applied sciences

MDPI

Article

Ultrasonic-Microwave and Infrared Assisted Convective Drying of Carrot: Drying Kinetic, Quality and Energy Consumption

Yousef Abbaspour-Gilandeh [1,*], Mohammad Kaveh [1] and Muhammad Aziz [2,*]

1 Department of Biosystems Engineering, College of Agriculture and Natural Resources, University of Mohaghegh Ardabili, Ardabil 56199-11367, Iran; Sirwankaweh@gmail.com
2 Institute of Industrial Science, the University of Tokyo, Tokyo 153-8505, Japan
* Correspondence: abbaspour@uma.ac.ir (Y.A.-G.); maziz@iis.u-tokyo.ac.jp or maziz@kyudai.jp (M.A.)

Received: 19 August 2020; Accepted: 1 September 2020; Published: 10 September 2020

Abstract: In this study, the drying time, effective moisture diffusivity (D_{eff}), specific energy consumption (SEC), and quality (color, shrinkage, and rehydration) of the ultrasound-pretreated (US) carrot slices were compared when dried by hot air drying (HD), microwave drying (MWD), infrared drying (INFD), and hybrid methods of MW–HD and INF–HD. Five mathematical models were considered to describe the drying kinetics in the carrots. The results show that US+MW–HD and INFD were the fastest and the slowest drying techniques compared to the HD technique with a 73% and 23% drying time reduction, respectively. The D_{eff} ranged from 7.12×10^{-9} to 2.78×10^{-8} m^2/s. The highest and lowest SECs were 297.29 ± 11.21 and 23.75 ± 2.22 MJ/kg which were observed in the HD and US+MWD, respectively. The color variation indices indicated that the best sample in terms of color stability was the one dried by US+MW–HD with the color variation of 11.02 ± 0.27. The lowest and highest shrinkage values were also observed in the samples dried by US+MWD and HD (31.8 ± 1.1% and 62.23 ± 1.77%), respectively. Samples dried by US+MWD and HD possessed the highest and lowest rehydration, respectively. Although the carrot slices dried at a higher pace by US+MW–HD (compared to US+MWD), the shrinkage and SEC of the samples dried by US+MWD were significantly lower than the US+MW–HD ($p < 0.05$). Therefore, it can be concluded that the application of the US+MWD method can be considered as a proper alternative for drying the carrot slices when compared to the HD, MWD, INFD, and hybrid methods.

Keywords: mathematical modeling; color; moisture diffusivity; shrinkage; rehydration ratio

1. Introduction

With the scientific name of *Daucus carota*, the carrot is a biennial plant from the Umbelliferae family. This plant has inhomogeneous tissue and is cultivated all around the globe. Carrot has been recognized as a significant source of vitamins, minerals and other essential nutrients in the human diet [1]. Carrot is rich in carotenoids, calcium, potassium, and vitamins A, E, B, C and D with a significant influence on human health [2,3]. Dried carrots are often used in soup, sweets, sauce, and spices [4].

As most vegetables are available in a specific period (seasonal), due to their high abundance at their harvesting seasons and decline of their price, they may be corrupted. In this regard, processing methods can be helpful in their preservation and the prevention of spoilage. Moreover, they can be in hand in the other seasons as well.

Drying is one of the important procedures in the processing of the agricultural products after their harvest and is aimed to enhance their storage [5]. By the decrease in the product moisture during the drying process, their microorganism activities will be reduced which can prolong the life of the product. The significance of the agricultural products as a supply for human food has motivated numerous studies in the field of agricultural crop drying, drying kinetics, and modeling. The diversity in the properties of the agricultural products (their size, shape, and internal texture) has resulted in a wide difference in their drying process [6].

Among more than 50 types of commercialized industrial dryers, solar, hot air, infrared (INF), and microwave (MW) dryers have been utilized in various industries, including food and agriculture, paper, textile, and chemical industries. Despite their widespread application, each of these dryers has its own benefits and limitations (long process time, low yield, high energy consumption, and product quality loss) [7]. Thus, the use of new dryers in combination with these dryers is considered can improve their performance by exploiting their benefits and resolving their drawbacks. In this context, the ultrasonic (US) pretreatment system has gained considerable interest as a new technology for drying the products at high quality and low cost. The US technique is a novel technology that can be employed in combination with various techniques, including hot air drying (HD), microwave drying (MWD), vacuum drying, and infrared drying (INFD). It is mainly aimed to enhance the processing pace and improve the quality of the final product [8]. Due to their mechanical effects, ultrasonic waves can enhance the moisture loss of the product without generating high levels of heat. Therefore, the application of the ultrasonic waves in the hybrid drying techniques has been recommended in the cases where the appearance and nutritional content of the product are of high priority [9,10].

The application of the US in drying of the food and agricultural products has recently increased. Szadzinska et al. [11] dried strawberries using four different dryers (HD, MW–HD, HD–US, and MW–HD–US). They showed that the application of ultrasound can reduce the specific energy consumption (SEC), color variation, and drying time. They also expressed that the lowest SEC was observed in the hybrid HD–MWD, while the lowest variations were recorded for samples dried by HD–US dryers. Abbaspour-Gilandeh et al. [12] employed the US pretreatment at three durations of 10, 20, and 40 min in an HD under three temperatures (40, 50, and 60 °C) and three MW powers (270, 450, and 630 W) to compare the drying properties, SEC, and quality of the dried walnuts. According to their results, the application of US pretreatment in both dryers can significantly decline the drying time and SEC.

Recently, numerous researchers have employed various drying methods for different agricultural products and compared the properties of different dryers. Junqueira et al. [13] investigated the drying time and the quality of pumpkin slices dried by HD, MWD, and MW–HD hybrid dryers at different temperatures, inlet airspeeds, and powers. Their results indicated that drying the pumpkin slices by MWD was faster than the other methods. In addition, it was also described that the highest moisture diffusion coefficient and the lowest rehydration ratio were observed in the drying with MWD, while the lowest shrinkage and the highest color variations were detected in the samples dried by HD.

Xu et al. [14] dried broccoli by hot air, freezing, vacuum, MW–vacuum, and MW–hot air methods under different conditions and addressed some of the thermal and physical features of the products. They showed that the lowest SEC was obtained in the MWD; whereas the highest value was earned in the drying with the freezing dryer. The highest and lowest variations in the physical properties (color and shrinkage) were obtained in the HD and freezing dryer, respectively. Moreover, the maximum rehydration coefficient was detected in the freezing dryer.

The literature review indicated that a combination of US treatment with different drying schemes can improve the operational indices of the dryers. Regarding the significance of carrot and the need for its proper processing, it seems that the use of this technology can enhance the final product quality in addition to the reduction of processing time and energy consumption. Therefore, the aim of this study was to compare the drying kinetics, SEC, quality (shrinkage, color, and rehydration) of carrots dried through different methods (HD, MWD, INFD, INF–HD, and MW–HD) and US pretreatment. Moreover, a proper model was considered to describe the moisture ratio of the carrot slices dried by any of the mentioned techniques.

