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Research Article

Optimization of Intermittent Drying of Rehydrated Dates

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Abstract

The intermittent drying of dates remains a neglected area in academic research, primarily due to factors such as varying cultivation patterns across regions and limited attention to the valorization of overdried dates. This study investigates the impact of drying parameters: air temperature, air velocity, and intermittency ratio, on the drying time and energy consumption of rehydrated dates using hot air drying. Employing Response Surface Methodology with a Central Composite Design and a desirability function, experiments were conducted within specific ranges of air temperatures (40–70 °C), air velocities (0.5–5 m/s), and intermittency ratios (0.2–1). Results show that while air velocity minimally affects drying time, it negatively influences energy efficiency. Conversely, air temperature is significant for both responses. Reducing the intermittency ratio from 1 to 0.3 resulted in a decrease in total energy consumption by up to 60%, particularly at lower temperatures, with negligible impact on total drying time. The study identifies optimal conditions for minimizing both drying time and energy consumption as an inlet temperature of 66 °C, air velocity of 2.5 m/s, and an intermittency ratio of 0.7. The experimental data were fitted to 7 mathematical drying models, the results indicated that Midilli-Kucuk model gave better performance to define the drying kinetics of intermittent drying of rehydrated dates.

Keywords: *Intermittent drying; hot air dryer; response surface methodology; rehydrated dates.*

1. Introduction

The Phoenix dactylifera L., commonly known as date palm, is an essential crop in arid regions located in Middle East and North Africa. It provides vital nutrients and health-enhancing elements, making it a significant contributor to maintaining nutritional security worldwide. In 2022, the global production of dates has increased about 18% and surpassed 8.53 million tons [1], owing to their high carbohydrate and dietary fiber content, as well as essential minerals and vitamins [2]. One of the most popular dates in North Africa is 'Deglet Nour' dates. Algeria and Tunisia are currently the dominant producers and exporters of this particular cultivar [3], it is highly prized due to its semi-soft texture, transparent hue, and overall clarity, which make it a valuable commodity in the global market. Deglet Nour dates is classified into many categories depending on its maturation and sugar content after harvesting, among these categories the 'freeza' dates category which represents a state of incomplete maturation where the dates have been overdried on the palm tree, this category is distinguished by a hard texture and very low moisture content which make it undesirable for consumption. Many studies have been carried out in order to valorize this dates category [3, 4], the common process in order to achieve a softer texture is a rehydration treatment which induce an increase in moisture content leading to sugar inversion and thus a complementary maturation of the fruit, followed by a drying in order to achieve a desired moisture content as recommended by the international standards (CEE/ONU DF-08) for a safe storage and preservation.

Drying is a crucial method for preserving food products. It involves removing water from the product to prevent microbial or enzymatic reactions and fungus growth. Additionally, it decreases the product's weight, making it easier to transport and store. One of the most commonly used drying methods is convective hot air drying, which is convenient for industries as it is easy to handle and saves time. However, it is energy-intensive and consumes approximately 10-25% of the total energy [5], Excessive heat exposure during the drying process can also degrade the final product's quality [6]. To overcome these issues, intermittent drying can be a viable solution [7-9], this method involves non-continuous drying, where the product is allowed to rest during tempering periods once the surface is already dried.

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This allows moisture to migrate from the center to the surface, leading to full water distribution and homogeneity, as well as surface rewetting. Consequently, the product can avoid many qualities degradation issues, while requiring no energy consumption during the tempering period, resulting in overall energy savings. Intermittent drying has been the subject of many research studies, Pan et al. [7] experimented drying of squash slices in a fluidized bed dryer, it was proven that intermittent drying reduced degradation of β-carotene of about 25% in comparison with conventional continuous drying. Md Saleh et al. [10] investigated the effect of intermittent drying on the quality of organic carrots. They observed that drying at 60°C with a 3-hour tempering period at 30% moisture content resulted in superior retention of total carotenoids (76.9%), minimal color change (8.1), and an optimal rehydration ratio (0.4) compared to continuous drying methods. Additionally, intermittent drying led to a reduction in energy consumption by up to 25%. Continuous and intermittent drying of rough rice were compared at temperatures of 50°C and 70°C by Pereira et al. [11], with intermittent drying showing up to 32.2% reduction in effective drying time, leading to energy savings. The intermittency ratio and tempering period significantly influenced drying kinetics, particularly at 50°C, with both methods reducing operation time by about 30.0% compared to continuous drying. The one-dimensional diffusion model accurately described the drying process, with intermittent drying resulting in increased mass diffusivity, accelerating drying and reducing energy consumption.

