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Modeling and Simulating the Change of Moisture and Temperature in Sliced Mangoes During Convective Drying

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ABSTRACT

This paper presents some research results on the modeling and simulation of temperature and moisture content change in sliced mangoes during convective drying. Based on a comprehensive review of the relevant scientific literature, the authors compiled theoretical equations, semi-empirical correlations, and experimental data related to heat and mass transfer in convective drying to develop a mathematical model that describes the variation in the parameters strongly affecting the quality of dried products. As a result, the coefficients of the Page drying kinetics model were determined ($k_s = 0.27\ h^{-n}$ and $n = 0.85$), and the model agreed well with the experimental data. In addition, the effective moisture diffusivity was calibrated against the experimental data, yielding $D_{ef} = 3.9\times10^{-10}\ m^2/s$ for the local Cat Chu variety. The paper also shows the outcomes of simulation that visually illustrate the evolution of the parameters through images, charts, and graphs generated by using MATLAB-based programs and finite difference method (FDM) to solve the mathematical model. The results from this study can be used for prediction of drying time, optimization of the drying process and for other research as a valuable reference.

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1. Introduction

Mango is one of the high-value tropical fruits in Vietnam, with an annual production of more than one million tons, mainly concentrated in the southern region [1]. However, due to its high moisture content and seasonal harvesting, mangoes are highly susceptible to deterioration. Drying is one of the effective methods for extending shelf life, increasing commercial value, and producing a variety of mango-based products.

Among the available drying methods, hot-air convective drying is the most widely used because of its relatively low investment and operating costs and its suitability for large-scale production. However, this technology still has several limitations, such as difficulties in precisely controlling drying conditions, which can result in low thermal utilization efficiency, high energy consumption, and potential deterioration of product quality due to elevated temperatures. To achieve high economic efficiency while maintaining product quality, it is necessary to control and optimize the drying conditions appropriately for each product. This can be achieved by developing mathematical models and simulating the drying process, thereby reducing the need for extensive conventional experimental studies.

This paper presents the results of modeling and simulation of temperature and moisture changes in mango slices during convective drying. The results provide a basis for development of computational software for drying-process design and for determining appropriate drying conditions for mangoes in particular and fruits in general.

2. Literature review

According to Castro et al. [2], modeling of the drying process involves the following mathematical models [2]:

- Equilibrium Moisture Content (EMC) model
- Drying kinetics model (Page, Midilli, Newton, etc.)
- Moisture transfer model (based on Fick's law of diffusion)
- Heat transfer model

These models are interrelated. Among them, the combined heat and moisture transfer model plays a central role in modeling the drying process.

2.1. Equilibrium Moisture Content Model

There are several mathematical models used to determine the equilibrium moisture content (Me), including the Henderson model, Chung–Pfost model, Halsey model, Oswin model, and GAB model. Among these, the GAB model is considered suitable for fruits with a gel-like flesh structure, such as mango, jackfruit, and banana [3]. Therefore, this study uses the GAB (Guggenheim–Anderson–de Boer) model to determine Me.

2.2. Drying Kinetics Model

Drying kinetics describes the change in the moisture content of a material over time under specified drying conditions, including air temperature, relative humidity, air velocity, and material thickness. To date, numerous drying kinetic models have been developed, including the Newton, Page, Henderson–Pabis, and Midilli models, for different groups of materials. Among these, the Page model is one of the most widely used models for drying gel-like and porous materials, including fruits [2].

A limitation of these models is that they describe only the average moisture content of the material as a function of time and do not represent the internal moisture distribution within the material.

2.3. Heat and Moisture Transfer Model

During the drying process, heat and moisture transfer are directly coupled. According to Onwude et al. [3], the heat transfer model consists of the heat conduction differential equation and the boundary-layer heat transfer equation. Similarly, the moisture transfer model consists of the moisture diffusion equation (Fick's law) and the boundary-layer moisture transfer equation [3].

These equations, together with the initial conditions, boundary conditions, and empirical data and correlations for determining material and drying-air properties, are used to model changes in the temperature and moisture content of the material being dried.

Although the coupled heat and moisture transfer model is relatively complex because it involves differential equations, advances in computing technology make it possible to calculate and simulate the temperature and moisture distributions within the material in both space and time in detail.

