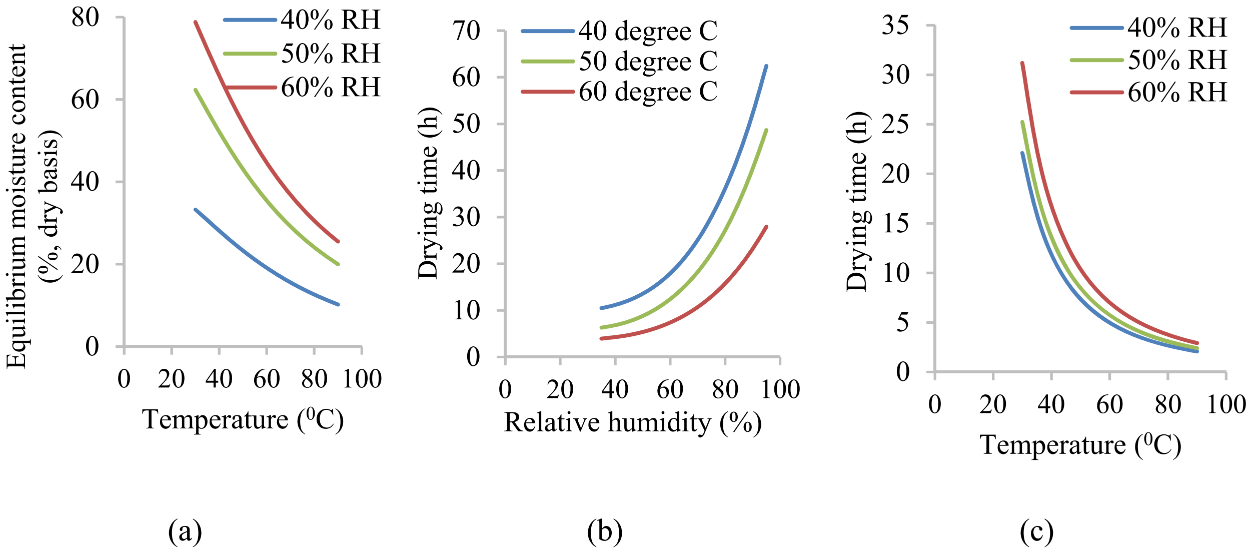


Fig. 5. (a) effect of temperature and relative humidity on equilibrium moisture content, (b) effect of relative humidity on drying time and (c) effect of temperature on drying time.

a moderate increment of drying temperature. However, temperature showed a higher effect on the drying rate constant compared to relative humidity. The drying rate constant was high at high temperatures and low relative humidity. In terms of food preservation, the equilibrium moisture content must be low to evade microbial contamination, and it would be attainable at low relative humidity and high temperature. Increasing temperature and reduction of relative humidity exponentially decreased the drying time which would exponentially decrease the process operating cost. Since the quality of dried food is commensurate with drying conditions, future studies will address the suitable drying conditions of lychee to retain the highest quality.

Data availability

Data will be made available on request.

CRediT authorship contribution statement

Shafaet Ahmed: Writing – original draft, Data curation. **Md Salatul Islam Mozumder:** Writing – review & editing, Supervision, Conceptualization. **Wahidu Zzaman:** Writing – review & editing, Supervision. **Md Yasin:** Investigation. **Shuvo Das:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] D.I. Onwude, N. Hanshim, R.B. Janius, N.M. Nawi, K. Abdan, Modeling the thin layer drying of fruits and vegetables: a review, Compr. Rev. Food Sci. Food Saf. 15 (3) (2016) 299–618.
[2] S. Ahmed, M.M. Hoque, W. Zzaman, M.U. Thakur, M.M. Hossain, Study on physicochemical and anti-oxidant properties of coconut cream extracted from two BARI varieties, Int. Food Res. J. 26 (1) (2019) 153–160.
[3] G. Amini, F. Salehi, M. Rasouli, Drying kinetics of basil seed mucilage in an infrared dryer: application of GA-ANN and ANFIS for the prediction of drying time and moisture ratio, J. Food Process. Preserv. 45 (3) (2021) e15258.
[4] D. Wang, M. Zhang, R. Ju, A.S. Mujumdar, D. Yu, Novel drying techniques for controlling microbial contamination in fresh food: a review, Dry. Technol. 41 (2) (2023) 172–189.
[5] A. Li, S. Qiao, M. Xia, Y. Lin, L. Wang, Y. Xie, J. Li, X. Li, Medium and short-wave infrared drying: principles, applications, and future trends, Dry. Technol. 41 (10) (2023) 1569–1582.