2. Materials and Methods

2.1. Materials

Fresh carrots were purchased from the local markets, and after sorting the samples, they were stored at 4 °C in a refrigerator. The samples were taken out from the refrigerator half an hour before the experiment to reach ambient temperature. Then, the carrots were sliced by a tunable slicer in 4 mm-thick slices with a diameter of 30.5 mm. To determine the initial moisture of the carrots, three samples were put in an oven (Memmert, UFB500, Schwabach, Germany) at 105 °C for 24 h to measure the dried weight [3]. The initial moisture of the carrots was 91.5% on a wet basis (w.b.).

2.2. Drying Treatments

2.2.1. Hot Air Dryer (HD)

In order to perform the experiments with this method, a hot air flow dryer, which was designed and fabricated in the Biosystem Engineering group of Mohaghegh Ardabili University, Iran, was used. To precisely determine the air circulation speed, a hot-wide anemometer (TES- 1340, Taipei, Taiwan) was employed. About 100 g of the carrot slices (in the form of a thin layer) were regularly placed on a meshed stainless steel tray (40×65 cm^2) and dried at 65 °C with the airspeed of 1 m/s. The weight measurements of dried carrot samples were performed with an HD dryer at intervals of 3 min.

2.2.2. Microwave Dryer (MWD)

In this method, a domestic MW oven with dimensions of $50 \times 30 \times 40$ cm^3 (Sharp R-I96T, Thailand) was used. It worked at the frequency of 50 Hz and a maximum thermal power of 900 W. In addition, its power could be set at 90, 180, 360, 450, 540, 630, and 900 W. About 90 g of the samples were dried as a thin layer with this method. After the samples reached a weight of 0.2 (d.b.), the drying was stopped. The weight of the samples was measured at intervals of 2 min.

2.2.3. Infrared Dryer (INFD)

The employed INFD possessed four INF lamps each with a power of 250 W. The lamps were situated above the samples at a 15 cm distance, and this dryer had the ability to control the lamp intensity. The drying procedure was conducted at the power of 500 W based on the error and trial. The dimensions of the dryer room were $70 \times 70 \times 50$ cm^3. Ninety-five grams of the samples were dried as a thin layer and the weight of the samples was measured at intervals of 3 min.

2.2.4. Microwave-Hot Air Dryer (MW–HD)

In this method, a hybrid MW–HD was designed and fabricated in the Biosystem Engineering group of Mohaghegh Ardabili University, Iran. This dryer included one centrifuge blower (1 hp, 3000 rpm), three air-heating elements, connecting tubes, a cylindrical container, MW, an inverter (LS, Gyeonggi-Do, Korea) for tuning the blower rotation speed, and a system to set the inlet air temperature. The main employed engine was a three-phase motor working at a rotation speed of 2800 rpm and a power of 250 W. To circulate the air and evacuate the moisture from the dryer container, a suction fan was employed. Two openings were embedded above the suction fan.

2.2.5. Infrared–Hot Air Dryer (INF–HD)

Similar to the MW–HD, a hybrid INF–HD dryer was also fabricated in the Biosystem engineering group of Mohaghegh Ardabili University, Iran. This dryer included a centrifuge fan (1 hp, 300 rpm), three elements with a total temperature of 1500, and four INF lamps each with a power of 250 W (total of 1000 W). K-type thermocouples (Lutron, TM-903, Taiwan, accuracy of ±0.1 °C) were also used to measure the air temperature inside the container. In addition, one thermostat (Atbin mega, Tehran, Iran) was employed to control the air temperature.

2.2.6. Ultrasonic Pretreatment (US)

To facilitate a US pretreatment of the carrot samples, a US bath (Panasonic 2600 s, 28 kHz, 70 W, Osaka, Japan) was employed. The carrot samples were placed in distilled water at 30 °C and exposed to US waves for 30 min. To achieve a uniform operation, the distilled water level in the US bath was raised to the recommended level. The details of the experiments are mentioned in Table 1.

Table 1. Description of the drying method.

No	Acronym	Description	Air		Power (W)		
			T (°C)	V (m/s)	MW	INF	US
1	HD	Hot air dryer	65	1	0	0	0
2	INFD	Infrared dryer	0	0	0	500	0
3	MWD	Microwave dryer	0	0	450	0	0
4	INF–HD	Infrared-assisted hot air dryer	65	1	0	500	0
5	MW–HD	Microwave-assisted hot air dryer	65	1	450	0	0
6	US+HD	Ultrasound-assisted hot air dryer	65	1	0	0	70
7	US+INFD	Ultrasound-assisted infrared dryer	0	0	0	500	70
8	US+MWD	Ultrasound-assisted microwave dryer	0	0	450	0	70
9	US+INF–HD	Ultrasound-assisted infrared-hot air dryer	65	1	450	0	70
10	US+MW–HD	Ultrasound-assisted microwave-hot air dryer	65	1	0	500	70

2.3. *Moisture Ratio, Drying Rate and Mathematical Model*

Having the initial moisture content of the product and its weight loss, the moisture and mass transport during the drying process can be determined by Equation (1) [15]:

$$MR = \frac{M_t - M_e}{M_b - M_e} \tag{1}$$

Furthermore, the drying rate of the carrot slices was calculated by Equation (2) [5,16]:

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \tag{2}$$

where MR is the moisture ratio (dimensionless), while M_t and M_e are the instant sample moisture and the equilibrium moisture (d.b.), respectively. M_b also denotes the initial moisture of the samples (d.b.). $M_{\mathrm{t + \Delta t}}$ is the moisture at t + Δt (g-water/g-dry-matter). Δt represents the time interval (min) and DR indicates the drying rate (g-water/g-dry-matter per min).

The majority of the thin-layer drying models of the agricultural, food, and pharmaceutical products rely on MR. MR can result in more uniform data and prevent their scattering [17]. Among the various drying models, five drying models shown in Table 2 were employed to model the agricultural product drying process whose data were compared with the experimental results of the present study. The thin-layer drying model was then selected as it exhibited a better coefficient of determination (R^2) and root mean square error (RMSE) values according to Equations (3) and (4):

$$R^2 = 1 - \frac{\sum_{i=1}^{N} [MR_{\exp,i} - MR_{pre,i}]^2}{\sum_{k=1}^{N} \left[\frac{\sum_{k=1}^{n} MR_{pre,i}}{N} - MR_{pre,i} \right]^2} \tag{3}$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} (MR_{pre,i} - MR_{\exp,i})^2 \right]^{\frac{1}{2}} \tag{4}$$

where N, z, $MR_{\mathrm{exp,i}}$ and $MR_{\mathrm{pre,i}}$ denote the number of observations, the number of the dryer constants, and the predicted and experimentally obtained MR of the i$^{\mathrm{th}}$ sample, respectively.

