

Research Article

Microwave Drying of Chili Pepper Slices: Estimating Moisture Loss and Color Changes and Characterizing Antioxidant Properties

Natoavina T. Faliarizao ¹, Kirk D. Dolan ^{1,2} and Muhammad Siddiq ¹

¹Department of Food Science and Human Nutrition, Michigan State University, East Lansing, Michigan, USA

²Department of Biosystems and Agricultural Engineering, Michigan State University, East Lansing, Michigan, USA

Correspondence should be addressed to Kirk D. Dolan; dolank@msu.edu

Received 15 April 2025; Revised 18 November 2025; Accepted 3 December 2025

Academic Editor: Andrea Bassani

Copyright © 2026 Natoavina T. Faliarizao et al. International Journal of Food Science published by John Wiley & Sons Ltd. This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Chili peppers (*Capsicum annuum* L.), valued for their flavor-enhancing properties, are rich in fiber, essential oils, vitamins, and bioactive compounds and exhibit strong antioxidant activity. Due to their high moisture, fresh chilies are dried using conventional methods to preserve quality; however, microwave drying has emerged as an alternative method for food drying applications, including chili pepper drying. Our objectives were to investigate the effect of microwave power levels (120–600 W) on moisture loss and color degradation using a kinetic modeling approach and to assess dried chili total color difference (ΔE), browning index (BI), total phenolic content (TPC), and antioxidant properties (DPPH, ABTS⁺, and FRAP). Microwave drying at higher power levels significantly reduced drying times ($p \leq 0.05$): 60 min at 120 W, 10.5 min at 480 W, and 7 min at 600 W. Drying at lower powers (120–240 W) yielded minimal color change, whereas BI increased at ≥ 300 W. Microwave power levels did not affect TPC and ABTS⁺ antioxidant value. By contrast, DPPH antioxidant values decreased (from 185.44 to 101.00 μmol Trolox equiv. [TE] g⁻¹) as the microwave power was increased from 240 to 600 W, and the FRAP values decreased significantly from 129.5 to 25.76 μmol TE g⁻¹ at 120 and 360 W, respectively. Although the Midilli primary model provided the best fit, the secondary Weibull/power law model was found more suitable for predicting the moisture loss kinetics of chili peppers under different microwave power levels (root mean squared error [RMSE] 0.013–0.029). Given the rising consumer demand for chili-based products, microwave drying can achieve similar product qualities as traditional drying while significantly reducing drying time. These findings can serve as a reference for spice processors to optimize color and antioxidant retention while increasing drying efficiency.

Keywords: capsicum red pepper; drying process; mathematical modeling; quality control; total antioxidant capacity

1. Introduction

Chili peppers (*Capsicum annuum* L.) are used worldwide in culinary applications to enhance the flavor of foods. They are rich in vitamins, minerals, and bioactive compounds, which contribute to their antioxidant and anti-inflammatory properties [1, 2]. Chili-based products are gaining in popularity in the Western market, leading to increasing demand. However, fresh chilies are highly perishable due to their water content of 88% [3, 4]. The shelf life of freshly harvested chili peppers is estimated to be 48–72 h at ambient temperature, based on a cumulative loss of 12%–

15% [5]. Even at refrigerated temperatures and 90%–95% relative humidity, fresh peppers can be kept for only 2–3 weeks [6]. Drying is necessary to address the shelf life problem and preserve the quality of chilies by reducing their moisture content to about 8%–10%. Additionally, drying treatments preserve the bioactive compounds in dried chili peppers while reducing the microbial load [7]. More versatile than chili powder, dried chilies can be stored for up to 12 months [8].

While open sun drying requires low investment, it depends on sunlight availability and is prone to contamination from foreign materials, bacteria, molds, and insects [9].

Such contamination would make the dried product unsafe for human consumption. Open sun drying requires a long drying time and a large open area [8]. To reduce contamination and shorten drying times, a variety of drying techniques have been investigated, such as hot air, vacuum, infrared, microwave, and combined or hybrid drying. One recent study [10] assessed ultrasonic and chemical pretreatments before drying peppers and showed how such pretreatments can mitigate nonenzymatic browning and retain antioxidant compounds under different drying modes (hot air vs. freeze). Microwave drying has several advantages over conventional drying methods, including faster processing times, improved product quality, and increased energy efficiency [11–13]. The technique utilizes electromagnetic waves for volumetric heating, resulting in reduced drying times and enhanced convenience for consumers [14]. Microwave-convective drying combines microwave and convective heating, further improving drying efficiency and food quality [15].

Dried chili quality depends on moisture level and color, which are influenced by drying conditions [16, 17]. Yap et al. [18] showed that higher drying temperatures increased total phenolic contents (TPCs) and capsaicinoids while reducing flavonoid content. Zhou et al. [19] observed that the decrease in antioxidant capacity of red chilies during drying was linked to a reduction in total phenolic compounds and capsaicinoids. Loss of flavor and browning due to enzymatic or nonenzymatic reactions can be caused by suboptimal drying techniques. Mathematical modeling can estimate optimal process parameters and scale the technology for industrial applications [15]. Research is needed to address quality retention challenges in commercial microwave processing. Some products, including mushrooms, can experience tissue damage and decreased capacity for rehydration [20], and high power can lead to charring [21].

Quality control during processing operations can be enhanced by using mathematical modeling as a tool to estimate changes in product moisture and other quality attributes. For red chili pepper, drying kinetic modeling was mainly conducted using primary models [2, 8, 11]. While primary models can accurately fit experimental drying curves, their predictive capacity is limited to the exact conditions under which the data were collected [22]. The use of secondary models in food drying offers a significant advantage over primary models because they extend beyond simply describing drying kinetics under fixed conditions to linking those kinetics with key processing factors such as temperature, air velocity, relative humidity, and even power level in emerging technologies like microwave, vacuum, or infrared drying [23, 24]. Secondary modeling offers a potent, resource-efficient tool for designing and optimizing drying processes because this approach enables food companies to explore “what if” scenarios (e.g., changing microwave power inputs without having to run full experiments each time), which would reduce costs and save time.

The primary objectives of this study were (1) to evaluate microwave drying of chili pepper slices at different power levels (120–600 W), (2) to describe the dynamics of moisture loss as affected by microwave power levels using primary

and secondary models, and (3) to assess the impact of microwave drying on the physical quality and antioxidant properties of dried chilies.

2. Materials and Methods

2.1. Fresh Chili Peppers, Chemicals, and Reagents. Fresh red chili peppers (*Capsicum annuum* L.) were purchased online from Webstaurant (Lititz, Pennsylvania, United States). The samples were selected based on maturity and sorted for any physical defects, followed by thorough washing under tap water. All chili pepper samples were stored at -4°C until processed or analyzed. All the analytical grade chemicals and reagents were obtained from Sigma-Aldrich (St. Louis, Missouri, United States).

2.2. Microwave Drying. Before drying, the fresh chili peppers were sliced lengthwise with a clean stainless-steel knife, and the sliced peppers were spread out evenly in a single layer for the drying process. Chili pepper samples, 40 g each, were dried in an LG 2450MHz microwave oven (LG Electronics, Denver, Colorado, United States) at five power levels (120, 240, 360, 480, and 600 W). The microwave radiation interacted with the water molecules in the chili peppers, causing them to vibrate and generate heat, removing moisture through evaporation. After dehydration, the chili samples were pulverized using a grinder (Krups, Millville, New Jersey, United States) to pass through US Sieve No. 40 (0.5-mm mesh size) and stored at -20°C in polyethylene bags until analyzed. All experiments were done using three replicates.

2.3. Moisture Loss Modeling. The moisture loss ratio (ML) of chili peppers at each drying time was calculated as follows:

$$\text{ML} = \frac{W_i - W_t}{W_i} \quad (1)$$

Here, ML is the moisture loss ratio, where W_i is the initial weight (grams) of the chili samples and W_t is the weight (grams) of the chili samples at each drying time point.

The Weibull distribution model [25, 26] was used to fit the moisture loss data of red chili peppers during microwave drying for constant power:

$$\text{ML} = 1 - \exp \left[- \left(\frac{t}{\alpha} \right)^{\beta} \right] \quad (2)$$

Here, ML represents the moisture loss ratio, t is the drying time in minutes, α denotes the scale parameter indicating the steepness of the moisture loss curve at constant power, and β is the shape parameter, which indicates whether the moisture loss rate remains constant ($\beta = 1$), decreases ($\beta < 1$) or increases ($\beta > 1$) over time. The two Weibull model parameters (α and β) were estimated for each microwave power level treatment using the *nlinfit* function in MATLAB Version 2024a.

For the secondary model, α can be calculated as a function of the power level (watts), which can be determined by Equation (3):

$$\alpha(P) = k \cdot (P)^n. \quad (3)$$

Here, P is the microwave power (watt) during the drying process; k is the coefficient that adjusts the influence of P on α ; and n denotes the exponent that determines the sensitivity or nonlinear relationship between P and α . By inserting Equation (3) in Equation (2), we obtain the secondary Weibull distribution model in Equation (4):

$$ML = 1 - \exp \left[- \left(\frac{t}{k \cdot (P)^n} \right)^\beta \right]. \quad (4)$$

Additional existing mathematical models were compared with the model developed above, as shown in Table 1.