3. Materials and Methods

3.1. Materials

The material investigated in this study was Cat Chu mango, one of the most common mango varieties in the Mekong Delta [4]. Ripe-but-firm mangoes were peeled and cut into slices with a thickness of 10±0.5 mm, while the width and length were in the ranges of 50±5 mm and 70±5 mm, respectively, as illustrated in Figure 1.

The initial moisture content of the mango slices was determined by drying method at 120°C for 24 h.

3.2. Method for developing mathematical models

The mathematical model was developed based on the physical laws governing heat and moisture transfer, combined with validated and published experimental data and empirical correlations describing the properties of the material and drying environment.

The parameters of the drying kinetic model were determined experimentally using an experimental dryer in the food laboratory of Mekong University. Drying operating parameters, including temperature, humidity, air velocity, were set on the experimental dryer according to the initial data used in the model. Samples. A sample of 2.5 kg of sliced mangoes was dried for 10 h using drying air at temperature 70±1 ºC

and relative humidity 20±2 %. The sample was weighed every hour to determine the change in moisture content. The thickness of the mango slices was also measured to evaluate the degree of shrinkage during drying. The experiment was conducted in triplicate to have data that were used to calibrate and validate the model against the actual drying process.

3.3. Method for simulating the drying process

The procedure for developing the simulation program was as follows:

1) Determine the geometric parameters of the material.
2) Determine the initial properties of the material and drying air.
3) Specify the boundary conditions.
4) Use the Finite Difference Method (FDM) to solve the coupled heat and moisture transfer model and determine the changes in the moisture content and temperature of the mango slice as a function of spatial position z and time t.
5) Solve the shrinkage model to determine the change in the dimensions of mango slice with time.
6) Update the moisture content, temperature, and dimensions of the mango slice.
7) Repeat Steps 1–6 until the required moisture content is reached.
8) Present and visualize the simulation results.

MATLAB software was used as the programming tool for developing the simulation program [5].

4. Results and discussion

4.1. Establishment of the physical model of the object

Cat Chu mango, as well as other species of mangoes in general, has a shape similar to an ellipsoid. After being sliced, the mango has an elliptical shape as shown in Figure 1.

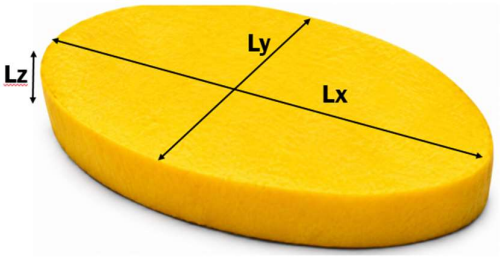


Figure 1. *Shape and dimensions of the mango slice after cutting.*

The physical model of the mango slices during drying is presented in Figure 2. In this model, the Z-axis is perpendicular to the mango slice and represents the position along the slice thickness, while the other axes represent the width and length directions of the slice.

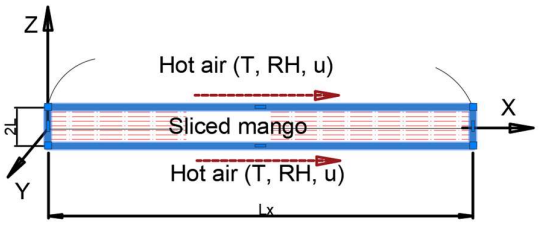


Figure 2. *Physical model of the sliced mango.*

Initial conditions:

- At the beginning of the drying process, the moisture content and temperature are uniform throughout the mango slice and are equal to the initial moisture content and ambient temperature, respectively: $M(z,0) = M_0$ and $T(z,0) = T_{env}$

- The mango slice is assumed to have an elliptical shape, with the slice thickness L_z much smaller than its width L_x and length L_y: ($L_z \ll L_x$ and $L_z \ll L_y$)
- Heat transfer is assumed to occur only in the Z-direction, from the hot drying air toward the center of the mango slice. Moisture transfer occurs in the opposite direction, from the center of the slice toward the surface.

4.2. Determination of input parameters

The input data and parameters for calculation and simulation are listed in Table 1.