Studies regarding the intermittent drying of dates are notably absent in academic literature. This absence can be attributed to several factors. Firstly, the geographical distribution and cultivation of dates vary widely, with certain regions having limited access to this fruit. Consequently, the lack of widespread cultivation may lead to a dearth of academic interest and research initiatives focused on date processing techniques such as intermittent drying. Additionally, the valorization of overdried dates has received relatively little attention in academic research, contributing to the scarcity of studies on this subject. This gap in research reflects broader limitations in the exploration of date processing techniques and their applications. Therefore, while the intermittent drying of dates may seem underrepresented in academic literature, it is more a consequence of these underlying factors rather than an indication of the fruit's insignificance or lack of potential for further exploration. Hence, recognizing the need to address this research gap, the aim of this study is to investigate the effect of different drying parameters including air temperature, air velocity and intermittency ratio on drying time and energy consumption of rehydrated dates in a hot air dryer and to determine the optimum drying conditions using response surface methodology.

2. Material and Methods

2.1 Sample Preparation

For the experiments, Deglet Nour dates were selected as the subject of investigation. These dates were harvested from Toggourt city, located in southern Algeria, renowned for its date production. To ensure proper preservation, the dates were stored in a plastic bag and kept in a refrigerator set at a temperature of 4°C throughout the entire duration of the experiments. This controlled storage condition was maintained to prevent any unwanted changes in the dates' characteristics. According to the method of AOAC (1990), the initial moisture content of the sample was determined to be 17.5% wet basis.

2.2 Rehydration Process

To initiate the rehydration process, 10 pieces of dates, each weighing approximately 75 grams, were placed in a beaker. Distilled water was added to the beaker until it reached a volume of 250 ml, ensuring that the dates were fully submerged. The beaker was then carefully transferred to a water bath, specifically a "Memmert" model, set at a constant temperature of 45 °C for about 6 hours to ensure a complete maturation through sugar inversion [3] which increases the water content inside the dates up to 33 (% w.b).

The samples were removed and wiped gently with a paper towel then placed in an airtight glass storage jar for 7 hours to assure the homogenization of the moisture inside the samples and to maintain the same humidity. The weight was measured again after the rehydration process before placing the samples on the tray in the drying chamber to begin the drying process in order to decrease the moisture content above the standard water content required for safe storage (<26 % w.b) according to The UNE CE DF-08 norm [3].

2.3 Drying Experiments

2.3.1 Description of the dryer

The drying experiments were conducted in a custom air conditioning laboratory unit provided by P.A. Hilton Ltd., bearing the serial number A573 / 53621. The unit was specifically modified and tailored to meet our testing

Figure 1. Experimental hot air dryer.

requirements. For the drying chamber, we utilized a section salvaged from an old refrigerator which ensure a good isolation, with dimensions measuring 60 cm in length, 26 cm in width, and 45 cm in depth (see Figure 1.). Within the drying chamber, we incorporated a perforated tray designed to hold the product being dried. This tray was positioned 30 cm away from the air inlet. The drying chamber and the air conditioning unit were connected using a PVC pipe with a diameter of 125 mm and a length of 160 cm. The modified air conditioning unit composed of: Five heating electrical resistances, totaling 5 kW of power, which provided the high temperatures necessary for the drying experiments. An electrical fan, coupled with a potentiometer to regulate the airflow effectively and manually. The control unit, which was based on an Arduino Mega 2560 board, allowing precise control and monitoring of the drying process.

Temperature control

To maintain a constant drying air temperature in the drying chamber during each experiment, a PID (proportional-integral-derivative) control has been installed in the Arduino. The temperature is measured with a type K thermocouple, it has 0.05 mm in diameter, 3 m of length, and can withstand temperatures up to 1370 K and provide an accuracy of 0.1 °C. The temperature is displayed on the Arduino, which can be controlled by sending commands to the solid-state relay-25DA a type FQFER to adjust the electrical resistances, and thus can increase or decrease the temperature accordingly.

Velocity control

The drying air velocity is measured using an Anemometer (EMC-9400SD) positioned on the tray inside the drying chamber before each experiment. The airflow is regulated by manually adjusting the potentiometer, which controls the power supply to the fan.

Energy consumption

In this study, the energy consumption of each drying experiment was monitored using an electric meter from the brand Energical. This specific energy meter, designed for precision and reliability, played a crucial role in quantifying the electrical energy usage throughout the experimental processes. Notably, the meter operates at a frequency of 50 Hertz, ensuring accurate measurements and providing valuable insights into the energy dynamics of the drying system.

Weight measurement

The weight of samples was measured using a balance KERN ABT 220-4M and recorded every 30 min during the drying. The average time required using a digital balance for weight registration was about 10 s.

2.3.1 Instrumentations

During the experiments, the temperature, the airflow through the dryer, moisture content levels, energy consumption, and mass of dates were monitored throughout the drying process. The measurements were conducted using specific instruments for each parameter.

