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Effect of temperature on drying kinetics, bioactive compounds, and antioxidant activity of okra seeds (*Abelmoschus esculentus*)

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ABSTRACT

Convection drying is a popular method for processing and preserving fruits and vegetables. In this study, four drying temperatures (50°C, 60°C, 70°C, and 80°C) were investigated in relation to the kinetics of moisture content, bioactive components, and antioxidant activity of okra seeds (OS). Eight popular drying models (Page, modified Page, Lewis, Henderson and Pabis, modified Henderson and Pabis, two-term, two-term exponential, and logarithmic) were fitted to determine which model would best describe the drying process. The effective moisture diffusivity and activation energy were computed using Fick's diffusion equation. The findings demonstrated that raising the drying temperature shortened the drying time, and the Page model best fit the experimental data. Throughout the examined temperature range, the effective moisture diffusivity varied from 6.5109×10^{-12} m^2/s to 1.5140×10^{-11} m^2/s. An Arrhenius-type relationship with an activation energy of 37.76 ± 0.98 kJ/mol between 50°C and 80°C defined the temperature dependency of the effective moisture diffusivity. The higher contents of bioactive compounds (phenolics, β-carotene, and Vitamin C) and 2,2-diphenyl-1-picrylhydrazyl radical scavenging capacity were found in OS dried at 60°C compared to other temperatures. These findings will offer further understanding of the suitable drying temperature for preparing OS as a material, a substitute, or for other applications.

1. INTRODUCTION

Okra (*Abelmoschus esculentus* L.) is one of approximately 200 species of the Malvaceae family, which are derived from the tropical and subtropical regions in the world [1]. The okra fruit is a greenish, fibrous-textured, six-chambered capsule that is 10–30 cm in length and 1–4 cm in diameter [2]. The nutritional content of okra is mostly found in its seeds [3]. With a high dietary fiber content and other bioactive elements, the round white seeds of immature okra fruits are best consumed fresh or quickly frozen [4]. The mature okra seeds (OS) can be ground into a fine powder after roasting for use as additives or components in coffee [5]. High-quality proteins and oils can be found in abundance in OS [6]. According to Benchasr [7], these seeds have an oil content of between 20% and 40% and are primarily made up of unsaturated fatty acids, particularly linoleic acids, which are vital for human nutrition. In addition, the major minerals (K, Na, Mg, and Ca) and essential trace elements (Fe, Zn, Mn, and Ni), which play very important roles in human metabolism, are also present in okra [8].

In addition to nutritional components, fruits and vegetables also contain an essential class of substances known as antioxidants or bioactive compounds that eliminate dangerous free radical intermediates produced during oxidation reactions [9]. DNA, lipids, and proteins are examples of macromolecules oxidized by free radicals, resulting in cell damage and death [10]. Dietary natural antioxidants can counteract their harmful effects. As a result, there is a growing need to find safe and alternative sources of food bioactive compounds, particularly those derived from plants [11]. Arapitsas [12] discovered that the seeds, which made up 17% of the fruit and had a higher concentration of phenolic compounds than the skin, were primarily made up of flavonol derivatives (3.4 mg/g of seeds) and oligomeric catechins (2.5 mg/g of seeds). OS were discovered to have the highest antidiabetic benefits and antioxidant ability when compared to other okra parts because of their higher concentration of phenolics [13].

In particular, 2,2-diphenyl-1-picrylhydrazyl (DPPH) was used to assess the antioxidant activity of OS extracts, and it rose in direct proportion to the extract's content [14]. Apart from phenolics, okra is abundant in other antioxidants, including β-carotene and Vitamin C [15]. Moreover, since OS have significant physiological benefits in preventing cancer, heart disease, and aging, their antioxidant properties have also steadily gained attention in studies [3].

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One of the most significant and traditional methods of food preservation is drying [16]. By removing moisture from raw materials, spoilage microorganisms cannot grow and reproduce, enzyme activity is slowed down, and numerous negative reactions linked to moisture are reduced [17]. Even though drying can successfully increase the shelf life of agricultural products, conventional drying methods inevitably result in a loss of nutritional quality, especially for heat-sensitive bioactive substances [18]. Kinetic studies are often used to describe the mechanism of mass transfer during drying. They are significantly influenced by the drying conditions, where temperature is one of the most crucial variables [19].

Therefore, the objective of this study is to gain a basic understanding of the kinetics of moisture content changes of OS during convection drying at different temperatures and to select the appropriate drying model from among the models implemented. The research also looked into how the drying temperature affected the amount of bioactive compounds and antioxidant potential in OS.

