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Optimizing the drying process of white onion in a heat pump assisted photovoltaic-thermal solar dryer

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ABSTRACT

A significant proportion of the global onion harvest is annually lost as a consequence of excessive production and insufficient processing techniques. Concurrently, the practice of drying represents a time-honored method of processing agricultural commodities, which has been historically regarded as a means to extend the shelf life of food products. In this context, the present study employed a photovoltaic-thermal solar dryer for the drying of white onions. In order to optimization of onion specimens, the response surface methodology was employed to analyze the influence of air temperature at three levels (50, 60, and 70 degrees Celsius) alongside the drying air flow rate at three varying levels (0.008, 0.016, and 0.024 kg/s). To achieve this objective, the optimum drying conditions were determined through the identification of the maximum values of the effective moisture diffusion coefficient, drying energy efficiency, specific moisture extraction rate, and vitamin C concentration, alongside the determination of the minimum durations of drying time and alterations in color. Based on the results obtained, the optimal drying conditions for white onion slices were established at an air temperature of 62.35 ˚C and an air flow rate of 0.024 kg/s. Moreover, at the point of optimality with a desirability of 0.59, the resultant values for the response variables, namely the effective moisture diffusion coefficient, drying duration, colorimetric differences, vitamin C content, specific moisture extraction rate, and drying energy efficiency were determined to be 3.81×10^{-9}, 196.82, 5.20, 797.37, 0.30, and 53.98, respectively.

1. Introduction

Onion (*Allium cepa*) is a member of the *Amaryllidaceae* family and one of the widely cultivated species [1]. With a production of about 111 million tons in 2022, it ranks second in global production after tomatoes, and Iran has been among the top ten onion-producing countries for years. According to the latest estimates, it ranks eighth after India, China, Egypt, the United States, Bangladesh, Turkey, and Indonesia [2]. The most widely used vegetable in the preparation of food around the world, especially in tropical countries, not only adds a delicious flavor and taste to dishes but also serves as a good medicinal compound for preventing cataracts and cardiovascular diseases, regulating and strengthening the immune system, controlling blood sugar levels, and cancer [3,4]. This product is mainly exported in the form of dried onions, canned onions, and pickled onions [5]. Dried onions are recognized as an important product in global trade and are produced in various forms such as flakes, finely chopped, and powdered [6].

Onions contain several beneficial chemical compounds such as fibers, vitamins, organic acids, phenolic compounds, and other antioxidants, some of which, like phenolic compounds and vitamin C, are significantly affected by temperature changes [7]. Therefore, careful application of various treatments after harvesting this product, as well as proper storage, seems essential for preserving these compounds. One of the methods for long-term storage and preservation of this product, which is particularly important in large food industries, is drying [8]. Onions are available in various types and colors, which leads to differences in determining their appropriate quality indices. However, in general, the color of the dried product is one of the very important parameters in determining its quality [5].

There are various methods and dryers available for drying agricultural products, each with its own advantages and disadvantages [9]. Solar drying is one of the common methods that has been of interest for a long time, and to address the drawbacks of the traditional method (drying in the sun), such as contamination and low quality of the dried product, solar dryers have been developed [10]. In this context, each of the food and agricultural products has its own optimal conditions for drying, and researchers use various drying methods or combinations of them to achieve the optimal point in terms of drying time, energy consumption, and product quality for different agricultural products. Since agricultural products have low thermal conductivity, the drying process requires a significant amount of energy and time, which in turn increases the costs of the process. In this context, each of the food and agricultural products has its own optimal conditions for drying, and researchers use various drying methods or combinations of them to achieve the optimal point [11] in terms of drying time, energy consumption, and product quality for different agricultural products [12,13].

Since agricultural products have low thermal conductivity, the drying process requires a significant amount of energy and time, which in turn increases the costs of the process [14]. The food industry is seeking to improve system performance and increase process efficiency without increasing costs and time. Therefore, finding conditions with the best output for a system or process is the main goal of optimization [15]. Response Surface Methodology (RSM) is a set of statistical and mathematical methods used for optimizing various processes where a specific response is influenced by multiple variables. One of the most important advantages of this method is the ability to assess the impact of interactions between independent variables on the process and to produce mathematical models [16].

Given the importance of the drying process and the impact of various factors on it, as well as the well-known capability of the response surface method for extracting predictive models and determining optimal process conditions, many researchers have utilized this method in their studies, such as determining the optimal drying conditions for red currants under vacuum [17], drying carrots with microwaves [18], drying turnip slices with a convective-infrared dryer [19], drying beetroot juice with a spray dryer [20], drying pumpkin seeds with a convective dryer [21], and drying peaches using osmotic methods [22]. However, the optimal conditions for drying white onions with a photovoltaic-thermal solar dryer equipped with a heat pump have not yet been determined.

