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Drying Kinetics and Mathematical Modelling of Foam-Mat Dried Wood Apple (*Limonia acidissima*)

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ABSTRACT

Wood apple is an underutilized wild fruit found in arid regions, known for its high nutritional value. However, due to limited awareness, much of this fruit goes to waste. To address this, wood apple powder was prepared using the foam mat drying method. This study evaluated the drying kinetics of foam-mat drying for wood apple, using 8% GMS as a foaming agent and 0.5% methyl cellulose as a foam stabilizer. The mixture was whipped for 10 minutes and dried in a cabinet dryer at varying temperatures (55, 60, and 65ºC) and foam mat thicknesses (2, 4, and 6 mm). Drying kinetic data were used to build drying curves, which were then analyzed using the Cubic, Page, Henderson and Pebris, and Logarithmic models. Results indicated that both the drying temperature and foam layer thickness significantly affected drying time, with the shortest drying time observed at the highest temperature and thinnest foam layer. Among the models tested, the Cubic followed by Page model most accurately represented the experimental drying curve data.

Keywords Wood apple, Foam-mat drying, Drying kinetics, Mathematical modelling.

INTRODUCTION

Wood apple

Wood apple belongs to the family Rutaceae Swingle (*Limonia acidissima* L., *Schinus limonia* L.). It is also called elephant apple, monkey fruit, curd fruit, vilampazham, kathbel and kaitha in India. States growing the fruit include Maharashtra, Rajasthan, Andhra Pradesh, Tamil Nadu, Kerala, Karnataka, Madhya Pradesh and the Western Himalayas (Singhania *et al.* 2020).

Almost all parts of this plant such as leaf, fruit, seed, bark and root have medicinal value. The fruits are spherical in shape with greyish-white rind and a woody hard outer shell. Its pulp is sour-sweet, sticky, brown, and resinous, with peculiar aroma and consists of white seeds (Vidhya and Narain 2011). Fruit pulp is eaten raw with or without sugar, or is blended with coconut milk and sugar syrup and drunk as a beverage

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or frozen as an ice cream.

It is used in many herbal remedies such as digestive, stimulant, astringent, carminative and as an antidiarrheal. It contains a number of phyto constituents. The raw fruit pulp is helpful in the treatment of gastro intestinal problems like flatulence, diarrhoea, dysentery and piles.

Wood apple is mainly seasonal crop available in winter season from October to February. The fruit after ripening causes fungal attack. So, to reduce post-harvest losses of wood apple, conversion into a value-added product that is available all year. Drying of pulp can be one of the best methods of preservation.

Food drying is one of the oldest methods of preserving food by lowering the moisture content. It is a complex operation involving heat and mass transfer. The problem of post-harvest losses can be solved by dehydrating the produce, due to which the availability of fruits and vegetable could be throughout the year as well as the farmer income can also be increased by producing value added product.

Foam-mat drying

Foam-mat drying is an innovative technique for drying liquid food materials with high water content, making it ideal for heat-sensitive, viscous, sticky, or otherwise difficult-to-dry fruits and vegetable extracts. This method effectively dries various food materials such as milk, vegetable puree, and fruit juices without compromising quality (Kanha *et al.* 2022).

In foam-mat drying, aqueous food concentrates are dried using air at lower temperatures to reduce moisture content, forming a stable, honeycomb-like porous sheet that can be milled into powders. A crucial step in this process is foaming, where air or gas is incorporated into the liquid or semi-solid food using a foaming agent and stabilizers to maintain the foam's structure (Franco *et al.* 2015).

The foamed product is spread as a thin sheet on an aluminum tray and heated between 50 and 80°C until the desired moisture content is achieved. The porous-foamed structure increases the liquid-gas interface, allowing faster dehydration at lower temperatures. The foaming agent reduces surface tension at the air-liquid interface, enhancing foaming ability and decreasing foam density (Brar *et al.* 2020).

Foods that are particularly thermosensitive, sticky, viscous, and heavy in sugar can be dehydrated using foam-mat drying (Franco *et al.* 2015). Compared to other drying methods, foam-mat drying is simple, cost-effective, and time-efficient (Hardy and Jideani 2017).