For each mathematical model, all the parameters were estimated simultaneously using nonlinear regression in MATLAB using the *nlinfit* function. The root mean square error (RMSE) and corrected Akaike information criterion (AICc) were the statistical indices used to assess the goodness of fit of the selected models, as described by Faliarizao et al. [31]. The coefficient of determination (R^2) and reduced mean square of the deviation (χ^2) were also used to evaluate the quality of the fit:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (y_{obs,i} - y_{pred,i})^2}{n - p}}, \quad (5)$$

$$AIC_c = n \cdot \ln \left(\frac{SSR}{n} \right) + 2 \cdot K + \frac{2 \cdot K(K+1)}{n - K - 1}, \quad (6)$$

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_{pred,i} - y_{obs,i})^2}{\sum_{i=1}^n (y_{obs,i} - \bar{y}_{obs})^2}, \quad (7)$$

$$\chi^2 = \frac{\sum_{i=1}^n (y_{obs,i} - y_{pred,i})^2}{n - p}. \quad (8)$$

Here, $y_{obs,i}$ is the experimental moisture loss, $y_{pred,i}$ denotes the model estimated moisture loss, n represents the number of observations, p is the number of parameters, K is the number of estimated parameters plus 1, and SSR denotes the sum of squared residuals.

The accuracy and correlations of parameter estimates can be evaluated with the help of scaled sensitivity coefficient (SSC) plots, as detailed by Dolan and Mishra [32]. Briefly, when the two parameters were highly correlated (correlation coefficient absolute value ≥ 0.99), they could not be estimated together. Therefore, n was set to different constant values to avoid the high correlation between k and n . The parameters β and k were then estimated simultaneously, and their errors were computed [32].

2.4. Color Evaluation. The instrumental color of the chili peppers was measured with a colorimeter, model ColorFlex EZ (HunterLab, Reston, Virginia, United States), both prior to and following drying. Color values L^* (lightness), a^*

(redness), and b^* (yellowness), which are measured CIELab parameters, were recorded to assess color changes. For each treatment ($n=3$), approximately 10 g of chili peppers was weighed in two technical replicates, and the mean color values were computed. From the Hunter L^* , a^* , and b^* values, total color difference (ΔE), hue angle (h°), and chroma (C) values were computed using the following formulas [33]:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}, \quad (9)$$

$$\text{Hue angle}(h^\circ) = \tan^{-1} \left(\frac{b^*}{a^*} \right), \quad (10)$$

$$\text{Chroma}(C) = \sqrt{(a^*)^2 + (b^*)^2}. \quad (11)$$

The browning index (BI) of pepper was measured according to the method of Lee et al. [34]. Water-soluble pigments were extracted from 100 mg of dried red chili peppers with 50 mL of distilled water. The mixture was shaken at 25°C for 2 h. The resulting solution was then centrifuged at $8000 \times g$ for 8 min. To remove suspended particles, the supernatant was filtered through Whatman No. 4 filter paper (pore size 20–25 μm), and the absorbance of the filtrate was measured at 420 nm using a spectrophotometer.

To describe the dynamic color change kinetics of chili peppers, existing kinetics models were evaluated, as shown in Table 2.

Here, C_0 denotes the initial color scale value, C_f is the color scale value of the sample at the end of drying, t represents the drying time, k is the constant for color change rate, and (+) and (−) denote the increase and decrease of the color parameter values, respectively. For the color change kinetics, the parameter estimations were performed using ordinary least squares (OLS) minimization in MATLAB. The statistical significance of each parameter was judged by whether the 95% confidence interval did not contain zero, which is equivalent to $p < 0.05$.

2.5. TPC and Antioxidant Capacity (ABTS⁺, DPPH, and FRAP [Ferric Reducing Antioxidant Power]). The TPC was determined according to the method of Singleton and Rossi [37]. Briefly, ~1 g of microwave-dried chili powders was combined with 20 mL of 80% methanol, and the mixture was shaken on a water-bath shaker for 1 h before being centrifuged at $10,000 \times g$ for 10 min. To enhance extraction, the residue was further treated with two successive rounds of vortexing (1 min each) and centrifugation (5 min at $10,000 \times g$), using an additional 10 mL of 80% methanol for each round. The three supernatants were combined, and absorbance was measured using spectrophotometry at 765 nm and reported as gallic acid equivalent (GAE), as mg GAE 100 g^{-1} .

The procedure for extracting samples for antioxidant analyses was the same as for the total phenolics. For all the assays that followed, antioxidant capabilities were represented as $\mu\text{mol Trolox equivalent (TE)} \text{ g}^{-1} \text{ dry basis (db)}$. All spectrophotometric measurements were performed

TABLE 1: Selected mathematical models to estimate the value of the drying speed constant (k).

Model	Equation	Reference
Logarithmic	$ML = 1 - (a \exp(-kt) + c)$	[27]
Midilli	$ML = 1 - (a \exp(-kt^n) + bt)$	[28]
Page	$ML = 1 - (\exp(-kt^n))$	[29]
Verma	$ML = 1 - (a \exp(-kt) + bt)$	[30]
Weibull-modified (Weibull/power law)	$ML = 1 - \exp\left[-(t/k \cdot (P)^n)^\beta\right]$	This study

Note: a , k , c , b , n , and β are model parameters.

Abbreviations: ML, moisture loss; t , time.

TABLE 2: Selected mathematical models to estimate the dynamic color change parameters.

Model	Equation	Reference
Zero order	$C = C_0 \pm kt$	[35]
First-order fractional	$C - C_f/C_0 - C_f = \exp(\pm kt)$	[36]
Modified fractional-Weibull	$C - C_f/C_0 - C_f = \exp(\pm kt^n)$	This study

using a UV/Vis microplate reader (Enspire 2300, PerkinElmer, Waltham, Massachusetts, United States).

The ABTS⁺ radical cation decolorization methodology of Re et al. [38] was slightly modified to analyze the ABTS⁺ antioxidant activity of chili powder. Briefly, ABTS⁺ radical cation (ABTS⁺) stock solution was prepared by mixing a 7 mM ABTS⁺ solution with 2.45 mM potassium persulfate in a 1:1 ratio and letting the mixture stand in the dark for 12–16 h. An 80% methanol solution was added to this solution to dilute it until the absorbance at 734 nm was 0.70 ± 0.02 . After mixing for 6 min, 30 μ L of the sample, standard, or blank, with 3 mL of the ABTS⁺ working solution, the absorbance was measured using spectrophotometry at 734 nm. An 80% methanol solution was used to run the blank, and a 0.3–1.5 mM Trolox solution was used to create a standard curve.

For the DPPH radical scavenging activity determination, the DPPH solution in methanol was used according to the procedure described by Brand-Williams et al. [39]. Briefly, 10 parts of 80% methanol were combined with one part DPPH stock solution (0.24 g 100 mL⁻¹ methanol) to create a working solution that had an absorbance of 1.10 ± 0.02 at 515 nm. After blending 0.6 mL of blank, standard, or sample mixture with 3.0 mL of DPPH working solution, the mixture was placed in the dark for 20 min, and the absorbance at 515 nm was measured. The 80% methanol blank was utilized to compute the radical scavenging activity through the use of a 50–250 μ mol Trolox solution standard curve.

FRAP of dried chili peppers was analyzed according to the method of Benzie and Strain [40]. A stock solution consisting of 10 mM TPTZ solution, 20 mM FeCl₃·6H₂O solution, and 300 mM acetate buffer in 40 mM HCl was prepared. TPTZ solution, ferric chloride solution, and acetate buffer were combined at a 10:1:1 ratio to create a fresh working solution. After mixing 0.3 mL of the working solution with 3 mL of the blank, standard, or samples, the mixture

was incubated for 5 min, and the absorbance was measured at 595 nm. The blank and standard curves were prepared using 80% methanol and 50–250 μ mol Trolox solution, respectively.

2.6. Statistical Analysis. All experiments were performed with three replicates. To evaluate how drying methods affected the physicochemical and antioxidative qualities of chili pepper powders, one-way analysis of variance (ANOVA) was used. Data analysis was done using JMP 9.0 software (SAS Institute Inc., Cary, North Carolina, United States). Means were separated using Tukey's HSD test, with a statistical significance threshold of $p \leq 0.05$.

3. Results and Discussion

3.1. Moisture Loss Kinetics for Chili Drying at Different Microwave Power Levels. The moisture loss curves for chili peppers using the Weibull distribution model at different microwave powers are plotted against the observed data in Figure 1. The slices of chili pepper had an initial moisture content of 89.5%–89.8% db. Sample microwave-dried at 120, 240, 360, 480, and 600 W resulted in final moisture contents of 17.71% db, 15.26% db, 16.33% db, 15.14% db, and 15.15% db, respectively. As the drying time increased, the moisture loss gradually increased, reaching more than 80%. Microwave drying at 600 and 120 W resulted in the shortest and longest times to achieve 80% moisture loss, taking 7 and 60 min, respectively. When compared to microwave drying at 120 W, drying time at 600 W was 88% shorter. As expected, at the higher power levels (360–600 W), chili moisture was removed rapidly, as it increased the temperature of the material by promoting vibration and friction of the water molecules. The findings concur with those of Krzykowski et al. [2], who found that, depending on the microwave