Therefore, the aim of this research is to optimize the independent variables of temperature and air flow rate for drying in order to achieve optimal conditions for drying white onions using a photovoltaic-thermal solar dryer equipped with a heat pump, as well as to extract predictive models from three perspectives: kinetic, energy, and qualitative.

2.Materials and Methodes

2-1- Introduction of photovoltaic-thermal solar dryer equipped with a heat pump.

In this research, a photovoltaic-thermal solar dryer equipped with a heat pump unit was used to dry samples of white onion slices. This drying system includes a photovoltaic-thermal solar collector, a drying chamber, a blower, a compressor, a condenser, an evaporator, an expansion valve, an electric heater, and a proportional-integral-derivative (PID) control system for better temperature regulation. In each experiment, the airflow rate and temperature were adjusted on specified levels for the main variables.

2-2- Experimental Procedure

In each experiment, medium-sized white onions were procured from a vendor, and circular slices approximately 7 cm in diameter were prepared, each cut into 3 mm thickness using a sharp knife. Subsequently, 100 g of the slices were positioned on the tray of the drying chamber. The experiments were conducted until the moisture content of the product approximately reached 10%. A total of 27 experiments were carried out, encompassing 9 treatments, each with three replications. Prior to the commencement of drying, the dryer was activated one hour in advance under the predetermined conditions to enable the internal temperature of the chamber to attain equilibrium. The independent variables and their respective experimental levels are delineated in Table 1.

Table 1. Independent variables and related test levels

Independent variables	Level 1	Level 2	Level 3
Airflow temperature	50	60	70
Airflow rate	0.008	0.016	0.024

2-3- Effective Moisture Diffusion Coefficient

The rate of moisture movement and transfer within a product during the drying process is quantified using an index known as the effective moisture diffusion coefficient (D_{eff}), which is founded on Fick's second law as presented in equation (1) [23]. This law is applicable to substances with a planar geometry, such as uniformly spread sliced onion pieces on a tray, leading to the formulation of the effective moisture diffusion coefficient as represented in equation (2). It is pertinent to note that equation (2) may be simplified to equation (3) under conditions of prolonged drying durations. In this context, permeabilities are typically ascertained by plotting experimental drying data in the form of Ln

MR against drying time (t) [24]. The effective moisture diffusion coefficient is employed due to its dependence on variables such as composition, moisture content, temperature, and porosity of the material, particularly in light of the limited understanding of moisture movement mechanisms during drying and the inherent complexity of this process [25].

$$\frac{\partial MR}{\partial t} = D_{eff} \nabla^2 MR \quad (1)$$

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4H^2}\right) \quad (2)$$

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right) \quad (3)$$

Ultimately, by obtaining experimental data and constructing the curve of Ln (MR) versus time, the sought answer can be derived through linear fitting and the determination of the slope of the linear representation [26].

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

$$\text{Slope} = -\frac{\pi^2 D_{eff}}{4L^2} \quad (5)$$

In the aforementioned relations, MR represents the relative humidity, D_{eff} represents the effective moisture diffusivity ($m^2.s^{-1}$), L is the half-thickness of the sample (m), and t denotes the time (min).

2-4- Color Indices

The color of the product constitutes a critical quality parameter in the drying process that must be preserved at an acceptable level to ensure the desired marketability. A colorimeter (Hunter Lab colorimeter, Color Flex, Virginia, USA) was employed to assess the color of onions according to the color indices L* (lightness-darkness), a* (redness-greenness), and b* (blueness-yellowness) [11]. For this analysis, dried onions were initially ground and subsequently subjected to extraction utilizing the color data (L*, a*, b*). The calculation of color changes was then performed using equation (6).

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \quad (6)$$

In equation (6), the values of L*, a*, and b* represent the degree of lightness-darkness, redness-greenness, and blueness-yellowness of the samples, respectively. Additionally, L_0, a_0, and b_0 denote the values of the color attributes of fresh onion slices.

2-5- Vitamin C

The content of Vitamin C, identified as ascorbic acid (AA), was quantified through a titration method utilizing 6,2-dichlorophenol-indophenol. A standard curve for ascorbic acid was established at concentrations ranging from 0 to 50 ppm, resulting in the equation $y = -0.0043x + 0.3456$, with an R^2 value of 0.99. Subsequently, Vitamin C assays were conducted on the samples. Specifically, to determine the ascorbic acid content, 0.1 g of ground dried onion and 10 g of fresh onion were homogenized in 10 ml of 1% metaphosphoric acid and subsequently filtered. One milliliter of the filtered solution was combined with 9 ml of 2,6-dichlorophenol, resulting in a colorimetric change to pink. Ultimately, the concentration of Vitamin C was calculated by referencing the standard curve, based on the absorbance measured at a wavelength of 515 nm using a spectrophotometer [27].

