DOI: https://doi.org/10.22104/ift.2024.7082.2181
Innovative Food Technologies, 12(1), 17-33, Autumn 2024

Research Article

Optimization and modeling of stale bread drying using three different dryers

Samaneh Heirani[1], Kamyar Movagharnejad[1*], Sara Nanvakenari[1]

1. Faculty of Chemical Engineering, Babol Noshirvani University of Technology, Babol, Mazandaran, Iran

(Received: 03 September 2024, Revised: 09 December 2024, Accepted: 10 December 2024)

Abstract

The present study aims to investigate the drying process of stale bread to a moisture content of 8% (wet basis) using three different dryers: single convective, single microwave, and combined convective-microwave. The experiments were designed and analyzed using response surface methodology with a central composite design. Various operating parameters were examined, including air temperature (40–60 °C) and velocity (0.5–1.5 m/s) for the single convective and combined convective-microwave dryers, as well as microwave power (90–900 W) for the single microwave and combined convective-microwave dryers. The drying time, energy consumption, and water activity of stale bread were selected as the responses for the drying process. Comparing the results of the three drying methods, it was observed that the shortest drying time occurred with the combined microwave-convective dryer. The lowest energy consumption was associated with the single microwave dryer (0.019-0.116 kWh), followed by the combined convective-microwave dryer (0.046-0.584 kWh), and the single convective dryer (0.588-1.255 kWh). The range of water activity was found to be desirable for all three dryers. The process was then optimized to minimize drying time, energy consumption, and water activity. The optimal conditions were determined as 616 W for the single microwave dryer, 57 °C and 1.1 m/s for the single convective dryer, and 580 W, 50 °C, and 1.2 m/s for the combined convective-microwave dryer. Under optimal conditions, the combined convective-microwave dryer demonstrated the best performance, achieving 1.47 minutes of drying time, 0.083 kWh of energy consumption, and a water activity of 0.201.

Keywords: Combined microwave-convective dryer; Stale bread; Microwave dryer; Convective dryer; Response surface methodology.

How to cite this article:
Heirani, S., Movagharnejad, K., Nanvakenari, S., (2024). Optimization and modeling of stale bread drying using three different dryers. *Innov. Food Technol.,* 12(1), 17-33. https://doi.org/10.22104/ift.2024.7082.2181

* Corresponding Author: K-movaghar@nit.ac.ir

1. Introduction

Food is a fundamental need for all living organisms. One of the major challenges in the food industry is the difficulty in preserving fresh food products [1]. Drying is one of the oldest and most widely used methods of food preservation. By reducing water activity, drying inhibits the growth of microorganisms and slows down destructive enzymatic reactions, thereby extending the shelf life of food products. Additionally, drying reduces the mass and volume of the product, making it easier and more cost-effective to transport, store, and package [2, 3].

Numerous studies have investigated the drying process across a wide range of foodstuffs, crops, and biological products [4-6]. However, it is possible that some vitamins and nutrients may be lost during drying [7]. To preserve the nutritional and sensory quality of dried products, it is crucial to select the appropriate drying method and optimize the drying conditions. The drying process typically requires extended time and relatively high temperatures to reduce the moisture content to levels that ensure long-term storage. This is particularly true for products with high sugar content, such as fruits, which may lead to significant degradation in quality attributes, including flavor, color, rehydration capacity, shrinkage, and nutrient content [8-11]. The comparison of different dryers and drying methods has become a prominent research trend in recent years. Seyfi et al. compared the energy and environmental parameters of solar refractance window, conventional refractance window, and hot air dryers in the drying process of Aloe vera gel [12]. Motevali et al. examined the energy consumption of various dryers, including hot air, microwave, vacuum, and infrared dryers, using pomegranate arils as the raw material. Their study found that energy consumption was highest with vacuum drying and lowest with microwave drying [13]. In another study, Motevali et al. [14] compared the energy parameters of Roman chamomile across different dryers, revealing significant variations in energy usage across drying methods. Kaveh et al. [15] assessed the specific energy consumption and greenhouse gas (GHG) emissions associated with different dryers in the case study of Pistacia Atlantica.

In recent years, new drying methods have replaced traditional techniques. Some of these include freeze drying [16, 17], fluidized bed drying [18, 19], heat pump drying [20, 21], infrared drying [22, 23], and vacuum drying [24, 25]. To prevent the loss of food quality due to prolonged drying times, microwave drying has gained significant attention over the last decade. Microwaves are a form of long-wavelength electromagnetic radiation (with a frequency of 2450 MHz) [26]. Due to the polar nature of water molecules, they are attracted to the microwave field, causing them to rotate and create friction. This friction generates heat, which raises the temperature of the water and accelerates evaporation. In microwave drying, heat is generated within the food itself, which prevents surface damage or burning, unlike other drying methods where heat penetrates from the surface inward [27-29].

The energy crisis and the increasing demand for higher quality products have driven researchers to explore novel drying methods. New drying equipment must be designed in accordance with environmental and energy policies [30]. One such innovative approach is the combination of different drying methods. Since each drying method has its own inherent advantages and limitations, combining them can enhance the quality of the dried products. Microwave drying, for example, offers high efficiency and faster drying rates, but its main drawback is the high operating cost [31]. Many researchers have combined microwave drying with other methods, such as microwave-vacuum drying [32], microwave-freeze drying [33], microwave-fluidized bed drying [34], microwave-spouted bed drying [35], and microwave-infrared drying [36]. Microwave-convective drying, in particular, combines the benefits of reduced drying time and energy consumption from the microwave dryer with the advantage of removing surface moisture through the convective dryer. One of the main drawbacks of microwave drying is the condensation of moisture on the surface of the food, which can be mitigated by combining it with a convection dryer [37].

Another study compared the energy consumption of various single-function dryers, including hot air, microwave, vacuum, and infrared dryers, with combined microwave-vacuum and hot air-infrared dryers. The raw material used in this study was mushroom slices, and the results concluded that the combined dryers offered notable advantages, such as lower energy consumption and shorter drying times [38].

Due to subsidies on flour and traditional bread, Iran experiences one of the highest rates of bread waste in the world. Drying stale bread, which is no longer suitable for human consumption, and using it as animal feed could help reduce this significant waste. Staling occurs when bread loses moisture due to starch retrogradation, leading to a loss of texture, firmness, and some aromatic characteristics. As a result, people are often reluctant to consume stale bread [39]. The concept of bread waste may vary across societies, but generally, it refers to bread that is not consumed as food or surplus bread that has expired and is discarded. Currently, one of the most common uses of bread waste is its application as animal feed [40].

This study focused on the drying process of a traditional Iranian bread called Sangak. The drying characteristics of stale Sangak bread were investigated using three different drying methods: single convective, single microwave, and combined convective-microwave dryers. The aim of this research was to compare the performance of these dryers under various drying conditions using response surface methodology (RSM). Another objective was to determine the optimal conditions for each dryer to minimize drying time and energy consumption while maximizing the quality of the dried product. Since traditional Iranian breads like Sangak are not commonly baked in other countries, there is no published research on this topic, making the raw material novel. Additionally, the use of a dual combined convective-microwave dryer and its comparison with the two single dryers adds to the novelty of this study. Given the high rate of energy consumption in Iran, the findings of this research, which aim to identify optimal conditions for minimizing energy use, could be of significant value for the country's economy.