[6] Á. Calín-Sánchez, L. Lipan, M. Cano-Lamadrid, A. Kharaghani, K. Masztalerz, Á.A. Carbonell-Barrachina, A. Figiel, Comparison of traditional and novel drying techniques and its effect on quality of fruits, vegetables and aromatic herbs, Foods 9 (9) (2020) 1261.

[7] M. Araya-Farias, M. Macaigne, C. Ratti, On the development of osmotically dehydrated seabuckthorn fruits: pretreatments, osmotic dehydration, postdrying techniques, and nutritional quality, Dry. Technol. 32 (7) (2014) 813–819.

[8] K. Nakagawa, W. Ritcharoen, P. Sri-Uam, P. Pavasant, S. Adachi, Antioxidant properties of convective-air-dried *Spirulina maxima*: evaluation of phycocyanin retention by a simple mathematical model of air-drying, Food Bioprod. Process. 100 (2016) 292–302.

[9] F. Akter, R. Muhury, A. Sultana, U.K. Deb, A comprehensive review of mathematical modeling for drying processes of fruits and vegetables, International journal of Food Science (2022) 6195257.

[10] V. Chasiotis, D. Tzempelikos, D. Mitrakos, A. Filios, Numerical and experimental analysis of heat and moisture transfer of Lavandula x allardii leaves during non-isothermal convective drying, J. Food Eng. 311 (2021) 110708.

[11] E. Elangovan, S.K. Natarajan, Experimental study on drying kinetics of ivy gourd using solar dryer, J. Food Process. Eng. 44 (7) (2021) e13714.

[12] Z. Wang, J. Sun, X. Liao, F. Chen, G. Zhao, J. Wu, X. Hu, Mathematical modeling on hot air drying of thin layer apple pomace, Food Res. Int. 40 (2007) 39–46.

[13] R.K. Goyal, A.R.P. Kingsly, M.R. Manikantan, S.M. Ilyas, Mathematical modelling of thin layer drying kinetics of plum in a tunnel dryer, J. Food Eng. 79 (1) (2007) 176–180.

[14] M. Das Purkayastha, A. Nath, B.C. Deka, C.L. Mahanta, Thin layer drying of tomato slices, J. Food Sci. Technol. 50 (4) (2013) 642–653.

[15] N. Kumar, B.C. Sarkar, H.K. Sharma, Mathematical modelling of thin layer hot air drying of carrot pomace, J. Food Sci. Technol. 49 (1) (2012) 33–41.

[16] T.P.K. Murthy, B. Manohar, Hot air drying characteristics of mango ginger: prediction of drying kinetics by mathematical modeling and artificial neural network, J. Food Sci. Technol. 51 (2014) 3712–3721.

[17] M. Chanpet, N. Rakmak, N. Matan, C. Siripatana, Effect of air velocity, temperature, and relative humidity on drying kinetics of rubberwood, Heliyon 6 (10) (2020).

[18] E. Meisamiasl, S. Rafiee, A. Keyhani, A. Tabatabaeefar, Determination of suitable thin-layer drying curve model for apple slices (golab), Plant Omics 3 (3) (2010) 103–108.

[19] D.A. Tzempelikos, A.P. Vouros, A.V. Bardakas, A.E. Filios, D.P. Margaris, Case studies on the effect of the air drying conditions on the convective drying of quinces, Case Stud. Therm. Eng. 3 (2014) 79–85.

[20] H. Mirzaei-Baktash, N. Hamdami, P. Torabi, S. Fallah-Joshaqani, M. Dalvi-Isfahan, Impact of different pretreatments on drying kinetics and quality of button mushroom slices dried by hot-air or electrohydrodynamic drying, LWT 155 (2022). Article 112894.