2-6- Specific Moisture Extraction Rate (SMER)

The Specific Moisture Extraction Rate (SMER) is a metric utilized to quantify the efficiency of a drying process concerning energy consumption. This measure denotes the quantity of moisture extracted from a product per unit of energy expended throughout the drying procedure [28].

$$SMER = \frac{m_w}{E_{in}} \quad (7)$$

In the aforementioned equation, (kg) represents the mass of moisture extracted from the product, while (kJ) signifies the total energy consumed by the various components of the system during the drying duration.

2-7- Drying Energy Efficiency

Energy efficiency is defined as the ratio of the energy utilized to evaporate moisture from the sample to the total energy consumption, which encompasses thermal, mechanical, and electrical energy. This ratio is calculated using Equation (8) [29].

$$\eta_e = \frac{\dot{Q}_{ev}}{\dot{W}_{Total}} \quad (8)$$

The energy expended for the evaporation of moisture is determined using Equation (9) [30].

$$Q_{ev} = h_{fg} . m_w \quad (9)$$

The latent heat of evaporation of water (h_{fg}) can be treated as either a constant approximation or can be computed as a function of the absolute temperature (T) of the drying air, employing the equations provided [31].

$$h_{fg} = 2.503\times10^6 - 2.386\times10^3 \times (T - 273.16) \quad if: \ 273.16 \le T(k) \le 338.72$$
$$h_{fg} = (7.33\times10^{12} - 1.60\times10^7 \times T^2)^{0.5} \quad if: \ 338.72 \le T(k) \le 533.16 \quad (10)$$

According to the aforementioned equations, the latent heat of vaporization of water at temperatures of 50, 60, and 70 ˚C was determined to be 2384.082, 2360.222, and 2334.013 kJ/kg, respectively.

2-8- Optimization of Experimental Variables

The term "response surface method" refers to the graphical representation generated subsequent to the fitting of the mathematical model. Data analysis utilizing this method not only elucidates the effects of independent variables on dependent variables and offers an empirical model for the relationship between input and response variables, but also facilitates process optimization [32]. In this research, multinomial regression models employing the response surface method were utilized within Design-Expert® Software version 10 to predict the optimal values of the variables under investigation and to ascertain the degree of influence of each independent variable. Furthermore, the utility function method, designed for the simultaneous optimization of multiple attributes, was applied to optimize the variables of interest. The range of variation of the utility function spans from 0 to 1, reflecting the significance of each attribute, and its formulation is represented as the geometric mean of all variables under consideration, as articulated in equation (11).

$$D = (d_1 \times d_2 \times .... \times d_n)^{1/n} \quad (11)$$

In equation (11), D denotes the desirability function, d signifies the trait under examination, and n indicates the number of traits. To determine the optimal levels, the responses of the effective moisture diffusion coefficient, drying time, color, vitamin C content, specific moisture extraction rate, and drying efficiency were analyzed in relation to the independent variables of temperature and air flow rate.

3. Results and Discussion

Determining the suitability of the proposed models for characterizing the variables under investigation in a given process is essential for conducting optimization via response surface methodology. To this end, the coefficients of the regression equation and the statistical outcomes derived from the calculated models for the response variables are presented in Table 2. Positive and negative coefficients signify the direct and inverse effects of each independent variable on each response variable, respectively. Furthermore, the relative magnitude of the coefficients elucidates the significance of the independent variable in relation to each response. It is pertinent to note that in these equations, A represents the independent variable of air flow rate, while B denotes the independent variable of air temperature. For instance, regarding the specific moisture extraction rate index, the relative magnitude of the coefficient for the air flow rate factor (A) compared to that of air temperature (B) indicates a more pronounced effect of the former. Additionally, the positive sign of the coefficients for both factors highlights the direct relationship between these two variables and the specific moisture extraction rate index.

Table 2. Regression equation coefficients and statistical results from calculated models for response variables

Dependent variables	Regression model equation	Lack of fit (P-Value)	R^2
Effective moisture diffusivity (m^2/s)	$4.85\times10^{-8}A+8.32\times10^{-11}B-2.54$	0.25	0.86
Drying time (min)	$-8750A-2.44B+559.25$	0.95	0.94
Color changes	$-389.97A+0.19B+2.09$	0.53	0.89
Vitamin C content ($\mu g\ AA / g\ sample$)	$-14830.48A-10.79B+1826.43$	0.99	0.54
Specific moisture extraction rate (kg/kJ)	$5.97A+3.53B-0.06$	0.48	0.90
Drying efficiency (%)	$765.85A+0.26B+18.83$	0.98	0.38