The inaccuracies in the measurements determine the level of uncertainty in the results. Using appropriate equipment, all parameters were measured during the drying tests. The result I is obtained from the measured values y_1, $y_2, \dots y_n$, where each y_i represents an individual parameter recorded during the experiment. The uncertainty of I, denoted as U_I, is determined by the uncertainties u_1, u_2, …, u_n, where each u_i corresponds to the uncertainty associated with its respective measured parameter y_i.
U_I [12] is expressed by:

$$U_I = \left[\left(\frac{\partial I}{\partial y_1}u_1\right)^2 + \left(\frac{\partial I}{\partial y_2}u_2\right)^2 + \cdots + \left(\frac{\partial I}{\partial y_n}u_n\right)^2\right]^{1/2} \quad (1)$$

Errors occurred when measuring and calculating the variables are addressed by:

$$E_I = (U_I/I) \times 100 \quad (2)$$

2.3.2 Experimental procedure

Hot air drying was performed under the controlled conditions of airflow temperature, velocity and intermittency ratio. The coded values of these process variables and their ranges used in the hot air drying of dates are presented in Table 2, these coded values were determined when using the Central Composite Design (CCD) for the response surface methodology, which implies five levels assigned to each factor: (−α, −1, 0, +1, and +α), Where level 0 corresponds to the central points, levels -1 and + 1 correspond to the low and high levels, respectively, and – α and + α correspond to the axial points, the distance between the axial points and the central points is calculated using $\alpha = [2^n]^{1/4}$, where n is the number of process variables[13].

The required temperature of drying air in the heater were adjusted by the PID temperature controller on Arduino. The velocity of air was measured manually by the Anemometer. Total time taken by the system to attain the required air temperature and velocity were about 5 min. Approximately 105 g of dates (10 pieces) on a tray was placed perpendicularly to the hot airflow uniformly distributed.

An intermittent drying approach was implemented in this study. This involved periodically turning off completely the drying system for a specific duration, referred to as tempering period after a specific duration of drying. This cyclic pattern repeats hourly ($t_{on} + t_{off}$=60 minutes), forming a systematic alternation between the 'on' and 'off' states of the drying system until the desired moisture content was achieved. The length of each tempering period was determined by the intermittency ratio assigned to each experiment which can be written as follows:

$$\alpha = \frac{t_{on}}{t_{on} + t_{off}} \quad (3)$$

Table 1. Ranges and uncertainties of measuring instruments.

Independent variables	Instruments	Model	Range	Total uncertainty	Tolerance
Temperature	Thermocouple	K-type	-50 – 1300 C	0.287 °C	±1,5°C
Velocity	Digital anemometer	EMC-9400SD	0.4 – 25 m/s	0.173 m/s	± (2% + 0.2 m/s)
Mass measurement	Balance for moisture determination	KERN ABT 220-4M	0 – 220 g	0.224 g	± 0,0002 g

Table 2. Independent variables and their levels for central composite design.

Independent variable	Coded levels				
	-α	-1	0	1	+α
Temperature (°C) (X_1)	40	46.08	55	64	70
Velocity (m/s) (X_2)	0.5	1.4	2.75	4	5
Intermittency ratio (X_3)	0.2	0.36	0.6	0.84	1

2.4 Moisture Ratio and Mathematical Modelling Procedure

The reduction in mass was documented at 30-minute intervals throughout the drying until the desired moisture content was achieved 26% (w.b). The moisture ratio (MR) was calculated using the equation:

$$\mathrm{MR} = \frac{\mathrm{M_t} - \mathrm{M_d}}{\mathrm{M_0} - \mathrm{M_d}} \quad (4)$$

With M_t, M_d, and M_0 are the water content values respectively at time t, at desired moisture content and at initial moisture content (t = 0). To enhance comprehension, prediction, and optimization of the drying process, mathematical modelling is employed in this study. By applying mathematical models, researchers can effectively translate experimental findings to industrial-scale operations. These models aid in managing and optimizing performance within specified operational parameters. Moreover, they facilitate the identification of empirical or semi-empirical models that best fit experimental results. We used seven common models to analyze the experimental moisture data in drying agriculture products. These models provide safe and straightforward explanations for the drying process characteristics, as listed in Table 3**.**

The most suitable model was chosen from the seven equations proposed by previous researchers, as detailed in Table 3. We conducted regression analyses using the OriginPro 8.0 program. A 3 number of coefficients are important in this assessment procedure. One basic metric that shows how much of the variability in the data the model can explain is the coefficient of determination (R2). A better fit is indicated by a higher R2. Furthermore, the goodness of fit is revealed by the reduced chi-square (χ2), where lower values correspond to a more accurate depiction of the experimental data[13]. The root mean square error (RMSE) gives the deviation between the predicted and experimental values and it must reach zero [14]. These coefficients can be calculated as follows [15, 16]:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pré,i}\right)^2}{\sum_{i=1}^{N}\left(\overline{MR_{exp}} - MR_{exp,i}\right)^2} \quad (5)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pré,i}\right)^2}{N - n} \quad (6)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pré,i} - MR_{exp,i}\right)^2} \quad (7)$$

with:

$$\overline{MR_{exp}} = \frac{\sum_{i=1}^{N} MR_{exp,i}}{N} \quad (8)$$

where, $MR_{exp,i}$ is the moisture ratio the experimentally observed, $MR_{pré,i}$ is the predicted moisture ratio obtained by modelling, N and n are the number of observations and the number of constants respectively.