2.1. Samples preparation

Bread samples were purchased from the city of Babol, Mazandaran, Iran. The storage conditions for the samples to become stale were kept consistent, with the bread stored in freezer bags for 50 to 60 hours until it became completely stale. Next, 30 g of bread was cut into square pieces with a side length of 2.5 cm using a ruler and scissors. For each experiment, the initial moisture content of the bread was measured on a wet basis (w.b.) and recorded as a percentage using a moisture analyzer (A&D, MX-50, Japan). The initial moisture content of all samples was approximately the same, ranging from 25% to 30% (w.b.). The drying procedure continued until the moisture content reached 8% (w.b.).

2.2. Drying procedure

The drying of the samples was carried out using three drying methods: combined microwave-convective, single microwave, and single convective, each applied separately. A household microwave oven (Butan, M245, Iran), with a maximum power of 900 W, equipped with a rotating tray and digital controls for power and time adjustments, was used for the microwave drying experiments. Fig 1 shows the schematic of the dryer setup used during the experiments. The convective dryer section is depicted on the left side of the schematic. In this section, ambient air is drawn through a heater with multiple elements by a suction fan. The number of active heating elements and the fan speed are manually adjusted to achieve the desired temperature and air flow intensity. The air, now at the desired temperature and velocity, enters the chamber containing the samples, absorbs moisture, and then flows toward the outlet duct. The sample chamber is the same as the microwave oven chamber. The air inlet is connected to the microwave body through transfer pipes with a diameter of 15 cm. Holes were made in the side body of the microwave oven using a laser cutter to connect the air inlet and outlet pipes. The air inlet pipe is equipped with a metal mesh to ensure uniform air flow. The outlet air flow has a higher temperature than the ambient air and increased humidity due to moisture absorption from the bread samples. To make use of the heat from the outlet air, a shell-and-tube heat exchanger is installed at the beginning of the inlet air flow. As shown in Fig 1, the outlet air flow passes through the heat exchanger, transferring heat to the exchanger pipes, which in turn warms the inlet air flow. This setup prevents the heat from the outlet air of the sample chamber from being wasted and contributes to energy savings. Humidity and temperature sensors were installed inside the inlet and outlet pipes. These sensors are made of plastic and can withstand temperatures up to 70°C. Exceeding this temperature may cause damage and errors in the equipment. The apparatus features an electrical panel and a display monitor to show the humidity and temperature of the inlet and outlet air. The entire system is mounted on a stainless-steel chassis. It is important to note that both microwave and convective dryers are used simultaneously during the combined experiments, whereas in the single microwave experiments, only the microwave dryer is used. Similarly, during the convective experiments, the microwave oven is turned off, and only its chamber is used as the convective drying chamber.

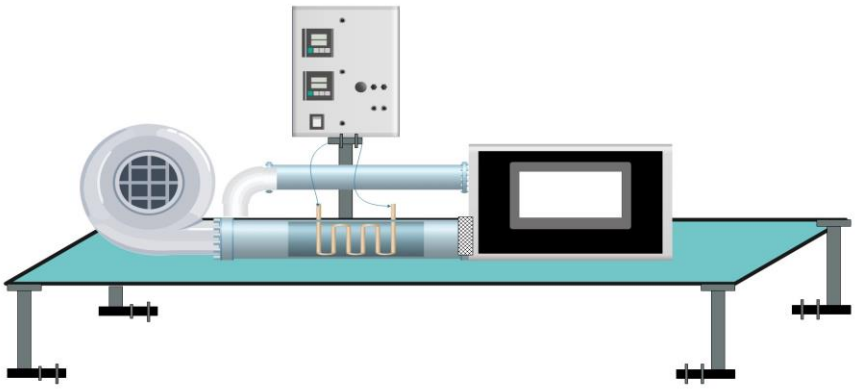

Fig 1. Schematic of the microwave-convective dryer.

2.3. Water activity measurement

The water activity (a_w) of the dried samples is a standard measure of the quality of the dried products. To determine this, a water activity meter (NOVASINA, Lab Swift, Switzerland) was used. The dried samples were gently shredded in a mortar and then placed into the special container of the water activity meter, ensuring that the bottom of the container was completely covered with the dried sample. The container was then placed inside the apparatus until the reading on the screen stabilized. This value represents the water activity of the dried sample.

2.4. Determination of the drying time and energy consumption

The drying time (t) was defined as the duration required to reduce the initial moisture content of the bread from 30% to 8% (w.b.) under various drying conditions. Energy consumption during the process is a crucial factor in evaluating its efficiency. Energy consumption is generally defined as the amount of energy used to evaporate a unit mass of water during the drying process. In this study, energy consumption under different drying conditions was measured using an electrical energy meter (Efergy, EMS-20, UK).

2.6. Experimental Design

RSM (Response Surface Methodology) is a collection of statistical and mathematical techniques that have been successfully applied to develop, improve, and optimize processes where an optimal response is influenced by various variables. The goal of RSM is to optimize this response [41]. It defines the effect of independent variables, either individually or in combination, on the process. Several examples of RSM applications in food process optimization can be found in the literature [42-44]. In this study, RSM was used to assess the influence of different parameters. Each process involves multiple variables, each of which has a specific impact on the response or responses of the process. Investigating all of these effects would require conducting numerous experiments, resulting in significant time and cost burdens. Moreover, mathematical modeling and process optimization can be achieved during the experimental design phase [45]. The independent variables in the microwave-convective dryer include microwave power (90-900 W), inlet air temperature (40-60°C), and inlet air velocity (0.5-1.5 m/s). In the single microwave dryer, the only independent variable is the microwave power, while the inlet air temperature and velocity are the independent variables in the convective dryer. For the combined microwave-convective dryer, the three independent variables are microwave power, inlet air velocity, and inlet air temperature. Due to the presence of only one variable in the microwave dryer, a one-factor design was applied, whereas the central composite design (CCD) was used for the combined microwave-convective and single convective dryers. To investigate the effects of microwave power, inlet air temperature, and inlet air velocity on drying time, energy consumption, and water activity of the samples, a total of 20, 7, and 13 experiments were designed for the combined, single microwave, and single convective dryers, respectively. Table 1 presents the designed experiments along with the obtained experimental results for the responses.

Table 1. The experimental design of convective, microwave and convective assisted microwave dryers and their responses.

Type of drying	Experimental design			Results		
	T (^{0}C)	U (ms^{-1})	MWP (W)	t(min)	a_w	E (KWh)
Convective	50	1	-	115	0.630	0.8
	50	1	-	103	0.612	0.79
	50	1	-	111	0.540	0.81
	50	1	-	109	0.579	0.783
	43	0.6	-	167	0.558	0.591
	57	0.6	-	148	0.442	0.964
	50	1.5	-	90	0.579	0.777
	40	1	-	147	0.580	0.532
	50	0.5	-	180	0.569	0.685
	43	1.4	-	109	0.676	0.588
	57	1.4	-	95	0.368	1.144
	60	1	-	94	0.278	1.255
	50	1	-	109	0.591	0.876

Microwave	-	-	90	43	0.515	0.106
	-	-	540	2.75	0.374	0.026
	-	-	900	1.666	0.635	0.037
	-	-	720	2.083	0.453	0.025
	-	-	900	1.95	0.594	0.039
	-	-	90	40	0.472	0.116
	-	-	270	11.533	0.335	0.048
Convective-Microwave	50	1	900	1.8	0.560	0.058
	56	0.7	270	7.25	0.471	0.188
	56	1.3	720	1.55	0.547	0.064
	50	1	540	1.85	0.375	0.068
	50	0.1	540	1.5	0.373	0.091
	50	1	90	15	0.542	0.351
	50	1	540	2.966	0.391	0.14
	50	1	540	1.416	0.360	0.055
	44	1.3	270	10.25	0.566	0.409
	50	1	540	1.5	0.441	0.099
	50	1	540	1.9	0.420	0.097
	44	0.7	270	12.416	0.536	0.584
	44	0.7	720	1.75	0.678	0.056
	40	1	540	1.75	0.472	0.467
	56	1.3	270	6.25	0.659	0.095
	60	1	540	1.666	0.317	0.091
	56	0.7	720	1.35	0.333	0.062
	44	1.3	720	1.416	0.583	0.156
	50	0.5	540	2.083	0.628	0.05
	50	1.5	540	1.5	0.696	0.046

The analysis of the experimental data was conducted using a full quadratic model (Eq. 1) [23], which is commonly used to define the relationships between the responses and independent variables.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i<j=1}^{k} \beta_{ij} X_i X_j \quad (1)$$

where Y indicates the response variable, β_0 is constant coefficient, β_i, β_{ii}, and β_{ij} are the coefficients of linear, quadratic, and interaction terms, respectively. Besides, X_i and X_j represent the independent variables affecting the response.