3-1 Effective Moisture Diffusion Coefficient

The simultaneous effect of temperature and air flow rate on the effective moisture diffusion coefficient under various experimental conditions is shown in Figure (1). According to the results obtained, the interaction effect of temperature and air flow rate on the effective moisture diffusion coefficient was not significant, but each of the simple effects was found to be significant. The values of R^2 (0.86), Adj-R^2 (0.84), Pred-R^2 (0.82), and C.V. (9.91) indicate the adequacy of the predicted model. Considering the increase in heat transfer and mass transfer rates at high temperatures [33], as the air temperature rises from 50 to 70 ˚C, the effective diffusion coefficient of moisture increased from 2.37×10^{-9} to 5.04×10^{-9} (m^2/s). The obtained values fall within the range provided for moisture diffusion in food materials (from 10^{-11} to 10^{-6} (m^2/s)) [34] and are consistent with the values reported for various vegetables and fruits in previous studies. Doymaz [35] studied the drying of sweet potatoes at three temperatures of 50, 60, and 70 ˚C and an air flow rate of 2 (m/s), reporting the effective moisture diffusion coefficient obtained from his research in the range of 9.32×10^{-11} to 1.76×10^{-10} (m^2/s). Maftoonazad et al. [24] also worked on the drying of onions using a hybrid hot air tunnel dryer equipped with microwaves at temperatures of 50, 60, and 70 ˚C, reporting the effective moisture diffusion coefficient obtained in the range of 6.81×10^{-9} to 1.51×10^{-7}.

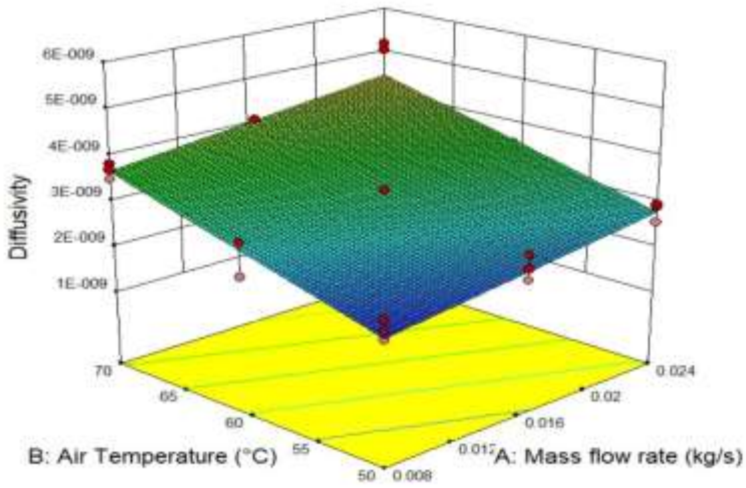

Fig 1. The interaction effects of airflow temperature and airflow rate on effective moisture diffusivity

3-2 Drying Time

The interaction effect of temperature and air flow rate on the drying time of white onion samples under different experimental conditions is shown in Figure (2). The interaction effect of temperature and air flow rate on drying time was not significant, but both simple effects were significant. The values of R2 (0.94), Adj-R2 (0.94), Pred-R2 (0.93), and C.V. (5.68) indicate the adequacy of the predicted model. According to the figure, the effect of air temperature and air flow rate on the drying time of white onions was found to be inverse. As the temperature rises from 50 to 70 ˚C, the drying time of onions has decreased from about 390 to 170 minutes.

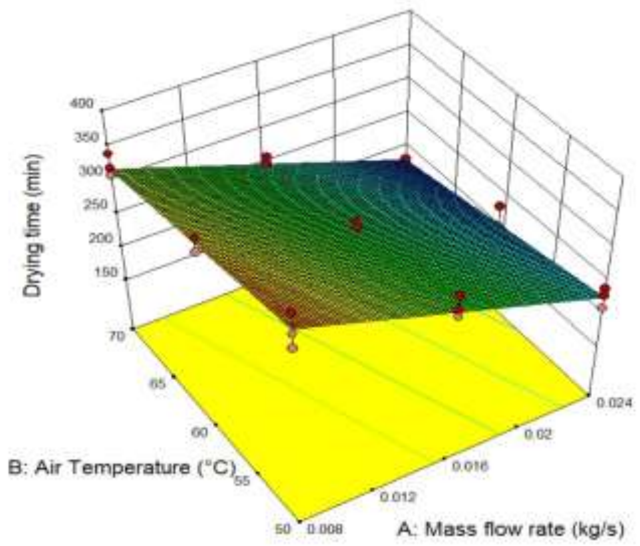

Fig 2. The interaction effects of airflow temperature and airflow rate on drying time

3-3 Color Indices

The simultaneous effect of temperature and air flow rate on the overall color changes of white onions during drying is shown in Figure (3). The changes in the overall color indices are derived from three color components L*, a*, and b* using Equation

