



Utilization of A mixed Mode Solar Dryer Assisted with An Auxiliary Electric Heater for Drying Sweet Potato Slices

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Abstract: Reducing post-harvest losses of perishable fresh products is a key strategic approach to increasing income, national security, and nutrition in the world. A hybrid solar dryer equipped with an auxiliary electric heater was developed and used to dry sweet potato slices, maximizing the use of available solar energy for food drying and producing a high-quality dried product. During the experiments, two different sweet potato cultivars (Abis and Balady) were dried at three different drying air temperatures (50, 60, and 70°C) and a constant slice thickness of 3 ± 0.5 mm after pre-treatment with sodium metabisulfite and citric acid. Eleven mathematical models were evaluated to determine the most accurate description of the drying behavior of potato slices. The effective moisture diffusivity, activation energy, and solar dryer efficiency were also calculated. Results indicated that the dryer reached the required temperature and maintained it throughout the experiment. The drying of sweet potato slices occurred during the falling rate period. The logistics model best describes the drying behavior of sweet potato slices from both varieties under the study conditions, followed by the Page model. The effective moisture diffusivity values were in the ranges of $(1.8329\times10^{-10}$ to $2.2888\times10^{-10})$ and $(1.8055\times10^{-10}$ to $2.2341\times10^{-10})$ m²/s for the Abis and Balady varieties, respectively. The activation energies were 10.274 and 9.772 kJ/mol for the Abis and Balady varieties, respectively. The overall thermal efficiency of the solar collector ranged from 65.1% to 70.4%. The overall thermal efficiency of the dryer ranged from 11.1245 to 12.5004%.

Keywords: Sweet potato; hybrid solar dryer; mathematical modeling.

1. Introduction

Sweet potato (*Ipomoea batatas*) has been cultivated in Egypt for many years. The area planted with sweet potatoes in Egypt in 2023 reached about 29,588 feddan, with a total production of approximately 423,423 tons [1]. In general, sweet potatoes are orange, though they can also be white, red, pink, violet, yellow, or purple. Typically, it serves as a foundational component for snacks, flour, and traditional confections. It is also processed into chips, which are deep-fried after being finely sliced. It is rich in minerals, ascorbic acid, and β -carotene, making it a healthy food [2]. Sweet potatoes are a great source of complex carbohydrates and simple starches. In addition to low levels of vitamins and minerals, the tuber contains useful substances such as polyphenols, anthocyanins, and beta-carotene, a provitamin A carotenoid [3]. Vitamins, minerals, dietary fiber, and antioxidants, including β -carotene, tocopherol, anthocyanins, and phenolic acids, are abundant in sweet potatoes. Sweet potato

phytochemicals have been shown to have radical-scavenging properties and several health-promoting effects on human conditions such as cancer, heart disease, and age-related neuronal degeneration [4]. Fresh sweet potato tubers contain high levels of moisture, up to about 70%, which makes them perishable and difficult to transport from one place to another. Therefore, it was necessary to use appropriate preservation technologies to extend their shelf life [5]. Drying is a food processing method that has been used safely for centuries to preserve fruits and vegetables for long-term storage. Drying methods aim to remove the most moisture from food at the lowest cost and highest efficiency [6]. The availability of dried sweet potato roots will increase their shelf life and facilitate reconstitution. The process of turning sweet potato tuber into powder is a remarkable opportunity to provide the product in a stable form [7].

The food drying process involves heat and mass transfer, which is accompanied by changes in the product's structure, shape, and biological quality. Therefore, it is necessary to understand and study the drying properties of various food materials to produce high-quality dried products [8]. Solar drying is one of the oldest methods used in food drying. This technology is very popular because it saves energy costs and is environmentally friendly [9]. However, there are limitations to the use of solar drying, such as the long drying time, low efficiency, difficulty in controlling drying conditions (e.g., temperature), and dependence on time of day, climate, and season [10,11]. Solar dryers can be divided into three categories: direct, indirect, and hybrid (mixed-mode) [3, 9]. Continuous research and development are being conducted on the use of hybrid solar dryers. These dryers use an additional heating system to accelerate the drying process, reduce the time required to complete drying, and control drying conditions such as temperature.

Several different heating technologies have been used to support solar dryers, such as heat from electric coils and other auxiliary heaters [12-15], waste heat [16], storage heat [17-19], and heat from biomass combustion [20-22]. Thin-layer drying models are mathematical models that are used to create and enhance current drying systems as well as to gain a better understanding of the thermal process [23,24]. Models of thin-layer drying offer a basis for comprehending the drying properties of any food item [25]. This work aims to study the drying kinetics of two different sweet potato varieties using a hybrid solar dryer equipped with an auxiliary electric heating unit at three different air temperature levels. In addition, effective moisture diffusion, activation energy, and mathematical modeling were studied by testing and evaluating 11 models to determine the most accurate for describing the drying behavior of sweet potato slices in the hybrid dryer. The study also aims to evaluate the thermal performance and calculate the efficiency of both the solar collector and the hybrid solar dryer.

2. Materials and Methods

To achieve the objective of this study, an experimental-scale mixed-mode hybrid solar dryer was developed and tested at the Agricultural Engineering Department, Faculty of Agriculture, Mansoura University. The latitude and longitude angles and the altitude above sea level of the experimental location are 31.045 oN, 31.37 oE, and 19.05 m, respectively. The dryer was used for conducting experimental work during July and August 2025.

2.1 Sample preparation:

Orange-colored sweet potatoes (Abis variety) and yellow (Balady variety) were obtained from a local farmer in Damietta and Kafr El-Sheik governorates during the 2025 harvest season and stored at room temperature until use. Before laboratory experiments, sweet potato roots were washed with water to remove dirt and foreign particles stuck to the root surface. Peeling was then performed to remove the outer skin of the potato roots, as well as any parts damaged by weevils and other pests, using hand knives. After peeling, the sweet potato roots were cut into 3 ± 0.5 mm-thick slices using a manual home slicer to increase their surface area during drying. After slicing, the sweet potato slices were immediately soaked in a 0.5% sodium metabisulfite and 1% citric acid solution for 30 minutes to prevent browning and preserve their color during drying [26, 27].

2.2 Solar dryer:

A mixed-mode hybrid solar dryer assisted by an auxiliary electrical heater was used for the experimental work. The forced-convection solar dryer consists of the parts shown in Figure 1.



(1) Solar collector; (2) auxiliary heating unit; (3) insulated air duct; (4) metallic frame; (5) solar dryer - drying chamber; (6) AC suction fan; (7) perforated pipe.

Figure 1. Overall features of the mixed-mode hybrid solar dryer.

The developed dryer consists of the following parts:

1. Solar collector: The solar collector consists of a frame made of steel angle (L) measuring 30 x 30 mm 2000 mm long, 1000 mm wide, and 250 mm high. Its transparent surface is made of acrylic with a transmittance coefficient of 95%, and the absorber plate is a 1 mm-thick corrugated aluminum plate painted matte black and insulated from below with a layer of glass wool. The solar collector is connected to both bases via a pyramid-shaped air inlet and outlet with a length of about 460 mm, covered from above with black matte-coated sheet metal, and equipped with air inlet and outlet pipes with a diameter of 76.2 mm. The collector's slope was set at 31° relative to the horizontal, calculated based on the dryer's location (the average optimum tilt angle for all months for the Department of Agricultural Engineering, Faculty of Agriculture - Mansoura University).

2. Auxiliary heating unit: a metal box measuring 550 mm long, 360 mm wide, and 310 mm high. It is internally insulated to reduce heat loss and equipped with 4 kW electric heaters to raise the drying air temperature to the required levels. It has an air inlet and outlet.

3. Insulated air duct :an externally insulated pipe 76.2 mm in diameter that transports air from the solar collector outlet to the auxiliary heating unit inlet and from the heating unit outlet to the air distribution pipe at the top of the drying chamber.

4. Solar dryer – drying chamber: The solar dryer is a rectangular chamber with a metal frame measuring 2000 mm long, 1000 mm wide, and 700 mm high, and a semicircular roof measuring 300 mm high, covered on the outside with a polycarbonate sheet with an effective transmittance of 90%. On each side of the drying chamber is a door measuring 960 x 700 mm for loading and unloading potato slices. The drying chamber consists of a perforated stainless-steel sheet fixed over an iron frame with dimensions of 1000 x 2000 mm to keep the sweet potato slices from falling down and to permit air to move through it. The frame rested on a plenum chamber made of iron angles covered with 0.5 mm-thick iron sheets.

