Optimization and modeling of the stale bread drying with three different dryers

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Research Article

Optimization and modeling of the stale bread drying with three different dryers

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Abstract

The present work is aimed to study the drying process of stale bread to a moisture level 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 central composite design. Different operating parameters were investigated including air temperature (40–60 °C) and velocity (0.5–1.5 m/s) for single convective and combined convective-microwave dryers and microwave power (90-900 W) for single microwave and combined convective-microwave dryers. The drying time, energy consumption, and water activity of the stale bread were selected as the responses of the drying process. Comparing the results of these three drying methods, it was indicated that the shortest drying time was occurred in the combined microwave-convective dryer. The lowest energy consumption was related to the single microwave dryer (0.019-0.116 kWh), followed by the combined convective-microwave dryer (0.046-0.584 kWh) and single convective dryer (0.588-1.255 kWh). Range of the water activity was obtained desirable for all of the three dryers. The process was then optimized to achieve the minimum drying time, energy consumption, and water activity. The optimal conditions were found to be 616 W for single microwave dryer, 57 ℃ and 1.1 m/s for single convective dryer and 580 W, 50 ℃, and 1.2 m/s for combined convective-microwave dryer. The combined convective-microwave dryer also showed the best performance in the optimal conditions consisted of 1.47 min drying time, 0.083 kWh energy consumption and 0.201 water activity.

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

1. Introduction

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Food is a basic need for all living creatures. One of the main problems in the food industry is the inability to preserve the fresh food products [1]. Drying is one of the oldest methods of food preservation. Reduction of water activity by drying to inhibit the growth of microorganisms and destructive enzymatic reactions lengthens the shelf life of the products. Drying reduces the mass and volume of the product in order to facilitate and save on transportation, storage, and packaging costs [2, 3].

There are many studies on the drying process, including a wide range of foodstuff, crops and biological products [4-6]. It is possible that some vitamins and nutrients could be lost during the drying process [7]. To maintain the nutrition and sensorial quality of the dried sample, it is very important to select the appropriate drying method and optimize the drying conditions. It takes a prolonged drying time and a rather high temperature to reduce the moisture content of products to the extent that can be stored for a long time, especially those with sugary compounds (such as fruits), therefore may lead to considerable degradation in quality properties such as flavor, color, reduced rehydration capacity, intense shrinkage, and reduction of nutrients [8-11]. Comparison of different dryers and drying methods is another research trend practiced by many researchers in recent years. Seyfi et al. compared the energy and pollution parameters of solar refractance window, conventional refractance window and hot air dryers in the drying process of *Aloe vera* gel [12]. Motevali et al. compared the energy consumption in different dryers including, hot air, microwave, vacuum and infrared dryers. Their raw material was pomegranate arils and their study showed that the amount of energy consumption was maximum in vacuum drying and minimum in microwave drying [13]. In another paper, Motevali et al [14] compared the energy parameters of *Roman chamomile* in different dryers. Their study showed that the energy parameters vary considerably in different drying methods. Kaveh et al. [15] evaluated the specific energy consumption and GHG emissions in different dryers for the case study of Pistacia Atlantica.

In recent years, new drying methods have replaced the old and traditional methods, some of which include freeze drying [16, 17], fluidized bed drying [18, 19], heat pump drying [20, 21], infrared drying [22, 23], and vacuum drying [24, 25]. In order to prevent the loss of the food quality (due to the prolonged drying time) microwave drying is one of the methods that has received a lot of attention in the last decade. Microwaves belong to long-wavelength electromagnetic radiation (frequency 2450 MHz) [26]. Due to polar nature of water molecules, they are attracted to the microwave field, that make rotation and friction between the water molecules. As a result, their temperature rises and evaporation occurs more rapidly. In this method, the heat is generated in the food texture and prevents damage and burning of the surface parts of the food while in the other drying methods, heat penetrates from the surface to the center parts [27-29].

The energy crisis and the need for better quality products have encouraged the researchers to find novel methods for drying. New drying equipment must be designed in accordance with environmental and energy policies [30]. Combination of dryers are one of these novel methods. Since each drying method has its own intrinsic advantages and drawbacks, the combination of these methods can improve the quality of the dried products. High efficiency and higher drying rates are the main advantages of the microwave drying, but high operating costs is the main problem of this kind of dryers [31]. So 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 dryer [35], and microwave-infrared drying [36]. Microwave-convective drying combines the advantage of saving the drying time and energy consumption by microwave dryer with the advantage of removing the surface moisture by convective dryer. Condensation of moisture on the surface of the food is the most important drawback of the microwave drying method, which is eliminated by combining with the convection dryer [37].

Another study compared energy consumption of different single function 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 it was concluded that the combined dryers had showed certain advantages such as lower energy consumption and shorter drying time [38].

Because of the subsidies given to flour and traditional breads, Iran suffers from one of the highest amounts of bread waste in the world. Drying the stale bread which is not suitable for people and using it as an animal feed may lower this really high rate of bread waste in the country. Staling occurs when bread begins to lose moisture after starch changes. As the texture, firmness, and some aromatic characteristics of the bread are lost, people are reluctant to consume stale bread [39]. The concept of bread waste may be different in various societies but generally, it means the bread that is not consumed as human food or as surplus bread that has expired and is discarded. Currently, one of the most important utilizations of the bread waste is its application as the animal feed [40].