Many fruits have benefited from the application of foam mat drying, such as muskmelon (Asokapandian *et al*. 2016), pineapple (Shaari *et al.* 2017), and passion fruit aril (Khamjae and Rojanakorn 2018) and Peach (Brar *et al.* 2020).

There has been limited research on value addition of wood apple and its drying characteristics. To our knowledge, foam-mat drying of wood apple has not yet been done. This technique can produce a nutritionally rich powder with low operational costs with high nutritional quality. Understanding the impact of foam mat thickness and temperature on the final product's quality is crucial. With this in mind, the following research objectives were established.

(1) To study the drying kinetics of foam-mat dried wood apple at different temperature and thickness.

(2) Mathematical modelling of drying kinetics of wood apple.

MATERIALS AND METHODS

Raw material and sample preparation

The wood apple purchased from local market of Udaipur. Freshness, color, size, state of ripeness and absence of any mechanical damage were used as the selection criteria. For sample preparation wood apple were washed with clean water to remove adhering material on the surface and dried at room temperature to remove surface moisture. The fruits were broken with the help of hammer and the pulp was extracted from it. After extraction of pulp the pre-treatment was given with hot water blanching at 80ºC for 5 minutes then addition of KMS 1.0% in pulp. Foaming was done with help of electric hand blender with addition of 8% GMS (glycerol-mono-stearate) as foaming agent, and 0.5 % MC as stabilizer. Then the prepared samples were mixed thoroughly with the help of hand blender for 10 min time intervals at maximum speed of blender.

Drying process

The hot-air drying process was carried out in a cabinet dryer. The foamed pulp was dried at air temperature of 55, 60, 65°C with foam thickness of 2,4 and 6 mm in a cabinet dryer at constant air velocity 2 m/s. All drying experiments were carried out in triplicate. Samples were placed as a thin-layer in a stainless-steel tray. Experiments were performed until an equilibrium condition was achieved and a constant weight of the samples was registered. The dried samples were ground in powder form then kept in sealed polypropylene bags.

Drying kinetics

Moisture content

The moisture content of wood apple samples was determined by using hot air oven method. The moisture content of the sample was determined by using the following formula

$$\text{Moisture content \% db} = \frac{W_1 - W_2}{W_2} \times 100 \quad .....(1)$$

Where,

W_1 = Initial weight of the sample (g)
W_2 = Final weight of the sample (g)

Moisture ratio

To examine the drying characteristics of wood apple and graphically represent its drying behavior, it is necessary to calculate the moisture ratio at various time intervals. Moisture ratio curves under different drying conditions provide a clearer depiction of the drying behavior compared to moisture content curves, as the initial value for all experiments is set to one. The Moisture Ratio (MR) was calculated by using the following Eq. 2 (Gomez-Daza and Ochoa-Martinez 2015).

$$MR = \frac{M - M_e}{M_o - M_e} \quad ......(2)$$

Where,

M= Moisture content at time t (min) during drying (% db)
M_e= Equilibrium moisture content (% db)
M_o= Initial moisture content ((% db)

The values of M_e were neglected because when compared to M_o and M the values of M_e (equilibrium moisture content) were very small for long drying time. Therefore, the following Eq. 3 was used to calculate the MR.

$$MR = \frac{M}{M_0} \quad ...\ (3)$$

Drying rate

The drying rate (DR) is defined as the quantity of moisture that evaporates over time (Nguyen *et al.* 2019). The drying rate of sample was calculated by using the following Eq. 4. (Erol 2022).

$$\text{Drying rate} = \frac{M_{t+dt} - M_t}{d_t} \quad ....\ (4)$$

Where,

M_{t+dt}= Moisture content at t + dt (g water/g dry matter)
dt = Time between two sample weighing (min)

Moisture diffusivity

Effective moisture diffusivity D_{eff} is an important property of food during drying process and it indicates the rapidness of removal of moisture from the food. In falling rate period of drying, mainly moisture is removed by molecular diffusion. Fick's diffusion equation was used for the effective moisture diffusivity calculation for infinite slab or cylindrical geometry biological products. For calculation of moisture ratio, the following equation was used (Kalyanamitra and Assawarachan 2022).

$$MR= \frac{8}{\pi^2} \exp \left(\frac{\pi^2 D_{eff} t}{4L^2} \right) \quad ..... (5)$$