***Table 1**. Input parameters of the mango slice and drying air.*

Parameters	Symbol	Values/Formula	References
Average dimensions of the mango slice	$L_xL_yL_z$	50x70x10 mm	Setting
Density of mango	ρ_s	1020 kg/m³	[6]
Thermal conductivity of air	k_{air}	0.03 W/(m.K)	[7]
Latent heat of vaporization of water	h_{fg}	2.30×10^6 J/kg	[7]
Initial moisture content of mango	M_0	4 kg/kg d.b.	Assumed
Ambient air temperature	T_{env}	25°C	Assumed
Initial relative humidity of ambient air	RH_0	80%	Assumed
Inlet hot-air temperature	T_1	70°C	Setting
Inlet hot-air relative humidity	RH	20%	Setting
Atmospheric pressure	P	1 bar = 10^5 Pa	[7]

4.3. Experimental results of drying samples

The results from the drying experiment are shown in Table 2. These data are used to evaluate the compatibility of the models.

***Table 2**. Collected data from the experiment for change of moisture content with drying time.*

Drying time (h)	Experimental data		
	Sample weight (kg)	Moisture content (M_{exp}) (kg/kg d.b.)	Slice thickness (L_{exp}) (mm)
0	2.50±0.006	3.96±0.008	9.8±0.10
1	2.14±0.010	3.25±0.009	9.4±0.10
2	1.88±0.012	2.72±0.010	9.1±0.10
3	1.65±0.011	2.28±0.009	8.8±0.11
4	1.46±0.012	1.90±0.010	8.5±0.09
5	1.32±0.011	1.62±0.009	8.3±0.08
6	1.16±0.010	1.30±0.008	8.1±0.08
7	1.06±0.012	1.11±0.009	7.9±0.09
8	0.98±0.009	0.94±0.008	7.7±0.07
9	0.87±0.010	0.72±0.008	7.6±0.07
10	0.86±0.008	0.68±0.006	7.5±0.80

4.4. Selected mathematical models for the mango drying processing

4.4.1. Equilibrium moisture content model (GAB)

$$M_e = \frac{X_m C K a_w}{(1 - K a_w)(1 - K a_w + C K a_w)} \quad (1)$$

where:

M_e is equilibrium moisture content of the mango (kg/kg d.b.)

a_w is water activity; $a_w = RH/100$

X_m is the monolayer moisture content (kg water/kg dry matter).

The parameters C and K depend on the material and air temperature. The study [8] on mango drying using air at 70°C reported the values as: $X_m = 0.123$ kg/kg, $C = 23$ and $K = 1.01$.

4.4.2. Mathematical model for heat transfer

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial z^2} + \frac{h_{fg}}{C}\frac{\partial M}{\partial t} \quad (2)$$

$$\frac{\partial T}{\partial z} = \frac{h}{k}(T_{air} - T_s) \quad (3)$$

where: T_s is the temperature on the surface of the sliced mango ($T_s = T$ at $z = L_z/2$).

k is the mango thermal conductivity that is calculated as [8]:

$$k = 0.084 + 0.55\frac{M}{1 + M} + 0.006T \quad (4)$$

Then, thermal diffusivity of mango: $a = \frac{k}{\rho C}$

C is specific heat of the mango [8]:

$$C = \frac{C_k + C_a M}{1 + M} = \frac{1700 + 4186M}{1 + M}\ \mathrm{J/(kgK)} \quad (5)$$

where:

C_k is the specific heat capacity of the dry matter;

C_a is the specific heat capacity of water.

The convective heat transfer coefficient (h) is calculated using the dimensionless correlation [9]:

$$h = 0.664\frac{k_{air}}{L_x}Re^{1/2}Pr^{1/3} \quad (6)$$

where: $Re = \frac{u.L_x}{\vartheta}$

Pr is the Prandtl number. For air, $Pr = 0.7$;

L_x is the width of the mango slice;

k_{air} is the thermal conductivity of air;

u is the air velocity (m/s); $u = 1$ m/s is selected;

ϑ is the kinematic viscosity of air [7].

$\vartheta = 1.7\text{x}10^{-5} + 4\text{x}10^{-8}\text{T}_{air} \approx 20\text{x}10^{-6}$ m^2/s.

4.4.3. Mathematical model for moisture transfer [2]:

$$\frac{\partial M}{\partial t} = D_{ef}\frac{\partial^2 M}{\partial z^2} \tag{7}$$

$$\frac{\partial M}{\partial z} = -\frac{h_m}{D_{ef}}(M_s - M_e) \tag{8}$$

where: D_{ef} is the effective moisture diffusivity of mango. Initially, a value of D_{ef} = 2.8×10⁻¹⁰ m²/s, reported by Corzo et al. [10], was assumed. This value was subsequently verified by comparison with the experimental data obtained for the material under investigation, and an appropriate value was then determined.