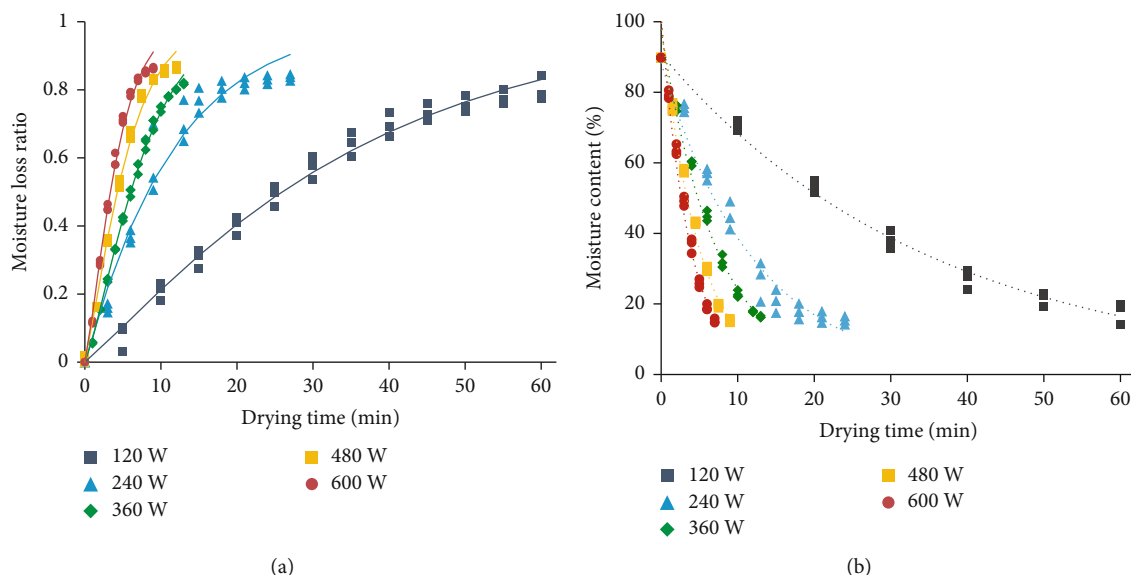


FIGURE 1: (a) Moisture loss kinetics of chili peppers during microwave drying modeled with the Weibull distribution model at different power densities: results represented as predicted curve (solid line) and data points from three replicates per treatment. (b) Variations of moisture content with drying time of chili pepper slices at different microwave powers (120–600 W).

power (50–100 W), the drying time for air-convective-microwave drying at 60°C decreased up to 50%.

Microwave power levels play a critical role in determining the kinetics of moisture reduction during the food drying process. For example, Arslan et al. [41] noted that drying at higher microwave power levels (450 W) effectively reduced drying time compared to lower microwave power settings. Increased microwave power has been shown to improve drying rates and moisture diffusivity over time. Ovando-Medina [42] noted that effective moisture diffusivity and drying rates increase with microwave power, confirming the advantages of microwave-assisted drying over traditional methods such as hot air drying. In addition, microwave drying can help maintain food quality while reducing overall drying time [43]. Microwave drying is a quick and efficient way of removing moisture from food, in which the drying time decreases with increased microwave power level.

Existing moisture kinetic models and Weibull-modified (Weibull/power law) model were fit to each of the ML data sets (Table 3). Additionally, the R^2 , χ^2 , and RMSE values were calculated for each selected mathematical model (Table 3). Because the five models had different numbers of parameters (Table 1, number of parameters are 3, 4, 2, 4, and 3, for logarithmic, Midilli, Page, Verma, and Weibull-modified models, respectively), the most appropriate criterion to compare the model fits was AICc, where lower values indicate a better model. The results indicated that the Midilli model is the best-fitted model overall across the microwave power level. For all the selected models, the predicted k values (drying rate constant) are particularly useful for the food industry and aid in experimental design [44]. For the Weibull-modified model, low AICc values confirm that the model can effectively describe the moisture loss across different microwave power levels, allowing the shape

parameter to be specified per power level. Furthermore, it was shown that the values of the β shape parameter were greater than 1 (Table 3), which indicates an initial lag phase in the drying process where the drying rate increases slightly before entering the falling rate phase [45, 46]. No significant differences in β were found at different microwave power levels for red chili peppers, suggesting that the factors do not have a significant influence on β . This is consistent with previous studies suggesting that β is more affected by the material condition and the drying method [47, 48].

Research indicates that the Weibull distribution model effectively describes moisture loss kinetics in food drying by utilizing two key parameters: the scale parameter (α), which signifies the drying rate constant, and the shape parameter (β), representing the mass transfer efficiency during the initial stages of drying [49]. In the context of drying chili peppers, studies have shown that this model can provide insightful predictions of moisture behavior, although it often coexists with other models, such as the Midilli model, which has been noted for its superiority in certain comparisons [42, 50]. While the Midilli model often fits experimental data better in various drying trials involving peppers, the Weibull distribution remains useful due to its clarity in defining early drying kinetics [42, 50].

In Figure 2, the SSC plot showed that the parameters β and n have higher estimation accuracy than k , because the SSC for β is uncorrelated (different shape) with the other two SSCs. Furthermore, SSC plots reveal parameter correlations; for example, the similar curvatures of k and n indicate a high correlation ($\rho_{k,n} = 0.995$). Due to the high correlation between k and n , simultaneous estimation was not possible. To solve this problem, n was set to the best-fit value of -1.29 , which indicated the optimized value with the lowest RMSE. The parameters for the secondary Weibull-modified model

TABLE 3: Parameter estimates and statistical results of drying models for chili microwave drying.

Model	Power (W)	k	Constant	χ^2	R^2	RMSE	AICc
Logarithmic	120	0.0264	$a = 1.047$	$9.658e - 04$	0.987	0.031	-138.53
	240	0.0987	$a = 0.996$ $c = 0.042$	0.003	0.971	0.053	-152.15
	360	0.0867	$a = 1.277$ $c = -0.256$	$5.623e - 04$	0.994	0.024	-172.70
	480	0.100	$a = 1.466$ $c = -0.452$	$5.341e - 04$	0.995	0.023	-150.97
	600	0.131	$a = 1.485$ $c = -0.456$	$7.386e - 04$	0.992	0.027	-166.15
Midilli	120	0.0135	$a = 0.998$ $n = 1.258$ $b = 0.002$	$7.075e - 04$	0.993	0.027	-142.76
	240	0.0427	$a = 1.002$ $n = 1.418$ $b = 0.006$	0.002	0.984	0.040	-164.78
	360	0.0642	$a = 0.997$ $n = 1.389$ $b = 0.006$	$9.056e - 05$	0.999	0.009	-214.47
	480	0.0982	$a = 0.993$ $n = 1.382$ $b = 0.004$	$1.069e - 04$	0.999	0.010	-182.45
	600	0.132	$a = 0.999$ $n = 1.496$ $b = 0.009$	$9.197e - 05$	0.999	0.010	-214.09
Page	120	0.0202	$n = 1.088$	$8.197e - 04$	0.990	0.029	-143.93
	240	0.0708	$n = 1.082$	0.003	0.971	0.052	-154.23
	360	0.0729	$n = 1.254$	$1.803e - 04$	0.998	0.013	-201.79
	480	0.1040	$n = 1.313$	$1.167e - 04$	0.998	0.011	-184.85
	600	0.1352	$n = 1.359$	$1.527e - 04$	0.998	0.012	-205.77
Verma	120	0.0298	$a = 1.067$ $b = 0.5792$	$7.961e - 04$	0.991	0.028	-142.59
	240	0.0888	$a = 1.000$ $b = 0.00$	0.003	0.972	0.052	-152.86
	360	0.1577	$a = 1.307$ $b = 0.545$	$1.346e - 04$	0.998	0.012	-207.01
	480	0.2765	$a = 2.112$ $b = 0.463$	$1.165e - 04$	0.998	0.011	-182.94
	600	0.3276	$a = 1.579$ $b = 0.825$	$1.107e - 04$	0.998	0.010	-211.69
Weibull-modified (Weibull/power law)	120	0.0423	$\beta = 1.089$ $n = 1.409$	$8.652e - 04$	0.990	0.029	-140.84
	240	0.0207	$\beta = 1.082$	0.003	0.971	0.053	-151.45

TABLE 3: Continued.

Model	Power (W)	k	Constant	χ^2	R^2	RMSE	AICc
			$n = 1.154$				
	360	0.0143	$\beta = 1.254$	$1.889e - 04$	0.998	0.014	-198.88
			$n = 1.077$				
	480	0.0108	$\beta = 1.313$	$1.232e - 04$	0.998	0.011	-181.77
			$n = 1.013$				
	600	0.0084	$\beta = 1.359$	$1.600e - 04$	0.998	0.013	-202.87
			$n = 0.977$				

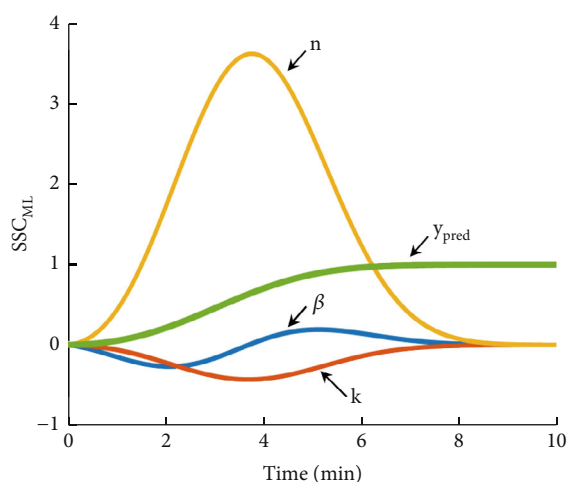


FIGURE 2: Example SSC plot from three-parameter estimation of moisture loss kinetics of chili peppers during microwave drying using the secondary Weibull distribution model (SSC = scaled sensitivity coefficient).

for moisture loss kinetics as influenced by microwave power are shown in Table 3.