The above equation can also written as:

$$\ln MR=tk_0 + \ln \frac{8}{\pi^2} \quad ....(6)$$

Where,

D_{eff} = Effective moisture diffusivity (m^2/s)
L= Thickness of pulp/slice thickness (m)

Experimental values of moisture diffusivity are calculated by plotting values of exponential drying data i.e. ln (MR) versus drying time. It gives a straight line and slope (k_0) of the line is used to calculate the effective moisture diffusivity (Kalyanamitra and Assawarachan 2022).

$$k_0= \frac{-\pi^2 D_{eff}}{4L^2} \quad .... (7)$$

$$D_{eff}= \frac{-4L^2 k_0}{\pi^2} \quad .... (8)$$

Mathematical modelling

In order to predict the best fit drying model for drying of wood apple the calculated moisture ratio values were used. Drying curve data i.e. moisture ratio calculated at different times obtained from all drying experiments were fitted in widely used four thin layered drying models as mentioned in (Table 1). For selecting the best model for describing the drying kinetics of wood apple. Non-linear regression analysis was carried out by using curve fitting Toolbox in curve expert and MATLAB 2024a software to determine the constant values of models. The best fit model and goodness of fit of selected models were selected based on the value of correlation coefficient (R^2) and root mean square error (RMSE). The best fit model was evaluated based on highest value of R^2 and lowest values of RMSE (Silva *et al.* 2014). These statistical significant values were calculated as (Bishnoi *et al.* 2020, Komonsing *et al.* 2021):

Table 1. Effective moisture diffusivity values at different conditions for tray dryer.

Temperature	Thickness	Diffusivity	Equation	R^2
	2 mm	7.09 ×10^{-9}	y = -0.0175x + 0.6187	0.9539
55 ºC	4 mm	1.94 ×10^{-8}	y = -0.012x + 0.6142	0.9025
	6 mm	3.50× 10^{-8}	y = -0.0096x + 0.8602	0.7252
	2 mm	7.83× 10^{-9}	y = -0.0193x + 0.5385	0.9497
60 ºC	4 mm	2.14× 10^{-8}	y = -0.0132x + 0.4094	0.7240
	6 mm	4.20 ×10^{-8}	y = -0.0096x + 0.8602	0.9008
	2 mm	1.31× 10^{-8}	y = -0.0324x + 1.0688	0.8885
65 ºC	4 mm	3.70× 10^{-8}	y = -0.0228x + 0.9554	0.8554
	6 mm	7.90× 10^{-8}	y = -0.0134x + 0.7602	0.8445

$$R^2= \frac{\sum_{i=1}^{N} (MR_{exp,i}-MR_{exp\ mean,i})^2 - (MR_{exp,i}-MR_{exp\ mean,i})^2}{\sum_{i=1}^{N} (MR_{exp,i}-MR_{exp\ mean,i})^2} \quad .....(9)$$

$$RMSE= \left[\frac{1}{N} \sum_{i=1}^{N} (MR_{exp,i} - (MR_{prei.i})^2 \right]^{1/2} \quad ..... (10)$$

Where,

$$MR = \text{Moisture ratio, } \frac{M - M_e}{M_o - M_e}$$

t = Time, h
k = Drying constant, h^{-1}
a, b, c, n = Drying parameters

RESULTS AND DISCUSSION

Drying kinetics of wood apple

Effect of foam-mat thickness and temperature on moisture reduction

The foam mat drying of wood apple pulp was continued from the initial moisture 566.66 % (db) to the final moisture level of 10.10 to 7.22% (db) at various drying air temperature and foam mat thickness combinations.