So it was decided to study the drying process of the waste of a traditional Iranian bread called *Sangak*. Different drying aspects of the sangak stale bread were studied using three different dryers: single convective, single microwave and combined convective-microwave dryer. The aim of this research was to study and compare the performance of these dryers in different drying conditions using response surface methodology (RSM). Another aim of this study was to find the optimal conditions of each dryer in order to minimize drying time and energy consumption and maximize the quality of the dried products. As the traditional Iranian breads like sangak are not baked widely in other countries, there is no published work on this subject. So, the raw material is completely novel and also the use of the dual combined convective-microwave dryer and its comparison with other two single dryers may also be considered as another novelty of this work. As the rate of energy consumption in Iran is very high, the results of this research which tries to find the optimal conditions for minimum energy consumption may be of high value for the country's economy.

2.1. Samples preparation

Bread samples were purchased from the city of Babol, Mazandaran, Iran. The storage conditions of the purchased samples to become stale were almost the same. The samples were stored between 50 to 60 hours inside the freezer bags to become completely stale. Then, 30 g of the 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 based on the 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 equal and in the range of 25% to 30% (w.b.). The samples underwent the drying procedure until reaching a moisture content of 8% (w.b.).

2.2. Drying procedure

Drying of the samples was performed using three drying methods of combined microwave-convective, single microwave, and single convective, separately. For this purpose, a household microwave oven (Butan, M245, Iran) with a maximum power of 900 W equipped with a rotating tray and digital power and time adjustments was used. Figure 1 presents the schematic of the dryer used during the experiments. The convective dryer section is visible on the left side of the schematic. In this section, the ambient air flow is passed through a heater with various elements by a suction fan. Depending on the desired temperature and air flow intensity, the number of the turned-on elements is adjusted and the blower (fan) velocity is changed manually. The air flow enters the chamber containing the samples with the desired temperature and air velocity and flows towards the outlet duct after absorbing moisture. The sample chamber is the same chamber as the microwave oven. The air inlet is connected to the microwave body by transfer pipes with a diameter of 15 cm. Using a laser cutter, holes were made in the side body of the microwave oven in order to connect the air inlet and outlet pipes. The air inlet pipe contains a metal mesh to unify the air flow. The outlet air flow has a temperature higher than the ambient temperature and its humidity is also higher due to the absorption of moisture from the bread samples. To utilize the heat of the outlet air flow, a shell and tube converter is used at the beginning of the inlet air flow. As shown in Figure 1, the outlet air flow passes through the converter and helps heating the converter pipes and thus the inlet air flow. This prevents the heat of the outlet air from the sample chamber to be wasted and helps in the energy saving. Humidity and temperature sensors were installed inside the inlet and outlet pipes. These sensors are made of plastic and tolerate the temperature up to 70°C. Applying higher temperatures, provides a possibility of damage and errors in this equipment. The apparatus has an electrical panel and display monitor to present the humidity and temperature of the inlet and outlet air. The whole apparatus is mounted on a stainless-steel chassis. It is clear that both microwave and convective dryers are used simultaneously during the combined experiments, while in the single microwave experiments, only the microwave dryer is used and similarly, the microwave oven is turned off during the convective experiments and only its chamber is used as a convective dryer chamber.

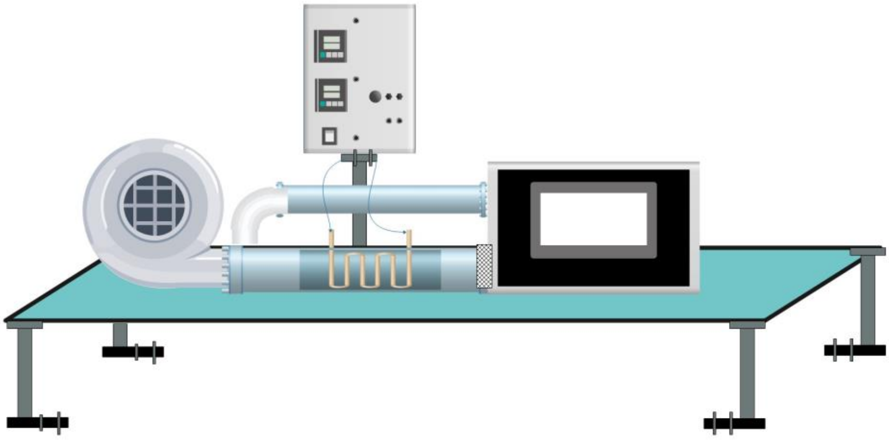

Figure 1. Schematic of the microwave-convective dryer.

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 quantity, a water activity meter (NOVASINA, lab swift, Switzerland) was used. The dried samples were slightly shredded inside a mortar and then poured into the special container of the water activity meter, such that the bottom of the container was covered completely with the dried sample. The container was put inside the apparatus until the number shown on the screen became fixed. This number presents the water activity of the dried sample.

2.4. *Determination of the drying time and energy consumption*

The drying time (t) was determined as the time required to reduce the initial moisture content of the bread from 30% to 8% (w.b.) in different drying conditions. The amount of energy consumption during a process, is a fundamental part of assessing that process. Energy consumption was generally defined as the amount of energy consumed to evaporate a unit mass of water through the drying process. In this work, the amount of energy consumption in different drying conditions was measured using an electrical energy meter (Efergy, EMS-20, UK).