2.5 Response Surface Analysis

Response surface methodology (RSM) is an effective statistical technique for optimizing complex processes. The main advantage of RSM is the reduced number of experimental trials needed to evaluate multiple parameters and their interactions [17]. In this study, (RSM) served as a powerful tool to delve into the primary effects of key process variables, namely drying temperature (X_1), air velocity (X_2), and intermittency ratio (X_3), on both drying time and energy consumption. The optimization factors ranges were thoughtfully selected based on insights gained from previous studies focusing on the drying of dates [3, 4, 18, 19].

For the experimental design, model construction, and data analysis, we have employed Statgraphics Centurion 18, a robust statistical software developed by Statpoint Technologies Inc. located in Warrenton, Virginia, USA. The design of experiments adopted a five-level strategy, employing The Central Composite Design (CCD) which has been chosen for its efficacy, which aligns with that discussed in a prior work [13], where detailed information on the design methodology and parameters can be found. This experimental design comprised 18 trials as shown in Table 4, strategically including four replicates at the central point to estimate experimental error accurately. Experimental data were fitted to a quadratic polynomial model and regression coefficients have been obtained. The quadratic polynomial model applied in the response surface analysis took the following form:

$$y = a_0 + \sum_{i=1}^{3} a_i x_i + \sum_{i=1}^{3} a_i x_i^2 + \sum_{i=1}^{3}\sum_{j>i}^{3} a_{ij} x_i x_j \quad (9)$$

Here, a_0, a_i and a_{ij}(coefficients) denote the intercept, linear, quadratic, and interaction terms, respectively. x_i and x_j stand for the coded independent variables. All model coefficients were established through multiple regression analysis, and the significance of these coefficients was scrutinized using analysis of variance (ANOVA).

To ensure a comprehensive exploration of the parameter space and minimize potential biases, trials were conducted in a random order, this systematic approach aimed at enhancing the reliability and validity of the experimental results. Fitting the response surface involved the application of a generalized quadratic polynomial model tailored for a three-factor analysis. This model effectively and significantly shows how the important factors and their effects are connected [20, 21] providing a detailed insight into the drying process. An optimization was undertaken to minimize both drying time and energy consumption, Results were explained through Pareto charts general trends, 3D response surface, and empirical mathematical model.

3. Results and Discussion

18 trials were carried out based on the experimental design as shown in Table 4, according to different independent variables: Temperature (X_1), velocity (X_2) and intermittency ratio (X_3), the response variables: Time and energy consumption, obtained of each trial are also presented.

Table 3. Mathematical models given by various authors for the drying curves.

N°	Models	Equations	References
01	Newton (Lewis, Exponential, single exponential) Model	MR = exp (-kt)	[22]
02	Page Model	MR = exp (- k(t) ^{n})	[23]
03	Modified Page Model	MR = exp (- (kt) ^{n})	[24]
04	Henderson and Pabis (single term, generalized exponential) Model	MR = a exp (-kt)	[25]
05	Logarithmic (Asymptotic,Yagcioglu et al.) Model	MR = a exp (-kt) +b	[26]
06	Midilli-Kucuk (Midilli, Midilli et al.) Model	MR = a exp (- kt ^{n}) + bt	[24]
07	Approximation of Diffusion (Diffusion Approach) Model	MR = a exp(-kt) +(1-a) exp (-kbt)	[27]

3.1.1 Analysis of variance (ANOVA) and estimated regression of each response

ANOVA is utilized to evaluate the accuracy and statistical significance of the quadratic model by examining the coefficients of determination (R^2 = 0.9087) for time and (R^2 = 0.8934) for energy consumption as responses, along with the associated P-values. The obtained P-values, which are both less than 0.05 (0.0027 for time and 0.0048 for energy consumption), indicate statistical significance. Thus, it can be concluded that the model significantly accounts for the variability observed in the responses, additionally diagnostic plots as shown in Figure 2, guarantee the accuracy of the model and illustrate the relationship between observed and predicted outcomes. The data points closely align with the straight line on the plot, indicating a strong agreement between the two datasets. Additionally, the data were normally distributed, affirming the statistical validity of the model. The experimental data was subjected to multiple linear regression analysis, resulting in the development of second-order polynomial equations to analyze the input variables data and correlate response function to coded variables and thus ascertain the notable impacts of process variables on each response [28]

To demonstrate the collective impact of two factors on a given response, response surface and contour plots were created for each fitted model, showcasing the relationship between two independent variables while holding the other constant at its central value. Three distinct response surface plots were presented, and the effects of variables on responses were analyzed through the interpretation of these plots.