5. AC Suction Fan: A 0.367 kW AC suction fan at 3000 rpm is employed to facilitate air circulation within the dryer, aiding the drying process.

6. Frame: all parts of the dryer are mounted on a metal frame measuring 6060 mm long by 1060 mm wide for easy movement and orientation.

7. Control unit: it contains the operating switches for the exhaust fan and electric heaters, a thermostat to adjust the air temperature inside the dryer, and an electric meter to measure the electric energy consumed by the electric heaters during the trial period.

2.3 Measurements

Air temperature and relative humidity: A temperature and relative humidity meter model HT-315, USA, with measuring range 0 to 80 °C± 0.1 °C for temperature and 0 to 95± 1.5% for air relative humidity, was used for measuring both parameters of the drying air and exhaust air during the experimental work. Also, a 12-channel datalogger model (No. 92000-05 Benchtop 230V) connected to 12 thermocouple sensors was used to read and record air temperature at different locations. **Air velocity:** The velocity of air passing through the dryer was measured using a digital air velocity instrument model 9515 (USA), with a measuring range of 0 to 20 ± 0.025 m/s, connected to a velocity probe. **Moisture content:** The initial and final moisture content of sweet potato slices were determined using a 24-hour oven drying method at 105°C [28]. **Sample weight:** A digital balance with an accuracy of 0.01g and a maximum weight of 200g was used to weigh the samples. **Intensity of solar radiation:** the solar radiation meter model SPM-1116SD, with an accuracy of ±0.1 W/m², was used to measure the incident solar radiation flux during the experimental work.

2.4 Experimental Procedure

All tests associated with the drying process were carried out at the Agricultural Engineering Department, Faculty of Agriculture, Mansoura University. The dryer was used for conducting experimental work during July and August 2025. After the sweet potato slices are prepared and soaked, they are arranged on a drying tray and placed in three sub-trays to measure the samples' weight at time intervals. The tray is placed inside the dryer, the doors are tightly closed, the fan and heaters are turned on, and the thermostat is set to the air temperature required for the experiment. The experiment starts at 8:00 a.m., and the sub-trays are weighed every half hour. The experiment ends when the sub-samples reach a constant weight, indicating an equilibrium moisture content with the drying air. To determine the moisture content of potato slices during drying, three small trays, 300 mm long and 150 mm wide, made of galvanized wire mesh, were placed inside the dryer. Each tray contained a sample of sweet potato slices weighing approximately 150 g. The trays were weighed every 30 minutes, and the weights were converted to moisture content.

2.5 Calculations

Moisture ratio: (MR) represents the dimensionless moisture ratio, which was calculated using the following formula [29]

$$MR = \frac{M_t - M_f}{M_o - M_f} \quad (1)$$

Where: MR is the moisture ratio, dimensionless; M_t is the moisture content at a specific time, (d. b.); M_f is the final moisture content, (d. b.); M_o is the initial moisture content, (d. b.).

Drying rate: the drying rate (DR) of sweet potato slices was calculated using the following equation, [29]

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \quad (2)$$

Where: M_t is moisture content at t ; $M_{t+\Delta t}$ is moisture content at $t + \Delta t$ (g water/g dry matter), and t is time (min).

2.6 Mathematical Modeling of Sweet Potato Drying

The present study aims to evaluate the effectiveness of eleven selected thin-layer drying models in the context of drying data analysis. The models are assessed based on their ability to accurately and efficiently predict the drying behavior of various products. Table 1 shows numerous thin-layer drying models used to analyze and describe the experimental data gathered during the drying process. These models were fitted to the experimental data for each drying process. The coefficients of the models were obtained using nonlinear regression analysis in Microsoft Excel and SigmaPlot 14. The most effective model was chosen based on parameters such as the lowest standard error (SE), chi-square (χ^2), root-mean-square error (RMSE), and the highest R^2 (coefficient of determination). The model that best matches the experimental data was identified using the previously indicated criteria [30, 31].

The following equations can be used to compute these parameters:

$$R^2 = 1 - \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{calc,i})^2}{[\sum_{i=1}^N (MR_{calc,i} - MR)^2]} \quad (3)$$

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{calc,i})^2}{N-n} \quad (4)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (MR_{calc,i} - MR_{exp,i})^2} \quad (5)$$

Where $MR_{exp,i}$ stands for the observed moisture ratio found in any measurement, $MR_{calc,i}$ is the calculated moisture ratio for this measurement, and MR represents the average predicted value. N and n are the number of observations and constants, respectively [32, 33].

Table 1. Selected mathematical models to demonstrate the drying process of sweet potato.

Model name	Model equation	Ref.	Eq
Lewis	$MR = \exp(-k \cdot t)$	[34]	(6)
Henderson and Pabis	$MR = a \exp(-k \cdot t)$	[35]	(7)
Logarithmic	$MR = a \exp(-k t) + c$	[36]	(8)
Page	$MR = \exp(-k t^n)$	[37]	(9)
Elfar et al model	$MR = a + b \exp(-k t) + c t$	[38]	(10)
Logistics	$MR = \frac{b}{b \exp(-k t) + 1}$	[39]	(11)
Modified Page III	$MR = k \exp(-\frac{t}{d^2})^n$	[40]	(12)
The two terms	$MR = a \exp(-k_0 t) + b \exp(-k_1 t)$	[41]	(13)
Modified Henderson and Pabis (three terms)	$MR = a \exp(-k_0 t) + b \exp(-k_1 t) + c \exp(-k_2 t)$	[42]	(14)
Modified two terms III	$MR = a \exp(-k t) + (1 - a) \exp(-k a t)$	[43]	(15)
Aghbashlo	$MR = \exp\left(-\frac{k_1 t}{1 + k_2 t}\right)$	[44]	(16)

Where: MR is the moisture ratio (dimensionless); k , k_0 , k_1 , and k_2 are the drying constants (min^{-1}); a , b , c , and n are the model constants (dimensionless); t is the drying time (min).

2.7 Effective moisture diffusivity and activation energy

In most studies on food drying, diffusion is considered the primary mechanism for moisture transfer from the interior of the material to its surface, where it evaporates [45]. To calculate effective moisture diffusivity, a solution to the Fick equation was developed, assuming moisture transfer by diffusion, negligible shrinkage, constant diffusion coefficients, and constant temperature for the laminates [46]. The equation was modified to the following form [47]:

$$MR = \left(\frac{8}{\pi^2}\right) \exp\left[\frac{-\pi^2 D_{eff} t}{4L^2}\right] \quad (17)$$

where L is half the thickness of the sweet potato slice ($3 \pm 0.5 \text{ mm}$); t is the drying time (sec), and D_{eff} is the effective moisture diffusivity (m^2/s).

The effect of temperature on effective moisture diffusion can be described by an Arrhenius-type relationship as follows [48]:

$$D_{eff} = D_o \exp\left[\frac{-E_a}{RT}\right] \quad (18)$$

Where: D_o : pre-exponential factor of the Arrhenius equation (m^2s^{-1}); R : universal gas constant ($8.314 \text{ Jmol}^{-1} \text{ K}^{-1}$); E_a : activation energy (kJ.mol^{-1}); T : the absolute temperature (K).