2.6. Experimental Design

RSM is a collection of statistical and mathematical techniques that have been successfully used to develop, improve and optimize the processes in which an optimal response is affected by various variables and the goal is to optimize this response [41]. The RSM defines the effect of independent variables alone or in combination on the processes. There are some examples of RSM applications for food process optimization [42-44]. So, the RSM was used in this study to consider the influence of different parameters. There are different variables in each process and each of these variables provides a special effect on the response or responses of the process. Investigating all of these effects requires performing a great number of experiments which leads to waste of time and high cost. Furthermore, the mathematical modeling and optimizing of the process is also possible during the experimental design [45]. The independent variables in the microwave-convective dryer are the microwave power (90-900 W), inlet air temperature (40-60℃), and the inlet air velocity (0.5-1.5 m/s). In the single microwave dryer, the only independent variable is the microwave power, and inlet air temperature and velocity are considered the two independent variables in the convective dryer. There are three independent variables for the combined convective-microwave dryer: microwave power, inlet air velocity and inlet air temperature. Due to the presence of only one variable in the microwave dryer, the one-factor design was employed, and in the combined microwave-convective and single convective dryers, the central composite design (CCD) was employed. To investigate the effects of microwave power, inlet air temperature, and inlet air velocity on the drying time, the energy consumption, and the 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 shows the designed experiments, as well as the obtained experimental results for the responses.

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

The analysis of the experimental data was performed using a full quadratic model (Eq.1) [23] that is generally capable of defining the relationships between the responses and independent variables.

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

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. Also, 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 and a quadratic model, which is a function of the microwave power (P), was considered for them. Moreover, other quadratic models that were a function of the inlet air temperature (T) and the inlet air velocity (U) were assumed for the responses of the convective dryer. The quadratic models for the combined microwave-convective dryer were considered to be the functions of the inlet air temperature (T), inlet air velocity (U), and microwave power (P). All of these quadratic models are presented in the Table 2.

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

The results shown in the Table 2 indicate that since the p-value of all models is less than 0.05, they are all acceptable. Lack of fit (LOF), describes the data diversity around the model as appropriate. P-values greater than 0.05 for the LOF, indicate a significant model correlation between the variables and process responses. The higher correlation coefficient (R^2) and closer to 1, the model will be more desirable and indicating the good agreement between the experimental and predicted. As can be seen from the Table 2, R^2 has an acceptable value for all of the models that are presented in figures. 2, 3, and 4 for different dryers. These figures show that there is a good agreement between the experimental data and the predicted results by the experimental design.