6. The variations in the L* values may be due to the formation of brown pigments and the oxidation of heat-sensitive nutrients [11]. High temperatures and excessive drying lead to an increase in a* values, which indicate a high level of redness and are indicative of browning reactions. Additionally, high b* values indicate a significant yellowness in the sample, which may occur due to the oxidation of compounds sensitive to the drying process [36,37]. As seen in the figure, the greatest overall color change occurred at the highest temperature and the lowest air flow rate. Conversely, the least overall color change occurred at the lowest temperature and the highest air flow rate. It should be noted that although a high airflow rate reduces overall color changes, if the airflow over the product is not uniform, this factor can lead to excessive temperature increases and negatively affect color changes. With an increase in temperature from 50 to 70 ˚C, the overall color change of white onions increased from 23.3 to 59.14. The values obtained for the color changes of white onions during drying in this study are, in turn, better than those reported in previous studies. Maftoonazad et al. [24] reported color change values in the range of 6.04 to 32 during the drying of white onions at temperatures of 50, 60, and 70 ˚C in a tunnel dryer equipped with microwave hot air, attributing this to the prolonged exposure of the samples to hot air. Meanwhile, some drying times in their research are shorter than those in the present study. Therefore, it can be concluded that different drying conditions have a significant impact on the results of the process. Kaveh et al. [38] also reported color changes in the range of 12.43 to 23.65 for onion drying in a semi-industrial multi-stage continuous dryer at temperatures of 40, 55, and 70 ˚C and air flow rates of 0.5, 1, and 1.5.

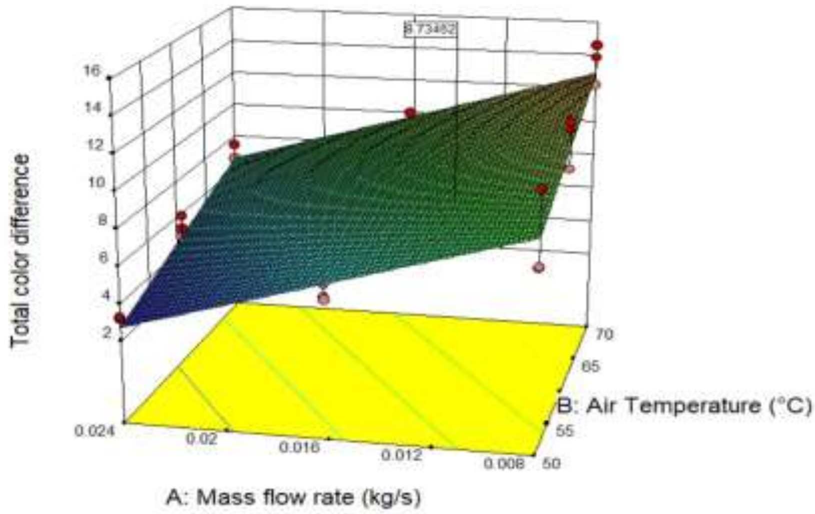

Fig 3. The interaction effects of airflow temperature and airflow rate on total color differences

3-4 Vitamin C

The simultaneous effects of temperature and air flow rate on the vitamin C content are shown in Figure (4). The amount of vitamin C in different treatments varied between 271.49-1193.02micrograms of ascorbic acid per gram of sample. Meanwhile, the amount of ascorbic acid in raw onion was estimated to be 9570.743 micrograms of ascorbic acid per gram of sample. The interaction effect of air temperature and air flow rate on vitamin C content was not significant, but the simple effects were significant.

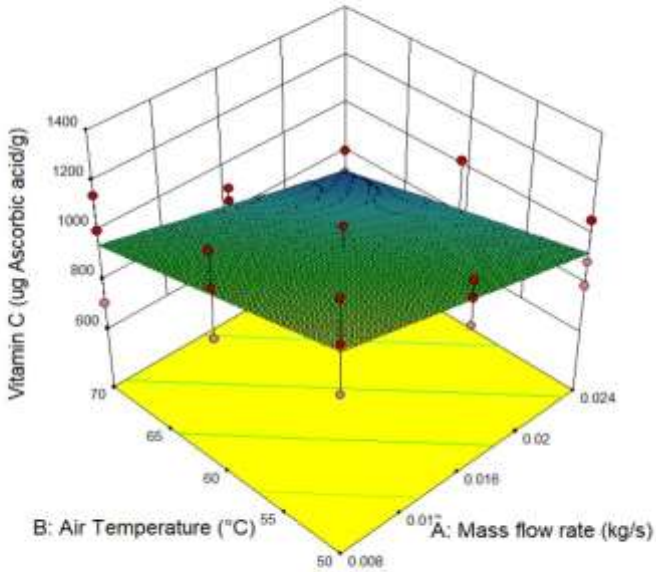

Fig 4. The interaction effects of airflow temperature and airflow rate on vitamin C content

As shown in Figure (4), higher temperature levels have lower vitamin C content; however, it was expected that the change in vitamin C content at different temperature levels would be greater and the slope of the changes would be steeper. On the other hand, it is observed that levels with higher air flow rates also have less vitamin C, which can be explained by the increase in air temperature resulting from the higher air flow rate. Based on the results obtained from this research and considering that increasing the airflow rate reduces drying time and makes heat transfer more uniform, it can be concluded that the drying time of onions has a significant impact on preserving the vitamin C content in this product, as evidenced by the similar levels of vitamin C content in treatments with different temperature levels. Therefore, reducing drying time and mitigating the negative effect of heat on the ascorbic acid content in onions leads to a greater preservation of vitamin C content in the dried onion samples.