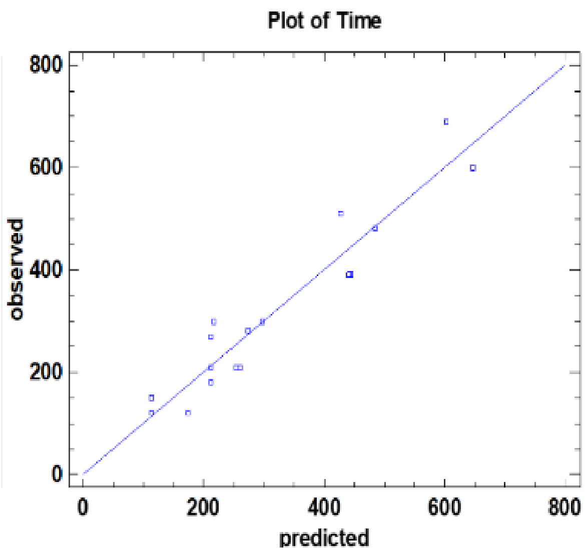

Figure 2.a. Diagnostic plots of energy consumption as response.

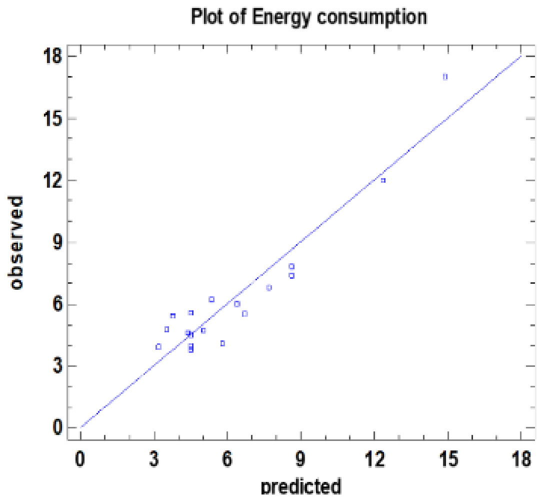

Figure 2.b. Diagnostic plots of energy consumption as response.

Table 4. The matrix of central composite design (CCD) and responses obtained from experimental tests.

Run	Independent variables			Responses	
	X_1 (°C)	X_2 (m/s)	X_3	Energy (kwh)	Time(min)
1	46	1.4	0.36	5.4	690
2	64	1.4	0.36	4.1	210
3	46	4	0.36	7.8	480
4	64	4	0.36	6.2	300
5	46	1.4	0.84	6	390
6	64	1.4	0.84	4.8	150
7	46	4	0.84	17	510
8	64	4	0.84	5.5	120
9	40	2.7	0.6	7.4	600
10	70	2.7	0.6	3.9	120
11	55	0.5	0.6	4.7	300
12	55	5	0.6	12	210
13	55	2.7	0.2	4.6	390
14	55	2.7	1	6.8	280
15	55	2.7	0.6	5.6	270
16	55	2.7	0.6	3.8	180
17	55	2.7	0.6	4.5	210
18	55	2.7	0.6	4	180

3.1.2 Effect of independent factors on drying time

The drying time is an important metric to consider when evaluating the effectiveness of a drying process. It has a substantial influence on the final product's quality attributes in addition to its function in process evaluation, even though this study does not specifically address the quality attributes of the dried dates, it is reasonable to assume that shorter exposure to heat during the drying process preserves the product's quality and minimizes the risk of quality degradation [29]. In other words, reducing the intermittency ratio leads to less effective drying time, which is favorable for quality and thus reducing the amount of time a product is exposed to heat, which is consistent with one of the objectives of improving both product quality and customer satisfaction. The ANOVA analysis of rehydrated dates samples shows that the linear terms: drying temperature and intermittency ratio and their square terms had a significant effect on drying time (P-value <0.05), however the velocity was not significant as presented in Table 5, moreover it can be seen from the table that for all the interaction terms and square term of velocity, the P-values are greater than 0.05 which indicate their insignificancy. The regression analysis yielded the following actual equation representing the relationship between drying time and the input variables:

$$\begin{aligned} Time\ [min] = {} & 4168{,}95 - 95{,}7787 X_1 \\ & - 219{,}601\, X_2 - 1645{,}65\, X_3 \\ & + 0{,}671208\, X_1^2 + 1{,}60256 X_1\, X_2 \\ & + 1{,}73611\, X_1\, X_3 + 12{,}9856\, X_2^2 \\ & + 84{,}1346\, X_2\, X_3 + 924{,}905\, X_3^2 \end{aligned} \qquad (10)$$

Three dimensional response surface plots have been demonstrated to interpret the effect of drying factors on drying time, Figure 3 illustrates the effect of temperature, intermittency ratio and velocity on drying time, it can be seen that changes in velocity have negligible impact, if any, on the drying time, similar results have been found in literature [30], When the moisture content in the food sample is high, the effect of air velocity on the drying rate becomes notable [31] and vice versa as is the case in this study since the initial moisture content for the rehydrated dates is low (33% w.b). When the moisture content is low, the dominant mechanism in drying is the transfer of water from the center of the sample to its surface, neglecting the influence of external factors such as air velocity. Increasing the velocity of the drying air may seem intuitive for accelerating drying through enhanced evaporation, but in this scenario, it would have little to no effect. The figures illustrate that reducing the intermittency ratio to a moderate level (0.55-0.85) can slightly decrease drying time as depicted more clearly in Figure 4. This reduction, although minor, is favorable. As previously discussed, minimizing heat exposure time enhances product quality [32]. Therefore, the key observation here is that decreasing the intermittency ratio does not lengthen drying time, except for low ratios. The critical factor here is temperature, as its increase significantly reduces drying time as shown in Figure 3.