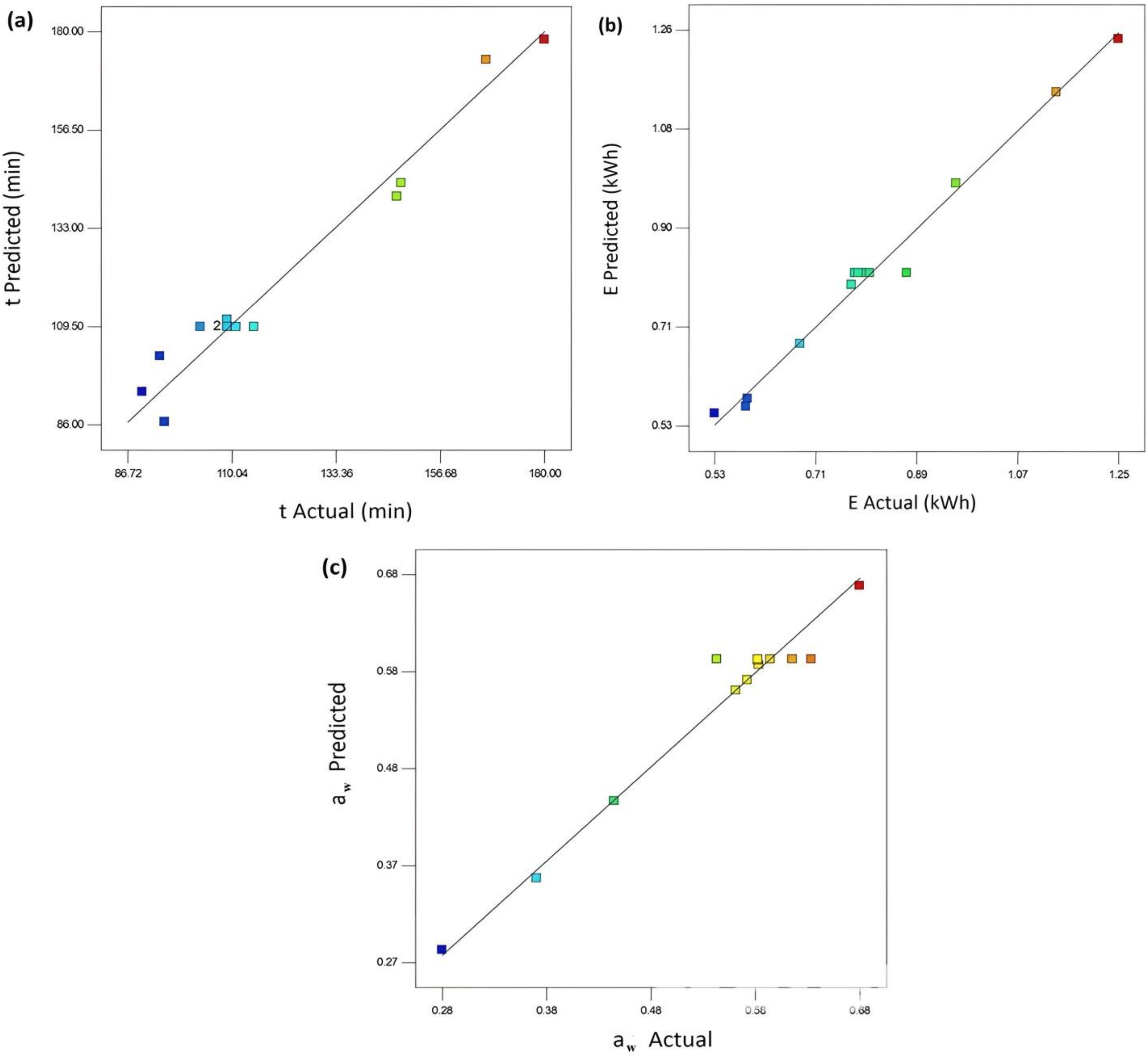

Figure 2. Predicted versus actual data plot for a) Drying time, b) Energy consumption, c) Water activity in the convective dryer.

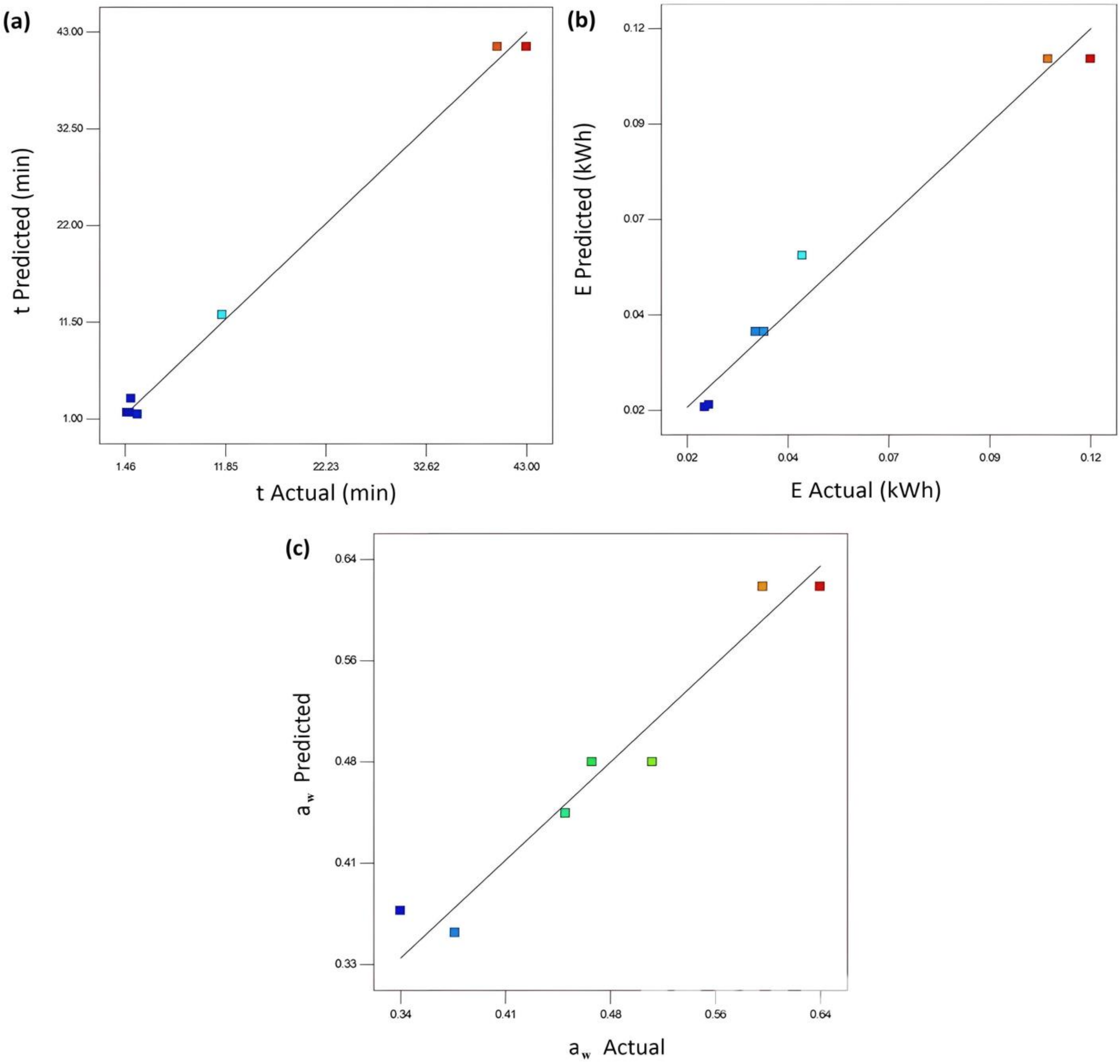

Figure 3. Predicted versus actual data plot for a) Drying time, b) Energy consumption, c) Water activity in the microwave dryer.