2. MATERIALS AND METHODS

2.1. Preparation of OS

The okra variety "Mai Vang" was grown in a farmer's garden in Vinh Trung Hamlet, Vinh Trach Commune, Phu Hoa Town, Thoai Son District, and An Giang Province. Okra fruits were harvested at the age of 15 days after fruit formation. In the laboratory, the fruits were washed with tap water, and damaged or defective fruits were removed. Then, the fruits were blanched in hot water at 95°C for 2 min. Thermal blanching is widely used before drying of agro-products. Its main objective is to maintain the color and flavor of products by deactivating the enzymes that cause undesirable darkening and off-flavors. Not only does it soften tissues to facilitate drying and eliminate intracellular air to prevent oxidation, but it also reduces the microbial burden of objects to extend their preservation [20]. Due to the improvement in color and appearance, Sharma *et al*. found that pre-treatments had an impact on the sensory quality evaluation findings of solar dehydrated okra. The dehydrated raw and blanched samples received mean ratings for overall acceptability of 6.0 and 7.0, respectively. Furthermore, the ascorbic acid level of the dried control and the blanched okra was determined to be 10.0 and 12.5 mg/100 g, respectively [21]. Deng *et al*. have demonstrated that blanching pre-treatments can effectively improve drying kinetics [20]. Each sample of 500 g okra was placed in a rectangular stainless steel mesh basket (25.5 cm × 10 cm × 6.5 cm) with 0.5 cm square mesh holes and immersed in a thermostatic bath with a material-to-water ratio of 1:4. The blanched fruits were rapidly cooled by immersing them in cold water (10°C) for 60 s to prevent further thermal damage. Okra fruits were then drained and cut in half lengthwise to separate the pod and seeds.

2.2. Experimental Design

The fruit seeds were spread on a stainless steel tray in a single layer and dried at four different temperatures (50°C, 60°C, 70°C, and 80°C) and an air velocity range of 1.0–1.2 m/s by a forced-convection dryer (DKN812, Yamato, Japan). The relative humidity values achieved were 24.2%, 16.3%, 10.6%, and 5.8%, respectively. The wet bulb and dry bulb thermometers were used to measure the temperature and relative humidity at 4-h intervals. The initial moisture content of the seeds was determined to be 74.91 ± 1.12% (on a wet basis) by drying at 105°C to constant weight. The sample weight was determined every 30 min using an analytical balance (JJ200, G&G, China, with an accuracy of 0.01 g) continuously throughout the drying process until a constant weight (equilibrium) was achieved. The seeds were then ground into a fine powder through a 100 µm sieve, contained in vacuum-sealed PA packaging, and stored at −18°C until analysis.

2.3. Modeling

The moisture ratio (MR) of OS during forced-convection drying was calculated using equation 1 [22]. Where M_o, M_t, and M_e are the initial moisture content, the moisture content at drying time of t, and the equilibrium moisture content, respectively. The equilibrium moisture content is the final moisture content for each drying temperature, and all values are in kg water/kg dry matter. The equilibrium moisture content of seeds was obtained experimentally. The seeds were exposed to the investigated drying temperatures until their mass was considered constant over three consecutive measurements taken at 30-min intervals.

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

Eight common drying models [Table 1] were fitted to select the best model describing the OS drying curve.

The drying rate constants and the model coefficients were determined by non-linear regression analysis using Statgraphics Centurion XV software (U.S.A., Version XV.I) [31]. The coefficient of determination (R^2) is an important criterion for selecting the best model to describe the drying curve. In addition, the value of χ2, which is the mean square of the deviation between the experimental value and the calculated value, and the value of the root mean square error (RMSE) were also used to determine the goodness of fit of the model. The higher the value of R^2 and the lower the value of χ^2 and RMSE, the better the goodness of fit [32].

The values of χ2 and RMSE were calculated according to equations 3 and 4 [32]. Where N is the number of experimental points, z is the number of model parameters, MR_{exp} and MR_{pre} are the experimental and predicted MR ratios, respectively.

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - z} \quad (2)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2\right]^{1/2} \quad (3)$$

Table 1: Typical drying curve models provided by several authors.

No.	Model	Equation	References
1	Lewis	MR=exp(−kt)	[23]
2	Page	MR=exp(−kt^n)	[24]
3	Modified Page	MR=exp[(−kt) ^{n}]	[25]
4	Henderson and Pabis	MR=a exp(−kt)	[26]
5	Logarit	MR=a exp(−kt) + c	[27]
6	Two-term	MR=a exp(−k_ot) + b exp(−k_1t)	[28]
7	Two-term exponential	MR=a exp(−kt) + (1−a) exp(−kat)	[29]
8	Modified Henderson and Pabis	MR=a exp(−kt) + (1−a) exp(−kbt)	[30]

k, k_o, k_1 are the drying rate constants; n, a, b are the model coefficients.