During prolonged drying, the content of vitamin C is negatively affected not only by the sample being exposed to high temperatures for an extended period but also by oxidation [39]. The values of R2 (0.54), Adj-R2 (0.50), Pred-R2 (0.40), and C.V. (13.59) indicate the adequacy of the predicted model.

3-5 Specific Moisture Extraction Rate

The simultaneous effects of air temperature and drying air flow rate on the specific moisture extraction rate are presented in Figure (5). As illustrated in the figure, increases in temperature and drying air flow rate lead to a higher specific moisture extraction rate. This indicates that specific energy consumption decreases at higher levels of temperature and air flow rate. It appears that increasing the air flow rate levels had a greater effect than temperature levels, which is attributed to the enhanced moisture regulation within the chamber under higher air flow conditions. However, it is important to recognize that these results pertain to the specific temperature and air flow rate ranges defined in the present study; testing different variable ranges could have yielded alternative outcomes. According to the obtained results, the interaction effect of air temperature and drying air flow rate on the specific moisture extraction rate was not statistically significant, though both main effects were statistically significant. Understanding the concept of the Specific Moisture Extraction Rate (SMER)—which represents the amount of moisture removed per unit of energy consumed—can facilitate process optimization. This not only reduces energy consumption but also lowers energy expenditures. A higher SMER further indicates a more rapid drying process, thereby reducing the likelihood of nutrient degradation in the product and resulting in better quality retention. The values of R^2 (0.90), Adj- R^2 (0.89), Pred- R^2 (0.87), and C.V. (6.81%) demonstrate the soundness of the predictive model.

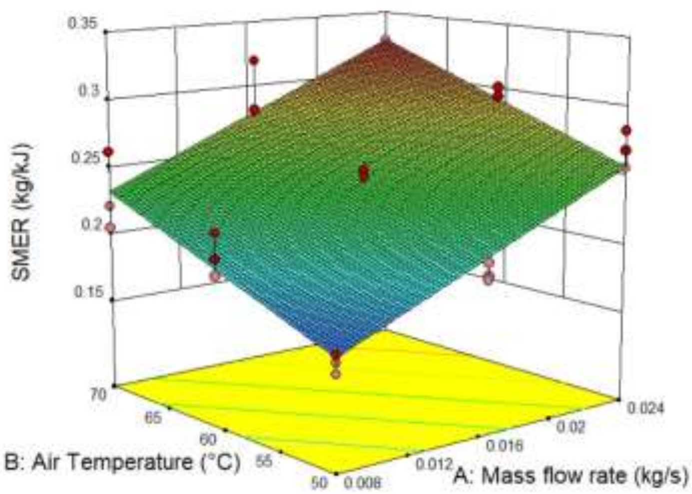

Fig 5. The interaction effects of airflow temperature and airflow rate on specific moisture extraction rate

3-6 Drying energy efficiency

Figure (6) illustrates the interaction effect of the independent variables—temperature and drying air flow rate—on drying energy efficiency. Although drying energy efficiency and the Specific Moisture Extraction Rate (SMER) are related concepts, each focuses on distinct aspects of the drying process. Specifically, SMER assesses a drying method's moisture removal capability relative to energy input. Whereas drying energy efficiency focuses on the overall system performance and process effectiveness by examining factors such as time, temperature, and the state of the material being dried, the results indicate that energy efficiency increases with higher temperature and drying air flow rate. Moreover, given the steeper curve slope, the air flow rate demonstrates a more pronounced effect than temperature. When air temperature rose from 50°C to 70°C, drying energy efficiency increased substantially—from 32.69% to 69.40%. The interaction effect of air temperature and drying air flow rate on energy efficiency was not statistically significant, though both main effects were statistically significant. The values of R^2 (0.38), Adj- R^2 (0.33), Pred- R^2 (0.21), and C.V. (15.57%) attest to the predictive model's adequacy. The obtained drying energy efficiency values are relatively higher than those reported in most prior studies. Mugi and Chandramohan [40] documented mean drying energy efficiencies of 20.13% and 24.95% for okra in indirect solar dryers under natural and forced convection modes, respectively. Notably, the superior energy efficiency of hybrid dryers is a well-established fact [41].