Table 2. Mathematical models for the prediction of the drying process.

Models	Equations	References
Page	$MR = \exp(-kt^n)$	[18]
Logarithmic	$MR = a\exp(-kt) + c$	[5]
Two-term	$MR = a\exp(-k_0 t) + b\exp(-k_1 t)$	[4]
Midilli et al.	$MR = a\exp(-kt^n) + bt$	[19]
Logistic	$MR = \frac{a}{(1+b\ \exp(kt))}$	[20]

a, b, c, and n are model parameters.

2.4. *Effective Moisture Diffusivity* ($\mathrm{D_{eff}}$)

The second Fick's law has been widely employed to describe the diffusion phenomenon during the drying of the agricultural products, as shown in Equation (5) [19]:

$$\frac{\partial X}{\partial t} = D_{eff}\frac{\partial^2 X}{\partial x^2} \tag{5}$$

where D_{eff} is the effective moisture diffusivity (m^2/s), while t and X represent the time (min) and spatial indices, respectively. In this law, it is assumed that the food sample is one-dimensional. After extending Equation (5) and applying the condition of long-term drying, the following equation can be written for the D_{eff} [21]:

$$MR = \frac{M_t - M_e}{M_b - M_e} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n+1)}\exp\left(\frac{-D_{eff}(2n+1)^2\pi^2 t}{4L^2}\right) \tag{6}$$

D_{eff} can be obtained from the slope (K) of ln(MR) plot versus time through Equation (7):

$$K = \left(\frac{D_{eff}\pi^2}{4L^2}\right) \tag{7}$$

where L denotes the half of the sample thickness (m).

2.5. *Specific Energy Consumption (SEC)*

SEC refers to the energy required to evaporate 1 kg of water from the carrot slices in different dryers (MJ/kg). The carrot samples were first pretreated by US; then, they were dried by different techniques. Regarding the various power sources of the different applied methods, the equations used for the calculation of SEC through US pretreatment and the HD, INFD, and MWD dryers are listed in Table 3. The SEC (kJ/kg) of the carrot slice drying can be determined by the following equation [6,22]:

$$SEC = \left(\frac{E_t}{M_w}\right) \tag{8}$$

where E_t is the energy consumption (kJ), EU_{ter} is the thermal energy consumption (kJ), A denotes the tray area (m^2), v represents the inlet air velocity (m/s), C_a represents the specific heat (kJ/kg·°C), ρ_a stands for air density (kg/m^3), ΔT is the temperature difference (°C), and t is the drying time (min). Moreover, EU_{mec} is the mechanical energy (kJ) and ΔP denotes the pressure difference (mbar). M_{air} is the volumetric flow rate of air (m^3/h), M_w represents the weight loss (kg), UP is the US power (W), while U and I are the applied voltage (V) and current (A) of the US generator, respectively. $Cos\ \varphi$ is the power factor and equals to 0.8. K is the lamp power (W).

$$EU_{ter} = (A\ v\ \rho_a\ C_a\ \Delta T\ t) \tag{9}$$

$$EU_{mec} = \Delta P\, M_{air}\, t \tag{10}$$

$$EU_{ter} = (A\, v\, \rho_a\, C_a\, \Delta T\, t + K\, t) \tag{11}$$

$$EU_{ter} = (P\, t)\, 3600 \tag{12}$$

$$UP = U\, I\, Cos\, \varphi \tag{13}$$

$$EU_{ter} = UP\, t \tag{14}$$

Table 3. Specific energy consumption (SEC) equations for different dryers and US pretreatment.

Energy Consumption at Dryer	Reference
E_t(HD) = Equations (9) + (10)	[10]
E_t(MW) = Equation (12)	[23]
E_t(MW–HD) = Equations (9) + (10) + (12)	[19]
E_t(US+INF) = Equations (11) + (14)	[24]
E_t(US+INF–HD) = Equations (10) + (11) + (14)	
E_t(INF) = Equation (11)	[25]
E_t(INF–HD) = Equations (10) + (11)	[26]
E_t(US+HD) = Equations (9) + (10) + (14)	[27]
E_t(US+MW) = Equations (12) + (14)	[28]
E_t(US+MW–HD) = Equations (9) + (10) + (12) + (14)	[12]

2.6. Color

The color variation of the carrot samples before and after the drying process were measured by a portable colorimeter (HP-200, China). To describe the color variations of the samples during the drying process, ΔE index (total color difference) was employed. This index is defined in Equation (15) in which L^* is the brightness index while b^* and a^* represent the yellow–blue and red–green indices, respectively [26,29]:

$$\Delta E = \sqrt{(L_0^* - L_i^*) + (a_0^* - a_i^*) + (b_0^* - b_i^*)} \tag{15}$$

0 and i subscripts stand for the fresh and dried samples, respectively.

2.7. Shrinkage

The carrot samples volume was measured by the toluene displacement method using a pycnometer device. Knowing the toluene density and the mean weight of the toluene-filled pycnometer, the volume of the samples inside the pycnometer can be determined, in this way, the volume of the sample before, and after drying was assessed. The shrinkage can be then determined by Equation (16) [30]:

$$Shrinkage = \frac{(\phi_i - \phi_f)}{\phi_i} \times 100 \tag{16}$$

In the above equation, φ_f is the final volume (cm^3) after drying and φ_i represents the initial volume of the samples (cm^3).

2.8. Rehydration Ratio (RR)

In order to measure the rehydration ratio of the samples, the samples were immersed in 150 mL distilled water at 50 °C for 1 h. Then, the samples were weighed after removing their surface water. The rehydration ratio was calculated by Equation (17) [19]:

$$RR = \frac{W_r}{W_d} \tag{17}$$

where W_r and W_d are the samples weights before and after the rehydration test, respectively.

3. Results

3.1. Kinetic and Drying Time

First, HD tests were performed to dry the carrot slices and considered as the standard for evaluation. Then, the effects of other dryers (single, hybrid and with US pretreatment) on the carrot slice drying were evaluated by studying the drying kinetics (drying time) (Table 4). Figure 1 shows the drying kinetics of the carrot slices dried by different dryers. Evidently, HD drying took significantly longer than the other methods (190 ± 10 min) ($p < 0.05$). According to Table 4, the use of MWD and INFD resulted in the faster drying process (55% and 23%, respectively). The use of MW radiation significantly affected the drying kinetics and accelerated the evaporation [31]. When INF–HD and MW–HD were employed, the carrot slices were dried at a higher pace at 28% and 50%, respectively. This shows that both MW radiation and INF illumination can accelerate the evaporation process. INFD and MWD waves, in combination with HD, can penetrate into the product and produce heat at the water sites, and this will displace the moisture from the center to the surface [29].

Table 4. Influence of the different drying methods on the drying parameters of carrots.