2.4. Calculation of Effective Moisture Diffusion and Activation Energy

The effective moisture diffusion of OS was estimated using the Fick diffusion model (equation 5) while accounting for shrinkage [33]. Where D_{eff} is the diffusion coefficient (m^2/s), u is the concentration (mol/m^3), t is the drying time (s), and x is the diffusion length (m).

$$\frac{\partial u}{\partial t} = D_{eff}\frac{\partial^2 u}{\partial x^2} \quad (5)$$

In the case of drying a spherical product, assuming unidirectional moisture migration with constant diffusion throughout the fruit, uniform initial moisture distribution, constant fruit surface concentration, and centre-directed shrinkage of the OS during drying, this law can be developed in the form of equation 6 proposed by Crank [34].

$$\mathrm{MR} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-n^2\pi^2\frac{D_{eff}t}{r^2}\right) \quad (6)$$

Where n is a positive integer, r is the seed radius, which can be expressed by formula 7 [35]. During drying, the average radius of the OS at each time interval (0.5 h) was determined to account for shrinking.

$$r = \sqrt[3]{\frac{3V}{4\pi}} \quad (7)$$

When the drying time is long (n = 1), equation 6 can be simplified by taking the logarithm of both sides to form a straight line equation (8) [36].

$$\ln(\mathrm{MR}) = \ln\left(\frac{6}{\pi^2}\right) - \left(\frac{\pi^2}{r^2}D_{eff}t\right) \quad (8)$$

The effective moisture diffusion was determined by plotting the experimental ln(MR) against (t/r^2) because the graph gives a straight line with a slope according to equation 9 [37].

$$\mathrm{Slope} = \pi^2 D_{eff} \quad (9)$$

The activation energy was computed based on the Arrhenius equation (10), which represents how temperature affects effective moisture diffusivity [20]. Where E_a is the activation energy (kJ/mol), D_o is the Arrhenius factor (pre-exponential factor, D_o is equivalent to the diffusion at infinitely high temperature) (m^2/s), R is the ideal gas constant (R = 8.314 J/mol.K), and T is the absolute temperature (K).

$$D_{eff} = D_o exp\left(-\frac{E_a}{RT}\right) \quad (10)$$

2.5. Determination of Bioactive Compounds Content and Antioxidant Activity

The bioactive compounds content and antioxidant activity of the OS powder were analyzed according to the previous references. Chlorophyll content was calculated using the equation of Trang *et al*. [38] after the powder was extracted in a solvent mixture of acetone: NH_4OH (9/1, v/v) at 25–30°C for 24 h and then measured on a Ultraviolet-Vis colorimeter (SPUVS, SP-1920, Japan) at wavelengths of 663 nm and 645 nm. The amount of β-carotene was determined by measuring the absorbance at 449 nm after extraction in an acetone solvent for 15 min at 4 ± 1°C [39]. The 2,4-dinitrophenylhydrazine method was chosen to measure the content of Vitamin C [40]. The total phenolic content of the methanol extracts was determined using the Folin–Ciocalteu reagent [41]. The antioxidant activity of OS powder, presented through the free radical scavenging activity of methanol extracts, was determined by the DPPH method [3].

2.6. Data Analysis

The experiment was performed with three replicates, and the data were presented as the mean value and standard deviation. Microsoft Excel software was used to graph the data. Portable Statgraphics Centurion XV software (U.S.A., Version XV.I) was used for statistical analysis using one-way analysis of variance (ANOVA) and the least significant difference (LSD) test to determine whether the treatment means differed significantly at 95% confidence ($P = 0.05$).

3. RESULTS AND DISCUSSION

3.1. Effect of Temperature on Moisture Change over Drying Time

The convection drying process altered the moisture content of the OS [Figure 1]. Although it was demonstrated that the moisture content decreased steadily over the drying process, the high free moisture content in the raw material [42] causes the rate of moisture loss to occur quickly in the early stages of the drying process, after which the drying rate progressively drops. Because heat and mass transfer processes are faster when the drying temperature is gradually raised [43], the time needed to dry OS samples from the initial moisture content to the equilibrium value was reduced. In particular, the OS had an initial wet basis moisture content of 74.91 ± 1.06%; this number steadily drops throughout the drying process, reaching equilibrium at 6.30% moisture after 11 h of drying at 50°C. Meanwhile, at higher temperatures (60°C, 70°C, and 80°C), the drying time was reduced to 8 h, 6.5 h, and 5.5 h, respectively, to achieve equilibrium moisture. It was clear that the drying temperature affected the drying time.

Temperature plays a vital role in the drying process by providing the energy needed to evaporate water from the food. Therefore, higher temperatures increase the rate of heat transfer to the food, causing moisture to evaporate more quickly and leading to a shorter drying time. Furthermore, the quantity of water vapor in the air relative to the greatest amount the air can contain at a specific temperature is known as relative humidity. It is a critical factor in determining the driving

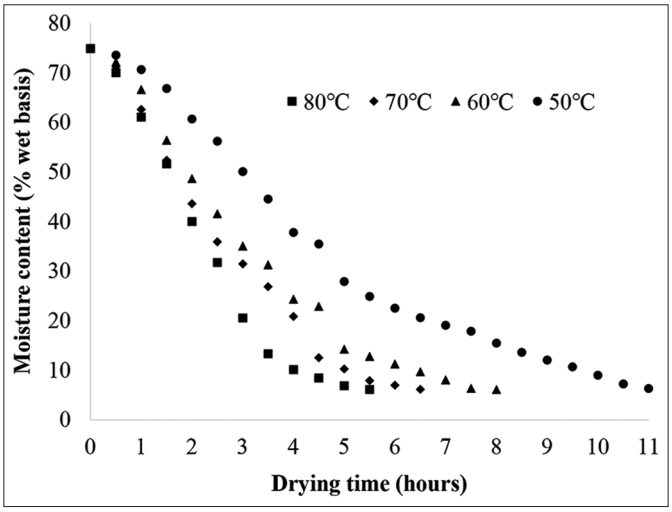

Figure 1: Changes in moisture content over drying time.

force for moisture removal. The higher the drying temperature, the lower the relative humidity achieved. The drying process relies on a vapor pressure difference between the moisture inside the food and the surrounding air. When the relative humidity of the air is low, the air is "drier" and has a greater capacity to absorb moisture, which creates a larger vapor pressure gradient, accelerating the rate at which water evaporates from the surface of food into the air.