2.8 Thermal efficiency of the solar collector:

To evaluate the thermal performance of a solar collector, a set of parameters must be calculated. These parameters can be calculated as follows [49]:

$$\text{Solar energy available} \quad Q = R \times A_c \quad (19)$$

Where: Q is Solar energy available, W; R : Solar energy flux incident on the surface of the solar collector, W/m²; A_c : Surface area of the solar collector, m²

$$\text{Absorbed solar energy:} \quad Q_a = \tau \cdot \alpha \cdot R \cdot A_c \quad (20)$$

Where: Q_a is Absorbed solar energy, W; τ : Effective transmittance of solar collector cover system, decimal; α = Effective absorptance of the absorber plate of the collector, decimal

$$\tau = \tau_{\max} - 0.00437 \exp [0.0936 (\theta - 30)] \quad (21)$$

$$\alpha = \alpha_{\max} - 0.00476 \exp [0.0940 (\theta - 35)] \quad (22)$$

Where: θ is Solar incident angle

$$\text{Absorption efficiency } (\eta_a): \quad \eta_a = \frac{Q_a}{Q} \times 100, \% \quad (23)$$

$$\text{Useful heat gain to storage } (Q_c): \quad Q_c = m_a \cdot c_p \cdot (T_{a_{oc}} - T_{a_{ic}}) \quad (24)$$

Where: Q_c is the useful heat gain to storage, W; m_a is the mass flow rate of air, kg/s; C_p is the specific heat of air, J/kg/ °C; $T_{a_{oc}}$ is the temperature of air just leaving the solar collector, °C; $T_{a_{ic}}$ is the air temperature before entering the solar collector, °C.

$$\text{Heat transfer efficiency:} \quad \eta_h = \frac{Q_c}{Q_a} \times 100, \% \quad (25)$$

$$\text{Solar collector heat losses:} \quad Q_L = Q_a - Q_c, \text{ Watt} \quad (26)$$

$$\text{Overall thermal efficiency:} \quad \eta_o = \frac{Q_c}{Q} \times 100, \% \quad (27)$$

2.9 Thermal efficiency of the solar dryer:

The thermal efficiency of a solar dryer is defined as the ratio of the energy required to evaporate moisture from the product (Q_{ev}) to the total energy available inside the dryer(Q_I), which is represented by the energy acquired by the air from the solar collector (Q_U), the energy acquired by the air from the auxiliary electric heating unit (Q_E), and the solar energy falling directly on the drying chamber (Q_d). It could be calculated as follows [50]:

$$\eta_{thd} = \frac{Q_{ev}}{Q_I} \times 100, \% \quad (28)$$

$$Q_{ev} = m_p C_{pp}(\Delta T_p) + m_{ev} \cdot h_{fg} \quad (29)$$

Where: Q_{ev} is the energy required to evaporate moisture from the product, kJ; m_p is the mass of the product, kg; C_{pp} is the specific heat of the product, kJ/kg °C; ΔT_p is a change in bulk temperature over a period of time, °C; m_{ev} is the mass of moisture evaporated, kg; h_{fg} is the latent heat of vaporization of water, kJ/kg.

$$C_{pp} = 1.672 + 0.025 MC_{wb} \quad (30)$$

$$h_{fg} = 2393.673(1 + 23 \exp(-0.4 MC_{db})) \quad (31)$$

Where: MC_{wb} and MC_{db} are the moisture content of the product [51].

$$Q_I = Q_U + Q_E + Q_d \quad (32)$$

Where: Q_I is the total energy available inside the dryer, kJ; Q_U is the Useful heat gain by the solar collector, kJ; Q_E is the electric energy of heaters, kJ; Q_d is the solar energy falling directly on the drying chamber, kJ

3. Results and Discussion

This experiment was conducted to evaluate the thermal performance and drying kinetics of two different varieties of sweet potato slices using a hybrid solar dryer equipped with an additional electric air heater at three different drying air temperature levels (50, 60, and 70°C), a constant air flow rate inside the dryer of (0.0721 m³/s), and a constant potato slice thickness (3 ± 0.5 mm). The moisture content of the potato slices was monitored over time until a constant value was reached.

3.1 Solar radiation flux incident:

To study the thermal performance of the solar dryer, it was necessary to determine the amount of incident solar radiation during the drying process. The average available solar hourly radiation was measured and recorded during the experimental work on July 23 and 24 and August 6, 7, 9, and 10, 2025, in Mansoura, Egypt. Table 2 shows the average solar radiation incident on a horizontal surface outside and inside the solar dryer and the solar radiation incident on the solar collector surface during laboratory experiments. The average incident solar radiation on a horizontal surface outside the solar dryer during the experimental period ranged between 398 and 1092 W/m². At the same time, the average incident solar radiation on the collector surface ranged between 370 and 1085 W/m². Meanwhile, the average incident solar radiation on a horizontal surface inside the solar dryer ranged from 285 to 765 W/m². Also, the average incident solar radiation on the horizontal surface outside the solar dryer, on the solar collector surface, and on the horizontal surface inside the solar dryer was 791, 770, and 559 W/m², respectively. Figure 2 shows the measured incident solar energy flux during the experimental work.

Table 2. Solar radiation flux incident during the experimental period.

Experiment day		R(hor.)	R(inc.)	R(inside)
23/07/2025	Max	1043.0	1023.0	754.2
	Min	430.0	370.0	310.9
	Mean	786.0	738.8	568.3
	SD	± 219.4	± 242.2	± 158.6
24/07/2025	Max	1012.0	1008.0	724.4
	Min	433.0	450.0	309.9
	Mean	800.9	786.4	573.3
	SD	± 210.1	± 206.7	± 150.4
06/08/2025	Max	1016.0	1045.0	705.8
	Min	443.1	420.0	307.8
	Mean	781.1	760.3	542.6
	SD	± 223.0	± 241.9	± 154.9
07/08/2025	Max	1092.0	1085.0	765.9
	Min	507.0	475.0	355.6
	Mean	847.8	799.1	594.6
	SD	± 211.5	± 222.9	± 148.3
09/08/2025	Max	1000.0	1006.0	692.5
	Min	423.0	430.0	292.9
	Mean	769.4	764.6	532.8
	SD	± 202.3	± 206.3	± 140.1
10/08/2025	Max	995.0	1013.0	712.7
	Min	398.0	422.0	285.1
	Mean	760.7	776.4	544.9
	SD	± 216.1	± 218.1	± 154.8

In general, solar radiation gradually increased from sunrise to noon, then gradually decreased to its minimum at sunset. The marked variation in available solar energy during the drying period affected the dryer's air-heating efficiency and the differences in air temperature and relative humidity between inside and outside the solar dryer. This demonstrated the need for auxiliary heaters to maintain a constant air temperature inside the drying chamber. In this case, drying behavior can be accurately described using well-studied mathematical models.

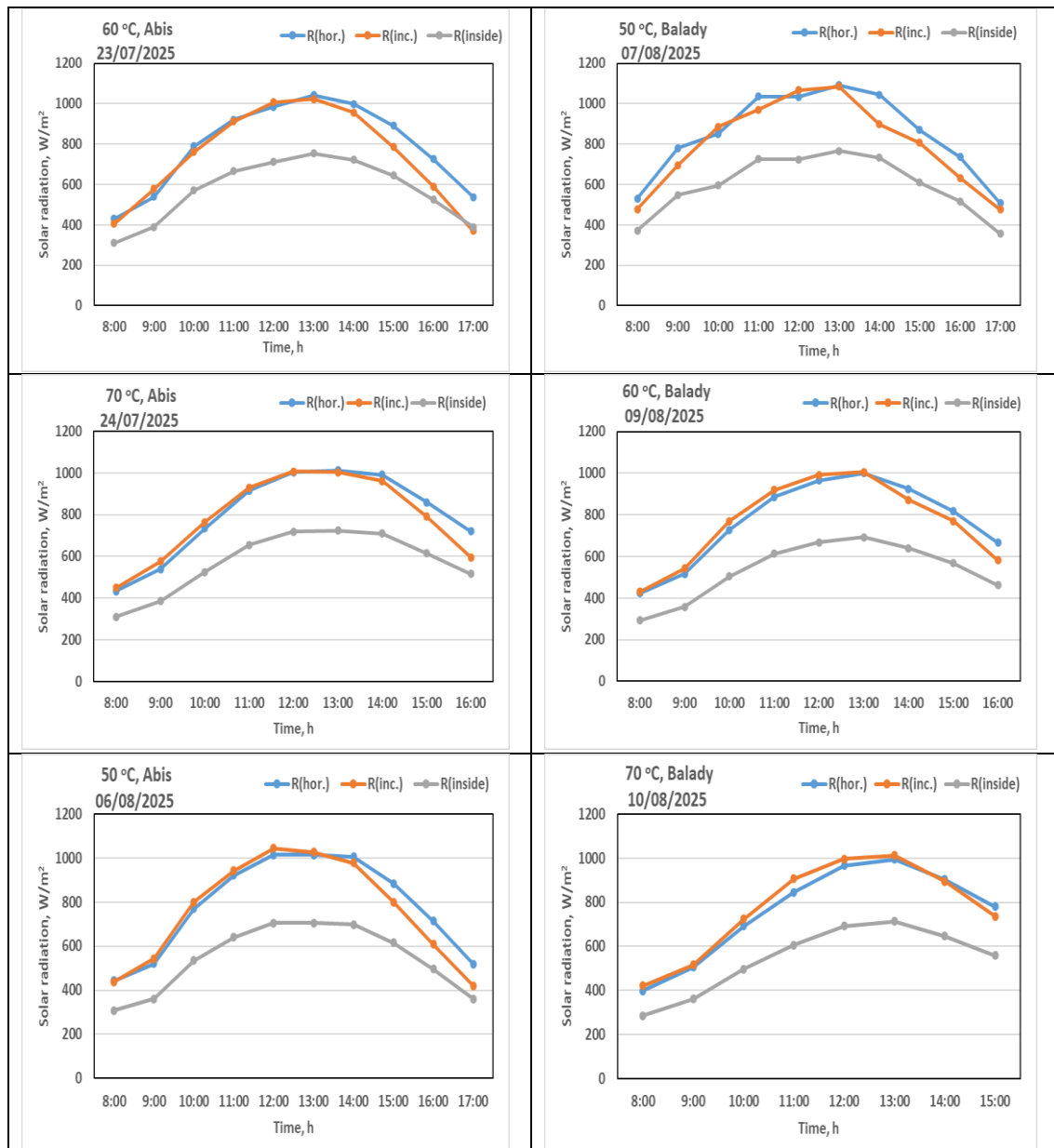


Figure 2. Solar radiation flux incident on the horizontal surface inside and outside the solar dryer, and on the solar collector surface, as a function of time during the experimental period.