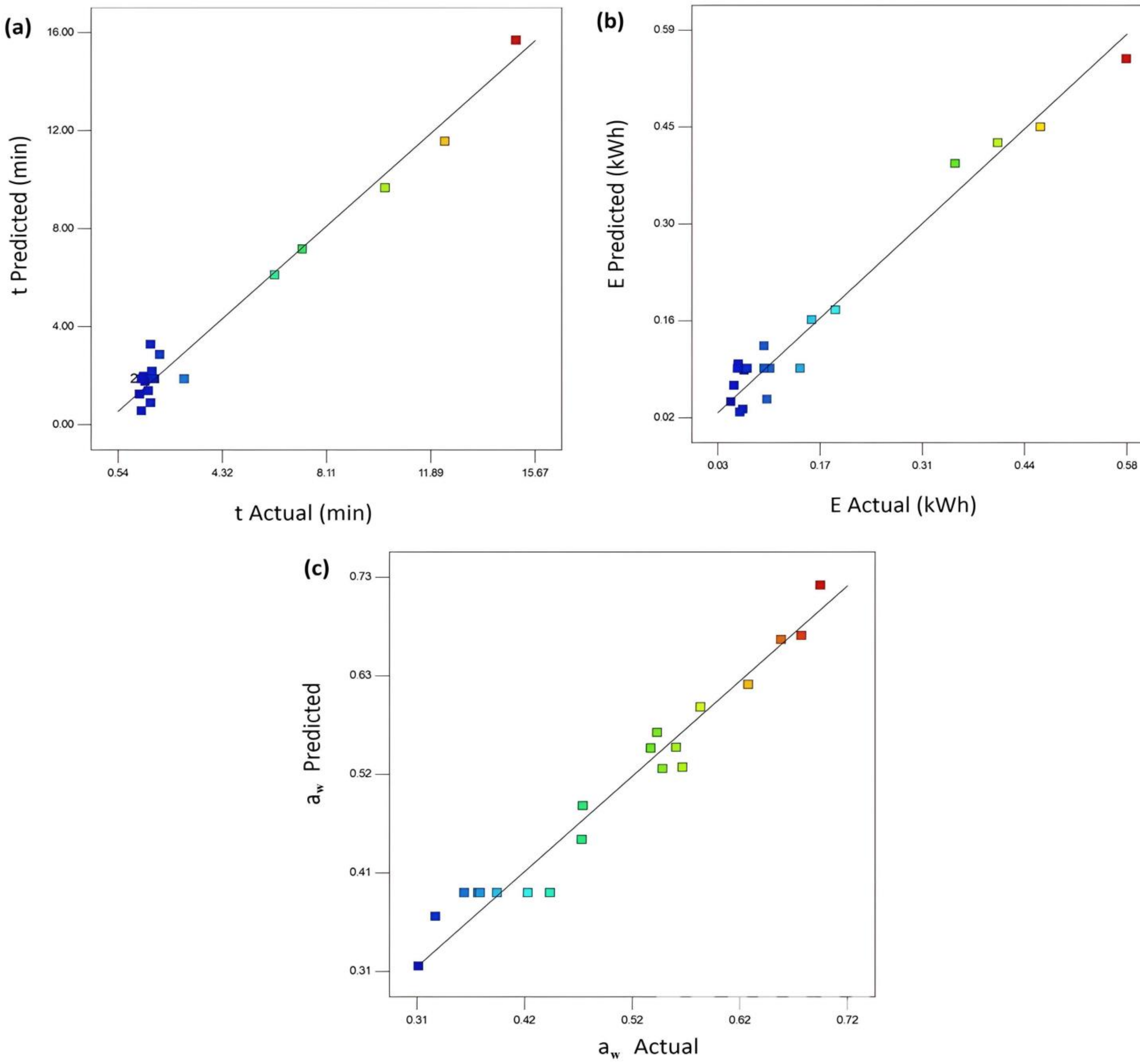

Figure 4. Predicted versus actual data plot for a) Drying time, b) Energy consumption, c) Water activity in the combined convective-microwave dryer.

3.2. Process analysis

3.2.1 Drying time

According to the results of Table (1), the drying time in the combined convective-microwave dryer was less than the microwave dryer and convective dryer, which means that the use of the microwave significantly reduced the drying time. Similar results were also reported by Motevali et al. [38] working on the mushroom slices as the raw material. Figure 5 (a and b) show that the drying time decreased with increasing microwave power and temperature. These results were consistent with other findings [46]. Bipolar molecules rotate with high frequency into the bread samples because of microwave radiation. This polar rotation makes friction and generates heat. The heat generated inside the bread causes moisture to distribute and escape out. Therefore, the combination of convection and microwave increases the amount of moisture leaving the surface [47]. It can also be seen that the amount of reduction in drying time is greater at higher microwave powers. Increasing the microwave power from 90 W to 900 W reduces the drying time by 88% because the mass transfer rate is increased and a large vapor pressure difference is created between the surface of the sample and its center. Zarein, Samadi, and Ghobadian (2015) mentioned this point in an apple drying case study [48]. As observed in Table 1 and Figure 5(c), the air velocity has no significant effect on the drying time (p> 0.05).