No	Drying Method	Drying Time (min)	Reduced Drying Time (%)	D_{eff} (m^2/s)	SEC (MJ/kg)
1	HD	190 ± 10g	-	7.12×10^{-9}	297.29 ± 11.21i
2	INFD	145 ± 7e	23	9.50×10^{-9}	120.83 ± 9.22f
3	MWD	85 ± 5c	55	1.79×10^{-8}	42.5 ± 3.22b
4	INF–HD	135 ± 10d	28	1.39×10^{-8}	186.49 ± 10.99h
5	MW–HD	95 ± 6c	50	1.43×10^{-8}	164.47 ± 8.24g
6	US+HD	170 ± 9f	10	8.28×10^{-9}	265.99 ± 4.44k
7	US+INFD	130 ± 6d	31	1.16×10^{-8}	54.58 ± 3.75c
8	US+MWD	70 ± 3b	63	2.09×10^{-8}	23.75 ± 2.22a
9	US+INF–HD	60 ± 4b	68	2.37×10^{-8}	111.9 ± 6.31e
10	US+MW–HD	50 ± 2a	73	2.78×10^{-8}	103.23 ± 4.89d

According to Figure 1 and the drying times reported in Table 4, the application of US pretreatment can reduce the drying time. This can be attributed to the cavitation phenomenon inside the product resulting in severe expansion and contraction which will eventually make the product texture spongy. Such a spongy texture can accelerate the moisture elimination compared to the conditions without the US pretreatment, and thus the application of ultrasound can decline the drying time [32,33]. The US+MW–HD was the most rapid drying technique since it dried the carrot slices 73% faster (compared to the HD method). This method benefited from the advantages of hybrid MW–HD as well as the US pretreatment resulting in a significant reduction of drying time. Different letters for the same segment represent statistically significant differences at a confidence level of 95%.

By investigating the walnut kernel drying by different methods (HD, MWD with US pretreatment), Abbaspour-Gilandeh et al. [12] concluded that US pretreatment can shorten the drying time in both methods. According to Kroehnke et al. [34], who studied the drying carrot by different methods (HD and MVD with US pretreatment), the longest drying time was observed in the samples dried by the HD method. They declared that the US pretreatment can shorten the drying time. Similar results were also reported by the other researchers, for instance: Szadzinska et al. [28] for drying raspberries, Cao et al. [35]

for drying broccoli floret, Szadzinska et al. [36] for drying red beetroot, and Samani et al. [37] for drying *Kelussia odoratissima*.

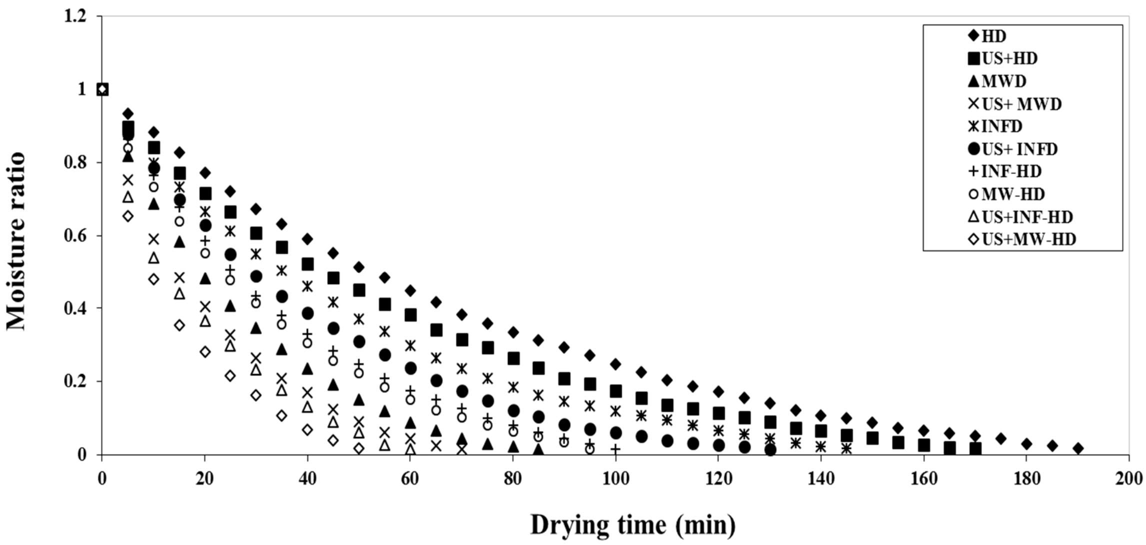

Figure 1. Drying kinetic of the carrot samples pretreated with ultrasound in different drying methods.

3.2. Drying Rate

The drying rates of the different dryers were calculated and their variation by time was plotted in Figure 2. At the beginning of the drying process, the product moisture content was high; thus, the moisture loss occurred at a higher pace. The evaporation rate of the product was gradually decreased by the decrease in the moisture content. The obtained results indicated that at the initial seconds, the evaporation rates showed a rapid enhancement for all treatments and reached a peak at which the evaporation rate was maximal. Then, by the passing of time and the decrease in the product moisture content, the evaporation rate decreased as well. According to Figure 2, the highest evaporation rate was observed in US+MW–HD (0.61 kg-water/(kg-dried-matter·min) while the HD method exhibited the lowest drying rate (0.11 kg-water/(kg-dried-matter·min) ($p < 0.05$). This is due to the increase in the internal mass transport resistance as the result of passing of time [31]. The results obtained by studying the raspberries drying with various dryers showing that the highest and the lowest evaporation rates were detected in MW–HD and HD, respectively [38]. Moreover, the application of US pretreatment increased the evaporation rate in comparison with the conditions in which no pretreatment was considered. It seems that US can cause pores in the carrot slices (cavitation phenomenon) and form fine channels on the cell walls. By reducing the internal resistance against the moisture diffusion and the number of boundary layers, US pretreatment can provide a proper condition for accelerated moisture removal during the drying process [39].

In the study performed by Szadzinska et al. [28] on raspberries drying with various dryers (MWD and HD with US pretreatment), the lowest evaporation rate was detected in the hot air dryer. They also indicated that the application of US pretreatment can elevate the evaporation rate. Moreover, they reported that the highest evaporation rate was obtained by the hybrid MW–HD with US pretreatment. The impact of various dryers (HD, INFD and US pretreatment) on the evaporation rate of potato sweet was addressed by Rashid et al. [40]. They declared that the highest evaporation rate can be obtained by US pretreatment.