To determine the moisture-transfer coefficient h_m, an analogous correlation [10] was used:

$$h_m = \frac{24.8 D_{ef}}{L.Di^{0.375}} \tag{9}$$

where:

Dincer number (*Di*): $Di = \frac{u}{k_s L}$

u is the air velocity (m/s)

k_s is drying constant (1/s); L is a half of the sliced mango thickness (m).

4.4.4. Model for drying dynamics

Page model is used to describe the dynamic drying process [2]:

$$MR = \frac{M(t) - M_e}{M_o - M_e} = \exp(-k_s t^n) \tag{10}$$

where: $M(t)$ is average moisture content of the material at drying time t;

M_e is equilibrium moisture content of the material with the surrounding environment.

The parameters k_s and n depend on the type of material and drying conditions and are determined experimentally. Using the data obtained from the experimental dryer, regression analysis was performed with the *curve_fitting_equation.m* program to determine the specific values of k_s and n, as presented in Table 3.

4.4.5. Mathematical model for shrinkage in thickness of the sliced mango with drying time [6]:

$$L(t) = L_0\left(\frac{M_{aver}(t)}{M_0}\right)^{\beta} \tag{11}$$

where:

$L(t)$ is the thickness of the mango slice as a function of drying time;

L_o is the initial thickness of the mango slice;

β is the shrinkage coefficient;

$M_{aver(t)}$ is the average moisture content of the entire mango slice at time t. This value is calculated from the results of the moisture-transfer model.

4.5. Results of calculation and simulation

4.5.1. Determination of the model coefficients

Using MATLAB software in combination with published research data, the equilibrium moisture content (*M*e) of mango slices under the specified drying conditions and the coefficients of the equations in the mathematical model were determined. The calculated results are presented in Table 3.

***Table 3**. Evaluation of determining Me and the other coefficients of the models.*

Parameters	Models/reference	Drying conditions	Results
EMC (*Me*)	[8]	T = 70°C; RH = 20%	Me = 0.13
coefficients of Page model (k_s and n) MR = exp(-$k_s t^n$)	Experimental data + *curve_fitting_equation.m*	T = 70°C; RH = 20%	$k_s \approx 0.27$ $n \approx 0.85$
Shrinkage (β)	[6]	T = 70°C; RH = 20%	β = 0.12
effective moisture diffusivity (D_{ef})	[10]	T = 70°C; RH = 20%	D_{ef} = 2.8x10^{-10} m²/s
moisture transfer coefficient h_m	$h_m = 2\frac{24.85 D_{ef}}{L_z Di^{0.375}}$	D_{ef} = 2.8×10^{-10} m²/s u =1 m/s L_z = 0.01 m	h_m =1.87x10^{-7} m/s

4.5.2. Results of dynamic drying simulation

a. Simulation of the drying process using Page equation:

Based on the experimental data, the MATLAB function *curve_fitting_equation.m* was used to determine the parameters k_s = 0.27 and n = 0.85. Accordingly, the specific Page equation for mango slices was obtained as follows:

$$M(t) = 0.13 + 3.87\exp(-0.27t^{0.85}) \quad (12)$$

The drying curve predicted by the Page model (Equation 12) is plotted in Figure 3 (as the solid line) representing the dropping moisture content of the mango slices with drying time, compared with the experimental data (represented by a dashed line).

As shown in the figure, the Page model can be used to describe the actual drying process, with an average error of no more than 5%.