Figure 5 displays the Pareto chart generated for drying time as the response variable. It is evident that both the linear and squared terms of temperature and intermittency ratio surpass the reference line, set at 2.365, indicating their significance in influencing drying time. Notably, temperature emerges as the most influential parameter.

Table 5. Analysis of variance for drying time and coefficients of predicted model.

Source	Coef estimate	Sum of squares	Df	Mean square	F-value	P-value
Model	4168,95		9			**0,0027**
A:Temperature (°C)	-95,7787	306629	1	306629	56,65	**0,0001**
B: Velocity (m/s)	-219,601	2749,42	1	2749,42	0,51	0,4963
C:Intermitteny ratio	-1645,65	35438,0	1	35438,0	6,55	**0,0337**
AA	0,671208	40303,5	1	40303,5	7,45	**0,0259**
AB	1,60256	2812,5	1	2812,5	0,52	0,4915
AC	1,73611	112,5	1	112,5	0,02	0,8889
BB	12,9856	6667,82	1	6667,82	1,23	0,2993
BC	84,1346	5512,5	1	5512,5	1,02	0,3425
CC	924,905	34574,4	1	34574,4	6,39	**0,0354**
Total error		43304,8	8	5413,11		
Total (corr.)		474494	17			

R-squared = 90,8735 percent

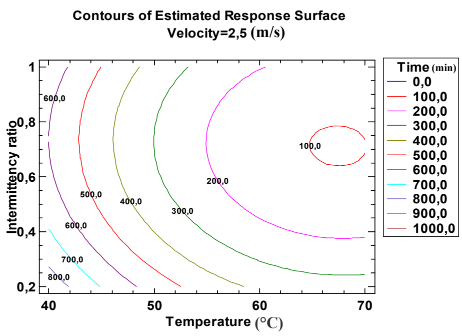

Figure 3. Contour plot showing the effect of intermittency ratio and temperature on dying time.

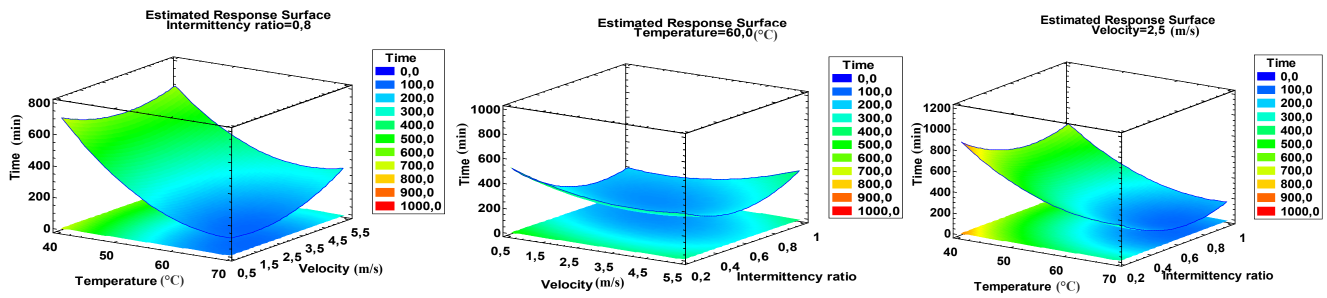

Figure 4. Response surface plot showing the effect of different parameters on drying time.

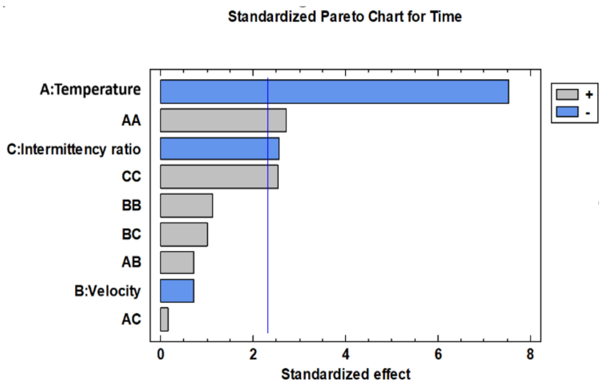

Figure 5. Pareto chart of the standardized effects on drying time.