[21] A. El-Beltagy, G.R. Gamea, A.H.A. Essa, Solar drying characteristics of strawberry, J. Food Eng. 78 (2007) 456–464.

[22] N. Hashim, D. Onwude, E. Rahaman, A preliminary study: kinetic model of drying process of pumpkins (*Cucurbita moschata*) in a convective hot air dryer, Agriculture and Agricultural Science Procedia 2 (2) (2014) 345–352.

[23] E.O.M. Akoy, Experimental characterization and modeling of thin-layer drying of mango slices, Int. Food Res. J. 21 (5) (2014) 1911–1917.

[24] K. Rayaguru, W. Routray, Mathematical modeling of thin layer drying kinetics of stone apple slices, Int. Food Res. J. 19 (4) (2012) 1503–1510.

[25] A.J. Hailwood, S. Horrobin, Absorption of water by polymers: analysis in terms of a simple model, Trans. Faraday Soc. 42B (1946) 84–102.

[26] J. Mitra, S.L. Shrivastava, P.S. Rao, Onion dehydration: a review, J. Food Sci. Technol. 49 (3) (2012) 267–277.

[27] M.S.I. Mozumder, L. Goormachtigh, L. Garcia-Gonzalez, H. De Wever, E.I.P. Volcke, Modeling pure culture heterotrophic production of polyhydroxybutyrate (PHB), Bioresour. Technol. 155 (2014) 272–280.

[28] M.S.I. Mozumder, M.S.A. Amin, M.F.R. Shishir, Unified model to predict and enhance the mixed culture polyhydroxyalkanoates (PHA) production, Bioresour. Technol. Rep. 11 (2020). Article 100537.

[29] A. Akcicek, E. Avci, Z.H. Tekin-Cakmak, M.Z. Kasapoglu, O. Sagdic, S. Karasu, Influence of different drying techniques on the drying kinetics, total bioactive compounds, anthocyanin profile, color, and microstructural properties of blueberry fruit, ACS Omega 8 (44) (2023) 41603–41611.

[30] K.O. Falade, E.S. Abbo, Air-drying and rehydration characteristics of date palm (*Phoenix dactylifera* L.) fruits, J. Food Eng. 79 (2007) 724–730.

[31] K. Nakagawa, A. Tamura, S. Adachi, Optimization of food dye (betanin) retention during hot air drying: design space calculation with consideration of reaction and substrate transfer kinetics, Dry. Technol. 36 (15) (2018) 1920–1929.

[32] E. Rurush, M. Alvarado, P. Palacios, Y. Flores, M.L. Rojas, A.C. Miano, Drying kinetics of blueberry pulp and mass transfer parameters: effect of hot air and refractance window drying at different temperatures, J. Food Eng. 320 (2022) 110929.

[33] A. Vega, P. Fito, A. Andŕes, R. Lemus, Mathematical modeling of hot-air drying kinetics of red bell pepper (var. Lamuyo), J. Food Eng. 79 (2007) 1460–1466.

[34] P.S. Madamba, R.H. Driscoll, K.A. Buckle, The thin-layer drying characteristics of garlic slices, J. Food Eng. 29 (1) (1996) 75–97.

[35] P. Gupta, J. Ahmed, U.S. Shivhare, G.S.V. Raghavan, Drying characteristics of red chilli, Dry. Technol. 20 (10) (2002) 1975–1987.

[36] İ. Doymaz, Drying behaviour of green beans, J. Food Eng. 69 (2) (2005) 161–165.

[37] S. Simal, A. Femenia, M.C. Garau, C. Rosselló, Use of exponential, Page's and diffusional models to simulate the drying kinetics of kiwi fruit, J. Food Eng. 66 (3) (2005) 323–328.

[38] D. Ibrahim, The kinetics of forced convective air-drying of pumpkin slices, J. Food Eng. 79 (1) (2007) 243–248.

[39] S.J. Babalis, V.G. Belessiotis, Influence of the drying conditions on the drying constants and moisture diffusivity during the thin-layer drying of figs, J. Food Eng. 65 (3) (2004) 449–458.