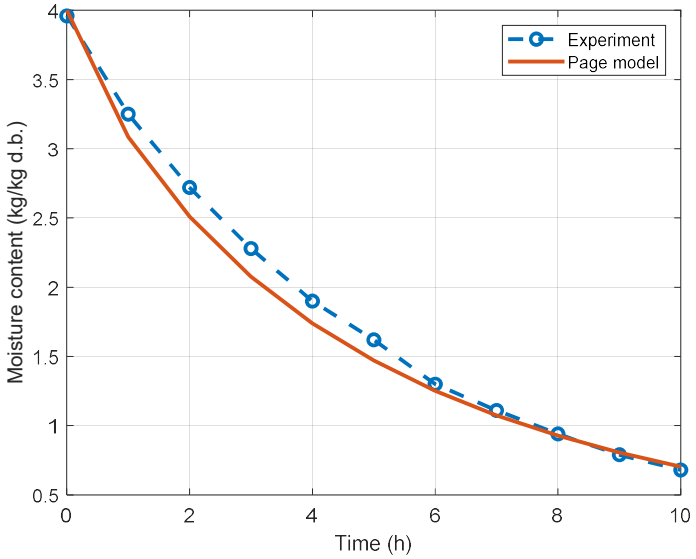


***Figure 3.** Drying curves of Page model compared with the experiment.*

b. Simulation of the drying process using heat and moisture transfer model

The results of the drying kinetics simulation based on the coupled heat and moisture transfer model are illustrated in charts from Figure 4 to Figure 9.

Figure 4 indicates that the effective moisture diffusivity, D_{ef}, has a significant effect on the agreement between the model predictions and the experimental results. When the value D_{ef} = 2.8×10^{-10} m²/s obtained from the study by [10] was used, the drying curve (asterisk-marked line) showed a considerable deviation from the experimental drying data.

After conducting multiple trial simulations with different values of D_{ef}, it was found that using the value D_{ef} = 3.9×10^{-10} m²/s produced a drying curve (the solid line) that was in good agreement with the experimental results. Compared with the experimental drying curve (dashed line), the heat and moisture transfer model with an effective moisture diffusivity of D_{ef} = 3.9×10^{-10} m²/s provides a good representation of the drying process of Cat Chu mango (Figure 4). The model shows a relatively high degree of agreement with the experimental results, with an average error of no more than 3%.

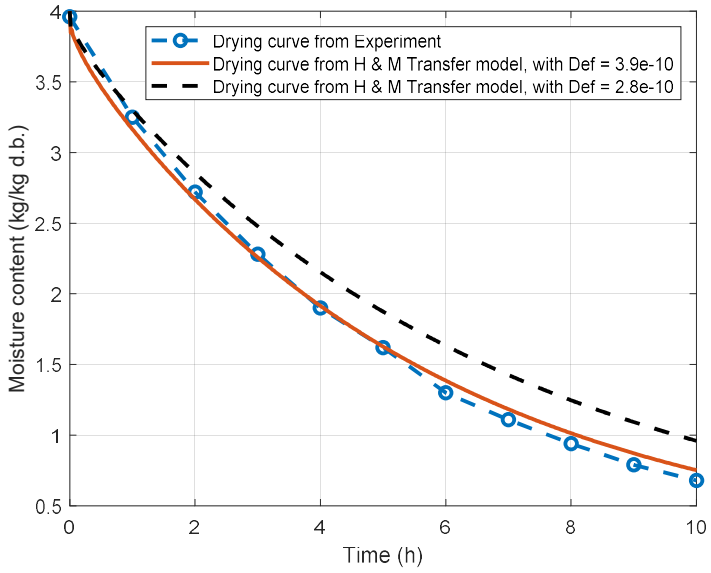


Figure 4. *Drying curves of heat and moisture transfer model compared with the experiment.*

4.5.3. Results of simulating change of mango temperature with time and location

The change in temperature, T, within the material as a function of position (z) and time (t) is simulated and presented in Figure 5. The mean temperature of the mango slice shown in Figure 6 indicates that the mean temperature of the sliced mango was just under 60°C after 10 h drying.