This trend also occurred similarly when drying horizontal cut or vertical cut okra using hot air and heat pump drying methods [22]. The drying time for OS was longer than that of other seeds, including pumpkin seeds (4.0 h), noni seeds (2.3 h), and niger seeds (0.9 h), but shorter than that of pomegranate seeds (10.8 h) at the same drying temperature of 60°C [44-47]. These results are from variations in initial moisture content, dimensions, structure, raw material pre-treatment methods, and drying conditions.

3.2. Drying Modeling

The appropriateness of the moisture content data over the drying time to eight popular drying models [Table 1] was then evaluated. The findings of the statistical analysis were displayed in Table 2. All of the R^2 values were higher than 0.98, suggesting that all of the models fit well. The suitability of the model was also assessed based on the χ^2 and RMSE values. In general, the R^2, χ^2, and RMSE values ranged from 0.9806 to 0.9995, 0.0000567 to 0.0019202, and 0.0075356 to 0.0459555, respectively. The calculation results indicated that the Page model provided a better fit than other models at all drying temperatures, with $R^2 > 0.995$, $\chi^2 < 0.0006$, and RMSE < 0.03. The graph in Figure 2 demonstrates the fit between the Page model and the experimental results at temperatures of 50°C, 60°C, 70°C, and 80°C. The reliability of the Page model was also assessed by comparing the calculated MR at different drying temperatures with the values obtained from the experimental data. The data values fluctuated close to a straight line with a 45°C slope, according to the results of the linear regression analysis. These findings indicated that the Page model was appropriate for explaining the convection drying process of OS, as evidenced by the data obtained at 80°C, which had an R^2 value of 0.9996. Similarly, the R^2 values at the remaining temperatures (50°C, 60°C, and 70°C) were 0.9976, 0.9955, and 0.9957, respectively [Figure 3]. Silva *et al*. [46] used forced air flow to dry niger seeds at 40–80°C. They then compared mathematical models to the experimental data and found that the Page model best described the data, with an R^2 value fluctuating between 0.98 and 0.99. When evaluating the drying kinetics of pumpkin seeds at 40–70°C in an oven with forced air circulation, de Oliveira *et al*. [44] also found that the same model worked well with R^2 values ranging from 0.9942 to 0.9969. In comparison to the drying of niger seeds and pumpkin seeds, the R^2 values derived from the Page model for OS were greater, further confirming that this model works particularly well for OS compared to some other seeds. The Page model is almost the empirical model equation that has been used most frequently in the investigation of water migration during drying. Page has been known to be successful at fitting the diffusion phenomena, which could be one explanation. In addition, by including the variable "*n*" in the empirical equation, the Page model makes up for the deficiency of the exponential model [48].

3.3. Effective Moisture Diffusion and Activation Energy

The effective moisture diffusivity (D_{eff}) value of OS at 50–80°C varied from 6.5109×10^{-12} to 1.5140×10^{-11} m^2/s [Table 3]. The D_{eff} value rose with a progressive increase in temperature, as predicted. The reason for this was that greater temperatures could speed up the movement

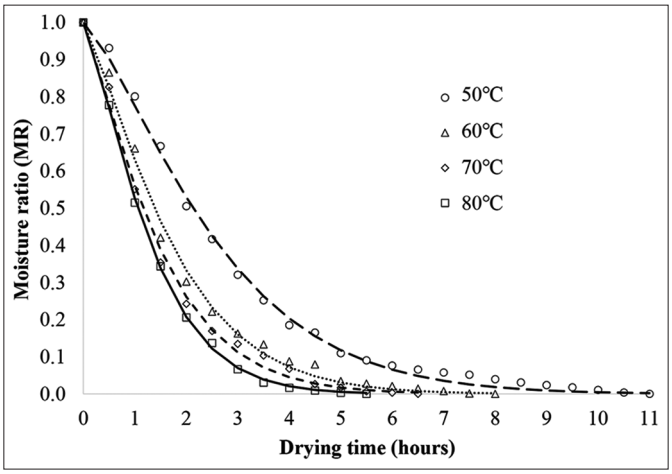

Figure 2: Variation in moisture ratio as a function of drying time at different temperatures.