3.1.3 Effect of independent factors on energy consumption

The ANOVA analysis of rehydrated date samples for energy consumption as a response is presented in Table 6, showing that all the drying parameters significantly ($p < 0.05$) influenced the energy consumption in linear terms, velocity influenced energy consumption in both square position and interaction term with temperature. Regression analysis yielded the following actual equation representing the relationship between energy consumption and the input variables:

$$Energy\ [kwh] = 2{,}40312 - 0{,}131673 X_1 + 1{,}6813\ X_2 + 15.931\ X_3 + 0{,}00552558\ X_1^2 + 0.113248\ X_1 + 0.56713\ X_1\ X_3 + 0.808506\ X_2^2 + 2.88462\ X_2\ X_3 + 9{,}67664\ X_3^2 \quad (11)$$

The effect of interaction of the drying parameters on energy consumption are illustrated in Figure 6. At constant intermittency ratio, the lowest energy consumption is observed when the inlet temperature is high and the air velocity is low, similar results were obtained by Majdi et al, [30] and Beigi [33], when air velocity is high, heaters consume more energy to maintain the desired temperature additionally to energy consumed by the fan which lead to maximum energy consumption. At constant moderate velocity, decreasing intermittency ratio from 1 to 0.3 with low temperatures reduces the total energy consumption up to 60%, this result is consistent with what found by Hajji et al [34] where increasing tempering periods (thus decreasing intermittency ratio) at 40°C led to energy consumption savings.

However, when drying at high temperatures, the effect of intermittency ratio becomes negligible, and energy consumption reaches its minimum value. This phenomenon may be attributed to the relatively small range of moisture content present in the samples studied, which accelerates the drying process, thereby limiting the opportunity for intermittent drying cycles to have a significant impact. In such cases, the rapid removal of moisture content at high temperatures may overshadow the potential energy savings that could be achieved through intermittent drying strategies.

Table 6. Analysis of variance for energy consumption and coefficients of predicted model.

Source	Coefficient estimate	Sum of squares	Df	Mean square	F-value	P-value
Model	2,40312		9			**0,0048**
A: Temperature (°C)	-0,131673	32,2525	1	32,2525	13,03	**0,0069**
B: Velocity (m/s)	1,6813	56,3298	1	56,3298	22,76	**0,0014**
C:Intermittency ratio	15,931	13,2317	1	13,2317	5,35	**0,0495**
AA	0,00552558	2,73139	1	2,73139	1,10	0,3242
AB	-0,113248	14,045	1	14,045	5,67	**0,0444**
AC	-0,56713	12,005	1	12,005	4,85	0,0588
BB	0,808506	25,8479	1	25,8479	10,44	**0,0120**
BC	2,88462	6,48	1	6,48	2,62	0,1443
CC	9	3,78451	1	3,78451	1,53	0,2513
Total error		19,8009	8	2,47512		
Total (corr.)		185,783	17			

R-squared = 89,3419 percent

3.2 Optimum Drying Conditions

The optimum conditions were estimated using Statgraphics 18 software. The software simulation suggested a combination of drying variables that would provide minimum values for total drying time, and energy consumption. Product quality was not assessed in this study, but we assume that decreasing intermittency ratio thus minimizing heat exposure periods leads to better quality retention. Therefore, in the present study, the optimal intermittent drying parameters were determined as temperature of 66°C (X_1), velocity of 2.5 m/s (X_2), and intermittency ratio of 0.7 (X_3). The values of drying time and energy consumption for final dried dates dried at these conditions were predicted as 96 minutes and 3 kwh respectively. These are best results in terms of achieving efficient drying, reducing drying time, and minimizing energy consumption. By carefully controlling and maintaining these optimal conditions, the drying process can be carried out effectively and with optimal efficiency. Figure 7 illustrates the desirability plot showcasing the performance of combined temperature and intermittency ratio at the

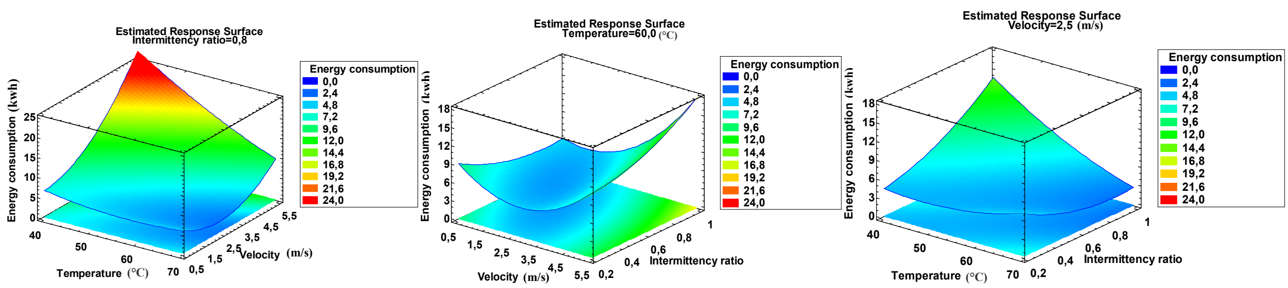

Figure 6. Response surface plot showing the effect of different parameters on energy consumption.

Table 7. Validation tests for predicted and experimental values of response surface model.