[40] G.K. Jayatunga, B.M.W.P.K. Amarasinghe, Drying kinetics, quality and moisture diffusivity of spouted bed dried Sri Lankan black pepper, J. Food Eng. 263 (2019) 38–45.

[41] T. Inazu, K.I. Iwasaki, T. Furuta, Effect of temperature and relative humidity on drying kinetics of fresh Japanese noodle (udon), LWT - Food Sci. Technol. (Lebensmittel-Wissenschaft -Technol.) 35 (8) (2002) 649–655.

[42] M. Djaeni, A.C. Kumoro, S.B. Sasongko, F.D. Utari, Drying rate and product quality evaluation of roselle (*Hibiscus sabdariffa* L.) calyces extract dried with foaming agent under different temperatures, International Journal of Food Science 11 (4) (2018) 1–8.

[43] G.S. Farmer, G.H. Brusewitz, R.W. Whitney, Drying properties of blue grass seed, Transaction ASAE (American Society Agricultural Engineers) 26 (1983) 234–237.

[44] A. Fudholi, M.Y. Othman, M.H. Ruslan, M. Yahya, A. Zaharim, K. Sopian, The effect of drying air temperature and humidity on the drying kinetics of seaweed, in: In Recent Research in Geography, Geology, Energy, Environment and Biomedicine, 2011, pp. 129–133.

[45] M.A. Hossain, J.L. Woods, B.K. Bala, Single-layer drying characteristics and colour kinetics of red chilli, Int. J. Food Sci. Technol. 42 (11) (2007) 1367–1375.

[46] L. Diamante, M. Durand, G. Savage, L. Vanhanen, Effect of temperature on the drying characteristics, colour and ascorbic acid content of green and gold kiwifruits, Int. Food Res. J. 45 (2) (2010) 441–451.

[47] W.P. Da Silva, A.F. Rodrigues, C.M.D.P.S. Silva, D.S. De Castro, J.P. Gomes, Comparison between continuous and intermittent drying of whole bananas using empirical and diffusion models to describe the processes, J. Food Eng. 166 (2015) 230–236.

[48] H. Darvishi, A.R. Asl, A. Asghari, G. Najafi, H.A. Gazori, Mathematical modeling, moisture diffusion, energy consumption and efficiency of thin layer drying of potato slices, J. Food Process. Technol. 4 (3) (2013) 1–6.

[49] W.P. Silva, C.M.D.P.S. Silva, F.J.A. Gama, J.P. Gomes, Mathematical models to describe thin-layer drying and to determine drying rate of whole bananas, Journal of the Saudi Society of Agricultural Sciences 13 (1) (2014) 67–74.

[50] M.K. Krokida, V.T. Karathanos, Z.B. Maroulis, D. Marinos-Kouris, Drying kinetics of some vegetables, J. Food Eng. 59 (2003) 391–403.

[51] T.S.B. Rao, S. Murugan, Experimental investigation of drying neem (Azadirachta indica) in an evacuated tube solar dryer: performance, drying kinetics and characterization, Sol. Energy 253 (2023) 270–284.

[52] A. Vega-Gálvez, H. Kong, C. Marcelo, V. Judith, M.M. Javier, G.S. Purificación, L.M. Roberto, D.S. Karina, Effect of temperature and air velocity on drying kinetics, antioxidant capacity, total phenolic content, colour, texture and microstructure of apple (var. Granny Smith) slices, Food Chem. 132 (1) (2012) 51–59.

[53] L.N.S. Dorneles, A.L.D. Goneli, C.A.L. Claudia Andrea Lima Cardoso, C.B. Silva, M.R. Hauth, G.C. Oba, V. Schoeninger, Effect of air temperature and velocity on drying kinetics and essential oil composition of Piper umbellatum L. leaves, Ind. Crop. Prod. 142 (2019) 111846.

[54] J.S. Roberts, D.R. Kidd, O. Padilla-Zakour, Drying kinetics of grape seeds, J. Food Eng. 89 (4) (2008) 460–465.

[55] J. Nudar, M. Roy, S. Ahmed, Combined osmotic pretreatment and hot air drying: evaluation of drying kinetics and quality parameters of adajamir (*Citrus assamensis*), Heliyon 4 (4) (2023) e19545.