3.2. Modeling the Dynamic Changes of Color. Microwave drying at 120 and 240 W was the optimal power settings for drying chili peppers, as they resulted in little to no burning of the dried product. Microwave drying of chili peppers at different power levels led to significant differences in the Hunter color values L^* , a^* , and b^* ($p \leq 0.05$). Fresh red pepper fruits have L^* , a^* , and b^* values of 40.50, 37.57, and 42.75, respectively. For all treatments, the hue angle was around 0.6° , which is characteristic of the color red (Table 4). The natural pigments responsible for the red color of red chili peppers are carotenoids, which are broken down by heat exposure during drying [51]. Table 4 shows that the highest value of chroma, that is, color intensity, was observed for chili peppers dried at 240 and 120 W. The apparent quality and consumer acceptance of dry foods are significantly influenced by the color attribute [52], including spices and seasonings.

The highest total color change (ΔE), indicating the greatest color loss, occurred at the highest microwave power (600 W), while the lowest ΔE was observed at 120 and

240 W. The ΔE measures the degree of color change between fresh and dried samples, with a ΔE of greater than 5 indicating a noticeable color change [52, 53]. Arslan et al. [41] reported that intermittent microwave drying at lower power levels (150–300 W) resulted in higher color quality for both organic and conventional sweet red peppers. In the present study, drying at lower microwave power levels of 120 and 240 W resulted in better quality retention and burning. Similarly, chili peppers dried at higher microwave power, 480 and 600 W, experienced greater color degradation, as shown by a higher BI (Table 4). The microwave-dried chili sample at 600 W showed the highest BI.

Microwave power impacts both the drying kinetics and color retention in chili peppers. A study on the drying kinetics of different chili pepper varieties showed that improper drying conditions led to significant color loss through carotenoid breakdown [54]. Elevated temperatures coupled with high microwave power can exacerbate this effect, leading to a loss of desirable red color due to the degradation of carotenoids [55]. As documented by Song et al. [56], higher microwave power is associated with a notable decline in total carotenoid content, including specific carotenoids such as all-trans- α -carotene and all-trans- β -carotene, which experience significant degradation as the power increases. This degradation often results in increased levels of cis isomers, such as 13-cis and 9-cis β -carotene, indicating a complex alteration of carotenoid profiles due to thermal processes [57].

Studies on other fruits and vegetables support these findings, showing that food drying conditions, such as microwave power levels, significantly affect both carotenoid retention and color integrity. For instance, Kamaruddin et al. [58] highlighted that high power levels beyond 630 W can drastically deteriorate carotenoid concentrations, a result consistent with findings in other studies focusing on different produce types, indicating a trend toward greater losses in carotenoids at elevated temperatures [56, 57, 59]. Moreover, the reduction in color quality can also be linked to the formation of brown pigments during Maillard reactions at higher temperatures [60]. At moderate to high temperatures, the Maillard reaction yields a range of brown pigments, such as melanoidins, which are responsible for the characteristic browning observed in dried foods. Liu et al. [61] addressed how the degree of browning correlates with the reaction conditions, indicating a direct relationship

TABLE 4: Hunter color parameters (L^* , a^* , b^* values), hue angle, chroma, total color difference (ΔE), and browning index (BI) of chili peppers dried via microwave at different power levels (120–600 W).

Microwave power	Hunter color values			Hue angle	Chroma	(ΔE)	BI
	L^*	a^*	b^*				
120 W	36.9 $\pm$ 1.4 ^c	36.1 $\pm$ 1.7 ^c	35.2 $\pm$ 3.6 ^c	0.68 $\pm$ 0.07 ^b	50.4 $\pm$ 3.8 ^c	8.54 $\pm$ 4.0 ^a	0.13 $\pm$ 0.02 ^a
240 W	39.2 $\pm$ 1.2 ^c	36.7 $\pm$ 2.0 ^c	40.6 $\pm$ 2.0 ^d	0.46 $\pm$ 0.04 ^a	56.9 $\pm$ 1.9 ^c	1.74 $\pm$ 1.2 ^a	0.25 $\pm$ 0.05 ^{ab}
360 W	31.2 $\pm$ 1.0 ^b	22.5 $\pm$ 2.5 ^b	25.9 $\pm$ 2.9 ^b	0.44 $\pm$ 0.03 ^a	34.4 $\pm$ 3.8 ^b	24.34 $\pm$ 3.8 ^b	0.38 $\pm$ 0.02 ^{bc}
480 W	26.8 $\pm$ 1.4 ^a	16.8 $\pm$ 1.1 ^a	19.8 $\pm$ 1.6 ^{ab}	0.42 $\pm$ 0.07 ^a	26.0 $\pm$ 1.9 ^a	33.77 $\pm$ 2.2 ^c	0.53 $\pm$ 0.07 ^{cd}
600 W	27.1 $\pm$ 2.2 ^{ab}	16.8 $\pm$ 11.0 ^a	18.8 $\pm$ 1.5 ^a	0.48 $\pm$ 0.02 ^a	25.3 $\pm$ 1.8 ^a	34.35 $\pm$ 2.5 ^c	0.55 $\pm$ 0.12 ^d

Note: Data are mean $\pm$ SD of three replicates. Means in each column with different letters differ significantly using Tukey's HSD test ($p \leq 0.05$).

between temperature and the extent of color change during food processing and storage. Temperature also affects the kinetics of the Maillard reaction, with higher temperatures generally increasing the rate of reaction. This acceleration may result in a rapid loss of color if the reaction progresses to the formation of undesirable brown pigments.

The low AICc values confirm that the modified fractional-Weibull model accurately describes the dynamic change of color parameters of chili pepper at different microwave power levels. Overall, for a^* value, chroma, and ΔE , the modified fractional-Weibull model was the best-fitted model compared to the zero-order and first-order fractional models (Table 5). Figure 3 shows the fit to the modified fractional-Weibull model for the chili pepper redness ($R^2 = 0.953$), chroma ($R^2 = 0.944$), and color difference ($R^2 = 0.901$). Color plays an essential role in the sensory perception and consumer acceptance of food [62]. These model parameters could be used to estimate the instrumental color of red chili peppers during microwave-based drying.

3.3. Total Phenolics and Antioxidant Capacity (ABTS⁺, DPPH, and FRAP). TPC of chili microwave drying ranged from 497.73 to 537.90 mg GAE g⁻¹; however, there were no significant differences among the power levels (Table 6). Microwave drying at 360 W resulted in the highest TPC (537.90 mg GAE g⁻¹), and then, the chili TPC values slightly decreased at 480 and 600 W. Higher microwave power levels generally enhanced the TPC by promoting increased solubility and faster mass transfer rates. Jalszynski et al. [63] noted increasing microwave power during microwave-vacuum drying of oregano in higher TPC, from 85.14 to 112.11 mg GAE g⁻¹ at 240 and 480 W, respectively. In addition, Arslan et al. [64] found that the TPC in microwave-dried mint increased (by 45%), whereas the amount decreased by 53% after air drying. Therefore, to maximize the extraction of phenolic compounds, it is essential to find the optimal microwave power by maximizing the retention of beneficial compounds.

For the ABTS⁺ radical scavenging capacity of dried pepper, higher microwave power levels during the drying process preserved the ABTS⁺ radical scavenging capacity of dried pepper. The antioxidant properties of the dried chili pepper samples, assayed by the ABTS⁺ method, ranged from 164.30 to 203.80 μ mol TE g⁻¹ db (Table 6). Microwave drying at 480 and 360 W showed greater ability to scavenge ABTS⁺ radicals compared to other power levels, with

120 W showing the lowest ABTS⁺ value. However, these differences were not significant ($p > 0.05$). Deng et al. [65] found a positive correlation between phenolics and antioxidant activity. In addition, Wojdyło et al. [66] indicated that the antioxidant capacity was influenced by the native polyphenol content rather than drying methods. Hence, the higher ABTS⁺ value during chili microwave drying could be attributed to the good retention of phenolic content. Another possible explanation is that the genus *Capsicum* has high antioxidant activity, due to high content of carotenoids, ascorbic acid, and α -tocopherol [67].

As expected, DPPH radical scavenging capacity decreased with increasing microwave power level (Table 6). Özkan-Karabacak et al. [68] found that microwave vacuum drying improved drying characteristics but reduced DPPH values compared to conventional vacuum drying methods. This reduction was attributed to the degradation of antioxidants during microwave treatment, indicating that excessive exposure to microwave energy could have detrimental effects on antioxidant compounds. Microwave heating was shown to result in lower phenolic profiles and reduced DPPH scavenging capacities in buckwheat samples [69]. According to Alam et al. [70], the DPPH method assesses antioxidant ability by measuring free radical scavenging through the reduction of metal complexes. In that study, primary antioxidant capacity was linked to natural antioxidants like polyphenols, ascorbic acid, flavonoids, and β -carotene, which are prone to degradation at higher microwave powers.

For FRAP, drying chili peppers at different microwave levels significantly influenced FRAP values ($p \leq 0.05$). The chili pepper dried at lower microwave power (120 and 240 W) showed better FRAP retention (Table 6). A wide range of FRAP values (265.76–129.51 μ mol TE g⁻¹) has been reported in various studies. The lowest FRAP value was obtained from the microwave drying at 360 W (25.76 μ mol TE g⁻¹ db); however, measurements at higher powers (480 and 600 W) showed no further significant decrease and remained similar to those at 360 W ($p > 0.05$). This suggests that most antioxidant degradation occurred at moderate power levels and that, at higher powers, rapid drying and reduced exposure time limited further loss. For fruits and vegetables, such as tomatoes, mangoes, bananas, and pineapples, microwave drying caused a 14%–56% loss in FRAP values, which was greater than hot air drying (6%–13% loss) [71]. Microwave-dried chili samples at lower microwave powers (120–240 W) showed superior FRAP values.

TABLE 5: Kinetic parameters of the color degradation for chili microwave drying.