The initial moisture content of the 2 mm sample was 566.67% (db) and it took 240, 300 and 300 min to dry to a moisture content of 7.22,7.40, 7.96% (db), at 65,60 and 55 ºC temperature respectively. Similarly, for 4 mm sample to dry from 566.68 to 7.91,8.20, and

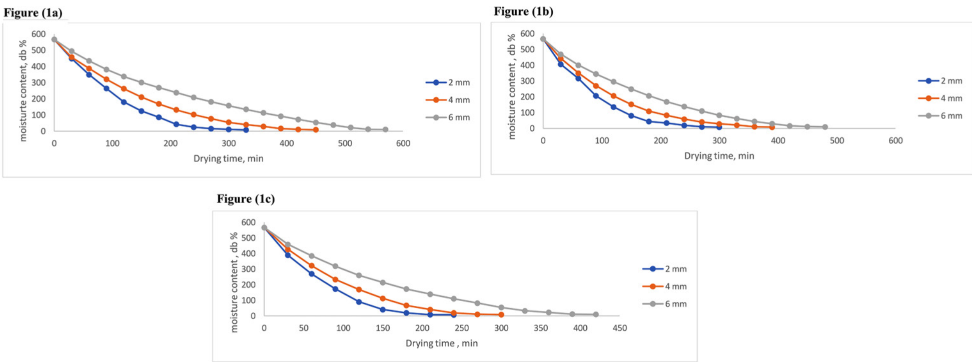

Fig. 1. Moisture content versus drying time for wood apple pulp at 55°C (1a), 60°C (1b) and 65°C (1c) for different foam layer widths.

8.37% (db) it took 300,390 and 460 min, for 6 mm sample to dry from 566.69 to 9.40, 9.85 and 10.10% (db) it took 420,480 and 570 min at 65,60 and 55ºC temperature. It was observed that for the samples of 2 mm thickness the moisture removal rate was faster when compared with 4 and 6-mm thick samples. It can be noted that the drying time for the samples to reach the final moisture content is following increasing pattern with increase in foam mat thickness i.e. 330.-240 min for 2 mm, 450-300 min for 4 mm and 570-420 min for 6 mm thick samples, at temperature range 55, 60 and 65ºC respectively. The drying time increased with an increase in foam mat thickness, because of less exposed area for moisture removal. Kandasamy *et al.* (2014), Asokapandian *et al.* (2016), Brar *et al.* 2020) found similar outcomes in their studies on the foam mat drying of papaya, muskmelon puree, and peaches, respectively, noting that an increase in drying temperature led to a reduction in drying time.

The relation of moisture change with respect to the required drying period of wood apple is given in (Fig. 1), which clearly shows a non-linear continuous decrease in moisture with the drying period. The variation of drying air temperature has been found reflected in values of the drying period. The total drying period and the drying temperature are inversely proportional to each other; as the drying temperature decreases, the drying period is prolonged.

Effect of process variable on drying rate of foam-mat drying of wood apple

The relationship between drying rate and moisture

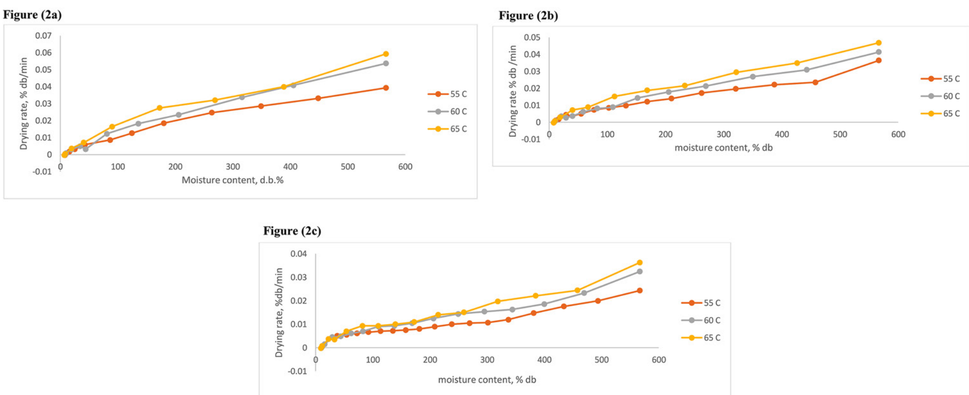

Fig. 2. Moisture content versus drying rate for wood apple pulp at 55°C , 60°C and 65°C for different foam layer thickness 2 mm (2a), 4 mm (2b), and 6 mm (2c) .