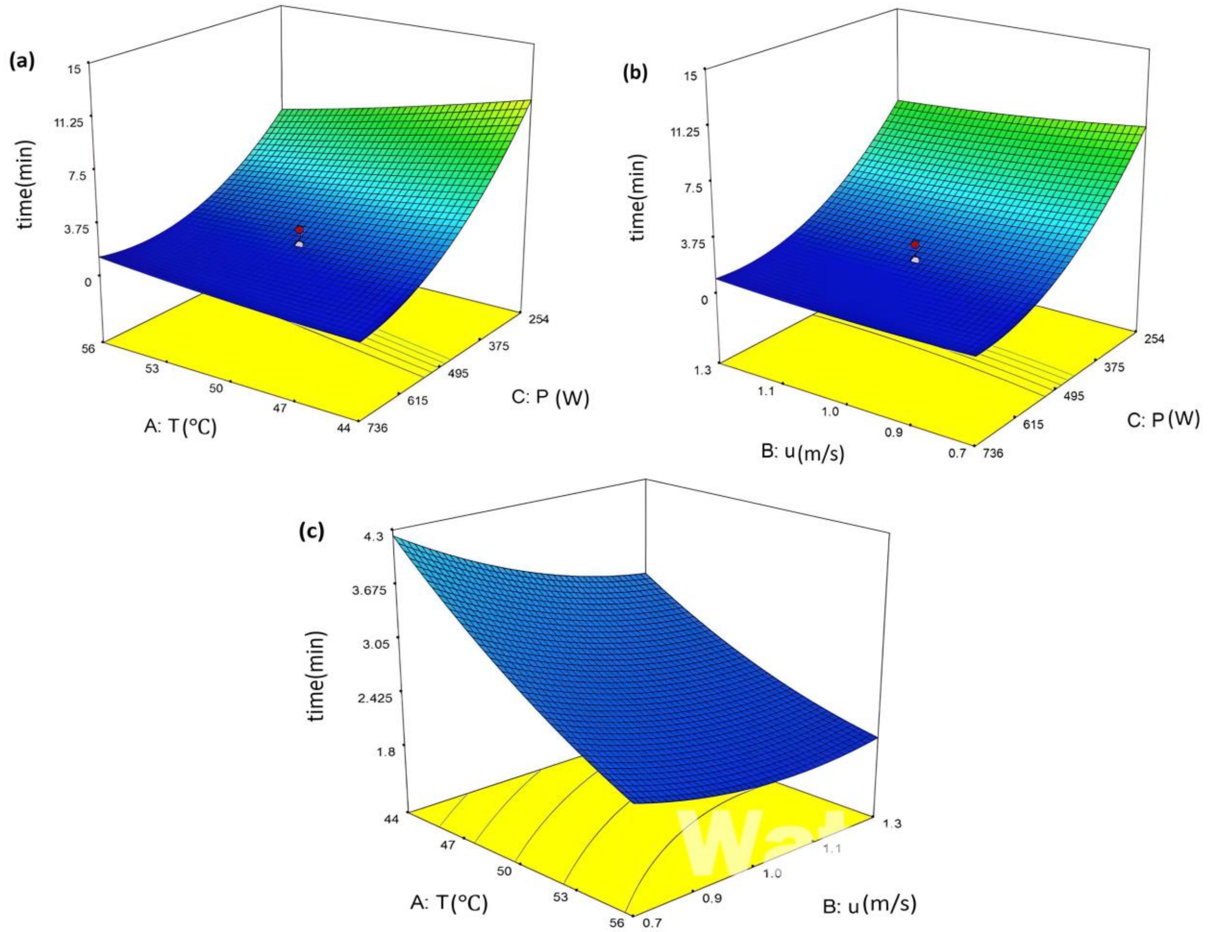

Figure 5. 3D response surface plot for drying time in combined dryer at a) Constant air velocity, b) Constant temperature and c) constant microwave power.

3.2.2 Energy consumption

Figure 6 shows the effect of temperature, air velocity and microwave power on the energy consumption in the combined dryer. It is clear that the consumed energy depends on the temperature and microwave power. As the temperature and microwave power increase at a constant air velocity, the amount of consumed energy decreases. However, the effect of temperature was greater than the microwave power. Also, like drying time, air velocity had no significant effect on the energy consumption (P> 0.05). The interaction of temperature and power in Figure 6(c) indicates that decreasing temperature and power simultaneously increases the energy consumption value. Examining the three drying methods and comparing them with respect to energy consumption, it is determined that the lowest energy consumption has occurred in microwave drying (0.019-0.116 kWh), followed by the convective-microwave drying (0.046-0.584 kWh) and convective drying (0.588-1.255 kWh) (Table 1). Similar results were also reported by Motevali et al. (2014) [14]. According to their findings, the combined convective-microwave dryer showed pretty better drying and energy efficiencies in comparison with single phase convective or microwave dryers.