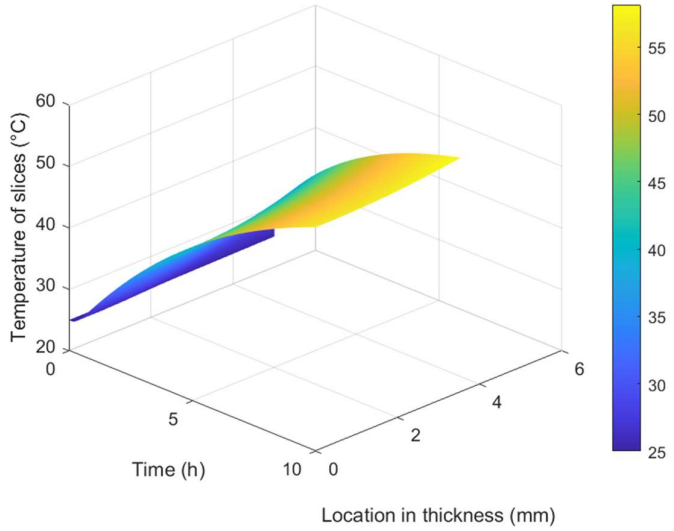


Figure 5. *Change of mango actual temperature with time and location.*

The simulation results show that the temperature gradually increases from the center toward the outer surface. When drying with air at a temperature of 70°C, the surface temperature of the mango slice gradually increases from approximately 55°C to 58°C over a drying period from beginning to 10 h (Figure 5). Meanwhile, the temperature of the inner layers of the mango slice also increases but remains lower than that of the outer surface. This indicates that, for a relatively short drying period, the temperature of the mango slice remains lower than the drying-air temperature because of the evaporative cooling effect caused by moisture evaporation from the mango slice.

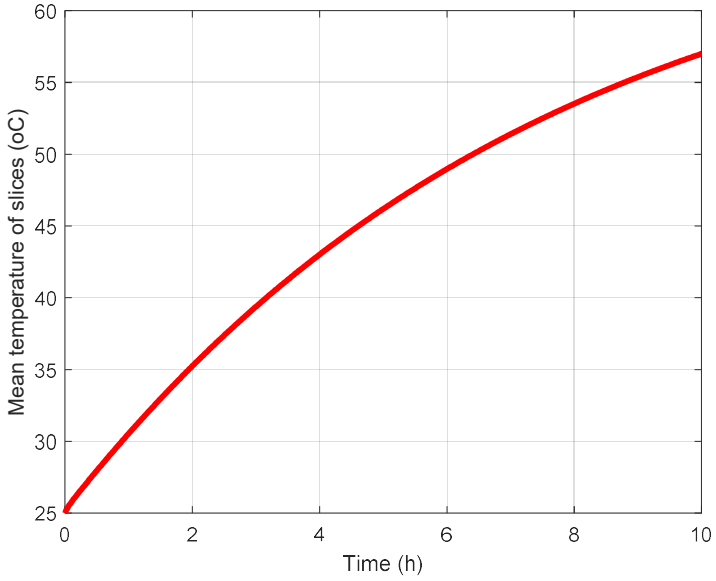


Figure 6. *Mean temperature of the mango slice increases with time.*

Figures 5 and 7 indicate that the temperature distribution within the mango slice is non-uniform during the drying process. Figure 7 presents the temperature distribution across the thickness of the mango slice at different drying times (2.5 h, 5 h, and 10 h).

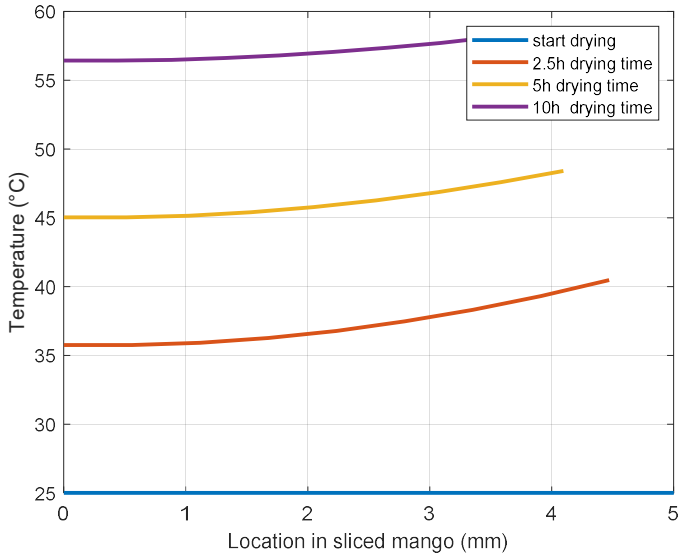


Figure 7*. Temperature distribution in mango slices with location after specific drying time.*

The temperature is lower at the center of the mango slice and gradually increases toward the outer surface, which is in direct contact with the hot air. However, the temperature gradient gradually decreases with increasing drying time.

4.5.4. Simulation results of moisture distribution in mango as a function of position and time

Similar to the heat-transfer simulation, the differential equations governing moisture transfer were discretized and subsequently implemented in MATLAB to develop the moisture-transfer simulation program. The resulting variation in moisture content within the material as a function of position (z) and time (t) is presented in Figure 8.