3. Results and discussion

3.1. Statistical analysis

The responses obtained from the microwave drying process were modeled using a quadratic model, which is a function of the microwave power (P). Additionally, other quadratic models were developed as functions of the inlet air temperature (T) and inlet air velocity (U) for the responses of the convective dryer. For the combined microwave-convective dryer, the quadratic models were formulated as functions of the inlet air temperature (T), inlet air velocity (U), and microwave power (P). All of these quadratic models are presented in Table 2.

Table 2. ANOVA results for response parameters in different dryers.

Responses	Final Equation For Responses	P_{value}	LOF	R^2
Microwave Dryer				
T	$t = +53.14 - 0.16 \times P + 1.16 \times P^2$	0.0016	0.0551	0.9605
E	$E = +0.14 - 3.83 \times P + 3.01 \times P^2$	0.0007	0.2260	0.9735
a_w	$a_w = +0.57 + 1.09 \times P + 1.27 \times P^2$	0.0027	0.4769	0.9481
Convective dryer				
T	$t = +722.96 - 14.51 \times T - 322.04 \times U + 106.4 \times U^2$	<0.0001	0.0864	0.9672
E	$E = +1.75 - 0.07 \times T - 0.2 \times U + 0.02 \times T \times U + 8.65 \times 10^{-4} \times T^2 - 0.3 \times U^2$	<0.0001	0.7795	0.9866
a_w	$a_w = -3.6 - 0.16 \times T - 0.02 \times T \times U - 1.57 \times 10^{-3} \times T^2$	<0.0001	0.9657	0.9662
Combined dryer				
T	$t = +72.83 - 1.16 \times T - 0.11 \times P + 8.88 \times 10^{-4} \times T \times P + 1. +3.90 \times 10^{-5} \times P^2$	<0.0001	0.0827	0.9750
E	$E = +7.87 - 0.24 \times T - 4.59 \times 10^{-3} \times P + 5.66 \times 10^{-5} \times T \times P + 7.04 \times 10^{-4} \times U \times P + 1.94 \times 10^{-3} \times T^2 + 6.07 \times 10^{-7} \times P^2$	<0.0001	0.1441	0.9660
a_w	$a_w = +2.77 - 0.03 \times T - 3.63 \times U + 0.03 \times T \times U - 3.77 \times 10^{5} \times T \times P + 1.10 \times U^2 + 9.99 \times 10^{-7} \times P^2$	<0.0001	0.4389	0.9610

The results presented in Table 2 indicate that since the p-value for all models is less than 0.05, all models are considered acceptable. The Lack of Fit (LOF) describes the variability of the data around the model, and p-values greater than 0.05 for the LOF indicate a significant correlation between the variables and the process responses. A higher correlation coefficient (R^2), closer to 1, reflects a more desirable model, indicating good agreement between the experimental and predicted results. As shown in Table 2, the R^2 values are acceptable for all models presented in Fig 2, 3, and 4 for different dryers. These figures demonstrate that there is good agreement between the experimental data and the predicted results obtained through the experimental design.

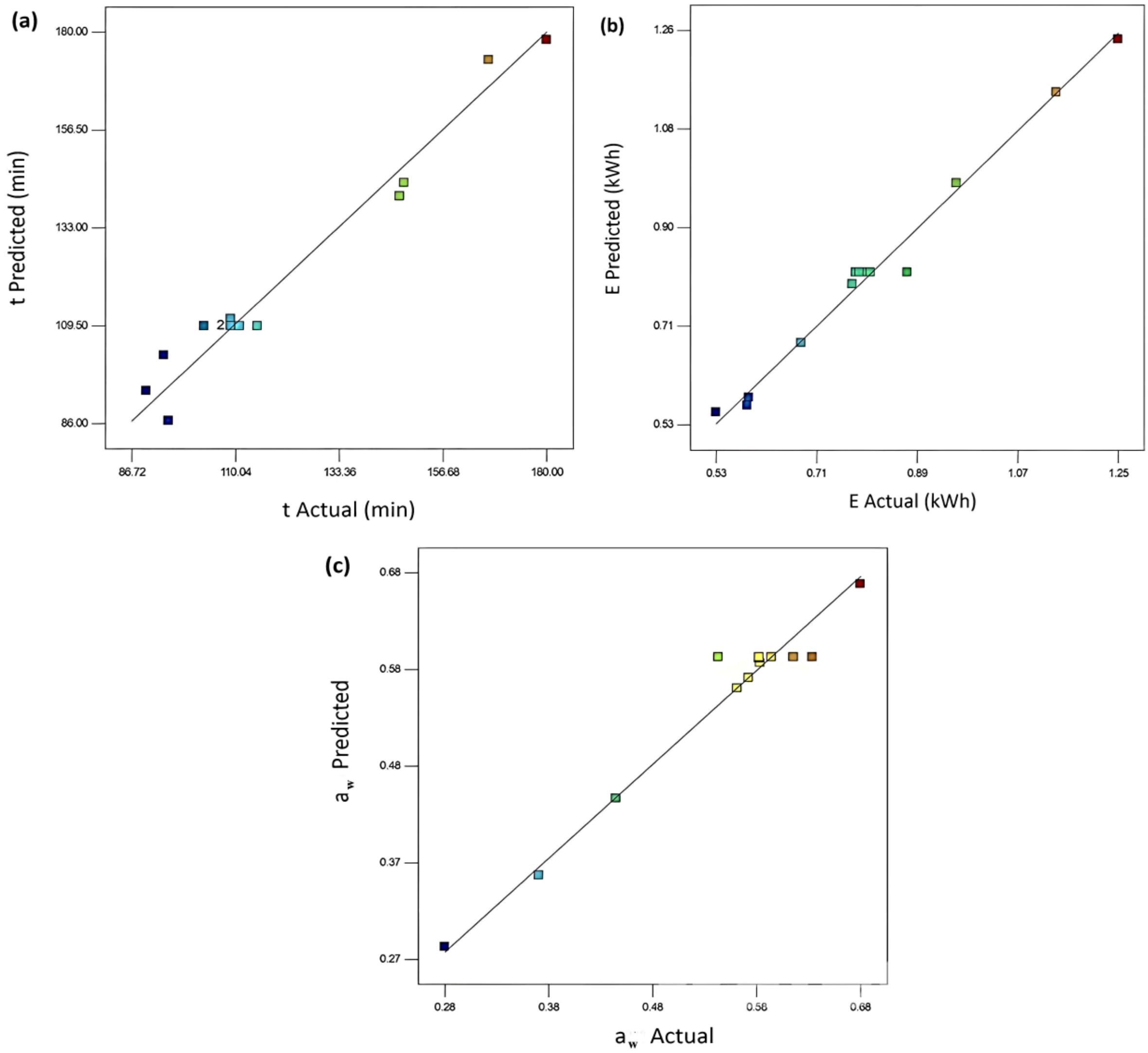

Fig 2. Predicted versus actual data plot for a) Drying time, b) Energy consumption, c) Water activity in the convective dryer.