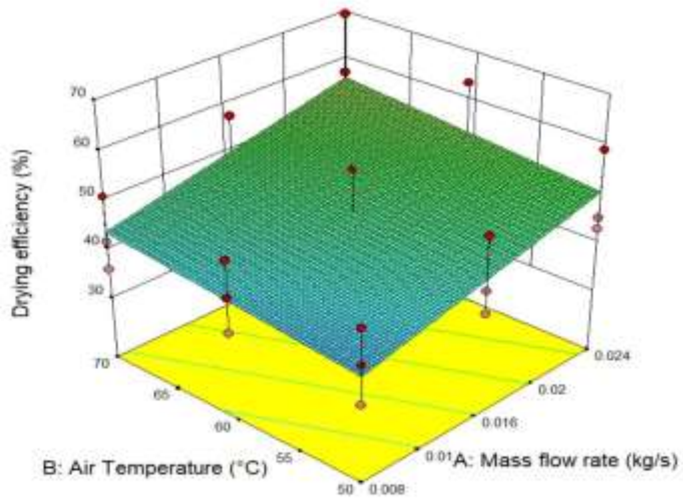

Fig 6. The interaction effects of airflow temperature and airflow rate on drying efficiency

3-7 Optimization

Using the desirability function approach, eight solutions were obtained for determining optimal white onion drying conditions, with desirability indices ranging between 0.58 and 0.59. The results of this analysis are presented in Table (3). Based on the desirability-index solutions, the optimal drying conditions for white onion were achieved at an air temperature of 62.35°C and an air flow rate of 0.024 kg/s. It should be noted that these optimal independent variable conditions were determined by maximizing the response variables of effective moisture diffusivity, vitamin C content, Specific Moisture Extraction Rate (SMER), and drying energy efficiency, while minimizing color change and drying time.

The optimized response values achieved at a desirability level of 0.59 were as follows: 3.81×10^{-9}, 196.82, 5.20, 797.37, 0.30, and 53.98 for effective moisture diffusivity (m^2/s), drying time (min), color change (ΔE), vitamin C content (mg/100g), SMER (kg/kWh), and drying energy efficiency (%), respectively. In the selected solution, it was observed that despite the decrease in vitamin C content at the proposed temperature and air flow rate, at this temperature the drying time and color change of the product were lower, while the Specific Moisture Extraction Rate (SMER), drying energy efficiency, and effective moisture diffusivity were higher. This proved advantageous for market acceptability, optimal energy utilization, and cost reduction.

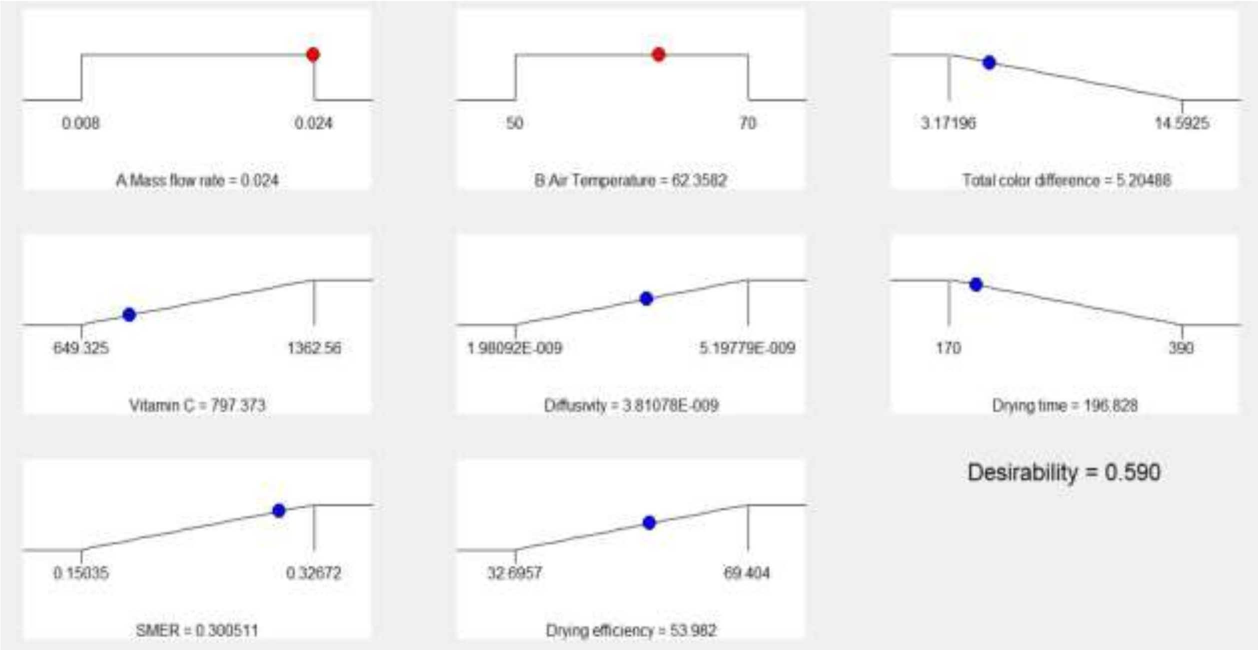

Fig 7. Desirability points for optimal drying process of onion slices in heat pump assisted photovoltaic-thermal solar dryer

Subsequently, to validate the software-derived data, experiments were conducted at these optimal levels. For this purpose, temperature and air flow rate were adjusted to the proposed values to evaluate the efficacy of the regression models in predicting optimal responses. The experimental results obtained from this test are also presented in Table (3). These results demonstrate the validity of the models developed based on empirical data, such that the lower the relative error between experimental and predicted values, the higher the model accuracy.