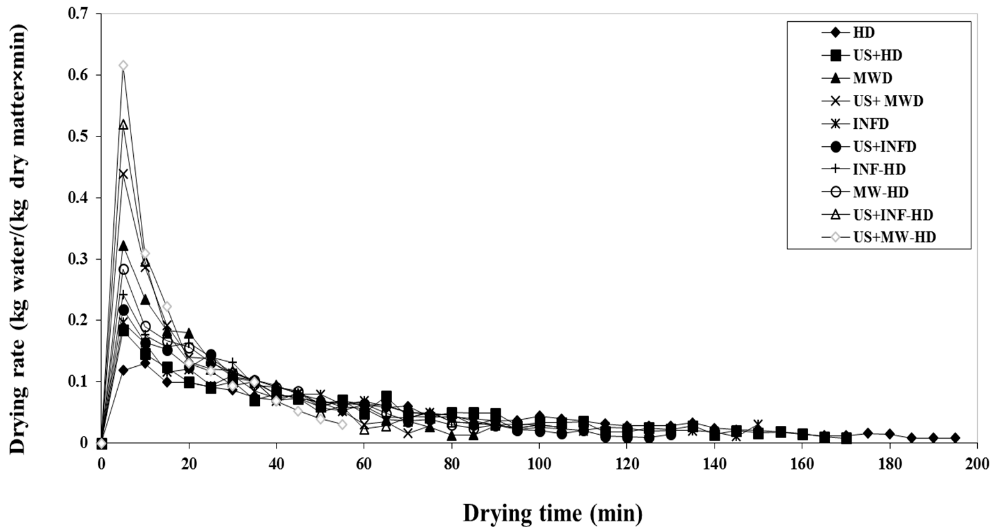

Figure 2. Drying rate of the carrot samples pretreated with ultrasound during different drying methods.

3.3. Modeling

After the determination of the MR of the pretreatments and fitting the model with the experimental data, R^2 and RMSE were obtained for each model in terms of all adopted dryers (Table 5). According to Table 5, R^2 of all models for all dryers varied in the range of 0.9937–0.9997, while their RMSE ranged from 0.0093 to 0.0612. Regarding Table 5, it can be said that the model of Midilli et al. could predict the *MR* of the carrot slices better as it showed the highest R^2 (0.9997) and the lowest RMSE (0.0093). Samani et al. [37] compared the mathematical model and experimental thin-film drying of *Kelussia odoratissima* using three different dryers (HD, US–INF–vacuum) under different conditions. Their results indicated that Page, modified Page, Handerson, and Pabis models performed better for HD, INFD, and US–INF–vacuum methods, respectively.

Table 5. Results of the non-linear regression analysis of different mathematical drying models.

Process	Page		Logarithmic		Two-Term		Midilli et al.		Logistic	
	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE
HD	0.9975	0.0284	0.9969	0.0339	0.9958	0.0452	0.9997	0.0105	0.9988	0.0175
INFD	0.9964	0.0396	0.9972	0.0305	0.9949	0.0537	0.9995	0.0116	0.9992	0.0145
MWD	0.9949	0.054	0.9962	0.0415	0.9955	0.0477	0.9989	0.0164	0.9979	0.0251
INF–HD	0.9967	0.0361	0.9975	0.0279	0.9968	0.0355	0.9992	0.0144	0.9985	0.0203
MW–HD	0.9977	0.0266	0.9982	0.0228	0.9978	0.0259	0.9995	0.0111	0.9986	0.0192
US+HD	0.9937	0.0612	0.9955	0.0482	0.9945	0.0569	0.9991	0.0155	0.9977	0.0268
US+INFD	0.9969	0.0344	0.998	0.0237	0.997	0.0321	0.9997	0.0101	0.9991	0.0151
US+MWD	0.9952	0.0503	0.9964	0.0392	0.9958	0.0449	0.9993	0.0132	0.9986	0.0194
US+INF–HD	0.9969	0.0347	0.9982	0.0226	0.998	0.024	0.9995	0.0118	0.9992	0.0139
US+MW–HD	0.9981	0.0234	0.9988	0.0172	0.9982	0.0223	0.9997	0.0099	0.9994	0.0124

3.4. D_{eff}

The D_{eff} of the carrot slices dried by different dryers was calculated by Doymaz et al. [2] method as listed in Table 4. According to the previous studies, the D_{eff} lies in the range of the 10^{-12}–10^{-7} m^2/s. As can be seen in Table 4, the D_{eff} of the carrot slices was in the same range for all applied dryers, reflecting a good consistency between this study and the previous ones. The highest D_{eff} was observed in the samples treated by the fastest drying method (i.e., US+MW–HD), which is 2.78×10^{-8} m^2/s; while the lowest value was for the slowest method (i.e., HD), which is 7.12×10^{-9} m^2/s) ($p < 0.05$). The application of US pretreatment increased the D_{eff} in all methods. US pretreatment opens capillary tubes due to the dispersion of the surface composition as well as the formation of the longer microscopic channels as the result of cellular deformations. Therefore, by deforming the cells and destroying the cell walls, US pretreatment can accelerate the moisture removal from the product [41]. Moreover, the application of the MW method can elevate D_{eff}, compared to the INFD and HD methods, because the MW power can increase the molecular movements of the water molecules and hence, enhance the D_{eff}.

Deepika and Sutar [21] dried lemon using various dryers (MW–HD and INF–HD) with different pretreatments (osmotic, blanching, and US). According to their results, the D_{eff} of the samples dried by INF–HD under various pretreatments varied from 1.01×10^{-9} to 8.44×10^{-9} m^2/s, while this range was 8.11×10^{-9}–4.05×10^{-8} m^2/s for those dried by MW–HD under various pretreatments. In the work of Szadzinska et al. [36], the D_{eff} of red beetroot ranged from 3.42×10^{-9} to 1.59×10^{-8} m^2/s for various dryers (HD, MW–HD and US pretreatment). The D_{eff} of apples dried by various dryers and US pretreatment ranged from 1.77 to 2.77×10^{-9} m^2/s [42]. In the study on the thermal properties of paddy under various drying methods (HD, INFD, and MW–rotary), Behera and Sutar [43] observed the lowest (0.81×10^{-8} m^2/s) and highest (3.68×10^{-8} m^2/s) D_{eff} obtained in the HD and MW–rotary dryers, respectively.

3.5. SEC

SEC is one of the major assessment parameters during the drying operation. The diminishing fossil fuel sources and their environmental concerns (greenhouse gas emissions), as well as the increase in the energy costs have motivated the industries to reduce their energy consumption [38]. The SEC of all dryers is listed in Table 4. The highest SEC was observed in the HD method (297.29 ± 11.21 MJ/kg) which could be due to the lower moisture loss of the product and hence, a prolonged drying time [14,22]. The lowest SEC was observed in US+MWD (23.75 ± 2.22 MJ/kg) which is only 1.73% of the total energy consumed during the drying ($p < 0.05$). By polarizing the water molecules, MW can increase the internal temperature of the product, destroy the product tissues, and form larger channels. This can prevent the surface hardening during the drying process and hence, better moisture loss; thus the SEC decreases [7,25]. According to Table 4, the methods involving the US pretreatment had a lower SEC compared to their corresponding US-free counterparts. This could be due to the fact that products, such as carrot, form a hard surface layer which may slow down the moisture removal from the surface. US pretreatment prevents the formation of such a layer which reduces the drying time and hence, the SEC [27,29]. Single dryers (MWD and INFD with respective SEC of 3.09 and 8.81% of the total energy consumption) had a lower SEC compared to the hybrid MW–HD and INF–HD methods.