3.2 Air temperature outside and inside the hybrid solar dryer:

As the air flows through the dryer, it passes through the solar collector where it touches the absorber plate. This causes its temperature to rise above the ambient temperature outside the dryer but below the level required for drying. It then passes through an additional heating unit to raise its temperature to the required level. It then passes into the drying chamber, where it evaporates moisture from the material and carries the vapor to the outside of the dryer as the suction fan draws it. Figure (3) presents the air temperature profile at different positions outside and inside the examined solar dryer (ambient $T_{a,c}$, leave the solar collector $T_{a,oc}$, and

inside the drying chamber T_{ad}). It can be seen from the Figure that the system maintained a nearly constant temperature inside the drying chamber from 10 am until the end of the experimental period. Table 3 shows the average air temperatures outside and inside the solar dryer, as well as the air leaving the solar collector during laboratory experiments. The table shows that the average air temperatures outside the dryer during laboratory experiments for drying the Abis variety were 36.6, 36.4, and 37°C. The solar collector raised the air temperature to 47.20, 48.8, and 47.1°C, with an average increase of 30.11%. During laboratory experiments on drying the Balady variety, the average air temperatures outside the dryer were 36.1, 39.3, and 41.5°C. The solar collector raised the air temperature to 47.4, 50.1, and 52.3°C, with an average increase of 28.27%. It is also shown that the system reached a temperature between 51.8 ± 1.48 and 51.8 ± 1.78 when the thermostat was set to 50°C. While the average temperature inside the dryer was 58.8 ± 2.13 to 59.5 ± 1.46 °C when the thermostat was set to 60°C. Meanwhile, the average temperature inside the dryer was in the range 68.9 ± 2.0 and 69.2 ± 1.57 when the thermostat was set at 70°C

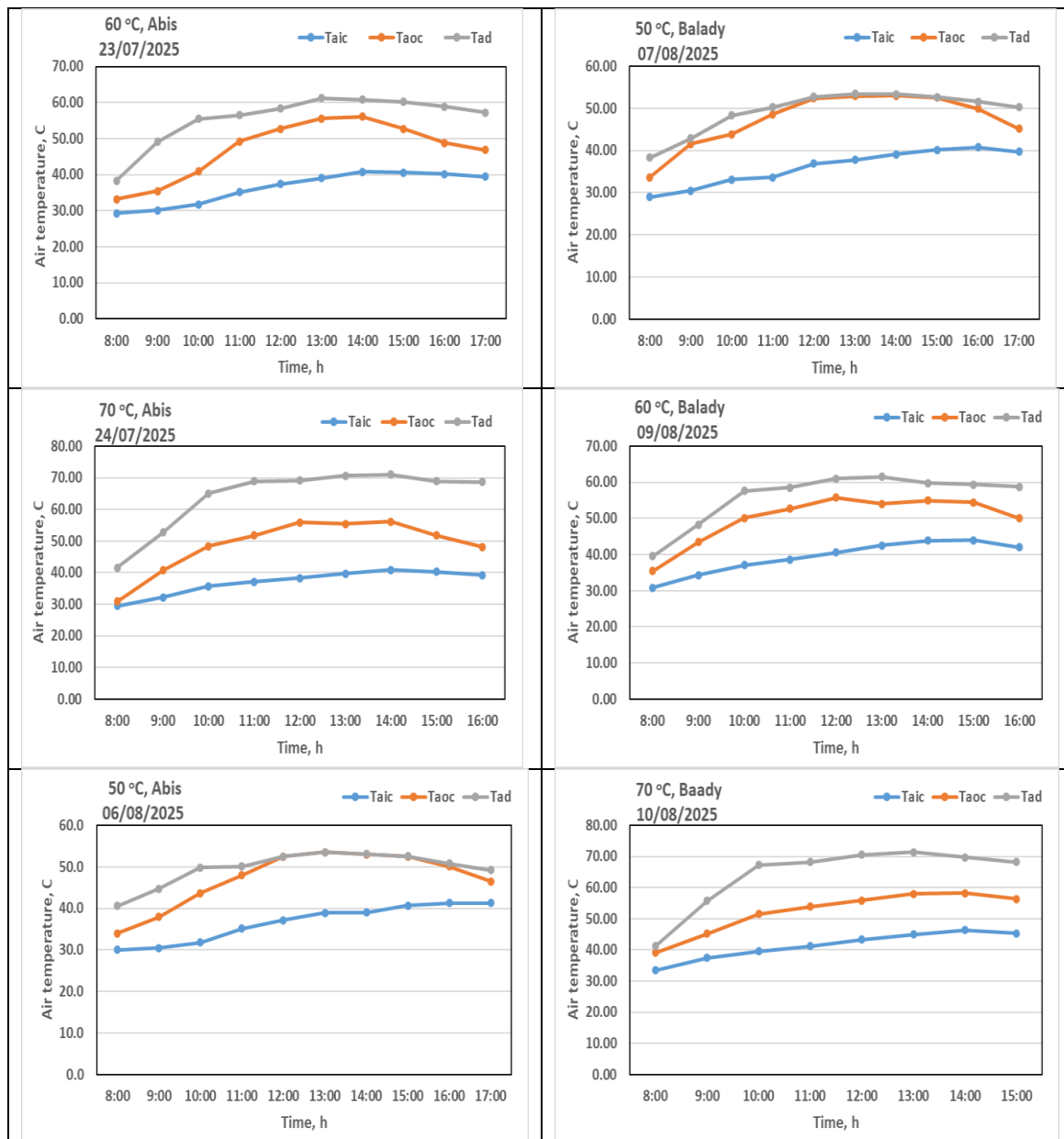


Figure 3. Air temperatures at different positions over time during the experimental period.

Table 3. Air temperature during the experimental period.

Experiment day		Ta _{ic}	Ta _{oc}	Ta _d
23/07/2025	Max	40.8	56.1	61.8
	Min	29.3	33.1	54.3
	Mean	36.4	47.1	58.8
	SD	±4.49	±8.10	±2.13
24/07/2025	Max	40.8	56.2	71.8
	Min	29.5	30.9	64.1
	Mean	37.0	48.8	68.9
	SD	±3.9	±8.31	±2.0
06/08/2025	Max	41.3	53.5	53.8
	Min	30.0	34.0	48.5
	Mean	36.6	47.2	51.8
	SD	±4.45	±6.76	±1.48
07/08/2025	Max	40.8	53.0	53.9
	Min	29.0	33.6	48.0
	Mean	36.1	47.4	51.8
	SD	±4.23	±6.36	±1.78
09/08/2025	Max	44.0	55.8	61.9
	Min	30.8	35.4	56.3
	Mean	39.3	50.1	59.5
	SD	±4.52	±6.68	±1.46
10/08/2025	Max	46.4	58.3	71.6
	Min	33.4	39.1	66.1
	Mean	41.5	52.3	69.2
	SD	±4.47	±6.81	±1.57

3.3 Drying curves

Sweet potato slices of Abis and Balady cultivars were dried in a hybrid solar dryer at three air temperatures in the drying chamber: 50, 60, and 70°C. Figure 4 shows the relationship between moisture ratio (MR) and time (t) at different air temperatures inside the drying chamber for both varieties. It could be observed that air temperature has a clear effect on moisture ratio MR, with MR decreasing as air temperature increases. The drying time required to reduce the moisture content of sweet potato slices of the Abis variety from an initial moisture content of 395.45 % (d.b.) to final moisture contents of 9.25, 9.06, and 8.85 % (d.b.) was 435, 435, and 405 min at 50, 60, and 70°C, respectively. While the drying time required to reduce the moisture content of sweet potato slices of Baladi variety from an initial moisture content of 394.11 % (d.b.) to a final moisture content of 9.60, 9.35, and 9.07 % (d.b.) was 465, 405, and 375 min at 50, 60, and 70°C, respectively. It can be observed that the drying time decreased with increasing drying air temperature.