of water molecules, increasing the moisture diffusivity [49]. This D_{eff} value was lower than in the previous study for drying horizontal cut or vertical cut okra (10^{-11}–10^{-9} m^2/s at 40–70°C) [22] or for peeled and sliced okra (3.13×10^{-11}–9.00×10^{-11} m^2/s at 50–80°C) [50]. The effective moisture diffusivity measured for OS was also lower than the values of $3.52.10^{-11}$–$13.15.10^{-11}$ m^2/s for pumpkin seeds at 40–70°C, $2.33.10^{-11}$–$15.69.10^{-11}$ for niger seeds at 40–80°C, $1.79.10^{-10}$–$3.39.10^{-11}$ for watermelon seeds, and $8.7.10^{-10}$–$23.71.10^{-10}$ for noni seeds at 40–80°C. The cause might be that the OS still has a layer of mucilage covering the outside, and when the drying process is carried out, the seeds are placed tightly together in a single layer on the tray. These things hinder the process of moisture diffusion from the seeds to the environment, especially in the early stages of the drying process.

The logarithm value of D_{eff} was expressed over the reciprocal of the absolute temperature [Figure 4]. The results showed a linear relationship due to the dependence of moisture diffusivity on temperature according to the Arrhenius model. The strong coefficient of determination value ($R^2 = 0.9548$) demonstrated this relationship.

Based on this, the calculated activation energy (E_a) was 37.76 ± 0.98 kJ/mol. The threshold, also known as the energy barrier, that must be broken in order to start mass diffusion from the wet material, is called activation energy [22]. In comparison to the values of 21.4–37.0 KJ/mol at 40–70°C for okra sliced horizontally or vertically utilizing hot air and heat pump drying techniques [22], this E_a value is larger. One possible explanation is that the mucilage layer on the surface and the narrow spacing between the particles prevent moisture from diffusing. Therefore, in drying processes, water diffusivity in the product increases with decreasing activation energy. This activation energy value is also higher than that of watermelon seeds (27.66 kJ/mol at 40–80°C) [51] and noni seeds (24.20 kJ/mol at 40–80°C) [45]. However, it is less than that of pumpkin seeds (39.34 kJ/mol at 40–70°C) [44] and niger seeds (46.83 kJ/mol at 40–80°C) [46]. Numerous factors, including variety, ripening state, physical and chemical characteristics, cutting type, and drying conditions, may influence E_a, which could explain this behavior [22].

3.4. Bioactive Compounds and Antioxidant Activity

Fresh OS after blanching contained bioactive substances, including chlorophyll 3.148 mg/100 g dry basis (d.b), β-carotene 0.7882 mg/100 g d.b., Vitamin C 122.12 mg/100 g d.b., and total

Table 2: Results of statistical analysis for the fitness of models to the drying data.

Model	Drying temperature (°C)	Model coefficients		Model constants		R^2	χ^2	RMSE
Lewis	50			k=0.3687		0.9806	0.0019202	0.0438162
	60			k=0.5577		0.9850	0.0015033	0.0387787
	70			k=0.6568		0.9882	0.0012269	0.0350317
	80			k=0.7434		0.9868	0.0015020	0.0387451
Page	50	n=1.3253		k=0.2536		0.9972	0.0002863	0.0169243
	60	n=1.2565		k=0.4603		0.9952	0.0005084	0.0225596
	70	n=1.2105		k=0.5792		0.9956	0.0004998	0.0223700
	80	n=1.2970		k=0.6404		0.9995	0.0000567	0.0075356
ModifiedPage	50	n=1.2055		k=0.2898		0.9885	0.0012091	0.0344350
	60	n=1.2139		k=0.5430		0.9849	0.0015037	0.0390121
	70	n=1.1493		k=0.5879		0.9861	0.0013872	0.0361892
	80	n=1.3183		k=0.7078		0.9828	0.0017576	0.0421383
Henderson and Pabis	50	a=1.0937		k=0.4004		0.9884	0.0012035	0.0346882
	60	a=1.0658		k=0.5911		0.9891	0.0011675	0.0341766
	70	a=1.0505		k=0.6870		0.9908	0.0010345	0.0321703
	80	a=1.0492		k=0.7750		0.9894	0.0013308	0.0364700
Logarithmic	50	a=1.1093	c=−0.0282	k=0.3702		0.9902	0.0010672	0.0326653
	60	a=1.0790	c=−0.0219	k=0.5550		0.9904	0.0011020	0.0332039
	70	a=1.0664	c=−0.0249	k=0.6398		0.9923	0.0009492	0.0308181
	80	a=1.0853	c=−0.0507	k=0.6775		0.9943	0.0007912	0.0281211
Two-term	50	a=0.5469	b=0.5469	k_o=0.4004	k_1=0.4004	0.9884	0.0013302	0.0364682
	60	a=0.5330	b=0.5330	k_o=0.5908	k_1=0.5915	0.9891	0.0013471	0.0367116
	70	a=0.5328	b=0.5328	k_o=0.6208	k_1=0.6208	0.9844	0.0019503	0.0401078
	80	a=0.5051	b=0.5051	k_o=0.7303	k_1=0.7303	0.9902	0.0014027	0.0328083
Two-term exponential	50	a=0.9926		k=0.3689		0.9806	0.0020116	0.0448474
	60	a=0.9872		k=0.5581		0.9850	0.0016036	0.0400508
	70	a=0.9881		k=0.6571		0.9882	0.0013291	0.0364623
	80	a=0.9943		k=0.7438		0.9868	0.0016522	0.0406363
Modified Henderson and Pabis	50	a=0.8427	b=1.0069	k=0.3682		0.9806	0.0021122	0.0459555
	60	a=−6.0315	b=1.0639	k=0.3544		0.9987	0.0012946	0.0359872
	70	a=2.0711	b=0.7649	k=0.4844		0.9914	0.0010629	0.0326126
	80	a=2.5493	b=0.7691	k=0.4861		0.9947	0.0008905	0.0270806

Table 3: Effective moisture diffusion values of okra seeds at different drying temperatures.