Łechtanska et al. [44] used five types of dryers (HD, INF–HD, MW–HD, INF+MW–HD, and HD with MW and INF pretreatments) to dry green pepper. They reported that the highest energy consumption was observed in the HD method. Mierzwa et al. [38] employed HD, MW–HD and US pretreatment to dry raspberries; they observed that the highest SEC was in the HD method. Moreover, the US pretreatment decreased the energy consumption.

Kowalski et al. [8] applied HD and MW–HD dryers by US pretreatment to dry raspberries and they showed that the US pretreatment can reduce the SEC. Their results indicated that the largest energy consumption was obtained in HD without US pretreatment; thus, they concluded that US waves were able to decrease the SEC. Szadzinska et al. [11] also employed various dryers (HD, MW–HD, HD–US, MW–HD–US) to dry strawberries and declared that the application of HD can elevate the energy consumption.

3.6. Color

The color of the biological products is one of the major indices in the evaluation of the heat-induced damages. In marketing, color is one of the main concerns in product acceptance by consumers [45]. As a result of the study, the highest color variations (24.37 ± 0.57) were observed in HD method ($p < 0.05$). In these dryers, the product color became darker due to the long drying process. Moreover, the prolonged drying process also enhanced the level of non-enzymatic browning reaction, hence, elevating the color variation [3]. As suggested in Figure 3, the lowest color variations (11.02 ± 0.27) were observed in the samples dried by US+MWD–HD ($p < 0.05$). The application of US pretreatment decreased the color variation in all the tested methods. As the lower color variation indicates the better performance of the drying process in preserving the product color, it can be said that the best color quality of the carrot slices can be achieved by US pretreatment combined with MW–HD which can be attributed to a higher drying rate of the mentioned method [46].

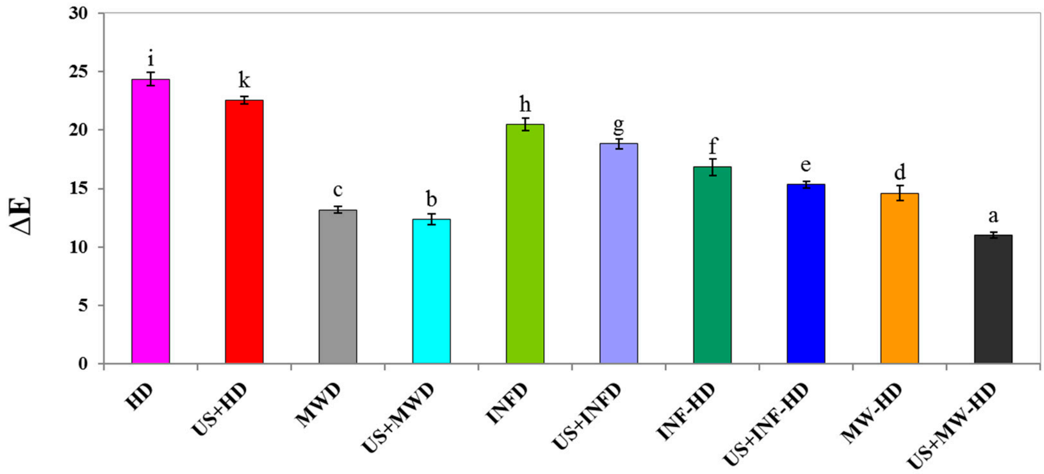

Figure 3. The effects of the different drying methods on the color values of carrots.

Jiang et al. [47] dried orka snacks by different dryers (HD, freezing, MWD, freezing–MWD, and MWD–HD) and observed that the lowest color variation was achieved in the MWD method. Łechtanska et al. [44] also used different dryers (HD, INF–HD, MW–HD, and US+MW–HD) to dry green pepper. They observed the highest color variation in the samples dried by the HD method along with the INF pretreatment; while the lowest color variation was related to those dried by HD combined with INF+MW pretreatments. In addition, Wang et al. [45] dried the gills of shiitake mushrooms by employing the HD, INFD, and MW–HD dryers and investigated their color variations. They recorded the highest color variation in the HD method, while the lowest value was obtained in the samples dried by MW–HD. The color variation of the broccoli samples dried by different dryers (HD, freezing, MWD, vacuum, MW–HD, and MW–vacuum) was investigated, and the highest and lowest color variations were observed in the samples dried by HD and freezing methods, respectively [14].

3.7. Shrinkage

Shrinkage can affect various physical properties, such as the porosity, density and hence, the final shape of the product, which is one of the major quality factors. According to Figure 4, the highest shrinkage was observed in the HD method (62.23 ± 1.77%) which might be due to the prolonged drying process ($p < 0.05$). The drying time in the HD method was very long, which resulted in cell wall decay and an increase in the shrinkage of the carrot slices [14]. As observed in Figure 4, the MWD treatment reduced the shrinkage. On the other hand, high water vapor pressure inside the carrot slices during MWD can expand the cells, known as the puffing effect. Therefore, the MWD-induced puffing effect can decrease the shrinkage in the carrot slices [48]. Moreover, US pretreatment can reduce the shrinkage in all drying methods (HD, INFD, MWD, INFD–HD, and MWD–HD) compared to the conditions without US pretreatment. The lowest shrinkage was recorded in US+MWD (31.8 ± 1.1%) ($p < 0.05$).

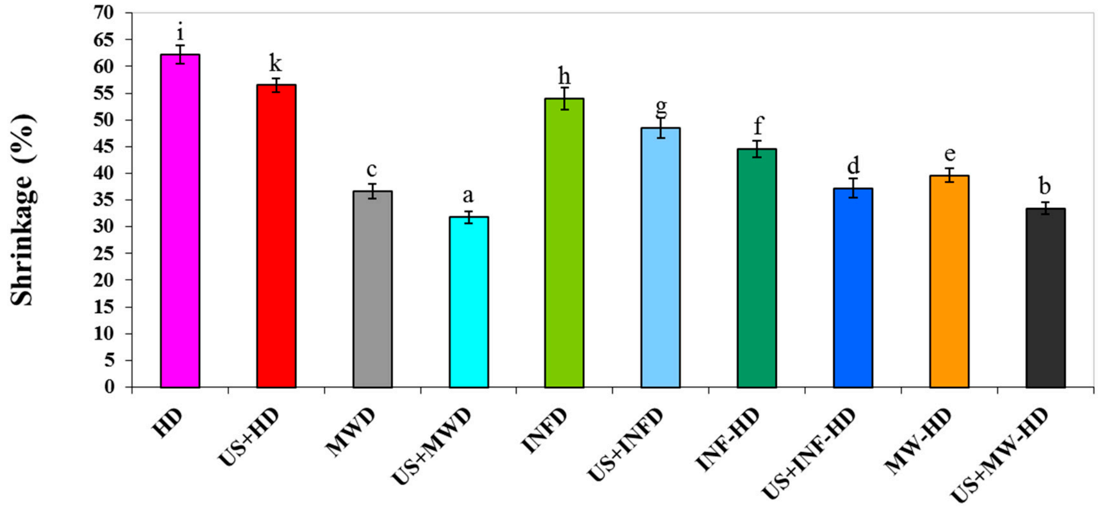

Figure 4. Shrinkage of the carrot samples by the different drying methods.