Table 3. Experimental and predicted values of variables under optimization

Dependent variables	Predicted values	Experimental values	Relative errors (%)
Effective moisture diffusivity (m^2/s)	3.81×10^{-9}	3.95×10^{-9}	3.53
Drying time (min)	196.82	192.08	2.41
Color changes	5.20	5.01	3.65
Vitamin C content ($\mu g\ AA / g\ sample$)	797.37	746.5	6.36
Specific moisture extraction rate (kg/kJ)	0.30	0.31	3.34
Drying efficiency (%)	53.98	57.19	5.6

Various studies have been conducted on optimization to determine optimal conditions for agricultural products. Sumic et al. [16] performed research on optimizing the shiitake mushroom drying process in a vacuum dryer using response surface methodology to produce dried samples with suitable shelf-life. They dried samples at temperatures of 46–74°C and pressures of 20–580 mbar, obtaining optimal temperature and pressure conditions of 57.1°C and 100 mbar, respectively. Liu et al. [42] considered microwave power density, hot air temperature, and product-basis moisture content as three independent variables to determine optimal conditions for hybrid microwave-hot air drying of purple cabbage, with anthocyanin content, antioxidant capacity, chewiness, color change, water rehydration ratio, and drying rate as response factors. They achieved the optimal point at a microwave power density of 2.5 W/g, hot air temperature of 55°C, and product-basis moisture content of 4 g/g dry product. Despite existing research, studies remain necessary due to varying drying conditions across different products and systems.

4.Conclusion

In this research, the effects of the independent variables—temperature and drying air flow rate—on response variables were evaluated using response surface methodology to determine optimal drying conditions for white onion in a photovoltaic-thermal solar dryer equipped with a heat pump. According to the obtained results, optimal drying conditions for white onion were identified at an air temperature of 62.35°C and an air flow rate of 0.024 kg/s. Additionally, the optimal values for the response variables—effective moisture diffusivity, drying time, color change, vitamin C content, Specific Moisture Extraction Rate (SMER), and drying energy efficiency—were obtained as 3.81×10^{-9}, 196.82, 5.20, 797.37, 0.30, and 53.98, respectively. The validation results of the developed models and the software-proposed optimal conditions were also confirmed based on empirical data.

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چکیده

سالیانه بخش زیادی از محصول پیاز در سطح جهان به دلیل تولید زیاد و نبود امکان فراوری مناسب، به هدر می‌رود. در این میان، خشک کردن یکی از روش‌های سنتی فرآوری محصولات کشاورزی بوده که از دیرباز به منظور طولانی کردن دوره انبارمانی مواد غذایی مورد توجه بوده است. در همین راستا در این پژوهش از یک خشک‌کن خورشیدی فتوولتائیک- حرارتی برای خشک کردن پیاز سفید استفاده گردید. برای بهینه‌سازی نمونه‌های پیاز از روش سطح پاسخ به منظور بررسی تاثیر دمای هوا در سه سطح (۵۰، ٦۰ و ۷۰ درجه سلسیوس) و نرخ جریان هوای خشک کردن در سه سطح (۰/۰۰۸، ۰/۰۱٦ و ۰/۰۲٤ کیلوگرم بر ثانیه) استفاده شد. به همین منظور، شرایط بهینه خشک کردن براساس انتخاب مقدارهای بیشینه ضریب نفوذ موثر رطوبت، بازده انرژی خشک کردن، نرخ استخراج رطوبت ویژه و ویتامین ث و انتخاب مقدارهای کمینه زمان خشک کردن و تغییرات رنگ استخراج گردید. با توجه به نتایج بدست‌آمده، شرایط بهینه خشک کردن پیاز سفید در دمای هوای ٦۲/۳۵ درجه سلسیوس و نرخ جریان هوای ۰/۰۲٤ کیلوگرم بر ثانیه بدست آمد. همچنین در نقطه بهینه با درجه مطلوبیت ۰/۵۹، مقدار متغیرهای پاسخ ضریب نفوذ موثر رطوبت، زمان خشک کردن، رنگ، ویتامین ث، نرخ استخراج رطوبت ویژه و بازده انرژی خشک کردن به ترتیب $۳/۸۱\times۱۰^{-۹}$، ۱۹٦/۸۲، ۵/۲۰، ۷۹۷/۳۷، ۰/۳۰ و ۵۳/۹۸ بدست آمدند.