Temperature (°C)	Effective moisture diffusion (m^2/s)
50	$(6.5109\pm0.1628)\times10^{-12}$
60	$(1.0337\pm0.0279)\times10^{-11}$
70	$(1.2281\pm0.0368)\times10^{-11}$
80	$(1.5140\pm0.0303)\times10^{-11}$

Each value represented the mean±standard deviation.

phenolic 677.64 mgGAE/100 g d.b. Drying extends the shelf life and reduces shipping and storage expenses of a product, while also enhancing the bioaccessibility and bioavailability of health-promoting ingredients in food. However, conventional drying causes significant degradation of bioactive components and quickly deteriorates the quality of heat-sensitive plant-based food [52]. It was evident from the results in Table 4 that the drying procedure decreased the amount of bioactive compounds in OS. Furthermore, bioactive substance content and the DPPH free radical scavenging activity of OS were directly impacted by the drying temperature, and there was a significant difference between samples at the 95% confidence level ($P < 0.05$).

Chlorophylls are regarded as naturally occurring bioactive substances found in food because of their capacity to function as anticarcinogens, antimutagens, and antioxidants. Because of their special chemical structure, chlorophylls can scavenge dangerous free radicals, prevent DNA damage, and modulate cellular processes that contribute to the development of disease [53]. Chlorophylls, however, are susceptible to heat treatment. The conversion of chlorophyll a into pheophytins,

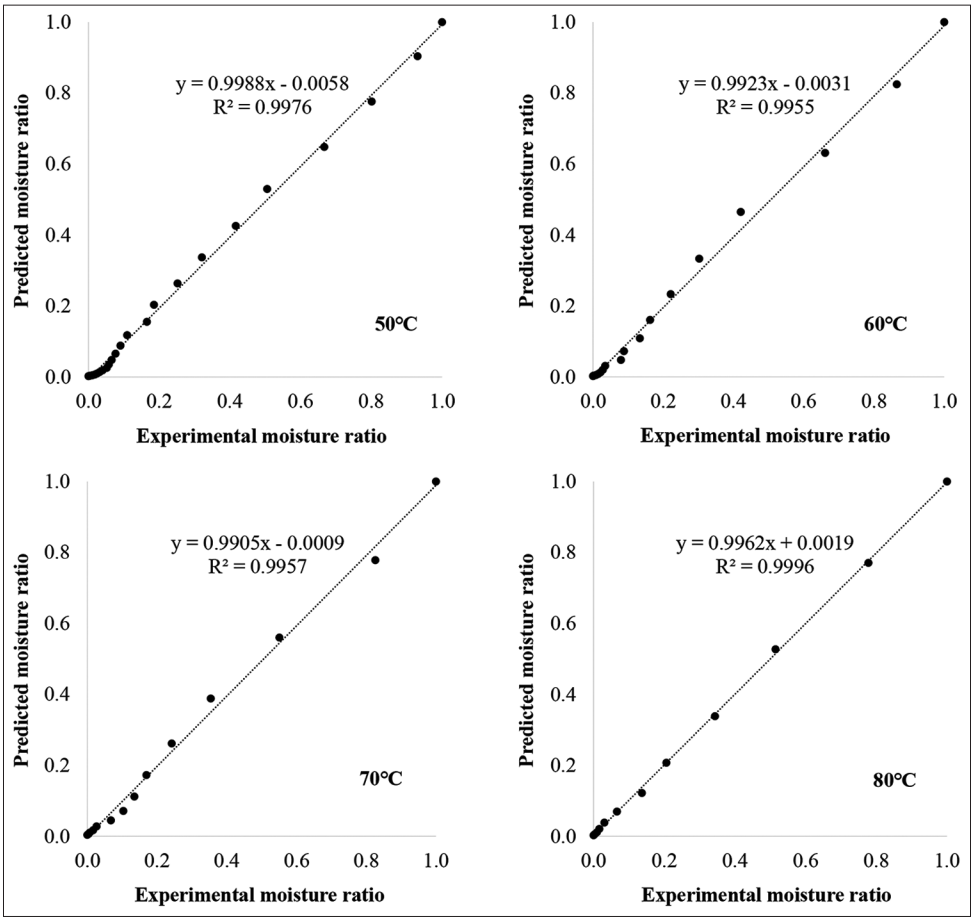

Figure 3: The fitness between experimental moisture ratio and predicted moisture ratio by the Page model at different temperatures.