Color variables	Model	Power (W)	k	C_0	Constant C_f	n	AICc	R^2
a^* value	Zero order	120	0.360	31.74	—	—	30.94	0.944
		240	0.899	33.32	—	—	32.97	0.948
		360	1.929	37.29	—	—	34.58	0.958
		480	2.236	39.55	—	—	49.72	0.857
		600	1.116	32.37	—	—	30.73	0.683
	First-order fractional	120	0.014	33.06	−5.49	—	27.72	0.958
		240	0.044	35.08	1.66	—	19.52	0.972
		360	0.002	37.34	−1.070	—	37.52	0.958
		480	−2.910	39.56	0.00076	—	52.84	0.857
		600	−1.350	32.37	0.00080	—	33.66	0.710
	Modified fractional–Weibull	120	0.027	32.55	8.48	1.384	29.24	0.962
		240	0.081	34.13	12.70	1.548	13.43	0.980
		360	0.069	36.64	−5.134	1.373	39.85	0.959
		480	0.145	37.61	15.299	2.241	51.60	0.885
		600	0.007	31.26	−2.170	0.002	34.39	0.738
Chroma	Zero order	120	0.410	36.70	—	—	48.21	0.906
		240	1.029	38.64	—	—	42.41	0.945
		360	2.055	43.09	—	—	55.53	0.916
		480	2.666	47.12	—	—	62.92	0.819
		600	1.154	38.06	—	—	42.37	0.617
	First-order fractional	120	−14.972	37.82	0.010	—	49.42	0.914
		240	−3.583	40.22	0.03	—	36.47	0.960
		360	353.990	42.93	−0.006	—	58.39	0.916
		480	39.960	39.96	−2.74e − 06	—	66.04	0.819
		600	−5.140	38.06	0.000223	—	45.29	0.617
	Modified fractional–Weibull	120	0.0281	37.15	11.00	1.524	51.34	0.920
		240	0.082	38.73	15.97	1.868	24.66	0.977
		360	0.127	40.64	17.20	2.799	53.69	0.939
		480	0.158	44.70	20.67	2.562	62.95	0.868
		600	0.178	36.11	28.43	9.380	34.40	0.787
ΔE	Zero order	120	3.659	0.48	—	—	64.29	0.861
		240	1.278	1.16	—	—	60.25	0.919
		360	2.175	0.86	—	—	58.66	0.915
		480	2.387	1.29	—	—	69.38	0.728
		600	1.053	1.96	—	—	52.398	0.469
	First-order fractional	120	−0.010	37.82	−14.97	—	49.42	0.914
		240	0.0003	38.63	3.830	—	45.30	0.944
		360	−0.0016	43.13	−1.250	—	58.45	0.916
		480	−0.0007	47.14	−3.580	—	66.04	0.819
		600	−0.0004	38.06	−2.680	—	45.29	0.617
	Modified fractional–Weibull	120	82.58	−0.245	−0.793	0.165	64.14	0.899
		240	0.004	−0.751	−147.23	0.733	62.40	0.929
		360	0.048	0.12	−27.577	0.726	64.55	0.916
		480	0.007	3.05	−1.150	1.437	74.58	0.746
		600	4.162	0.14	−1.263	0.211	55.82	0.526

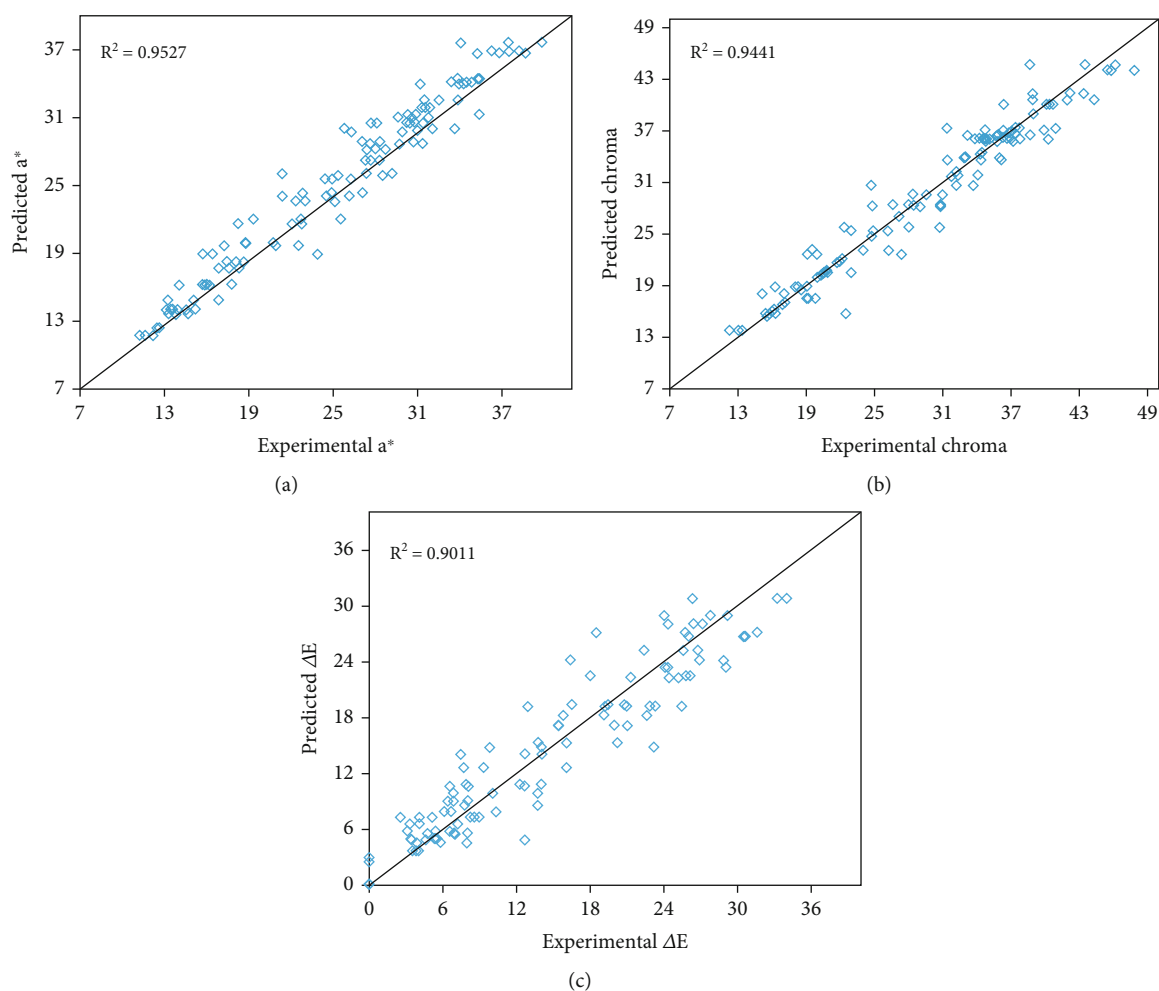


FIGURE 3: Comparison of experimental and predicted color parameters for chili microwave drying using the modified fractional-Weibull model.

TABLE 6: Effect of microwave drying at different power levels (120–600 W) on total phenolic content and antioxidant properties of dried chili peppers: DPPH, ABTS⁺, and FRAP.

Microwave power	Total phenolic content (mg GAE g ⁻¹ db)	Antioxidant capacity ($\mu\text{mol TE g}^{-1}$ db)		
		ABTS	DPPH	FRAP
120 W	497.73 $\pm$ 7.36 ^a	164.3 $\pm$ 46.97 ^a	202.33 $\pm$ 4.84 ^a	129.51 $\pm$ 4.87 ^a
240 W	530.07 $\pm$ 27.32 ^a	169.63 $\pm$ 38.74 ^a	185.44 $\pm$ 11.88 ^a	75.64 $\pm$ 18.26 ^b
360 W	537.90 $\pm$ 15.59 ^a	182.80 $\pm$ 48.98 ^a	136.88 $\pm$ 8.89 ^b	25.76 $\pm$ 2.32 ^c
480 W	525.57 $\pm$ 4.25 ^a	203.38 $\pm$ 28.54 ^a	114.77 $\pm$ 13.18 ^{bc}	33.19 $\pm$ 3.15 ^c
600 W	529.90 $\pm$ 24.19 ^a	166.13 $\pm$ 31.86 ^a	101.00 $\pm$ 26.33 ^c	38.48 $\pm$ 3.40 ^c

Note: Data are mean $\pm$ SD of three replicates. Means in each column with different letters differ significantly using Tukey's HSD test ($p \leq 0.05$).

Abbreviation: db, dry basis.

3.4. Comparative Analysis of Drying Methods. In hot air-microwave drying, raising microwave power from 50 to 100 W at 60°C reduced drying time by 50% but caused the largest ΔE and lowest carotenoid retention [2]. Arslan et al. [41] noted that in intermittent microwave drying, increasing power from 150 to 450 W reduced drying time from ~330 to 120 min, but higher antioxidant and color retentions occurred at 150–300 W. Similarly, microwave-assisted hot

air drying reduced drying time by over 50% compared to hot air drying (e.g., ~110 vs. ~240 min at 60°C), with phenolic retention of ~80% at 180–360 W but ~60% at 540 W [72]. In comparison, vacuum drying offered intermediate quality with moderate kinetics, while freeze drying offered the highest carotenoid and polyphenol retention but required much longer times [2]. Moreover, microwave drying prevented browning due to long sun exposure, while cutting drying

TABLE 7: Comparative analysis of drying methods for red chili peppers: Effects on drying time, color retention, and bioactive compound preservation.