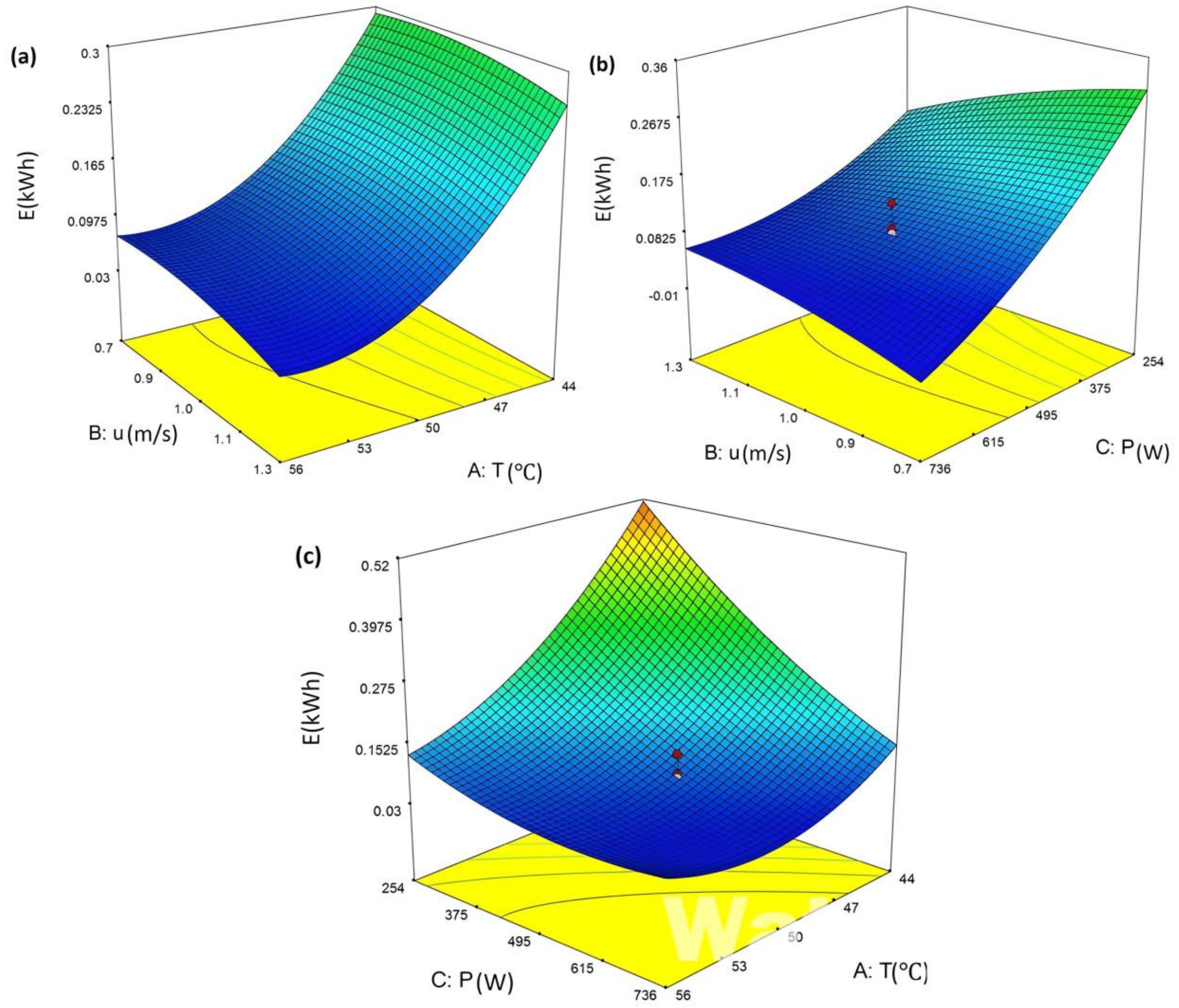

Figure 6. 3D response surface plot for energy consumption in combined dryer at a) Constant microwave power, b) Constant temperature and c) Constant air velocity.

3.2.3 Water activity

The effect of operating parameters on water activity in the convective-microwave dryer is shown in figure 7. It is completely obvious that with increasing temperature, the amount of water activity has decreased. The results showed that water activity declined with raising air velocity up to 1 m/s but as observed, can have expected increased afterward. As well as, table 1 and figure 7(b and c) indicated the microwave power did not significantly influence water activity values. The interaction of temperature×air velocity and temperature×microwave power was effective in water activity. In such a way that with increasing temperature and decreasing air velocity simultaneously or with increasing power and temperature simultaneously, the water activity of the samples reduced. By assessing and comparing the results of the three drying methods, it can be found that the amount of water activity in all methods was almost in the same range. Lafuente et al. [49] reported that lowering the water activity in bread may reduce the danger of fungal contamination, mycotoxin levels and undesirable microorganism growth and increase the shelf time.