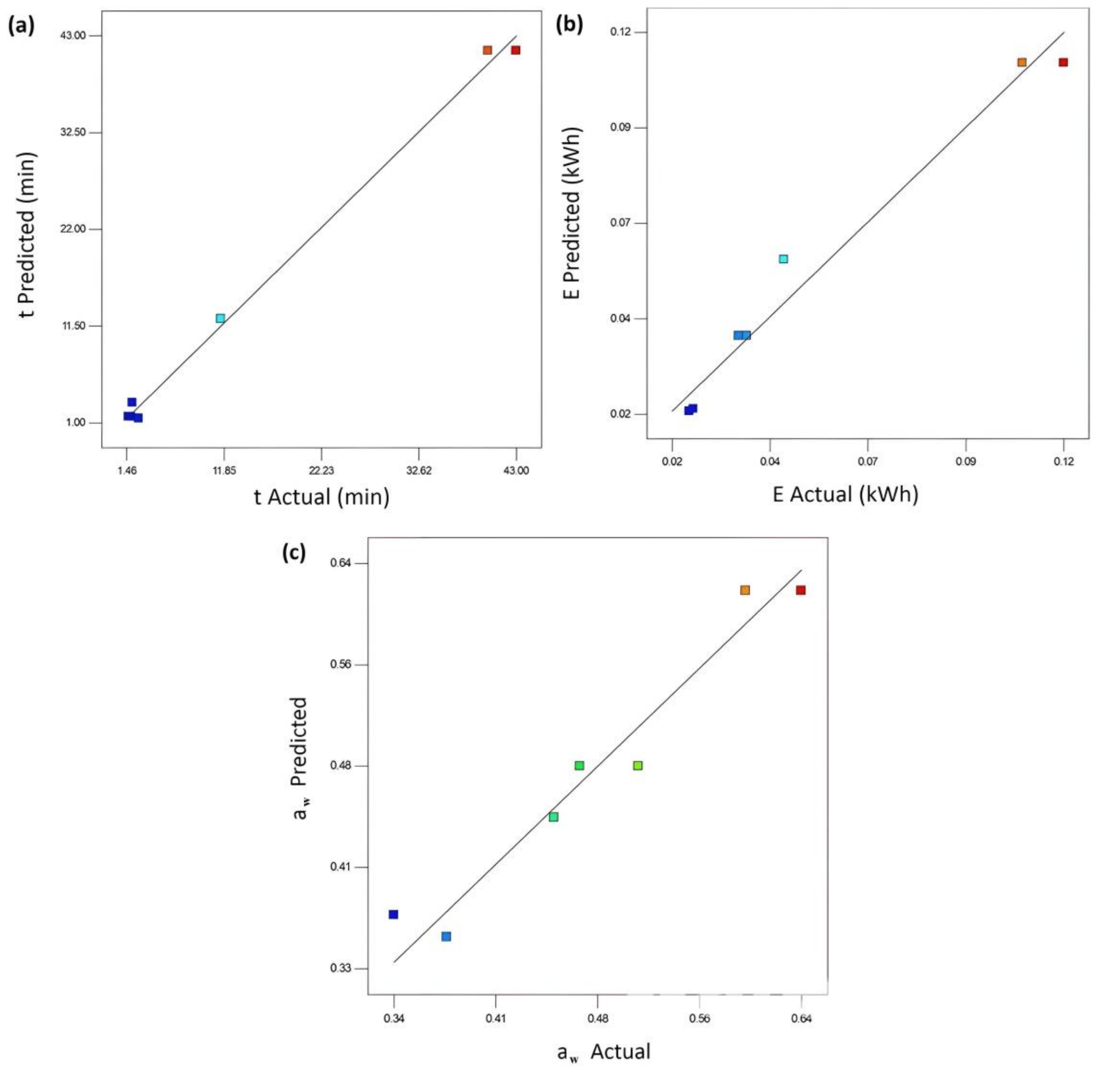

Fig 3. Predicted versus actual data plot for a) Drying time, b) Energy consumption, c) Water activity in the microwave dryer.

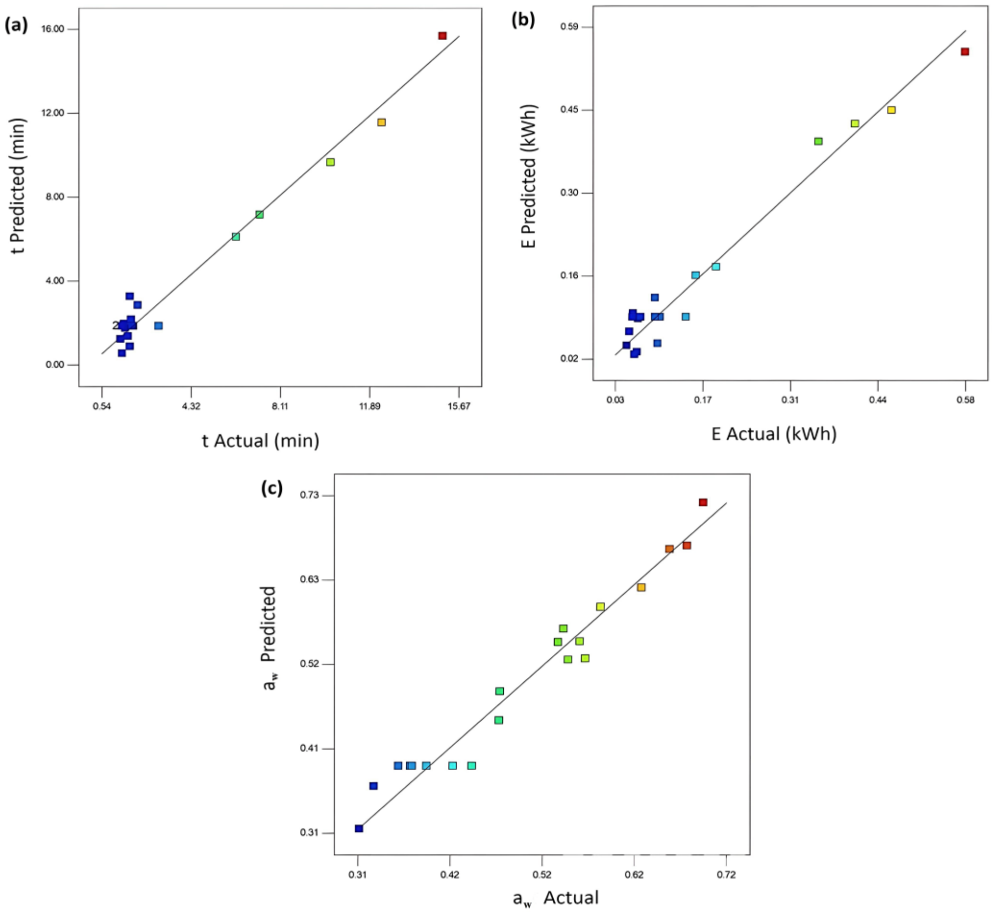

Fig 4. Predicted versus actual data plot for a) Drying time, b) Energy consumption, c) Water activity in the combined convective-microwave dryer.