References	Drying method(s)	Conditions	Drying-time reduction or kinetics	Color retention	Antioxidants and bioactive compounds	Notes/optimal conditions
Present study	Microwave drying (MD)	MD at 120–600 W	Raising the microwave power from 120 to 600 W reduced drying by 88%.	MD at 120–240 W: Yielded higher a^* (redness) and lower ΔE .	Antioxidant activity decreased less at 120–240 W than at 480–600 W.	The Midilli model best fitted the drying data. Optimal: 120–240 W.
[2]	Hot air drying (AD), hot air–microwave drying (AMD), vacuum drying (VD), freeze drying (FD)	40°C and 60°C; AMD at 50 and 100 W	Raising the temperature from 40°C to 60°C reduced drying by 37% (VD), 32% (FD), 67% (AD), and 48% (AMD). Increasing AMD from 50 to 100 W reduced the time by 39% (40°C) and 50% (60°C).	FD and VD: Best color (lowest ΔE). AD and AMD: Darker, higher b^* (yellow). AMD at 100 W: Largest ΔE .	Carotenoids are highest in FD, lowest in AMD at 100 W. Capsaicinoids declined with temperature. Polyphenols are highest in FD.	The Midilli model is the best fit. Most efficient: 70-min AMD at 60°C, 100 W. AMD at 50 W has balanced speed and quality better than 100 W.
[41]	Intermittent microwave drying (IMD)	150–450 W; pulsed regimes	Drying time decreased from ~330 min (150 W) to ~120 min (450 W).	IMD at 150–300 W: Powders had higher a^* (redness) and lower ΔE vs. 450 W.	Antioxidant activity decreased less at 150–300 W than at 450 W.	IMD at 150–300 W is recommended for the best color and antioxidant retention.
[72]	Microwave-assisted hot air drying (MAHD)	180–540 W; air 40°C–70°C	MAHD reduced drying time by > 50% vs. AD alone (e.g., ~110 min vs. ~240 min at 60°C).	At 180–360 W and 40–50°C: Low ΔE (< 5). At 540 W or 70°C: Browning occurred ($\Delta E > 10$).	Total phenolic retention: ~80% at 180–360 W and 40°C–50°C; fell to ~60% at 540 W and 70°C.	Optimal: 180–360 W with 40°C–50°C hot air.
[8]	Sun drying and microwave drying (MD)	Sun: ~30°C, ~8–10 h/day. MD: Power level not specified	99%-time reduction: 40 min (MD) vs. 66 h (sun drying).	No L^* , a^* , b^* data reported. Browning was noted for sun drying.	Not quantified; note loss of flavor and actives during sun drying.	MD superior for drying rate; Verma model best fit.

time by 99% (40 min compared to 66 h for sun drying) when compared to sun drying [8]. Overall, the data indicated that the best balance between efficiency, pigment stability, and bioactive retention is achieved with moderate microwave powers: 120–240 W (present study) and 150–360 W [41, 72]. Intermittent and hybrid approaches help to further reduce the quality degradation caused by prolonged exposure to high-power microwaves. These results (Table 7) demonstrate that microwave-based techniques are fast and energy-efficient; however, the power input needs to be carefully selected to maintain the nutritional value and bioactive compounds of chili peppers. Lučić et al. [10] demonstrated that applying ultrasonic and chemical pretreatments before drying peppers can reduce nonenzymatic browning and improve antioxidant retention across different drying methods.

Based on the body of research surrounding chili microwave drying, there is not yet a secondary kinetic model integrating the effect of different power levels on the drying kinetics. Here, we have developed a global secondary model understanding of how microwave power level affects the

drying rates of chili peppers. The findings provide important insights into improving microwave drying of red chili peppers to preserve the overall quality and antioxidant properties of red chili peppers. Future work could include additional quality indicators such as capsaicinoids, ascorbic acid (vitamin C), and carotenoids. Krzykowski et al. [2] noted that capsaicin and dihydrocapsaicin, which determine pungency and contribute to both sensory and functional quality, may degrade at elevated temperatures or prolonged heat exposure. Heat-labile micronutrients, including ascorbic acid and carotenoids, play key roles in color stability and antioxidant capacity of red chili peppers [8, 72]. Incorporating these parameters into future analyses would enhance the predictive capacity of the quality models and further validate microwave drying as an alternative to conventional drying methods.

4. Conclusion

Microwave drying demonstrated the ability to shorten drying times while preserving the color quality of chili peppers.

Modeling of the dynamic moisture loss and color change kinetics indicated that microwave power and drying time play a role in color retention and appearance of chili peppers. The Midilli model and the modified fractional-Weibull model are the best-fitted models for the dynamic moisture loss and the color change, respectively. Chili peppers retained more color and showed less degradation when dried at lower microwave power (120–240 W). Higher ΔE values and BI were observed at higher power levels of 480 and 600 W. While TPC and ABTS⁺ activity were similar across power levels, the DPPH decreased with increasing power levels. For FRAP, while the overall trend indicates a decrease in FRAP value with increasing power up to 360 W, the values appear to plateau beyond that point. Response surface modeling indicated that microwave power and drying time play a role in color retention and appearance of chili peppers. Overall, microwave drying at 120 and 240 W better preserved the overall color and antioxidant potential of dried chili peppers. Given the growing consumer demand for chili-based products (e.g., hot sauces, hot honey, and spicy snacks), microwave drying could be used to achieve similar product functional properties as traditional drying while reducing drying time.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Conflicts of Interest

The authors declare no conflicts of interest.

Funding

This work was supported in part by the US Department of Agriculture, National Institute of Food and Agriculture, Hatch Project 1010216.

Acknowledgments

This work was supported in part by the US Department of Agriculture, National Institute of Food and Agriculture, Hatch Project 1010216.

References

- [1] S. Idrees, M. A. Hanif, M. A. Ayub, A. Hanif, and T. M. Ansari, "Chili Pepper," in *Medicinal Plants of South Asia*, eds. M. A. Hanif, H. Nawaz, M. M. Khan, and H. J. Byrne (Elsevier, 2020), 113–124, <https://doi.org/10.1016/B978-0-08-102659-5.00009-8>.
- [2] A. Krzykowski, S. Rudy, R. Polak, et al., "Drying of Red Chili Pepper (*Capsicum annum* L.): Process Kinetics, Color Changes, Carotenoid Content and Phenolic Profile," *Molecules* 29, no. 21 (2024): 5164, <https://doi.org/10.3390/molecules29215164>.
- [3] A. Quraishi, P. S. Champawat, S. K. Jain, and K. Dhake, "Drying Characteristics of Green Chilli and Quality Attributes of Developed Powder," *Pharma Innovation Journal* 10 (2021): 1127–1133.
- [4] USDA, "FoodCentral Data" 2024, accessed September 2024, Available at <https://fdc.nal.usda.gov/>.
- [5] M. A. Hossain and B. K. Bala, "Thin-Layer Drying Characteristics for Green Chilli," *Drying Technology* 20, no. 2 (2002): 489–505, <https://doi.org/10.1081/DRT-120002553>.
- [6] A. González-Zamora, E. Sierra-Campos, R. Pérez-Morales, et al., "Measurement of Capsaicinoids in Chiltepin Hot Pepper: A Comparison Study Between Spectrophotometric Method and High Performance Liquid Chromatography Analysis," *Journal of Chemistry* 2015, no. 1 (2015): 709150, <https://doi.org/10.1155/2015/709150>.
- [7] M. Arya, P. Kumari, G. Kumar, A. S. Chauhan, and P. Giridhar, "Insights Into the Chili Phytochemicals, Bioactive Components, and Antioxidant Activity of Instant Premixes (Green and Red Chilies) and Their Reconstitution Products," *Food Production, Processing and Nutrition* 6, no. 1 (2024): 72, <https://doi.org/10.1186/s43014-024-00248-2>.
- [8] S. U. Handayani, I. Mujiarto, A. P. Siswanto, D. Ariwibowo, I. S. Atmanto, and M. Mustikaningrum, "Drying Kinetics of Chilli Under Sun and Microwave Drying," *Materials Today: Proceedings* 63 (2022): S153–S158, <https://doi.org/10.1016/j.matpr.2022.02.119>.
- [9] G. Thamkaew, I. Sjöholm, and F. G. Galindo, "A Review of Drying Methods for Improving the Quality of Dried Herbs," *Critical Reviews in Food Science and Nutrition* 61, no. 11 (2021): 1763–1786, <https://doi.org/10.1080/10408398.2020.1765309>.
- [10] M. Lučić, N. Potkonjak, I. Sredović Ignjatović, et al., "Influence of Ultrasonic and Chemical Pretreatments on Quality Attributes of Dried Pepper (*Capsicum annum*)," *Foods* 12, no. 13 (2023): 2468, <https://doi.org/10.3390/foods12132468>.
- [11] N. Faliarizao, *Impact of Microwave-Based Drying on Salmonella Inactivation Kinetics, Antioxidant Properties and Quality of Red Pepper (Capsicum annum)* (Michigan State University, 2024).
- [12] D. Wray and H. S. Ramaswamy, "Novel Concepts in Microwave Drying of Foods," *Drying Technology* 33, no. 7 (2015): 769–783, <https://doi.org/10.1080/07373937.2014.985793>.
- [13] Y. Yue, Q. Zhang, G. Ma, et al., "Quality Evaluation and Heat and Mass Transfer Mechanism of Microwave Vacuum Drying of Astragalus Roots," *Foods* 13, no. 19 (2024): 3075, <https://doi.org/10.3390/foods13193075>.
- [14] Y. Kumar, "Application of Microwave in Food Drying," *International Journal of Engineering Studies and Technical Approach* 1 (2015): 9–24.
- [15] C. Kumar and M. A. Karim, "Microwave-Convective Drying of Food Materials: A Critical Review," *Critical Reviews in Food Science and Nutrition* 59, no. 3 (2019): 379–394, <https://doi.org/10.1080/10408398.2017.1373269>.
- [16] E. Getahun and D. T. Ebissa, "Investigation of Optimal Drying Conditions of Red Chili Peppers in a Hot Air Cabinet Dryer," *Case Studies in Thermal Engineering* 59 (2024): 104586, <https://doi.org/10.1016/j.csste.2024.104586>.
- [17] E. Getahun, M. A. Delele, N. Gabbiye, S. W. Fanta, and M. Vanierschot, "Studying the Drying Characteristics and Quality Attributes of Chili Pepper at Different Maturity Stages: Experimental and Mechanistic Model," *Case Studies in Thermal Engineering* 26 (2021): 101052, <https://doi.org/10.1016/j.csste.2021.101052>.