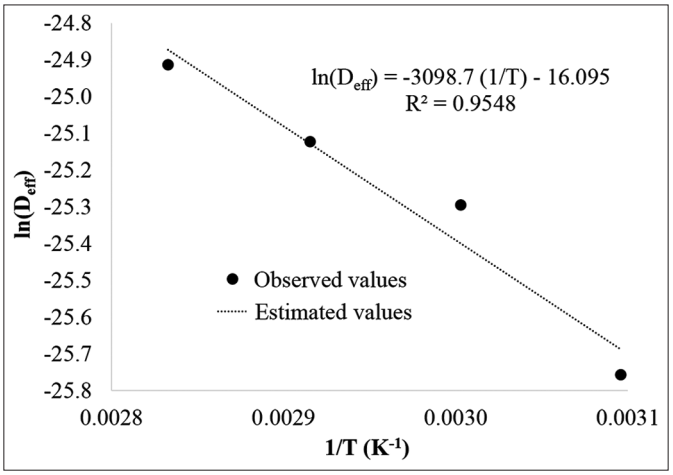

Figure 4: Arrhenius relationship between effective moisture diffusivity and temperature.

which occurs when two hydrogen ions replace the magnesium ion in the chlorophyll's porphyrin ring, is a primary cause of the loss of green color following heat treatment [54]. Therefore, it was evident that when the okra drying temperature rose, the chlorophyll content tended to decrease steadily.

Among the carotenoids, beta-carotene is found naturally in a variety of fruits and vegetables. Although it is commonly recognized as a precursor to Vitamin A, this substance has additional health benefits, such as providing antioxidant protection, preventing cardiovascular diseases, preventing metabolic diseases such as diabetes and obesity, preventing various cancers such as breast, prostate, lung, colon, and skin cancer, and promoting skin health [55]. It has been proposed that Vitamin C can help prevent and treat the common cold, lower the risk of preterm birth and pre-eclampsia, lower the risk of cardiovascular disease and cancer, and improve quality of life by preventing dementia and blindness. Numerous alleged health advantages of Vitamin C are believed to result from lowering the body's concentration of free radicals [56]. Similarly, it has been scientifically demonstrated that plant phenolics, because of their strong antioxidant qualities, can prevent a number of chronic diseases, including cancer, heart disease, and neurological disorders, as well as oxidative stress-related illnesses [57].

Unlike chlorophyll, the changes in β-carotene, Vitamin C, and phenolic compounds increased as the drying temperature rose from 50°C to 60°C. However, as the drying temperature climbed further to 80°C, the changes tended to diminish. As heat, oxygen, and light-sensitive substances, β-carotene, Vitamin C, and phenolics will gradually lose their content as higher temperatures break down their molecular structures [58-60]. However, the concentration of these components was higher at 60°C than at 50°C. One possible reason is that the high drying temperature allows for the release of chemicals that are primarily bound and connected to the cell walls [61]. Insoluble phenolics are covalently bound to structural proteins, cellulose, hemicellulose, pectin, and lignin, which are components of the

Table 4: Effect of drying temperature on the content of bioactive compounds and DPPH free radical scavenging activity of okra seeds.

Drying temperature (°C)	Bioactive compounds				DPPH (%)
	Chlorophyll (mg/100 g d.b)	β-carotene (mg/100 g d.b)	Vitamin C (mg/100 g d.b)	Phenolic (mgGAE/100 g d.b)	
50	2.681±0.076^{c}	0.4239±0.0127^{a}	82.57±2.48^{a}	365.5±10.9^{a}	88.31±2.65^{b}
60	2.523±0.080^{c}	0.7098±0.0213^{b}	86.34±2.59^{b}	642.4±19.2^{c}	99.82±2.99^{d}
70	1.572±0.047^{b}	0.3345±0.0145^{a}	86.40±2.17^{b}	496.8±14.6^{b}	82.98±2.48^{a}
80	1.350±0.041^{a}	0.3522±0.0106^{a}	83.70±2.51^{ab}	481.3±13.5^{b}	97.14±2.81^{c}

Each value represented the mean±standard deviation. Values with different superscripts within a column were significantly different at 5% significance level (P<0.05), d.b. (dry basis).

cell wall [62]. These phytochemicals are essential components of the cell wall because they provide chemical and physical barriers, prevent pathogen penetration, act as an astringent to discourage insect and animal attacks, and have antibacterial, antifungal, and antioxidant properties [63]. Phenolic acids, such as hydroxybenzoic and hydroxycinnamic acids, create ester bonds with structural proteins and carbohydrates through their carboxylic group and ether bonds with lignin through their hydroxyl groups in the aromatic ring [64]. Several food processing techniques can enhance the release of bound phenolics. These consist of thermomechanical processes, as well as fermentation and malting [65]. The current findings are consistent with those of other studies. According to a study on black rosehip fruit, drying disrupted the cell structure and improved the extraction of antioxidant components; hence, hot air drying may increase phenolic compounds [58]. Similarly, Arlai *et al*. discovered that the organic okra that was blanched, boiled, or vacuum-fried had more beta-carotene than the conventional okra [66]. Furthermore, drying at a temperature too low (50°C) exposes the product to light and oxygen for an extended period, which can cause oxidation, especially of Vitamin C [67].