3.2. Process analysis

3.2.1 Drying time

According to the results in Table 1, the drying time in the combined convective-microwave dryer was shorter than in both the microwave dryer and convective dryer, indicating that the use of microwave energy significantly reduced the drying time. Similar results were reported by Motevali et al. [38] in their study on mushroom slices as the raw material. Fig 5 (a and b) show that drying time decreased with increasing microwave power and temperature. These results align with other findings [46]. The high-frequency rotation of bipolar molecules in the bread samples, due to microwave radiation, generates friction and heat. This internal heat distribution helps moisture to move and escape from the bread. Therefore, the combination of convection and microwave drying enhances the moisture removal from the surface [47]. It can also be observed that the reduction in drying time is more pronounced at higher microwave powers. Increasing the microwave power from 90 W to 900 W reduces the drying time by 88%, as the mass transfer rate increases and a larger vapor pressure difference is created between the surface of the sample and its center. Zarein, Samadi, and Ghobadian (2015) highlighted this point in a case study on apple drying [48]. As shown in Table 1 and Fig 5(c), air velocity has no significant effect on drying time ($p > 0.05$).

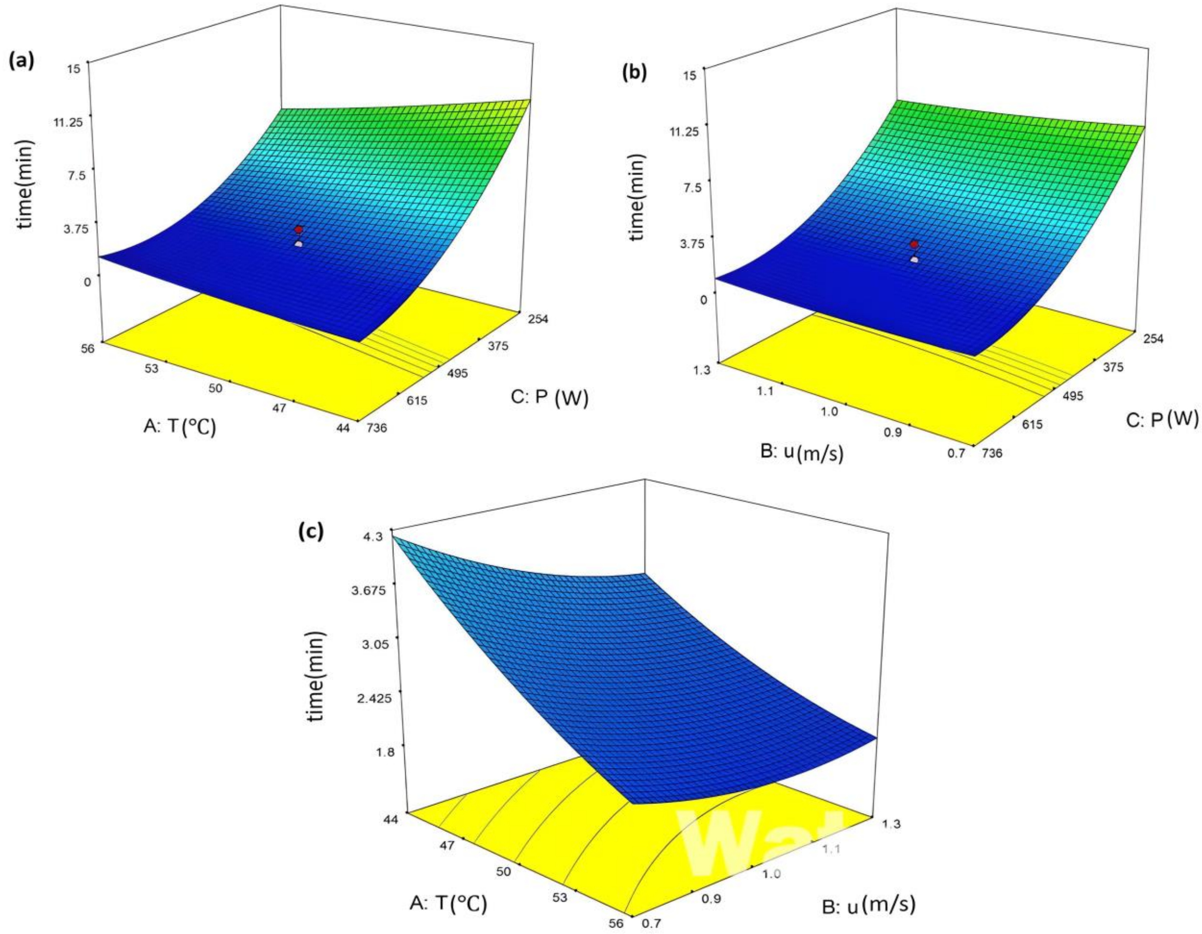

Fig 5. 3D response surface plot for drying time in combined dryer at a) Constant air velocity, b) Constant temperature and c) constant microwave power.

3.2.2 Energy consumption

Fig 6 shows the effect of temperature, air velocity, and microwave power on energy consumption in the combined dryer. It is clear that energy consumption depends on both temperature and microwave power. As temperature and microwave power increase, at a constant air velocity, the amount of energy consumed decreases. However, the effect of temperature was greater than that of microwave power. Additionally, similar to drying time, air velocity had no significant effect on energy consumption ($p > 0.05$). The interaction between temperature and power in Fig 6(c) indicates that simultaneously decreasing temperature and power increases energy consumption. When comparing the three drying methods with respect to energy consumption, it was found that microwave drying had the lowest energy consumption (0.019–0.116 kWh), followed by convective-microwave drying (0.046–0.584 kWh) and convective drying (0.588–1.255 kWh) (Table 1). Similar results were reported by Motevali et al. (2014) [14], who found that the combined convective-microwave dryer showed better drying and energy efficiencies compared to single-phase convective or microwave dryers.