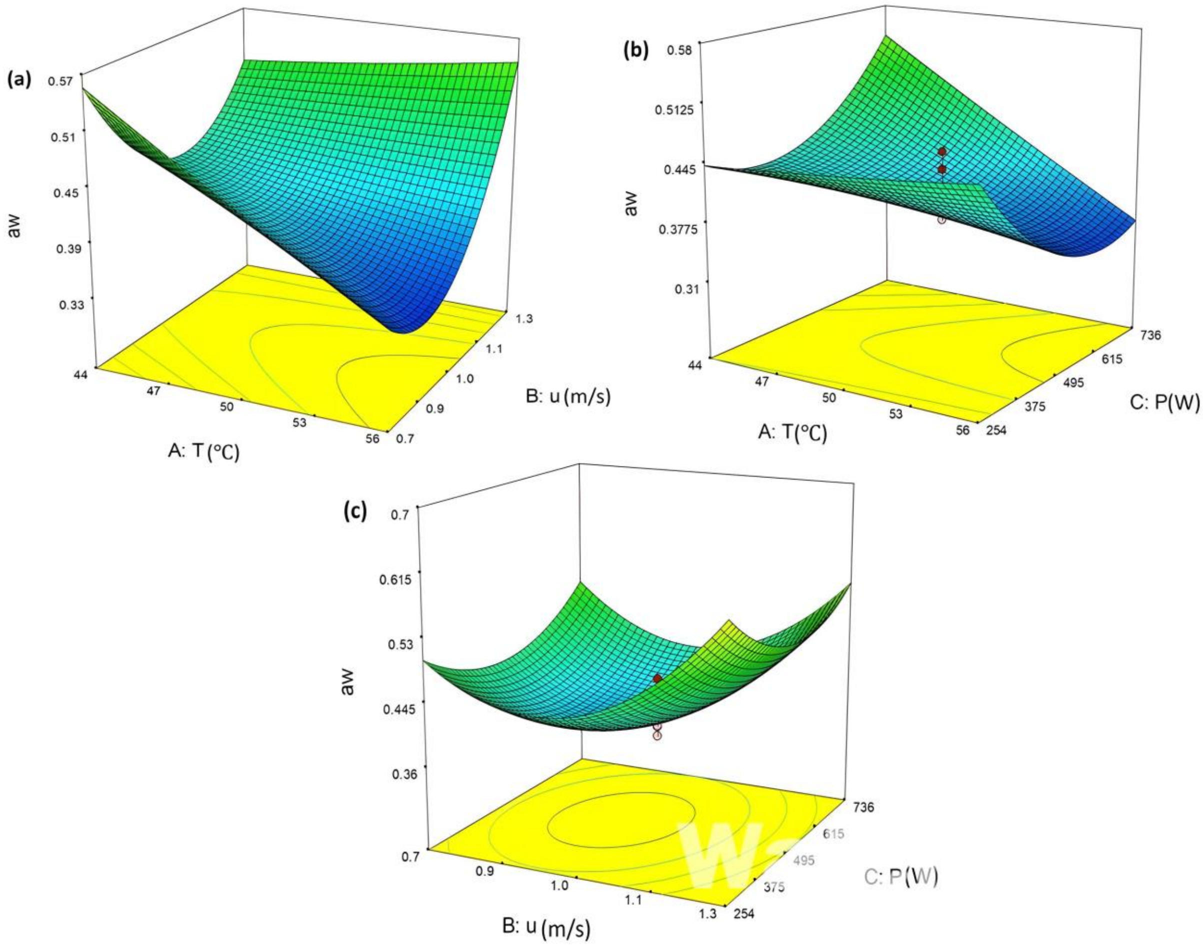

Figure 7. 3D response surface plot for water activity in combined dryer at a) Constant microwave power, b) Constant air velocity and c) Constant temperature.

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 best power for the microwave drying was 616 W. The best temperature and air velocity in convective drying were 57 ℃ and 1.1 m/s, respectively. The optimal drying conditions for combined convective-microwave dryer were 580 W, 50 ℃, and 1.2 m/s. The drying time in the convective-microwave dryer compared to the single convective in its optimal operating point (57 ℃ and 1.1 m/s) has been significantly reduced from 100 min to 1.47 min. Energy consumption also decreased from 1.109 kWh to 0.083 kWh. In addition, comparing the optimization results of the convective-microwave dryer with the single microwave dryer, it was found that the drying time of the samples in the combined drying has been decreased from 1.92 to 1.47 compared to the microwave drying. The water activity reduced from 0.399 for the microwave drying to 0.201 for the combined dryer.

4. Conclusion

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

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Conflict of interest

The authors declare that there is no conflict of interest.

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

	Experimental design			Results		
Type of drying	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

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

Responses	Final Equation For Responses	P_{value}	LOF	R^2

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

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

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چکیده

هدف از انجام تحقیق حاضر بررسی فرآیند خشک کردن نان تا رطوبت نسبی ۸٪ با استفاده از سه خشک کن مختلف همرفتی ، میکرو ویو و ترکیبی همرفت- میکروویو می باشد. آزمایشها با استفاده از روش سطح پاسخ و طراحی مرکب مرکزی آنالیز و طراحی شدند. پارامترهای عملیاتی شامل دمای هوا $(40-60^0C)$و سرعت هوا $(0.5-1.5m/s)$برای خشک کن های همرفت و ترکیبی میکروویو-همرفتی و توان میکروویو $(90-900W)$ برای خشک کن های 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 خشک کن ترکیبی همرفت-میکروویو روی داد. کمترین انرژی مصرفی متعلق به خشک کن میکروویو $(0.019-0.116kWh)$و سپس خشک کن میکروویو-همرفتی $(0.046-0.584kWh)$و خشک کن همرفتی $(0.588-1.255kWh)$بود. محدوده فعالیت آبی برای هر سه نوع خشک کن در حد مطلوب بدست آمد. سپس فرآیند برای بدست آوردن نقاط کمینه زمان خشک کردن، مصرف انرژی و فعالیت آبی بهینه سازی شد. نقطه بهینه برای خشک کن میکروویو توان 616W ، برای خشک کن همرفتی دمای 57^0C و سرعت هوای $1.1m/s$ و برای خشک کن میکروویو-همرفتی توان 580W ، دمای 50^0C و سرعت هوای $1.2m/s$ بدست آمد. خشک کن ترکیبی میکروویو-همرفتی بهترین عملکرد را در شرایط بهینه با زمان خشک کردن $1.47\min$، انرژی مصرفی $0.083kWh$ و فعالیت آبی 0.201 بدست داد.

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

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