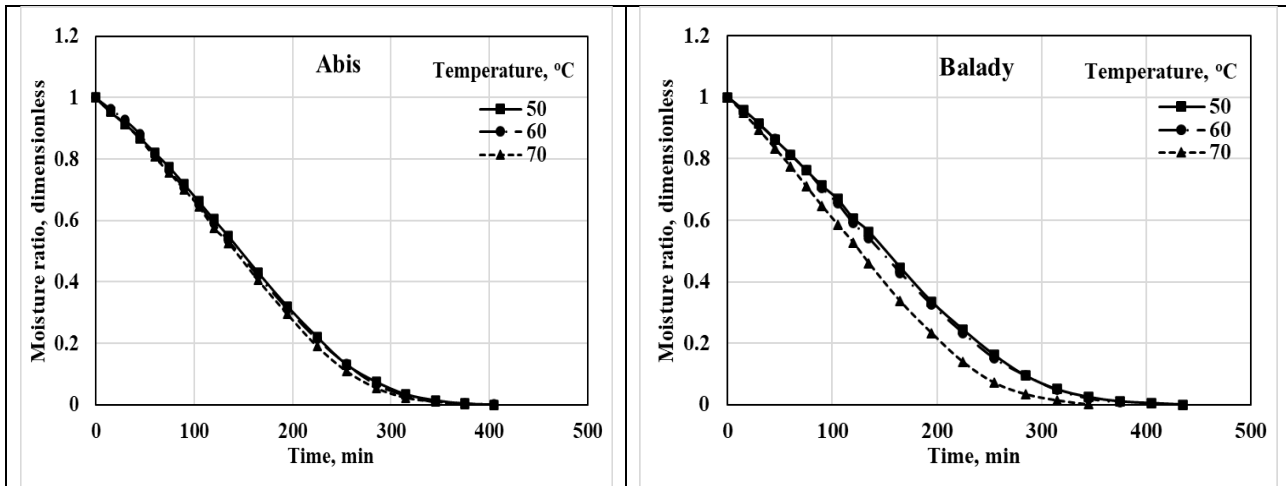


Figure 4. Variation of moisture ratio MR for sweet potato slices at different air temperatures.

3.4 Drying rate

The changes in the drying rates versus moisture content for the drying air temperatures of 50, 60, and 70 °C for both sweet potato varieties are shown in Figure 5. The drying rate increased with increasing drying air temperature. It can also be observed that there was no constant-rate drying period in the drying of sweet potato slices for both studied varieties, and all drying processes occurred in the falling-rate period. This showed that diffusion was the dominant physical mechanism governing moisture movement in the samples [45]. These results are consistent with those obtained for some vegetables, such as pumpkin slices [52], white radish slices [48], and tomato [53].

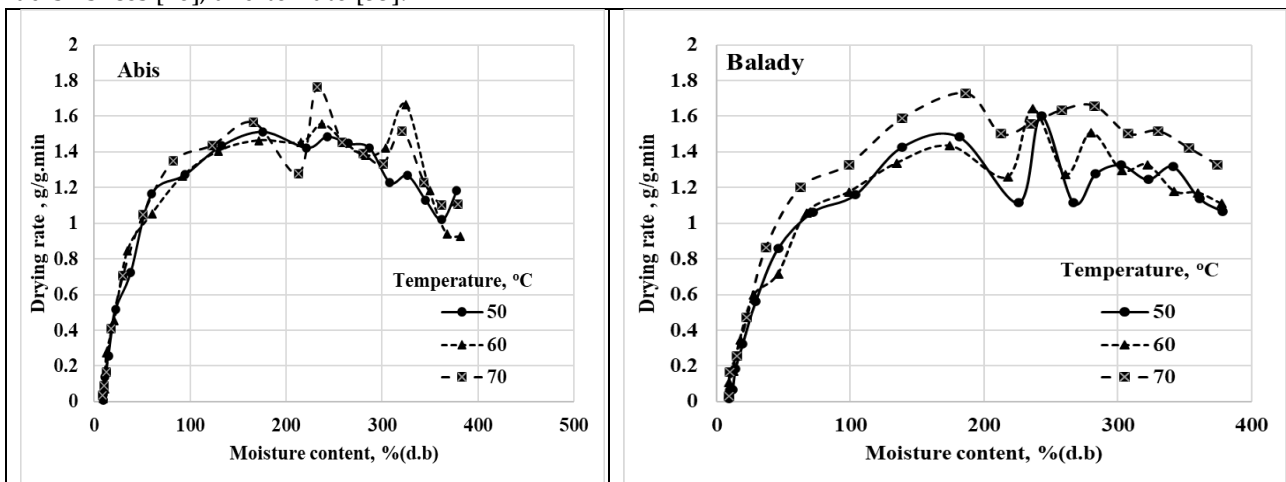


Figure 5. Drying rate of sweet potato versus moisture content at different air temperature levels.

3.5 Evaluation of drying models

Using mathematical models to determine the drying kinetics of agricultural products is crucial. Understanding the underlying transport mechanisms involved in thin-layer drying of agricultural materials is essential for simulating the entire process and scaling it up to improve or control operating conditions. Experimental drying practices that do not account for the mathematical aspects of drying kinetics significantly reduce dryer efficiency, increase production costs, and degrade the quality of the dried product. Therefore, to ensure effective process design, optimization, energy integration, and control, an effective mathematical model is essential [43]. Moisture content readings at different times were converted to moisture ratio (MR), and eleven mathematical models were used to evaluate them and determine the most accurate one for describing the drying behavior of sweet potato slices under experimental conditions. The mathematical models were compared using the coefficient of determination (R^2), standard error (SE), chi-square (χ^2), and root mean square error (RMSE). The best model to describe the drying behavior in a thin layer is the one that

gives a higher value for (R^2) and lower values for (SE), (χ^2), and (RMSE) [30, 31, 54]. The results of the statistical analysis show that all the drying models had an overall high coefficient of determination (R^2) within the range (0.9587 to 0.9994) for the Abis variety and (0.9302 to 0.9995) for the Balady variety, as shown in Tables 4 and 5. From the results shown in Tables 3 and 4, it can be said that the logistics model is the best in describing the drying behavior of sweet potato slices of both Abis and Balady varieties under the study conditions, followed by the Page model.

Figures (6 and 7) represent the comparison between the observed moisture ratio (MR) and the calculated MR obtained from the first and second appropriate drying models for both varieties of sweet potato slices at different drying temperatures.

Table 4. Statistical analysis of the examined mathematical thin-layer models for the Abis variety.

	T, C	k				R ²	SE	χ ²	RMSE
Lewis	50	0.0057				0.9791	0.0533	0.0095	0.0950
	60	0.0058				0.9799	0.0505	0.0093	0.0939
	70	0.0059				0.9802	0.0514	0.0094	0.0942
	Average					0.9797	0.0517	0.0094	0.0944
Henderson and Pabis		a	k			R ²	SE	χ ²	RMSE
	50	1.1291	0.0065			0.9818	0.0726	0.0071	0.0798
	60	1.1350	0.0066			0.9829	0.0703	0.0066	0.0771
	70	1.1275	0.0067			0.9828	0.0702	0.0070	0.0789
	Average				0.9825	0.0710	0.0069	0.0786	
Logarithmic		a	k	c		R ²	SE	χ ²	RMSE
	50	1.6186	0.003	-0.5608		0.9954	0.0427	0.0027	0.0480
	60	1.5614	0.0032	-0.4953		0.9956	0.0409	0.0024	0.0453
	70	1.7042	0.0029	-0.6501		0.9962	0.0470	0.0025	0.0460
	Average				0.9957	0.0435	0.0025	0.0465	
Page		k	n			R ²	SE	χ ²	RMSE
	50	0.00039	1.5539			0.9947	0.0430	0.0026	0.0481
	60	0.00029	1.6097			0.9963	0.0359	0.0017	0.0396
	70	0.00067	1.4299			0.9964	0.0308	0.0016	0.0376
	Average				0.9958	0.0366	0.0020	0.0418	
Elfar		a	b	k	c	R ²	SE	χ ²	RMSE
	50	-40.630	41.6909	0.0005	0.0160	0.9945	0.0384	0.0034	0.0523
	60	-41.002	42.0698	0.0005	0.0169	0.9587	0.0290	0.0251	0.1418
	70	-38.474	39.5310	0.0005	0.0156	0.9728	0.0304	0.0163	0.1135
	Average				0.9753	0.0326	0.0150	0.1026	
logistics		a	b	k		R ²	SE	χ ²	RMSE
	50	0.1202	1.0945	0.0159		0.9994	0.0137	0.0002	0.0144
	60	0.1376	1.1244	0.0156		0.9993	0.0145	0.0003	0.0151
	70	0.1273	1.1047	0.0163		0.9993	0.0146	0.0003	0.0155
	Average				0.9993	0.0143	0.0003	0.0150	
Mod page 3		k	d	n		R ²	SE	χ ²	RMSE
	50	1.1291	2.8367	0.0522		0.9818	0.0726	0.0075	0.0798
	60	1.1350	2.8387	0.0534		0.9829	0.0703	0.0070	0.0771
	70	1.1275	2.8512	0.0547		0.9828	0.0702	0.0074	0.0789
	Average				0.9825	0.0710	0.0073	0.0786	