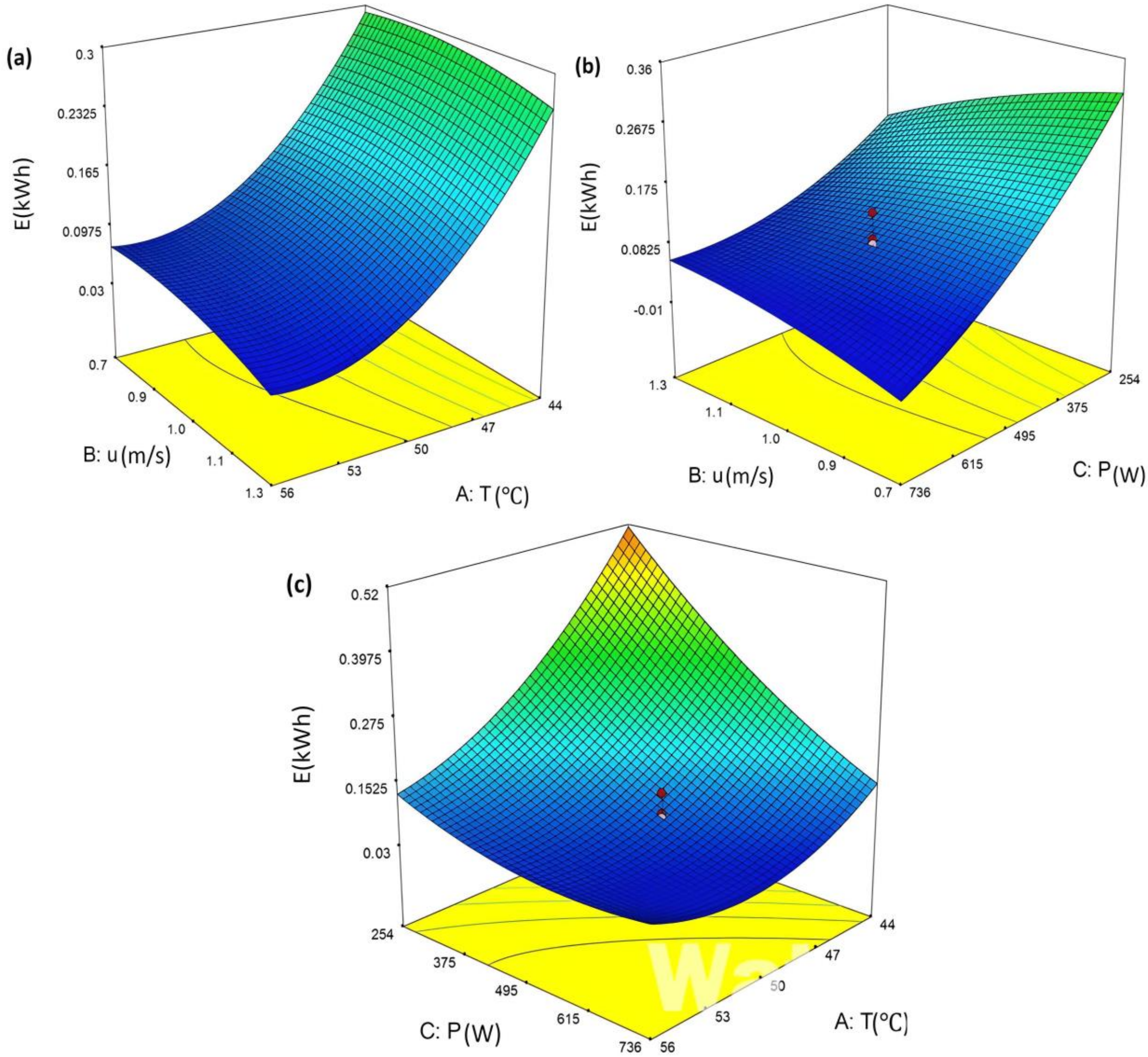

Fig 6. 3D response surface plot for energy consumption in combined dryer at a) Constant microwave power, b) Constant temperature and c) Constant air velocity.

3.2.3 Water activity

The effect of operating parameters on water activity in the convective-microwave dryer is shown in Fig 7. It is clear that with increasing temperature, water activity decreases. The results also showed that water activity declined with increasing air velocity up to 1 m/s, but, as observed, it started to increase afterward. Additionally, Table 1 and Fig 7(b) and 7(c) indicate that microwave power did not significantly influence water activity values. The interactions of temperature × air velocity and temperature × microwave power were effective on water activity. Specifically, with the simultaneous increase in temperature and decrease in air velocity, or with the simultaneous increase in temperature and microwave power, the water activity of the samples decreased. By assessing and comparing the results of the three drying methods, it can be observed that water activity values in all methods were within a similar range. Lafuente et al. [49] reported that lowering water activity in bread may reduce the risk of fungal contamination, mycotoxin levels, and undesirable microorganism growth, thereby increasing shelf life.

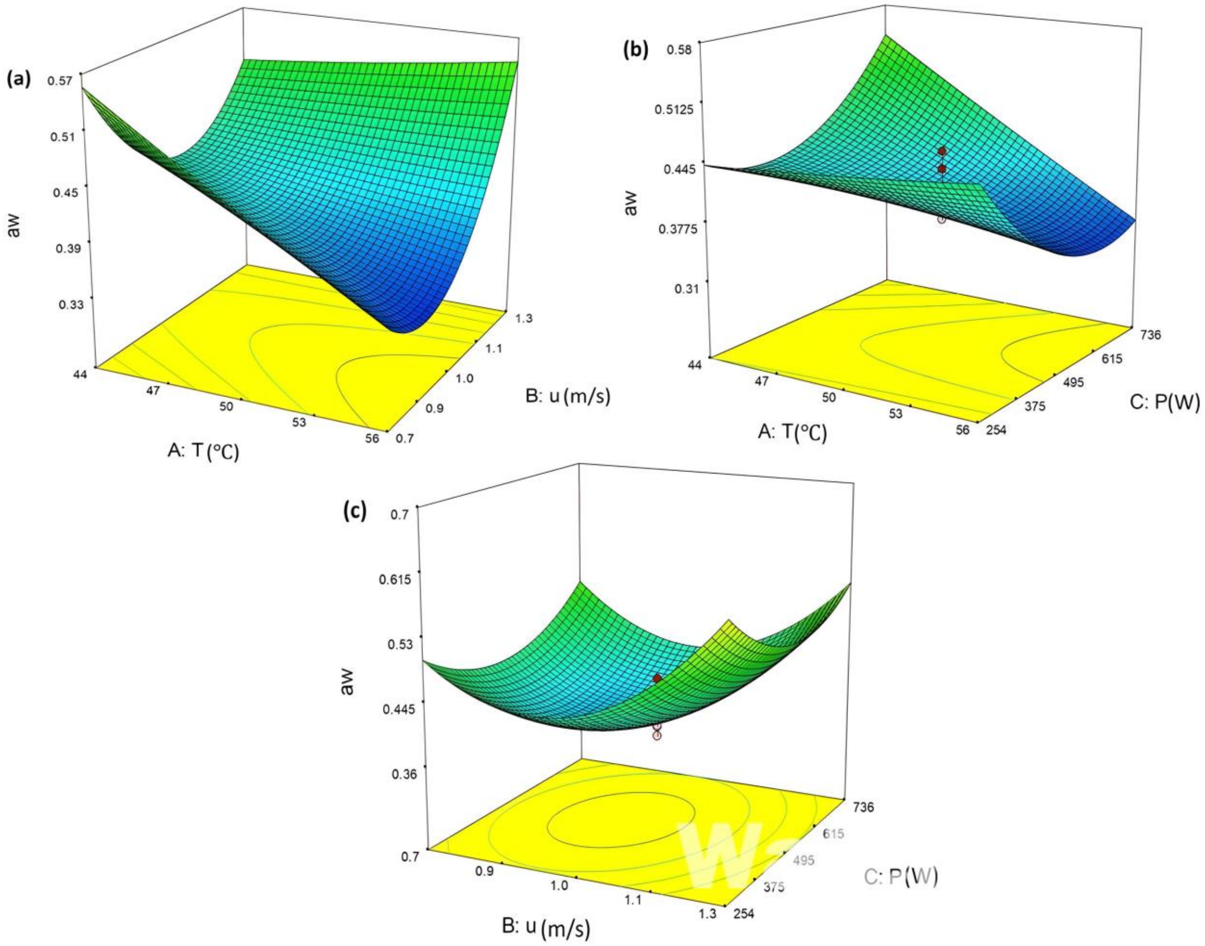

Fig 7. 3D response surface plot for water activity in combined dryer at a) Constant microwave power, b) Constant air velocity and c) Constant temperature.