The application of the hybrid dryers (INF–HD and MW–HD) resulted in less shrinkage compared to the single dryers (HD, INFD, and MWD). This could be assigned due to the extensive internal heat generation which accelerated the water removal from the carrot tissues. In addition, Xu et al. [14] showed higher shrinkage in the broccolis dried by HD compared to those dried by freezing, MW–vacuum, vacuum, MW–vacuum–HD. In line with the present report, Jiang et al. [47] and Ashtiani et al. [49] reported that the highest shrinkage in okra snacks and nectarine slices was obtained with the HD method.

3.8. Rehydration Ratio

Rehydration is one of the prominent quality indices for dried food products. During the drying process, some undesired changes, such as textural variation, migration of the solutes and removal of the volatile compounds, may occur. Moreover, heat decreases the elasticity of the cell walls; hence, the water retention capacity of the dried sample decreased, resulting in the increase in shrinkage [50]. In this regard, rehydration can be recognized as one of the criteria to measure the structural damages to the food during the drying process [31]. Figure 5 represents the rehydration ratio values of the carrot slices dried by various methods. As can be observed, the lowest rehydration (4.08 ± 0.16) was detected in the samples dried by the HD method ($p < 0.05$).

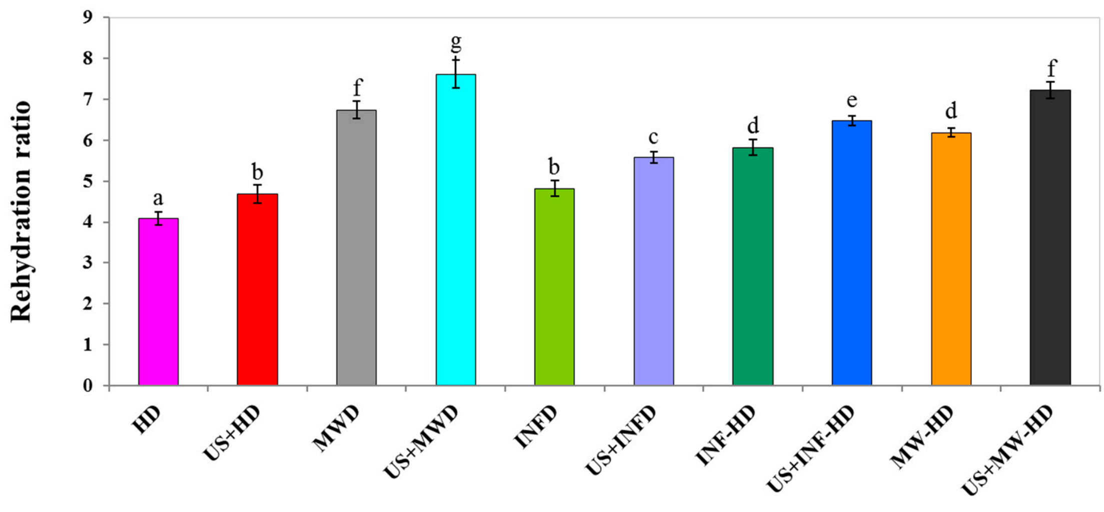

Figure 5. The effect of the different drying methods on the rehydration ratio of carrot.

HD took a relatively long drying time resulting in higher cellular damage and hence, the lowest rehydration. The highest rehydration ratio was observed in US+MWD (7.61 ± 0.34) ($p < 0.05$). Regarding the dependence of the rehydration on the cellular and structural damage extent and porosity level, it can be concluded that US+MWD caused lower damage to the texture and by causing more porosity increased the rehydration of the carrot slices [51]. Moreover, according to Figure 5, the US-pretreated samples exhibited higher rehydration values. Therefore, it can be concluded that US pretreatment reduced the textural damages and formed microscopic channels in the carrot slices [36]. Similar effects of US pretreatment were reported on the carrot, pear slices, and kiwifruit by Wiktor and Witrowa-Rajchert [52], Liu et al. [53], and Wang et al. [54], respectively.

In drying persimmon chips by different dryers (HD, MW–HD, and freezing vacuum), Jia et al. [55] observed the lowest and highest rehydration in HD and MW–HD, respectively. Roknul et al. [56] dried stem lettuce by hot air, hot air-assisted radio frequency, INFD, and MW–HD and observed the highest and lowest rehydration in the stem lettuce dried by INFD and hot air-assisted radio frequency methods, respectively.

4. Conclusions

The results of this study showed that drying with US pretreatment can effectively dry carrot. The application of US waves positively affected the kinetics of the process, quality, and SEC of all the studied techniques. Regarding the obtained results, carrot slices were dried rapidly in the US+MW–HD method. At the beginning of the drying process, the drying rate of the carrots was descending due to their high moisture content; at the end of the process, the drying rate declined due to low content of free moisture. The highest D_{eff} was observed in the US+MW–HD method. The lowest SEC and shrinkage (23.75 ± 2.22 MJ/kg and 31.8 ± 1.1%, respectively) were also detected in the US+MWD method. The rehydration ratio of the carrots dried by US+MWD was significantly higher than the other methods. The samples treated by HD also exhibited the highest SEC, shrinkage, and color variation, as well as the lowest rehydration ratio. Although the drying time was far lower in the US+MWD–HD method, the quality (shrinkage and rehydration) of the products produced by US+MWD was better. Moreover, US+MWD had lower energy consumption. Therefore, MWD along with US pretreatment can be considered as a proper technology to dry the carrot slices. Due to the shorter drying time, an increase in product quality, and lower energy consumption, this technique can be proposed for further commercial development.

Author Contributions: Conceptualization, Y.A.-G. and M.K.; methodology, Y.A.-G., M.K. and M.A.; software, M.K.; validation, Y.A.-G., M.K. and M.A.; formal analysis, Y.A.-G. and M.K.; investigation, Y.A.-G., M.K. and M.A.; resources, Y.A.-G., M.K. and M.A.; data curation, Y.A.-G. and M.K.; writing—original draft preparation, M.K.; writing—review and editing, Y.A.-G. and M.A.; visualization, M.K.; supervision, Y.A.-G.; project administration, Y.A.-G.; funding acquisition, Y.A.-G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the University of Mohaghegh Ardabili, Iran, under grant 19006-98-08-19.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kaveh, M.; Chayjan, R.A.; Taghinezhad, E.; Abbaspour-Gilandeh, Y.; Younesi, A.; Sharabiani, V.R. Modeling of thermodynamic properties of carrot product using ALO, GWO, and WOA algorithms under multi-stage semi-industrial continuous belt dryer. *Eng. Comput.* **2019**, *35*, 1045–1058. [CrossRef]
2. Doymaz, I. Drying kinetics, rehydration and colour characteristics of convective hot-air drying of carrot slices. *Heat Mass Transfer* **2017**, *53*, 25–35. [CrossRef]
3. Xu, B.; Wang, L.; Wei, B.; Zeng, R. Low frequency ultrasound pretreatment of carrot slices: Effect on the moisture migration and quality attributes by intermediate-wave infrared radiation drying. *Ultrason. Sonochem.* **2018**, *40*, 619–628.