The antioxidant activity of dried OS was expressed through the ability to scavenge DPPH free radicals. The higher the percentage of DPPH free radical scavenging, the stronger the antioxidant activity. Heat-induced phenolic compound release and the production of high-antioxidant Maillard reaction products, namely melanoidins, may be the cause of the increase in antioxidant activity upon drying [68]. The sample dried at 60°C had the highest DPPH value, followed by the sample dried at 80°C, and the sample dried at 50°C had the lowest, according to the data.

In summary, the findings above demonstrated that the highest value of bioactive components and DPPH value was found in the OS dried at 60°C. At this temperature, the levels of chlorophyll, β-carotene, Vitamin C, phenolic, and DPPH free radical scavenging activity in OS were 2.523 mg/100 g d.b., 0.71 mg/100 g d.b., 86.34 mg/100g d.b., 642.37 mgGAE/100 g d.b., and 99.82%, respectively.

When compared to the three remaining drying temperatures (50°C, 70°C, and 80°C), the discovery that 60°C is an efficient temperature for drying OS also has important practical and financial ramifications. Drying at 50°C takes longer for each batch, slowing down the overall process. As a result, a commercial business would see a lower daily throughput from its drying equipment, which would require either longer processing times or larger machinery to handle the same volume of goods. Conversely, it takes more energy to heat the drying air at higher temperatures. Particularly in continuous operation, the difference in energy consumption between 60°C and 70°C or between 60°C and 80°C may be substantial.

4. CONCLUSION

Among the eight applied mathematical models, the Page model was selected to describe the convection drying kinetics of OS because of a higher compatibility than the remaining models at the drying temperatures investigated ($R^2 > 0.995$, $\chi^2 < 0.00006$, and RMSE < 0.03). The effective moisture diffusivity ranged from 6.5109×10^{-12} m^2/s to 1.5140×10^{-11} m^2/s. The activation energy was 37.76 ± 0.98 kJ/mol, as determined through the Arrhenius equation, which revealed a temperature dependence of the effective moisture diffusivity. It was also demonstrated that OS dried at 60°C among the four investigated temperatures could retain the bioactive components the best; hence, this sample exhibited the strongest antioxidant activity, as seen by the maximum DPPH free radical scavenging ability.

OS powder can be used as a main ingredient or supplement in many products, such as bread, soup, or healthy drinks, to increase bioactive compound content and antioxidant capacity. Xu *et al*. examined the phenolic and carbohydrate fractions of fine and coarse flours made from OS and seedless pods, as well as their effects on the nutritional and physical qualities of wheat bread. With only a 5% substitution of OS, the amount of extractable and non-extractable hydrolyzable phenolics in wheat breads was significantly boosted using okra flours, reaching up to 210.8 and 2944.8 mg/100 g, respectively [6]. Another study developed various recipes for OS soup and evaluated the proximate composition and sensory acceptance of the soup samples. Five distinct soup recipes were created, each incorporating 4, 8, 12, 16, and 20 g of OS flour per 100 mL of soup. The control sample was 0 g of soup devoid of OS flour. The study found that compared to the control sample, soups made with OS flour had higher levels of crude protein, ash, crude fat, and fiber. The panelists approved of soup samples containing 4 g, 8 g, and 12 g of OS flour, demonstrating that 4–12 g/100 mL of soup might yield acceptable soups [69]. In the research of Cornelia and Anggraini (2020), green tea extract was added to OS juice in this study in an effort to create a nutritious beverage. The extract from Jawa tea, which had a half maximal inhibitory concentration (IC_{50}) of 85.28 ± 0.21 µg/mL, was mixed with an OS extract in a 1:4 ratio. The IC_{50} for antioxidant activity of this particular healthy beverage is 222.16 ± 1.38 µg/mL. Five hundred ppm drinks inhibited cholesterol up to 47.55 ± 0.76% *in vitro*. After 21 days of consumption, there was a significant drop in cholesterol levels, with HDL increasing to 94.74 ± 16.53%, triglycerides decreasing to 19.39 ± 3.10%, LDL decreasing to 34.76 ± 2.62%, and cholesterol decreasing to 35.50 ± 2.37% [70].

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6. AUTHORS' CONTRIBUTIONS

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agree to be accountable for all aspects of the work. All the authors are eligible to be an author as per the International Committee of Medical Journal Editors (ICMJE) requirements/guidelines.

7. CONFLICTS OF INTEREST

The authors report no financial or any other conflicts of interest in this work.

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9. ETHICAL APPROVAL

This study does not involve experiments on animals or human subjects.

10. DATA AVAILABILITY

Datasets from the current study are available from the corresponding author upon request.

11. PUBLISHER'S NOTE

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12. USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that they have not used artificial intelligence (AI)-tools for writing and editing of the manuscript, and no images were manipulated using AI.

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