3.3 Process Optimization

After investigating the effect of variables on drying time, energy consumption, and water activity of dried stale bread samples, the process was optimized to achieve the minimum drying time, energy consumption, and water activity. The optimization results showed that the optimal microwave power for drying was 616 W. The best temperature and air velocity for convective drying were 57°C and 1.1 m/s, respectively. The optimal drying conditions for the combined convective-microwave dryer were 580 W, 50°C, and 1.2 m/s. When compared to single convective drying at its optimal operating point (57°C and 1.1 m/s), the drying time in the combined convective-microwave dryer was significantly reduced from 100 minutes to 1.47 minutes. Energy consumption also decreased from 1.109 kWh to 0.083 kWh. Furthermore, comparing the optimization results of the convective-microwave dryer with the single microwave dryer, it was found that the drying time in the combined dryer was reduced from 1.92 minutes to 1.47 minutes compared to microwave drying. The water activity decreased from 0.399 for microwave drying to 0.201 for the combined dryer.

4. Conclusion

Stale sangak bread with an initial moisture content of 30% (w.b.) was dried to a final moisture content of 8% (w.b.). The effect of three drying methods (convective, microwave, and combined convective-microwave drying) on drying time, energy consumption, and water activity was investigated. The results showed that the drying time in the combined dryer was shorter than in the other two methods. Increasing the temperature and microwave power reduced drying time, while air velocity had no significant effect. The lowest energy consumption was associated with single microwave drying. The changes in water activity for all three drying methods were nearly the same. Optimal conditions for combined drying were found to be 580 W, 50°C, and 1.2 m/s. It can be concluded that combining microwave with convection improved the process performance. According to the statistical analysis, a full quadratic model was applied due to the high R^2 value and the simplicity of the relationship between the operating parameters and the responses. The obtained results showed that the experimental data were in good agreement with the predicted data.

Acknowledgments

This study was supported by the Babol Noshirvani University of Technology (BNUT), under grant number [BNUT/370675/99].

Conflict of interest

The authors declared no conflict of interest.

References

[1] Jairaj K, Singh S, Srikant K. (2009). A review of solar dryers developed for grape drying. *Sol Energy,* 83 (9), 1698-1712.

[2] Ruhanian S, Movagharnejad K. (2016). Mathematical modeling and experimental analysis of potato thin-layer drying in an infrared-convective dryer. *Eng Agric Environ Food,* 9 (1), 84-91.

[3] Doymaz I. (2017). Drying kinetics, rehydration and colour characteristics of convective hot-air drying of carrot slices. *Heat Mass Transf* , 53 (1),25-35.

[4] Midilli A, Kucuk H. (2003). Mathematical modeling of thin layer drying of pistachio by using solar energy. *Energy Convers Manag*, 44 (7), 1111-1122.

[5] Jain D, Pathare PB. (2004). Selection and evaluation of thin layer drying models for infrared radiative and convective drying of onion slices. *Biosyst Eng,* 89 (3), 289-296.

[6] Tasirin S, Kamarudin S, Jaafar K, Lee K. (2007). The drying kinetics of bird's chillies in a fluidized bed dryer. *J Food Eng*, 79 (2), 695-705.

[7] Di Scala K, Crapiste G. (2008). Drying kinetics and quality changes during drying of red pepper. *LWT* , 41 (8), 789-795.

[8] Tregunno N, Goff H. (1996). Osmodehydrofreezing of apples: structural and textural effects. *Food Res Int*, 29 (5-6), 471-479.

[9] Feng H, Tang J. (1998). Microwave finish drying of diced apples in a spouted bed. *J Food Sci* , 63 (4), 679-683.

[10] Krokida M, Karathanos V, Maroulis Z. (1998). Effect of freeze-drying conditions on shrinkage and porosity of dehydrated agricultural products. *J Food Eng* , 35 (4), 369-380.

[11] Maskan M. (2001). Drying, shrinkage and rehydration characteristics of kiwifruits during hot air and microwave drying. *J Food Eng* , 48 (2), 177-182.

[12] Seyfi A., Rezaei Asl A., Motevali A. (2021). Comparison of the energy and pollution parameters in solar refractance window (photovoltaic-thermal), conventional window, and hot air dryer. *Solar Energy*, 229, 162-173.

[13] Motevali A., Minaei S., Khoshtagaza H. (2011). Evaluation of energy consumption in different drying methods. *Eng. Con. & Man.*, 52, 1192-1199.

[14] Motevali A., Minaei S., Banakar A., Ghobadian B., Khoshtaghaza M. H. (2014). Comparison of energy parameters in various dryers. *Eng. Con. & Man.*, 87, 711-725.

[15] Kaveh M., Amiri Chayjan R., Taghinezhad E., Rasooli Sharabiani V., Motevali A. (2020). Evaluation of specific energy consumption and GHG emissions for different drying methods (Case study: Pistacia Atlantica). *J. Cleaner Prod.* 259, 120963.

[16] Prosapio V, Norton I. (2017). Influence of osmotic dehydration pre-treatment on oven drying and freeze drying performance. *LWT,* 80, 401-408.

[17] Harguindeguy M, Fissore D. (2020). On the effects of freeze-drying processes on the nutritional properties of foodstuff: A review. *Dry Technol* , 38 (7), 846-868.
[18] Nanvakenari S, Movagharnejad K, Latifi A. (2021). Evaluating the fluidized-bed drying of rice using response surface methodology and artificial neural network. *LWT*, *147*, 111589.
[19] Luthra K, Sadaka S. (2020). Investigation of rough rice drying in fixed and fluidized bed dryers utilizing dehumidified air as a drying agent. *Dry Technol*, 39,8,1-15.
[20] Taşeri L, Aktaş M, Şevik S, Gülcü M, Seckin GU, Aktekeli B. (2018). Determination of drying kinetics and quality parameters of grape pomace dried with a heat pump dryer. *Food Chem*, 260, 152-159.
[21] Aktaş M, Taşeri L, Şevik S, Gülcü M, Uysal Seçkin G, Dolgun EC. (2019). Heat pump drying of grape pomace: Performance and product quality analysis. *Dry Technol*, 37 (14), 1766-1779.
[22] Doymaz I, Kipcak AS, Piskin S. (2015). Characteristics of thin-layer infrared drying of green bean. *Czech J Food Sci* ,33 (1), 83-90.
[23] Jafari F, Movagharnejad K, Sadeghi E. (2020). Infrared drying effects on the quality of eggplant slices and process optimization using response surface methodology. *Food Chem*.127423.
[24] Orikasa T, Koide S, Okamoto S, Imaizumi T, Muramatsu Y, Takeda J, Shiina T, Tagawa A. (2014). Impacts of hot air and vacuum drying on the quality attributes of kiwifruit slices. *J Food Eng*, 125, 51-58.
[25] Šumić Z, Vakula A, Tepić A, Čakarević J, Vitas J, Pavlić B. (2016). Modeling and optimization of red currants vacuum drying process by response surface methodology (RSM). *Food Chem*, 203, 465-475.
[26] Li H, Shi S, Lin B, Lu J, Lu Y, Ye Q, Wang Z, Hong Y, Zhu X. (2019). A fully coupled electromagnetic, heat transfer and multiphase porous media model for microwave heating of coal. *Fuel Process Technol,* 189, 49-61.
[27] Prabhanjan D, Ramaswamy H, Raghavan GV. 1995). Microwave-assisted convective air drying of thin layer carrots. *J Food Eng*, 25 (2), 283-293.
[28] Ozkan IA, Akbudak B, Akbudak N. (2007). Microwave drying characteristics of spinach. *J Food Eng* , 78 (2), 577-583.
[29] Cao X, Zhang M, Fang Z, Mujumdar AS, Jiang H, Qian H, Ai H. (2017). Drying kinetics and product quality of green soybean under different microwave drying methods. *Dry Technol*, 35 (2), 240-248.
[30] Mujumdar AS. Handbook of industrial drying, CRC press. 2014.
[31] Jia Y, Khalifa I, Hu L, Zhu W, Li J, Li K, Li C. (2019). Influence of three different drying techniques on persimmon chips' characteristics: A comparison study among hot-air, combined hot-air-microwave, and vacuum-freeze drying techniques. *Food Bioprod Process*, 118, 67-76.
[32] Giri S, Prasad S. (2007). Drying kinetics and rehydration characteristics of microwave-vacuum and convective hot-air dried mushrooms. *J Food Eng*, 78 (2), 512-521.
[33] Jiang H, Zhang M, Mujumdar AS. (2010). Microwave freeze-drying characteristics of banana crisps. *Dry Technol* , 28 (12), 1377-1384.
[34] Saniso E, Prachayawarakorn S, Swasdisevi T, Soponronnarit S. (2020). Parboiled rice production without steaming by microwave-assisted hot air fluidized bed drying. *Food and Bioproducts Processing*, *120*, 8-20.
[35] Feng YF, Zhang M, Jiang H, Sun JC. (2012). Microwave-assisted spouted bed drying of lettuce cubes. *Dry Technol* , 30 (13), 1482-1490.
[36] Heydari MM, Kauldhar BS, Meda V. (2020). Kinetics of a thin-layer microwave-assisted infrared drying of lentil seeds. *Legume Science*, *2*(2), e31.
[37] Kouchakzadeh A, Shafeei S. (2010). Modeling of microwave-convective drying of pistachios. *Energy Convers Manag*, 51 (10), 2012-2015.
[38] Motevali A., Minaei S., Koshtaghaza MH., Amirnejat H. (2011). comparison of energy consumption and specific energy requirements of different methods for drying of mushroom slices. *Energy*, 36, 6433-6441.
[39] Yuksel F, Kayacier A. (2016). Utilization of stale bread in fried wheat chips: Response surface methodology study for the characterization of textural, morphologic, sensory, some physicochemical and chemical properties of wheat chips. *LWT* , 67, 89-98.
[40] Demirtaş B, Kaya A, Dağıstan E. (2018). Consumers' bread consumption habits and waste status: Hatay/Turkey Example. *Turkish J Agric Food Sci Technol*, 6 (11),1653-1661.
[41] Hinkelmann K. Design and analysis of experiments, volume 3: special designs and applications, John Wiley & Sons; 2012.
[42] Golpour I, Kaveh M, Amiri Chayjan R, Guiné RP. (2020). Optimization of infrared-convective drying of white mulberry fruit using response surface methodology and