Table 4. Statistical analysis of the examined mathematical thin-layer models for the Abis variety. (continue)

		a	k _o	b	k ₁			R ²	SE	χ ²	RMSE
Two terms	50	0.5927	0.0064	0.5335	0.0064			0.9819	0.0711	0.0080	0.0799
	60	0.5969	0.0066	0.5354	0.0066			0.9829	0.0698	0.0074	0.0771
	70	0.5907	0.0067	0.5333	0.0067			0.9828	0.0695	0.0079	0.0790
	Average							0.9825	0.0701	0.0078	0.0787
		a	k _o	b	k ₁	c	k ₂	R ²	SE	χ ²	RMSE
Three terms	50	0.3922	0.0064	0.3778	0.0064	0.3562	0.0064	0.9819	0.0711	0.0091	0.0799
	60	0.3951	0.0066	0.3798	0.0066	0.3575	0.0066	0.9829	0.0698	0.0085	0.0771
	70	0.3915	0.0067	0.3769	0.0067	0.3557	0.0067	0.9828	0.0695	0.0091	0.0790
	Average							0.9825	0.0701	0.0089	0.0787
		a	k					R ²	SE	χ ²	RMSE
Mod two term 3	50	1.00	0.00568					0.9791	0.0533	0.0100	0.0950
	60	1.00	0.00577					0.9799	0.0505	0.0098	0.0939
	70	1.00	0.00589					0.9787	0.0514	0.0099	0.0942
	Average							0.9792	0.0517	0.0099	0.0944
		k ₁	k ₂					R ²	SE	χ ²	RMSE
Aghbashlo	50	0.0057	0					0.9791	0.0533	0.0100	0.0950
	60	0.0058	0					0.9799	0.0505	0.0098	0.0939
	70	0.0059	0					0.9802	0.0514	0.0099	0.0942
	Average							0.9797	0.0517	0.0099	0.0944

Table 5. Statistical analysis of the examined mathematical thin-layer models for the Balady variety.

	T, C	k			R ²	SE	χ ²	RMSE
Lewis	50	0.0056			0.9813	0.0506	0.0081	0.0877
	60	0.0056			0.9842	0.0474	0.0079	0.0866
	70	0.0065			0.9838	0.0469	0.0074	0.0834
	Average			0.9831	0.0483	0.0078	0.0859	
Henderson and pabis		a	k		R ²	SE	χ ²	RMSE
	50	1.1221	0.0063		0.9839	0.0687	0.0059	0.0734
	60	1.1172	0.0064		0.9863	0.0648	0.0058	0.0722
	70	1.1121	0.0074		0.9858	0.0631	0.0056	0.0705
	Average			0.9853	0.0655	0.0058	0.0720	
Logarithmic		a	k	c	R ²	SE	χ ²	RMSE
	50	1.3883	0.0037	-0.3242	0.9954	0.0384	0.0021	0.0420
	60	1.7693	0.0026	-0.7264	0.9972	0.0366	0.0017	0.0377
	70	1.5798	0.0035	-0.5352	0.9962	0.0403	0.0019	0.0399
	Average			0.9963	0.0385	0.0019	0.0399	
Page		k	n		R ²	SE	χ ²	RMSE
	50	0.0004	1.5141		0.9954	0.0400	0.0020	0.0429
	60	0.0006	1.4612		0.9972	0.0326	0.0014	0.0355
	70	0.0006	1.4870		0.9973	0.0357	0.0017	0.0389
	Average			0.9966	0.0361	0.0017	0.0391	

Table 5. Statistical analysis of the examined mathematical thin-layer models for the Balady variety. (continue)

		a	b	k	c			R ²	SE	χ ²	RMSE
Elfar	50	-42.839	43.900	0.0005	0.0173			0.9962	0.0319	0.0015	0.0353
	60	-29.669	30.713	0.0005	0.0121			0.9302	0.0198	0.0550	0.2084
	70	-33.665	34.710	0.0006	0.0163			0.9691	0.0236	0.0194	0.1228
	Average							0.9652	0.0251	0.0253	0.1222
		a	b	k				R ²	SE	χ ²	RMSE
logistics	50	0.1463	1.1208	0.0146				0.9993	0.0148	0.0003	0.0148
	60	0.1610	1.1409	0.0145				0.9995	0.0129	0.0002	0.0137
	70	0.1661	1.1431	0.0166				0.9994	0.0137	0.0003	0.0145
	Average							0.9994	0.0138	0.0002	0.0143
		k	d	n				R ²	SE	χ ²	RMSE
Mod page 3	50	1.1221	2.8376	0.0509				0.9839	0.0687	0.0063	0.0734
	60	1.1173	2.8390	0.0513				0.9863	0.0648	0.0062	0.0722
	70	1.1121	2.9144	0.0625				0.9858	0.0631	0.0060	0.0705
	Average							0.9853	0.0655	0.0061	0.0720
		a	ko	b	k1			R ²	SE	χ ²	RMSE
Two terms	50	0.5925	0.0063	0.5296	0.0063			0.9839	0.0683	0.0066	0.0734
	60	0.5814	0.0063	0.5314	0.0063			0.9863	0.0635	0.0066	0.0722
	70	0.5799	0.0073	0.5286	0.0073			0.9858	0.0622	0.0064	0.0705
	Average							0.9853	0.0646	0.0066	0.0720
		a	ko	b	k1	c	k2	R ²	SE	χ ²	RMSE
Three terms	50	0.3926	0.0063	0.3765	0.0063	0.353	0.0063	0.9839	0.0683	0.0075	0.0734
	60	0.3858	0.0063	0.3733	0.0063	0.3538	0.0063	0.9863	0.0635	0.0076	0.0722
	70	0.3848	0.0073	0.3721	0.0073	0.3516	0.0073	0.9858	0.0622	0.0075	0.0705
	Average							0.9853	0.0646	0.0075	0.0720
		a	k					R ²	SE	χ ²	RMSE
Mod two term 3	50	1.0	0.0056					0.9813	0.0506	0.0085	0.0877
	60	1.0	0.0056					0.9842	0.0474	0.0084	0.0866
	70	1.0	0.0065					0.9838	0.0469	0.0078	0.0834
	Average							0.9831	0.0483	0.0082	0.0859
		k1	k2					R ²	SE	χ ²	RMSE
Aghbashlo	50	0.0056	0					0.9813	0.0506	0.0085	0.0877
	60	0.0056	0					0.9824	0.0474	0.0084	0.0866
	70	0.0065	0					0.9838	0.0469	0.0078	0.0834
	Average							0.9825	0.0483	0.0082	0.0859

3.6 Effective Moisture Diffusivity

The drying process of food materials generally occurs during the falling rate period. To calculate effective moisture diffusivity values at different levels of drying air temperature, the relationship between the logarithm of the moisture ratio (lnMR) and time (t) was established as shown in Figure 8. The results presented in Table 6 showed that the effective moisture diffusivity values were in the range of 1.8329×10^{-10} to 2.2888×10^{-10} m²/s for Abis variety and 1.8055×10^{-10} to 2.2341×10^{-10} m²/s for Balady variety, which are generally within the range of 10^{-11} to 10^{-6} m²/s given for food materials' moisture diffusion coefficient [55-57]. It can also be seen that the effective moisture diffusivity increased with increasing drying air temperature. This can be explained by the fact that increasing the heat to raise the drying temperature increases the mobility of water molecules, thereby increasing the rate of moisture diffusion. It can also be noted that the moisture diffusivity values of the Balady

variety were lower than those of the Abis variety at all levels of drying air temperature. This can be attributed to the internal composition of both varieties.