- [18] E. S. P. Yap, A. Uthairatanakij, N. Laohakunjit, and P. Jitareerat, "Influence of Hot Air Drying on Capsaicinoids, Phenolics, Flavonoids and Antioxidant Activities of 'Super Hot' Chilies," *PeerJ* 10 (2022): e13423, <https://doi.org/10.7717/peerj.13423>.
- [19] L. Zhou, Z. Cao, J. Bi, et al., "Degradation Kinetics of Total Phenolic Compounds, Capsaicinoids and Antioxidant Activity in Red Pepper During Hot Air and Infrared Drying Process," *International Journal of Food Science & Technology* 51, no. 4 (2016): 842–853, <https://doi.org/10.1111/ijfs.13050>.
- [20] G. R. Askari, Z. Emam-Djomeh, and S. M. Mousavi, "An Investigation of the Effects of Drying Methods and Conditions on Drying Characteristics and Quality Attributes of Agricultural Products During Hot Air and Hot Air/Microwave-Assisted Dehydration," *Drying Technology* 27, no. 7-8 (2009): 831–841, <https://doi.org/10.1080/07373930902988106>.
- [21] L. M. Ahrné, N. R. Pereira, N. Staack, and P. Floberg, "Microwave Convective Drying of Plant Foods at Constant and Variable Microwave Power," *Drying Technology* 25, no. 7-8 (2007): 1149–1153, <https://doi.org/10.1080/07373930701438436>.
- [22] B. S. Kalsi, S. Singh, M. S. Alam, and S. Bhatia, "Microwave Drying Modelling of *Stevia rebaudiana* Leaves Using Artificial Neural Network and Its Effect on Color and Biochemical Attributes," *Journal of Food Quality* 2023 (2023): 2811491, <https://doi.org/10.1155/2023/2811491>.
- [23] F. C. Topuz, E. Bakkalbaşı, A. Aldemir, and I. Javidipour, "Drying Kinetics and Quality Properties of Mellaki (*Pyrus communis* L.) Pear Slices Dried in a Novel Vacuum-Combined Infrared Oven," *Journal of Food Processing and Preservation* 46, no. 10 (2022): <https://doi.org/10.1111/jfpp.16866>.
- [24] S. K. Verma, R. Sasikala, P. Kishore, et al., "Effects of Different Microwave Power on the Drying Kinetics and Physicochemical Quality of Brown Shrimp (*Metapenaeus dobsoni*)," *Sustainable Food Technology* 2 (2024): 141–151, <https://doi.org/10.1039/D3FB00144J>.
- [25] W. Weibull, "A Statistical Distribution Function of Wide Applicability," *Journal of Applied Mechanics* 18 (1951): 287–293, <https://doi.org/10.1115/1.4010337>.
- [26] R. C. Yang, A. Kozak, and J. H. G. Smith, "The Potential of Weibull-Type Functions as Flexible Growth Curves," *Canadian Journal of Forest Research* 8, no. 4 (1978): 424–431, <https://doi.org/10.1139/x78-062>.
- [27] M. H. T. Mondal, M. Akhtaruzzaman, and M. S. H. Sarker, "Modeling of Dehydration and Color Degradation Kinetics of Maize Grain for Mixed Flow Dryer," *Journal of Agriculture and Food Research* 9 (2022): 100359, <https://doi.org/10.1016/j.jafr.2022.100359>.
- [28] A. Midilli and H. Kucuk, "Mathematical Modeling of Thin Layer Drying of Pistachio by Using Solar Energy," *Energy Conversion and Management* 44, no. 7 (2003): 1111–1122, [https://doi.org/10.1016/S0196-8904\(02\)00099-7](https://doi.org/10.1016/S0196-8904(02)00099-7).
- [29] F. Salehi and M. Kashaninejad, "Modeling of Moisture Loss Kinetics and Color Changes in the Surface of Lemon Slice During the Combined Infrared-Vacuum Drying," *Information Processing in Agriculture* 5, no. 4 (2018): 516–523, <https://doi.org/10.1016/j.inpa.2018.05.006>.
- [30] L. R. Verma, R. A. Bucklin, J. B. Endan, and F. T. Wratten, "Effects of Drying Air Parameters on Rice Drying Models," *Transactions of the ASAE* 28 (1985): 296–0301, <https://doi.org/10.13031/2013.32245>.
- [31] N. T. Faliarizao, J. Fanfan, N. Randriamiarintsoa, M. Siddiq, T. M. Bergholz, and K. D. Dolan, "Modeling the Combined Impact of Water Activity and Temperature on *Salmonella* Montevideo Thermal Inactivation on Dried Chili Peppers," *Journal of Food Science* 90, no. 4 (2025): e70201, <https://doi.org/10.1111/1750-3841.70201>.
- [32] K. D. Dolan and D. K. Mishra, "Parameter Estimation in Food Science," *Annual Reviews in Food Science and Technology* 4, no. 1 (2013): 401–422, <https://doi.org/10.1146/annurev-food-022811-101247>.
- [33] J. E. Lozano and A. Ibarz, "Colour Changes in Concentrated Fruit Pulp During Heating at High Temperatures," *Journal of Food Engineering* 31, no. 3 (1997): 365–373, [https://doi.org/10.1016/S0260-8774\(96\)00079-9](https://doi.org/10.1016/S0260-8774(96)00079-9).
- [34] D. S. Lee, S. K. Chung, H. K. Kim, and K. L. Yam, "Nonenzymatic Browning in Dried Red Pepper Products," *Journal of Food Quality* 14, no. 2 (1991): 153–163, <https://doi.org/10.1111/j.1745-4557.1991.tb00056.x>.
- [35] G. Dadali, E. Demirhan, and B. Özbek, "Color Change Kinetics of Spinach Undergoing Microwave Drying," *Drying Technology* 25, no. 10 (2007): 1713–1723, <https://doi.org/10.1080/07373930701590988>.
- [36] H. Xiao, C. Law, D. Sun, and Z. Gao, "Color Change Kinetics of American Ginseng (*Panax quinquefolium*) Slices During Air Impingement Drying," *Drying Technology* 32, no. 4 (2014): 418–427, <https://doi.org/10.1080/07373937.2013.834928>.
- [37] V. L. Singleton and J. A. Rossi, "Colorimetry of Total Phenolics With Phosphomolybdic-Phosphotungstic Acid Reagents," *American Journal of Enology and Viticulture* 16, no. 3 (1965): 144–158, <https://doi.org/10.5344/ajev.1965.16.3.144>.
- [38] R. Re, N. Pellegrini, A. Proteggente, A. Pannala, M. Yang, and C. Rice-Evans, "Antioxidant Activity Applying an Improved ABTS Radical Cation Decolorization Assay," *Free Radical Biology and Medicine* 26, no. 9-10 (1999): 1231–1237, [https://doi.org/10.1016/S0891-5849\(98\)00315-3](https://doi.org/10.1016/S0891-5849(98)00315-3).
- [39] W. Brand-Williams, M. E. Cuvelier, and C. L. W. T. Berset, "Use of a Free Radical Method to Evaluate Antioxidant Activity," *LWT-Food Science and Technology* 28, no. 1 (1995): 25–30, [https://doi.org/10.1016/S0023-6438\(95\)80008-5](https://doi.org/10.1016/S0023-6438(95)80008-5).
- [40] I. F. Benzie and J. J. Strain, "The Ferric Reducing Ability of Plasma (FRAP) as a Measure of 'Antioxidant Power': The FRAP Assay," *Analytical Biochemistry* 239, no. 1 (1996): 70–76, <https://doi.org/10.1006/abio.1996.0292>.
- [41] A. Arslan, Y. Soysal, and M. Keskin, "Mathematical Modeling, Moisture Diffusion and Color Quality in Intermittent Microwave Drying of Organic and Conventional Sweet Red Peppers," *AgriEngineering* 2, no. 3 (2020): 393–407, <https://doi.org/10.3390/agriengineering2030027>.
- [42] V. M. Ovando-Medina, "Infrared Drying Kinetics of *Capsicum annum* L. var. *glabrusculum* (Piquin Pepper) and Mathematical Modeling," *Journal of Food Process Engineering* 46, no. 7 (2023): <https://doi.org/10.1111/jfpe.14333>.
- [43] A. Hazervazifef, P. A. Moghaddam, and A. M. Nikbakht, "Microwave Dehydration of Apple Fruit: Investigation of Drying Efficiency and Energy Costs," *Journal of Food Process Engineering* 40, no. 3 (2017): e12463, <https://doi.org/10.1111/jfpe.12463>.
- [44] E. Karacabey and S. Buzrul, "Modeling and Predicting the Drying Kinetics of Apple and Pear: Application of the Weibull Model," *Chemical Engineering Communications* 204, no. 5