development of a predictive model through artificial neural network. *Int J Fruit Sci, 20*(sup2), S1015-S1035.

[43] Bhat MI, Shahi NC, Singh A, Malik S. (2020). Response surface optimization of quality parameters of turmeric slices in an innovative infrared assisted hybrid solar dryer. *IJCS* , *8*(3), 1958-1967.

[44] Darvishi H, Farhudi Z, Behroozi-Khazaei N. (2020). Multi-objective optimization of savory leaves drying in continuous infrared-hot air dryer by response surface methodology and desirability function. *Comput Electron Agric, 168*, 105112.

[45] Garcia-Diaz A, Phillips DT. (2006). Principles of experimental design and analysis, Chapman & Hall; 1995.

[46] Alibas I. Characteristics of chard leaves during microwave, convective, and combined microwave-convective drying. *Dry Technol* , 24 (11), 1425-1435.

[47] Sadeghi M, Mirzabeigi Kesbi O, Mireei SA. (2013). Mass transfer characteristics during convective, microwave and combined microwave–convective drying of lemon slices. *J Sci.Food Agric*, 93 (3), 471-478.

[48] Zarein M, Samadi SH, Ghobadian B. (2015). Investigation of microwave dryer effect on energy efficiency during drying of apple slices. *J Saudi Soc Agric Sci* , 14 (1), 41-47.

[49] Lafuente C., de Melo Nazareth T., Dopazo V., Meca G., Luz C. (2024). Enhancing bread quality and extending shelf life using dried sourdough. *LWT,* 203, 116379.

DOI: https://doi.org/10.22104/ift.2024.7082.2181
فصلنامه فناوری‌های جدید در صنعت غذا، دوره ۱۲، شماره ۱، صفحه ۳۳- ۱۷، پائیز ۱۴۰۳

مقاله پژوهشی

مدلسازی و بهینه سازی خشک کردن نان بیات با سه خشک کن مختلف

سمانه حیرانی[1]، کامیار موقرنژاد[1]*، سارا نانواکناری[1]
۱. دانشکده مهندسی شیمی، دانشگاه صنعتی نوشیروانی بابل، بابل، مازندران، ایران
(تاریخ ارسال: ۱۴۰۳/۰۶/۱۳، تاریخ بازنگری: ۱۴۰۳/۰۹/۱۹، تاریخ پذیرش: ۱۴۰۳/۰۹/۲۰)

چکیده

هدف از انجام تحقیق حاضر بررسی فرآیند خشک کردن نان تا رطوبت نسبی ۸٪ با استفاده از سه خشک‌کن مختلف همرفتی، میکروویو و ترکیبی همرفت- میکروویو می‌باشد. آزمایش‌ها با استفاده از روش سطح پاسخ و طراحی مرکب مرکزی آنالیز و طراحی شدند. پارامترهای عملیاتی شامل دمای هوا (°C ۶۰-۴۰) و سرعت هوا (m/s ۱/۵-۰/۵) برای خشک‌کن‌های همرفت و ترکیبی میکروویو-همرفتی و توان میکروویو (۹۰۰W – ۹۰) برای خشک‌کن‌های میکروویو و ترکیبی میکروویو - همرفتی مورد ارزیابی قرار گرفتند. زمان خشک کردن، انرژی مصرفی و فعالیت آبی به عنوان پاسخ‌های فرآیند خشک کردن در نظر گرفته شدند. مقایسه نتایج این سه روش خشک کردن نشان داد که کمترین زمان خشک کردن در خشک‌کن ترکیبی همرفت- میکروویو روی داد. کمترین انرژی مصرفی متعلق به خشک کن میکروویو (Wh ۰/۱۱۶-۰/۰۱۹) و سپس خشک کن میکروویو- همرفتی (kWh ۰/۵۸۴-۰/۰۴۶) و خشک کن همرفتی (kWh ۱/۲۵۵ -۰/۵۸۸) بود. محدوده فعالیت آبی برای هر سه نوع خشک کن در حد مطلوب به‌دست آمد؛ سپس فرآیند برای به‌دست آوردن نقاط کمینه زمان خشک کردن، مصرف انرژی و فعالیت آبی بهینه سازی شد. نقطه بهینه برای خشک کن میکروویو توان W ۶۱۶، برای خشک‌کن همرفتی دمای °C ۵۷ و سرعت هوای m/s ۱/۱ و برای خشک کن میکروویو- همرفتی توان W ۵۸۰، دمای °C ۵۰ و سرعت هوای m/s ۱/۲ به‌دست آمد. خشک کن ترکیبی میکروویو- همرفتی بهترین عملکرد را در شرایط بهینه با زمان خشک کردن min ۱/۴۷، انرژی مصرفی kWh ۰/۰۸۳ و فعالیت آبی m/s ۰/۲۰۱ به‌دست آمد.

واژه‌های کلیدی: خشک کن ترکیبی میکروویو- همرفتی، نان بیات، خشک کن میکروویو، خشک کن همرفتی، روش سطح پاسخ.

---

*نویسنده مسئول: k-movaghar@nit.ac.ir