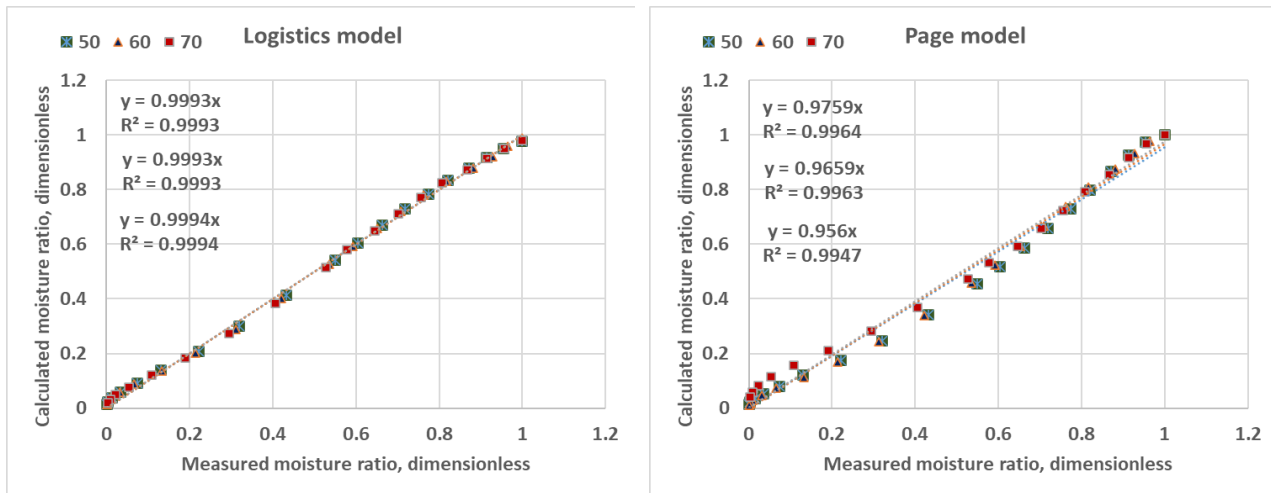


Figure 6. The observed and calculated moisture ratios (MRs) for the Abis variety at different drying temperatures.

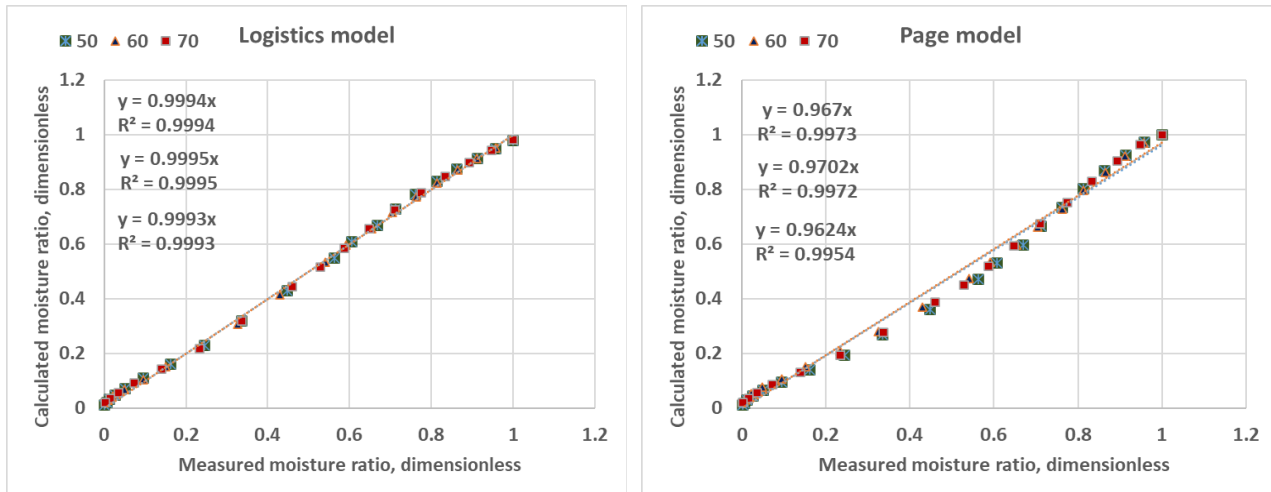


Figure 7. The observed and calculated moisture ratios (MRs) for the Balady variety at different drying temperatures.

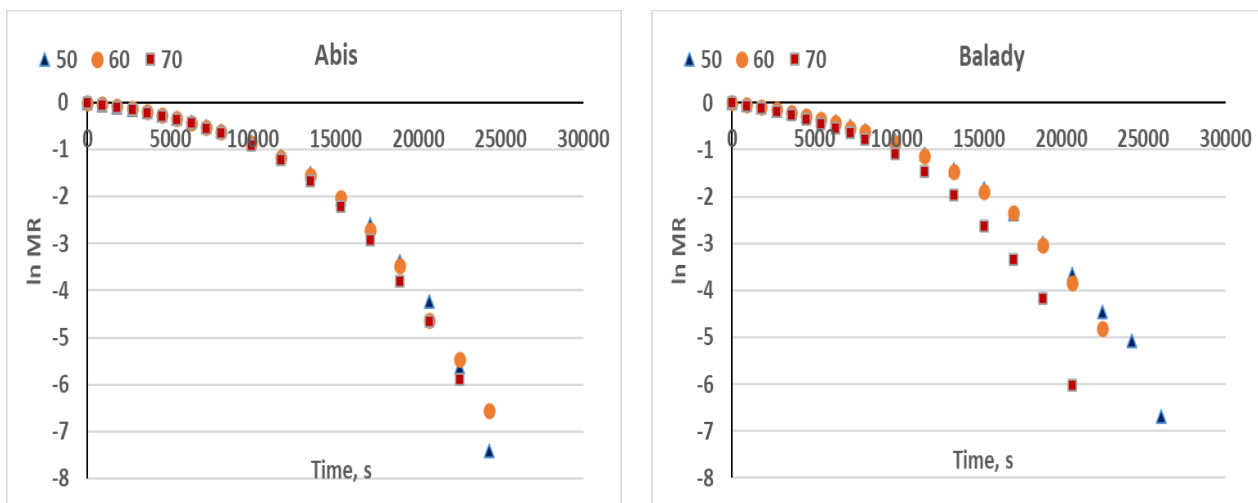


Figure 8. The relation between $\ln(MR)$ and drying time at different drying air temperatures.

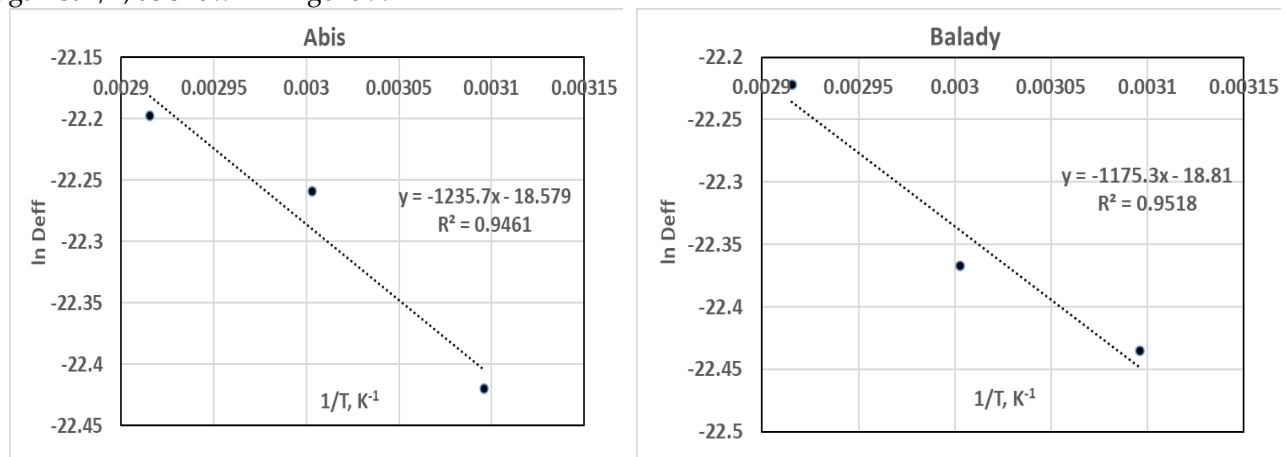
Table 6. Values of (D_{eff}) for Abis and Balady sweet potato at different levels of drying air temperature.