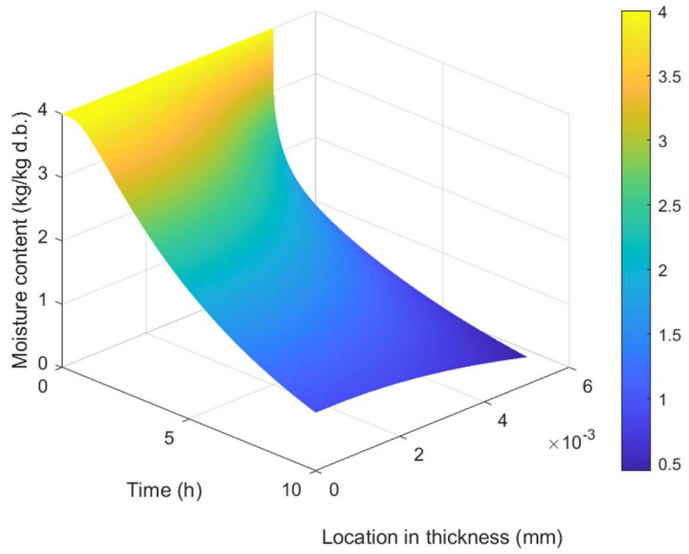


Figure 8. *Change in moisture content of the sliced mango with time and location.*

For more detailed representation, the simulation results are presented in a 2D plot showing the change in moisture content across the mango slice, from the center toward the outer surface, at three different drying times (Figure 9).

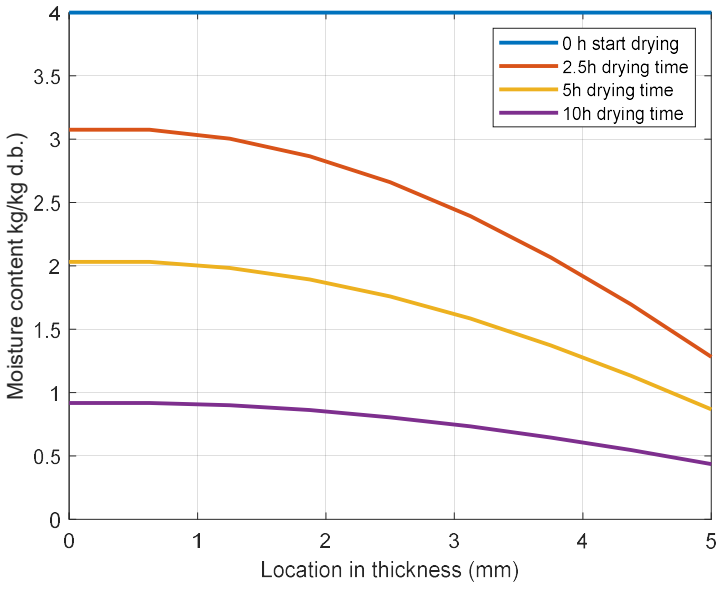


Figure 9. *Moisture distribution in mango slices with location after specific drying time.*

Figures 8 and 9 show that the moisture distribution within the mango slice is non-uniform during the drying process. The moisture content is highest at the center of the mango slice and gradually decreases toward the outer surface, which is exposed to the drying air. However, the difference in moisture content between the interior and exterior regions gradually decreases as the drying time increases.

5. Conclusions

This study developed and further refined a mathematical model describing the variation of drying-process parameters with drying time, including a system of equations governing heat transfer, moisture transfer, energy balance, and mass balance. The initial data and boundary conditions were proposed as the basis for solving the system of equations.

Based on the fundamental drying kinetics model (Page model) combined with experimental data, the authors determined the appropriate parameters $k = 0.27$ and $n = 0.85$ for the Page model. For the coupled heat and moisture transfer model, MATLAB was used to develop simulation programs for describing the changes in temperature and moisture content of mango during drying. An effective moisture diffusivity of $D_{ef} = 3.9\times10^{-10}$ m²/s was determined to provide a good representation of the actual drying process.

Furthermore, the coupled heat and moisture transfer simulation provides a visual representation of the variation in material properties in both time and space. These features can be considered among the novel aspects of the present study compared with previously published studies.

The simulation program can serve as a basis for predicting drying time and the achievable moisture content of the product after a specified drying period. The simulation results may also provide useful reference information for investigating the drying technology of other fruit products.

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Conflict of Interest

The authors declare no conflict of interest.

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