	Validation test 1		Validation test 2	
Drying parameters	$X_1 = 60°C$, $X_2=2$ m/s, $X_3=0.7$		$X_1 = 70°C$, $X_2=4$ m/s, $X_3=0.5$	
Response's result	Predicted	Experimental	Predicted	Experimental
Drying time (min)	135	150	168	150
Energy consumption (kwh)	3.51	3.8	4.51	4.3

optimum air velocity. This plot offers a comprehensive overview of the desirability values ranging from 0 to 1, representing the degree of fulfillment of multiple criteria simultaneously. By analyzing the desirability values across various combinations of temperature and intermittency ratio at the optimal air velocity, we can discern the most favorable conditions that strike the best balance between conflicting objectives. This visualization aids in identifying the optimal parameter settings that maximize performance and efficiency in the drying process.

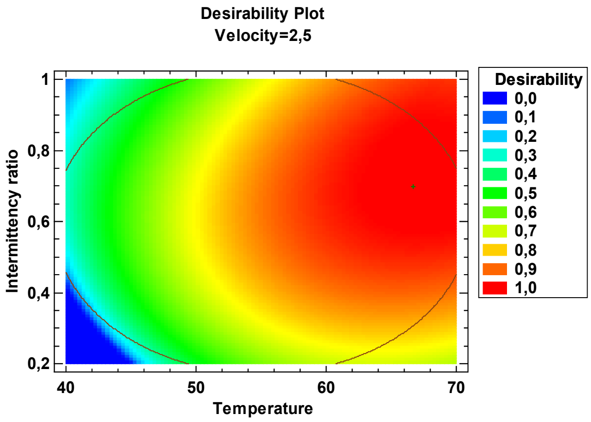

Figure 7. Contour plot illustrating optimal conditions for desirability as function of temperature and intermittency ratio at the optimum velocity.

3.3 Validation Tests

Validation tests was performed in order to validate the adequacy of response surface models by running other tests with random drying conditions and compare it with the predicted responses, two experiments were carried out under different drying conditions as mentioned in Table 7, the differences between the predicted and experimental values are not extreme indicating that the response surface models for the response were acceptable.

3.4 Modeling of Drying Kinetics of Rehydrated Dates

Figure 8 illustrates the variations in moisture ratio over time during intermittent drying of dates. A notable common feature observed in the depicted curves is their tendency towards a declining drying rate, indicative of the falling rate period of the drying curve. This characteristic can be attributed to the relatively low initial moisture content of rehydrated dates used in the experiments.

Seven drying models were employed to characterize drying curves, with their respective model numbers, constants or coefficients, and correlation coefficients presented in Table 3. Model selection was based on the criterion of the highest coefficient of determination (R^2), the lowest reduced chi-square (χ^2), and root mean square error (RMSE). In comparison with other models, the Midilli-Kucuk model, the Algorithmic model, and the approximation of diffusion model, respectively, gave the best agreement between the experimental and predicted moisture ratio.

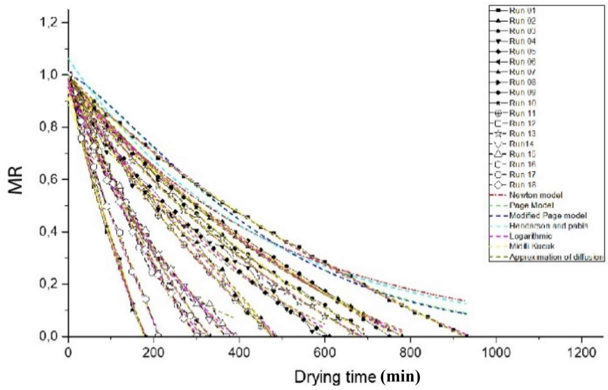

Figure 8. Moisture ratio removed variation under different drying conditions using Midilli-Kucuk, algorithmic and the approximation of diffusion models.

4. Conclusion

The rehydrated dates were dried from an initial moisture content of approximately 33% w.b to a target moisture content of 25% w.b for safe storage using the convective drying method. The experiments were conducted within the range of air temperatures of 40–70 °C, air velocities ranging from 0.5 to 5 m/s, and intermittency ratios spanning from 0.2 to 1, utilizing Response Surface Methodology (RSM) with a Central Composite Design and employing a desirability function. The responses targeted for optimization were drying time and energy consumption. While air velocity did not significantly impact drying time, it negatively affected energy efficiency. Conversely, air temperature played a crucial role in all responses; increasing tempering periods resulted in energy savings, especially at lower temperatures with minimal impact on total drying time. Overall, the findings suggest that energy savings and improved product quality can be achieved without extending total drying time.

The optimal conditions for minimizing both drying time and energy consumption were identified as an inlet temperature of 66 °C, air velocity of 2.5 m/s, and an intermittency ratio of 0.7.

The Midilli-Kucuk model demonstrated superior performance when compared to other models in characterizing the drying kinetics of intermittently dried rehydrated dates.

Nomenclature

α	Intermittency ratio
t_{on}	Time when drying is on (s)
t_{off}	Tempering period (s)
MR	Moisture ratio
w.b	Wet basis (%)

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