Variety	Drying temperature, °C	Linear equation	R ²	Deff, m ² /s
Abis	50	$\ln(MR) = 0.9396 - 0.000201(t)$	0.8509	1.8329×10^{-10}
	60	$\ln(MR) = 0.8755 - 0.000236(t)$	0.8863	2.1521×10^{-10}
	70	$\ln(MR) = 0.7616 - 0.000251(t)$	0.8872	2.2888×10^{-10}
Balady	50	$\ln(MR) = 0.8017 - 0.000198(t)$	0.8946	1.8055×10^{-10}
	60	$\ln(MR) = 0.5688 - 0.000212(t)$	0.8995	1.9332×10^{-10}
	70	$\ln(MR) = 0.7180 - 0.000245(t)$	0.8750	2.2341×10^{-10}

These results are also consistent with the results obtained by [58] when drying sweet potato slices using a hot air dryer with a temperature ranging between 50 and 70°C, where the results they obtained showed that the average values of effective moisture diffusivities of sweet potato slices ranged from 3.66×10^{-10} to 2.11×10^{-9} m²/s within the given drying temperature range.

3.7 Activation Energy (Ea)

The activation energies for the examined varieties of sweet potato were obtained by plotting $\ln D_{eff}$ against $1/T$, as shown in Figure 9.

**Figure 9.** Plot of $\ln D_{eff}$ against $1/T$ for both sweet potato varieties.

As shown in Equations (33) and (34), the drying air temperature has a noticeable effect on the effective moisture diffusivity (D_{eff}) of sweet potatoes.

$$D_{eff} = 8.54 \times 10^{-9} \exp \left(-\frac{1235.7}{T} \right) \quad (R^2 = 0.9461) \quad \text{for Abis variety} \quad (33)$$

$$D_{eff} = 6.76 \times 10^{-9} \exp \left(-\frac{1175.3}{T} \right) \quad (R^2 = 0.9518) \quad \text{for Balady variety} \quad (34)$$

The coefficients of determination for the fitted lines based on the experimental data were mostly close to unity, indicating a strong correlation. The activation energy was found to be 10.274 kJ/mol for the Abis variety and 9.772 kJ/mol for the Balady variety. The values obtained in this study were in a close range to 12.7–110 kJ/mol for various foods reported by [59]. The values obtained from this study are also close to those obtained by [45] for sweet potato cubes (11.38 kJ/mol) and close to the values obtained by [60] for sweet potato slices (8.74 – 34.76 kJ/mol).

3.8 Thermal efficiency of the solar collector:

Table 7 shows the calculated thermal efficiency of the solar collector. As shown in the table, the solar collector's absorption efficiency ranged from 77.25 to 81.88%, and its heat transfer efficiency ranged from 81.6 to 84.0%. In contrast, the overall thermal efficiency of the solar collector ranged from 65.1% to 70.4%.

Table 7. Solar collector thermal performance and efficiency.

Date	Variety	Air temperature, C	solar radiation W/m ²	Ambient air temperature, C	Air temperature at the outlet of solar	Solar energy available Q, W	Absorbed solar energy Q _a , W	absorption efficiency ζ_a	Useful heat gain Q _c , W	Heat transfer efficiency, ζ_h	Solar collector heat losses, Q _l , W	Overall thermal efficiency ζ_o
06/08/2025	Abis	50	760.3	36.6	47.2	1520.7	1202.1	0.7729	989.7	0.825	212.4	0.651
23/07/2025		60	738.8	36.4	47.1	1477.5	1204.3	0.8188	1007.3	0.816	197.0	0.682
24/07/2025		70	786.4	37.0	48.8	1572.8	1263.9	0.7962	1106.7	0.836	157.2	0.704
07/08/2025	Balady	50	799.1	36.1	47.4	1598.2	1261.0	0.7725	1057.9	0.840	203.1	0.662
09/08/2025		60	764.6	39.3	50.1	1529.2	1226.1	0.7923	1011.7	0.832	214.3	0.662
10/08/2025		70	776.4	41.5	52.3	1552.8	1258.4	0.8026	1013.4	0.823	245.0	0.653

3.9 Energy consumption and thermal efficiency of the solar dryer:

Results in Table 8 showed that the total heat energy provided varied across treatments due to differences in the solar energy available and the energy required for drying. Table 8 also showed that the overall thermal efficiency of the developed solar dryer with the auxiliary heaters ranged from 11.1245 to 12.5004%, and the solar collector provided 95.60 – 96.18%, 91.88 – 93.28%, and 89.04 – 91.61% of the total heat energy consumption for air heating to the level of 50, 60, and 70 OC respectively. It can be said that the main parameters affecting the proportions of heat energy consumption in the form of electrical and solar energy were solar collector surface area, ambient air temperature, available solar energy, and the drying air temperature required for the drying process. Previous studies have shown that the overall efficiency of hybrid dryers is low because the total available energy is much greater than the energy required to dry and evaporate moisture from the product. The overall efficiency of the hybrid solar dryer equipped with a biomass thermal heating unit was 15.59% when drying ginger [61]. The overall drying efficiency of the hybrid solar dryer with a biomass combustion unit for drying fresh pineapples was 13% [62]. The overall drying efficiency of chili was 11.06% using a hybrid dryer system that combines an unglazed transpired solar collector, a rock bed, and a biomass gasifier stove with a heat exchanger [63]. In addition, climate change has led to an increase in solar radiation, with intensity exceeding 1000 W/m² during laboratory experiments, thereby increasing the total available energy inside the dryer.

Table 8. Thermal efficiency and energy consumption of the solar dryer.

Date	Variety	Useful heat gain by the collector, kJ	Sensible heat, kJ	mass of moisture removed, kg	Average latent heat of evaporation, kJ/kg	Latent heat of evaporation, kJ	Total heat energy required for drying, kJ	Average heat energy gain by auxiliary heaters, kJ	Useful heat gain by the solar dryer, kJ	Total heat energy available, kJ	average thermal efficiency of the dryer	average energy saving by solar collector and solar dryer	Average energy saving by solar collector and dryer
06/08/2025	Abis	35628.4	167.669	3.7805	2569.884	9110.351	9278.020	2880	36853.56	75361.96	12.3113	96.1784	
23/07/2025		36261.4	190.744	3.7824	2581.225	9118.311	9309.055	5400	38681.92	80343.32	11.5866	93.2788	93.69
24/07/2025		35857.1	173.374	3.8625	2554.214	9314.356	9487.730	6480	34918.27	77255.37	12.2810	91.6122	
07/08/2025	Balady	38084.9	171.868	3.7120	2528.261	8930.485	9102.353	3600	40138.04	81822.94	11.1245	95.6003	
09/08/2025		32780.2	140.970	3.6209	2484.492	8728.984	8869.954	5760	32416.98	70957.18	12.5004	91.8824	92.18
10/08/2025		29184.7	146.328	3.2728	2538.02	7898.114	8044.442	7200	29331.97	65716.67	12.2411	89.0439	

4. Conclusions

This research was conducted to examine the drying behavior of two varieties of sweet potato slices in a mixed-mode hybrid solar dryer assisted by an electric heating unit. The regression analysis showed that the Logistics models, among eleven thin-layer drying models, provide the best prediction of the moisture ratio for sweet potato slices, followed by the Page model. The effective moisture diffusivity values were in the ranges of $(1.8329 \times 10^{-10}$ to $2.2888 \times 10^{-10})$ and $(1.8055 \times 10^{-10}$ to $2.2341 \times 10^{-10})$ m²/s for the Abis and Balady varieties, respectively. The activation energies were 10.274 and 9.772 kJ/mol for the Abis and Balady varieties, respectively. The overall thermal efficiency of the solar collector ranged from 65.1% to 70.4%. The overall thermal efficiency of the dryer ranged from 11.1245 to 12.5004%. This indicates that the total available thermal energy inside the dryer was much greater than the energy required for drying, and therefore, the amount of product to be dried could be increased to maximize the use of this energy.

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