- (2017): 573–579, <https://doi.org/10.1080/00986445.2017.1291427>.
- [45] M. Bantle, K. Kolsaker, and T. M. Eikevik, “Modification of the Weibull Distribution for Modeling Atmospheric Freeze-Drying of Food,” *Drying Technology* 29, no. 10 (2011): 1161–1169, <https://doi.org/10.1080/07373937.2011.574242>.
- [46] Y. Xie, Z. Gao, Y. Liu, and H. Xiao, “Pulsed Vacuum Drying of *Rhizoma dioscoreae* Slices,” *LWT-Food Science and Technology* 80 (2017): 237–249, <https://doi.org/10.1016/j.lwt.2017.02.016>.
- [47] H. Ju, H. Xiao, X. Zheng, et al., “Effect of Hot Air Relative Humidity on Drying Characteristics of Carrot Slabs,” *Transactions of the Chinese Society Agricultural Engineering* 31 (2015): 296–304, <https://doi.org/10.11975/j.issn.1002-6819.2015.24.038>.
- [48] W. P. Zhang, Z. J. Gao, H. W. Xiao, Z. A. Zheng, H. Y. Ju, and L. Xie, “Drying Characteristics of *Poria cocos* With Different Drying Methods Based on Weibull Distribution,” *Transactions of the CSAE* 31 (2015): 317–324, <https://doi.org/10.11975/j.issn.1002-6819.2015.19.043>.
- [49] J. W. Dai, H. W. Xiao, L. H. Zhang, et al., “Drying Characteristics and Modeling of Apple Slices During Microwave Intermittent Drying,” *Journal of Food Process Engineering* 42, no. 6 (2019): e13212, <https://doi.org/10.1111/jfpe.13212>.
- [50] T. V. L. Nguyen, P. B. D. Nguyen, T. T. V. Tran, B. L. Tran, and T. P. Huynh, “Low-Temperature Microwave-Assisted Drying of Sliced Bitter Melon: Drying Kinetics and Rehydration Characteristics,” *Journal of Food Process Engineering* 45, no. 12 (2022): e14177, <https://doi.org/10.1111/jfpe.14177>.
- [51] K. K. Hnin, M. Zhang, R. Ju, and B. Wang, “A Novel Infrared Pulse-Spouted Freeze Drying on the Drying Kinetics, Energy Consumption and Quality of Edible Rose Flowers,” *LWT-Food Science and Technology* 136 (2021): 110318, <https://doi.org/10.1016/j.lwt.2020.110318>.
- [52] N. N. An, W. H. Sun, B. Z. Li, et al., “Effect of Different Drying Techniques on Drying Kinetics, Nutritional Components, Antioxidant Capacity, Physical Properties and Microstructure of Edamame,” *Food Chemistry* 373, pt. B (2022): 131412, <https://doi.org/10.1016/j.foodchem.2021.131412>.
- [53] W. Li, Y. Wang, L. Xing, W. Song, and S. Lu, “Analysis of Volatile and Non-Volatile Components of Dried Chili Pepper (*Capsicum annuum* L.),” *Food* 14, no. 5 (2025): 712, <https://doi.org/10.3390/foods14050712>.
- [54] E. T. D. Andrade, V. G. Figueira, L. P. Teixeira, A. P. Martinazzo, and K. G. D. L. Araujo, “Effect of Drying Kinetics on Color of ‘Dedo de Moça’ Chili Peppers (*Capsicum baccatum*),” *Engenharia Agrícola* 39, no. 5 (2019): 659–667, <https://doi.org/10.1590/1809-4430-Eng.Agric.v39n5p659-667/2019>.
- [55] X. Guo, W. Liu, L. Zhang, X. Wang, and S. Mi, “A Combined Impact of Low-Voltage Electrostatic Field and Essential Oil on the Postharvest Properties of Chili Pepper: Insights Into Related Molecular Mechanisms,” *Food* 13, no. 22 (2024): 3686, <https://doi.org/10.3390/foods13223686>.
- [56] J. Song, X. Wang, D. Li, L. Meng, and C. Liu, “Degradation of Carotenoids in Pumpkin (*Cucurbita maxima* L.) Slices as Influenced by Microwave Vacuum Drying,” *International Journal of Food Properties* 20, no. 7 (2017): 1479–1487, <https://doi.org/10.1080/10942912.2016.1212875>.
- [57] D. B. López-Lluch, M. Cano-Lamadrid, F. Hernández, et al., “Hydroxycinnamic Acids and Carotenoids of Dried Loquat Fruit cv. ‘Algar’ Affected by Freeze-, Convective-, Vacuum-Microwave- and Combined-Drying Methods,” *Molecules* 25, no. 16 (2020): 3643, <https://doi.org/10.3390/molecules25163643>.
- [58] A. H. Kamaruddin, N. A. Zamanhuri, and R. Raslan, “Extraction Yield of Palm Oil and Carotenoids Value From Microwave-Sterilized Oil Palm Mesocarp,” *Advances in Science and Technology* 127 (2023): 23–34, <https://doi.org/10.4028/p-ai6477>.
- [59] S. Rudy, D. Dziki, B. Biernacka, et al., “Impact of Drying Process on Grindability and Physicochemical Properties of Celery,” *Foods* 13, no. 16 (2024): 2585, <https://doi.org/10.3390/foods13162585>.
- [60] Q. Chen, W. Qi, J. Peng, R. Tang, D. Liu, and X. Guo, “The Vacuum and Light-Avoided Packaging Ameliorate the Decline in Quality of Whole Chili During Storage,” *Journal of Food Quality* 2022 (2022): 5129220, <https://doi.org/10.1155/2022/5129220>.
- [61] P. Liu, X. Lu, N. Li, Z. Zheng, and X. Qiao, “Characterization, Variables, and Antioxidant Activity of the Maillard Reaction in a Fructose–Histidine Model System,” *Molecules* 24, no. 1 (2019): 56, <https://doi.org/10.3390/molecules24010056>.
- [62] S. Ghosh, T. Sarkar, A. Das, and R. Chakraborty, “Natural Colorants From Plant Pigments and Their Encapsulation: An Emerging Window for the Food Industry,” *LWT-Food Science and Technology* 153 (2022): 112527, <https://doi.org/10.1016/j.lwt.2021.112527>.
- [63] K. Jalszynski, A. Figiel, and A. Wojdylo, “Drying Kinetics and Antioxidant Activity of Oregano,” *Acta Agrophysica* 11 (2008): 81–90.
- [64] D. Arslan, M. M. Özcan, and H. O. Mengeş, “Evaluation of Drying Methods With Respect to Drying Parameters, Some Nutritional and Colour Characteristics of Peppermint (*Mentha x piperita* L.),” *Energy Conversion and Management* 51, no. 12 (2010): 2769–2775, <https://doi.org/10.1016/j.enconman.2010.06.013>.
- [65] L. Z. Deng, Z. Pan, A. S. Mujumdar, et al., “High-Humidity Hot Air Impingement Blanching (HHAIB) Enhances Drying Quality of Apricots by Inactivating the Enzymes, Reducing Drying Time and Altering Cellular Structure,” *Food Control* 96 (2019): 104–111, <https://doi.org/10.1016/j.foodcont.2018.09.008>.
- [66] A. Wojdylo, M. Teleszko, and J. Oszmiański, “Antioxidant Property and Storage Stability of Quince Juice Phenolic Compounds,” *Food Chemistry* 152 (2014): 261–270, <https://doi.org/10.1016/j.foodchem.2013.11.124>.
- [67] P. M. Hanson, R. Y. Yang, S. Lin, et al., “Variation for Antioxidant Activity and Antioxidants in a Subset of AVRDC—The World Vegetable Center Capsicumcore Collection,” *Plant Genetic Resources* 2, no. 3 (2004): 153–166, <https://doi.org/10.1079/PGR200444>.
- [68] A. Özkan-Karabacak, B. Açoğlu, P. Yolci Ömeroğlu, and Ö. U. Çopur, “Microwave Pre-Treatment for Vacuum Drying of Orange Slices: Drying Characteristics, Rehydration Capacity and Quality Properties,” *Journal of Food Process Engineering* 43 (2020): e13511, <https://doi.org/10.1111/jfpe.13511>.
- [69] Y. Liu, C. Cai, Y. Yao, and B. Xu, “Alteration of Phenolic Profiles and Antioxidant Capacities of Common Buckwheat and Tartary Buckwheat Produced in China Upon Thermal Processing,” *Journal of the Science of Food and Agriculture* 99, no. 12 (2019): 5565–5576, <https://doi.org/10.1002/jsfa.9825>.
- [70] M. N. Alam, N. J. Bristi, and M. Rafiquzzaman, “Review on In Vivo and In Vitro Methods Evaluation of Antioxidant

- Activity,” *Saudi Pharmaceutical Journal* 21, no. 2 (2013): 143–152, <https://doi.org/10.1016/j.jsps.2012.05.002>.
- [71] R. J. Mongi, B. K. Ndabikunze, T. Wicklund, L. M. Chove, and B. E. Chove, “Effect of Solar Drying Methods on Total Phenolic Contents and Antioxidant Activity of Commonly Consumed Fruits and Vegetable (Mango, Banana, Pineapple and Tomato) in Tanzania,” *African Journal of Food Science* 9 (2015): 291–300, <https://doi.org/10.5897/AJFS2015.1232>.
- [72] I. Zahoor, T. A. Ganaie, and S. A. Wani, “Effect of Microwave Assisted Convective Drying on Physical Properties, Bioactive Compounds, Antioxidant Potential and Storage Stability of Red Bell Pepper,” *Food Chemistry Advances* 3 (2023): 100440, <https://doi.org/10.1016/j.focha.2023.100440>.