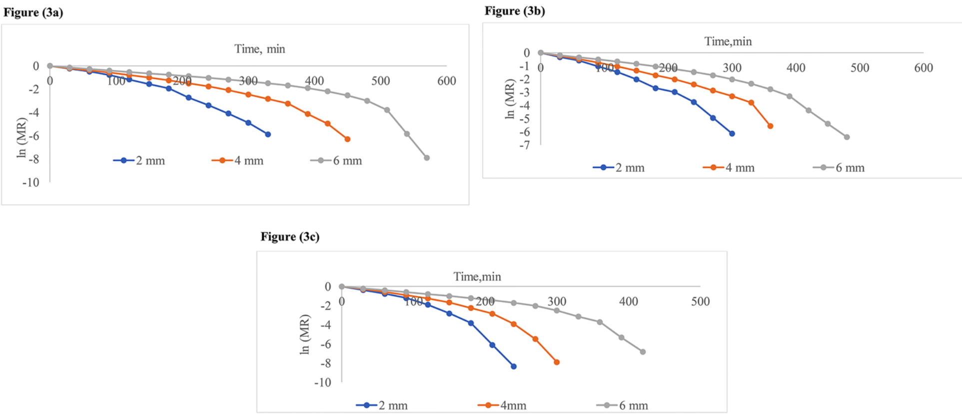

Fig. 3. ln (MR) versus drying time for wood apple pulp at 55°C (3a), 60°C (3b) and 65°C (3c) for different foam layer widths.

content is shown in (Figs 2a– 2c). From all the experiments it is clear that drying rate decreased with decrease in moisture content for all samples. During the initial stages of drying, the foamed puree had a high drying rate due to significant moisture loss and high moisture diffusion.

As drying progressed, the moisture content of the foamed material decreased, resulting in a reduced drying rate. Therefore, the drying curves for all different combinations show that most drying occurs during the falling rate period. The drying rate decreases with a decrease in moisture content, and few points of curves interacted unexpectedly. This was may be due to variations in experiments (Kohli *et al.* 2017).

The maximum drying rate 0.05932 g-w/g-dm-min was observed initially for 2mm thick pulp dried at 65°C. From the figures it can be observed that the drying rates were large at the start of the drying process and gradually decreased as the moisture contents of the products decreased. It was also observed that the drying rates for different drying temperatures varied during initial 120-240 min, but as the drying continues the drying rates became constant for all temperatures. The increase in drying rates with an increase in temperatures might be due to high moisture diffusivity at higher temperatures.

The hot air blowing over a thin layer of foamed wood apple pulp facilitates the easy removal of free water. Consequently, the drying rate was rapid initially due to the availability of unbound moisture. However, as drying continued, the rate slowed and stabilized because most of the free water was lost, leaving mainly bound water. These results are in line with the findings of several researchers worked on the drying characteristics of various fruits and vegetables like muskmelon (Asokapandian *et al.* 2016), for drying of asparagus roots (Kohli *et al.* 2022).

Effect of process variable on moisture diffusivity of foam-mat dried wood apple

Effective moisture diffusivities (D_{eff}) were determined by plotting ln (MR) versus time using experimental drying data. During foam mat drying of wood apple in tray dryer; the moisture loss data were analyzed and the moisture ratios were calculated at different time intervals. The effective moisture diffusivity for wood apple were determined by using the slope of graphs of the ln (MR) versus drying time (Fig. 3).

Effective moisture diffusivity is inversely proportional to tortuosity, which is the actual path length a molecule travels and directly proportional to food porosity. A steeper slope on the ln (MR) versus time plot indicates higher moisture diffusivity. As seen in (Fig. 3), the slope increases as foam thickness decreases, meaning thinner foam layers dry faster due to less resistance to moisture movement. However, (Table 1) shows that effective moisture diffusivity

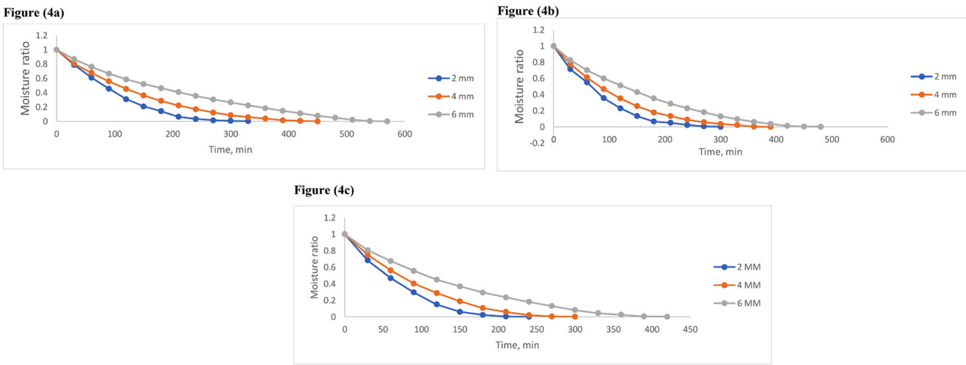

Fig. 4. Drying kinetics curves of the formulation at 55°C (4a), 60°C (4b) and 65°C (4c) for different foam layer widths.

(D_{eff}) actually increases with foam thickness because D_{eff} is proportional to the square of the foam thickness. Thus, thicker foams have higher moisture diffusivity despite requiring more travel distance for moisture. Similar results were also found by (Osama *et al.* 2022), during foam-mat drying of kadam fruit.

The variation in ln (MR) versus time graphs showed the linear inverse slope for all the experiments. From the figures, it may be seen that the value of effective moisture diffusivity increased with increase in drying air temperatures.

The values of effective moisture diffusivity as shown in (Table 1). indicates that these values affected by the thickness and drying air temperatures. In general, the diffusivity values increased with drying air temperature. The values of effective moisture diffusivities were varied from 7.09×10^{-9} to 7.90×10^{-8} m^2/s for tray dryer for various temperature and thicknesses (Table 1). At 55°C the values of effective diffusivity for samples were found in the range of 7.09×10^{-9} to 3.50×10^{-8} m^2/s. Whereas the effective diffusivity values for samples at 60°C was varied from 7.83×10^{-9} to 4.2×10^{-8} m^2/s. Similarly, at 65°C, the D_{eff} values for control samples ranged from 4.2×10^{-8} to 7.90×10^{-8} m^2/s.

Table 2. Mathematical thin layer drying models fitted to the drying curves of wood apple.

Sl. No.	Model name	Equations	References
1	Page	$MR = e^{-kt^n}$	Kohli *et al.* (2022)
2	Logarithmic	$MR = ae^{-kt} + c$	Patel and Panwar (2022)
3	Henderson and Pabis	$MR = ae^{-kt}$	Gomez-Daza and Ochoa-Martinez (2015)
4	Cubic	$MR = a+bt+ct^2+dt^3$	Kohli *et al.* (2022)

Mathematical modelling

The moisture ratio of each sample declined rapidly while the drying period was very short, but the rate of decrement of moisture ratio became quite slow as the drying time increased. The change of dimensionless moisture ratios related to the drying period used for the fitting of drying models is shown in (Fig. 4). The experimental results of moisture ratio during the drying process were fitted to four different models: Cubic, Page, Henderson and Pabis, and Logarithmic, to describe the drying characteristics of foam mat drying for wood apple pulp (Table 2).

Among all the thin-layer drying models, the Cubic model was considered the best model since it describes the change in moisture values over time with the highest average R^2 value, low RMSE value for almost all sets of experimental data. All other models also give good results of fitting in the descending sequence of best goodness of fit as Page, Logarithmic, and Henderson and Pabis (Table 3).

Specifically, for the Cubic model, R^2 values ranged from 0.9982 to 0.9999, and RMSE values

Table 3. Values of the drying constants and coefficients of mathematical models through non-linear regression analysis for wood apple pulp of 2 mm, 4 mm and 6 mm thickness.

Model name thickness	Temperature (ºC)	Parameters					RMSE
		a	c	k	d	R^2	
(2 mm)	55 ºC	1.1238	-1.049	1.5434	-	0.9966	0.0095
Logarithmic	60 ºC	1.1212	-0.142	1.3938	-	0.9388	0.0050
	65 ºC	1.1120	-0.122	1.4212	-	0.9927	0.0074
(4 mm)		a	c	k	-	R^2	RMSE
	55 ºC	1.0875	-0.090	1.8538	-	0.9993	0.0091
Logarithmic	60 ºC	1.0697	-0.064	2.0418	--	0.9995	0.0082
	65 ºC	1.1068	-0.098	1.9173	-	0.9986	0.0025
(6 mm)		a	c	k	-	R^2	RMSE
	55 ºC	1.1743	-0.197	1.0175		0.9987	0.0115
Logarithmic	60 ºC	7.8616	-0.152	1.0254	-	0.9140	0.1011
	65 ºC	1.113	-0.122	1.4215	-	0.9992	0.0060
2.(2 mm)	Temperature (ºC)	a	c	k	-	R^2	RMSE
Henderson	55 ºC	1.0491	-	10369	-	0.9855	0.0456
and Pebris	60 ºC	1.027	-	0.9218	-	0.9904	0.0360
	65 ºC	1.023	-	1.9268	-	0.9896	0.0347
(4 mm)	Temperature (ºC)	a	c	k	-	R^2	RMSE
Henderson	55 ºC	1.0251	-	1.1376	-	0.9919	0.030
and Pebris	60 ºC	1.0255	-	1.9567	-	0.9955	0.055
	65 ºC	1.0312	-	1.0607	-	0.9895	0.041
(6 mm)	Temperature(ºC)	a	c	k	-	R^2	RMSE
Henderson	55 ºC	1.0241	-	1.9682	-	0.9850	0.038
and Pebris	60 ºC	1.0264	-	1.9320	-	0.9876	0.037
	65 ºC	1.0235	-	1.9268	-	0.9892	0.034
2. (2 mm)	Temperature (ºC)	k		n	-	R^2	RMSE
	55 ºC	1.566		1.2965	-	0.9977	0.012
PAGE	60 ºC	2.311		1.3218	-	0.9968	0.021
	65 ºC	0.254		1.1441	-	0.9940	0.020
(4 mm)	Temperature (ºC)	k		n	-	R^2	RMSE
	55 ºC	1.7153		1.1504	-	0.9964	0.019
PAGE	60 ºC	1.8288		1.1396	-	0.9987	0.012
	65 ºC	1.8302		1.2104	-	0.9967	0.016
(6 mm)	Temperature (ºC)	k		n	-	R^2	RMSE
	55 ºC	1.3736		1.1420	-	0.9899	0.031
PAGE	60 ºC	1.6848		1.1630	-	0.9932	0.015
	65 ºC	2.5441		1.1461	-	0.9940	0.023
4. (2 mm)	Temperature (ºC)	a	b	c	d	R^2	RMSE
	55 ºC	1.003	-0.459	0.0636	-0.0023	0.9995	0.0004
CUBIC	60 ºC	0.995	-0.577	0.1124	-0.0073	0.9984	0.0002
	65 ºC	0.985	-0.601	0.1214	-0.0060	0.9974	0.0008
(4 mm)	Temperature (ºC)	a	b	c	d	R^2	RMSE
	55 ºC	0.9842	-0.341	0.0412	-0.0017	0.9994	0.0008
CUBIC	60 ºC	0.9953	-0.454	0.0745	-0.0438	0.9998	0.0005
	65 ºC	0.9940	-0.245	0.0654	-0.0321	0.9991	0.0006
(6 mm)	Temperature(ºC)	a	b	c	d	R^2	RMSE
	55 ºC	0.979	-0.022	0.0204	-0.0008	0.9987	0.0007
CUBIC	60 ºC	0.977	-0.285	0.0285	-0.0012	0.9999	0.0002
	65 ºC	0.980	-0.125	0.0274	-0.0018	0.9982	0.0008

ranged from 0.0002 to 0.0014 for different treatment combinations (Table 3). The cubic model is widely recommended by investigators for describing the drying behavior of various fruits and vegetables. Such as for Asparagus (Kohli *et al.* 2022).

CONCLUSION

Foam mat drying of the underutilized fruit wood apple was conducted at three temperatures (55, 60, 65ºC) and three thicknesses (2, 4, and 6 mm). The drying kinetics of the foam mat dried wood apple pulp were influenced by both temperature and foaming thickness. The thinnest foam layer dried the fastest at higher temperatures. Moisture diffusivity increased with rising temperature and thickness. Overall, the Cubic model, followed by the Page model, provided the best fits to the drying data, making them suitable for predicting the drying kinetics of wood apple pulp across all temperature and foam layer thickness.

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