4. Chen, Q.; Bi, J.; Chen, R.; Liu, X.; Wu, X.; Zhou, M. Comparative study on drying characteristic, moisture diffusivity, and some physical and nutritional attributes of blanched carrot slices. *J. Food Process. Preserv.* **2017**, *41*, e13201. [CrossRef]
5. Djebli, A.; Hanini, S.; Badaoui, O.; Haddad, B.; Benhamou, A. Modeling and comparative analysis of solar drying behavior of potatoes. *Renew. Energy* **2020**, *145*, 1494–1506. [CrossRef]
6. Ghanbarian, D.; Torki-Harchegani, M.; Sadeghi, M.; Pirbalouti, A.G. Ultrasonically improved convective drying of peppermint leaves: Influence on the process time and energetic indices. *Renew. Energy* **2020**, *153*, 67–73. [CrossRef]
7. Torki-Harchegani, M.; Ghanbarian, D.; Pirbalouti, A.G.; Sadeghi, M. Dehydration behaviour, mathematical modelling, energy efficiency and essential oil yield of peppermint leaves undergoing microwave and hot air treatments. *Renew. Sustain. Energy Rev.* **2016**, *58*, 407–418. [CrossRef]
8. Kowalski, S.J.; Pawłowski, A.; Szadzińska, J.; Łechtańska, J.; Stasiak, M. High power airborne ultrasound assist in combined drying of raspberries. *Innov. Food Sci. Emerg. Technol.* **2016**, *34*, 225–233. [CrossRef]
9. Siucińska, K.; Konopacka, D. Application of ultrasound to modify and improve dried fruit and vegetable tissue—A review. *Dry. Technol.* **2014**, *32*, 1360–1368. [CrossRef]
10. Rojas, M.L.; Silveira, I.; Augusto, P.E.D. Ultrasound and ethanol pre-treatments to improve convective drying: Drying, rehydration and carotenoid content of pumpkin. *Food Bioprod. Process.* **2020**, *119*, 20–30. [CrossRef]
11. Szadzinska, J.; Kowalski, S.J.; Stasiak, M. Microwave and ultrasound enhancement of convective drying of strawberries: Experimental and modeling efficiency. *Int. J. Heat Mass Transfer* **2016**, *103*, 1065–1074. [CrossRef]
12. Abbaspour-Gilandeh, Y.; Kaveh, M.; Jahanbakhshi, A. The effect of microwave and convective dryer with ultrasound pre-treatment on drying and quality properties of walnut kernel. *J. Food Process. Preserv.* **2019**, *43*, e14178. [CrossRef]
13. Junqueira, J.R.J.; Correa, J.L.G.; Ernesto, D.B. Microwave, convective, and intermittent microwave–convective drying of pulsed vacuum osmodehydrated pumpkin slices. *J. Food Process. Preserv.* **2017**, *41*, e13250. [CrossRef]
14. Xu, Y.; Xiao, Y.; Lagnika, C.; Song, J.; Li, D.; Liu, C.; Jiang, N.; Zhang, M.; Duan, X. A comparative study of drying methods on physical characteristics, nutritional properties and antioxidant capacity of broccoli. *Dry. Technol.* **2019**, in press. [CrossRef]
15. Das, M.; Akpinar, E.K. Investigation of pear drying performance by different methods and regression of convective heat transfer coefficient with support vector machine. *Appl. Sci.* **2018**, *8*, 215. [CrossRef]
16. Ozgen, F.; Celik, N. Evaluation of design parameters on drying of kiwi fruit. *Appl. Sci.* **2019**, *9*, 10. [CrossRef]
17. Motevali, A.; Minaei, S.; Khoshtaghaza, M.H.; Kazemi, M.; Nikbakht, A.M. Drying of pomegranate arils: Comparison of predictions from mathematical models and neural networks. *Int. J. Food Eng.* **2010**, *6*, 1–19. [CrossRef]
18. Kipcak, A.S.; Doymaz, I. Mathematical modeling and drying characteristics investigation of black mulberry dried by microwave method. *Int. J. Fruit Sci.* **2020**, in press. [CrossRef]
19. Wang, Y.; Li, X.; Chen, X.; Li, B.; Mao, X.; Miao, J.; Zhao, C.; Huang, L.; Gao, W. Effects of hot air and microwave-assisted drying on drying kinetics, physicochemical properties, and energy consumption of chrysanthemum. *Chem. Eng. Process.* **2018**, *129*, 84–94. [CrossRef]
20. Kaveh, M.; Abbaspour-Gilandeh, Y. Impacts of hybrid (convective-infrared-rotary drum) drying on the quality attributes of green pea. *J. Food Process Eng.* **2020**, *43*, e13424. [CrossRef]
21. Deepika, S.; Sutar, P.P. Combining osmotic–steam blanching with infrared–microwave–hot air drying: Production of dried lemon (Citrus limon L.) slices and enzyme inactivation. *Dry. Technol.* **2018**, *36*, 1719–1737. [CrossRef]
22. Kaveh, M.; Amiri Chayjan, R.; Taghinezhad, E.; Rasooli Sharabiani, V.; Motevali, A. Evaluation of specific energy consumption and GHG emissions for different drying methods (case study: Pistacia atlantica). *J. Clean. Prod.* **2020**, *259*, 120963. [CrossRef]
23. Motevali, A.; Minaei, S.; Banakar, A.; Ghobadian, B.; Khoshtaghaza, M.H. Comparison of energy parameters in various dryers. *Energy Convers. Manag.* **2014**, *87*, 711–725. [CrossRef]
24. Adabi, M.E.; Motevali, A.; Nikbakht, A.M.; Khoshtaghaza, M.H. Investigation of some pretreatments on energy and specific energy consumption drying of black mulberry. *Chem. Ind. Chem. Eng. Q.* **2013**, *19*, 89–105. [CrossRef]

25. Motevali, A.; Tabatabaei, S.R.T. A comparison between pollutants and greenhouse gas emissions from operation of different dryers based on energy consumption of power plants. *J. Clean. Prod.* **2017**, *154*, 445–461. [CrossRef]
26. Onwude, D.I.; Hashim, N.; Abdan, K.; Janius, R.; Chen, G. The effectiveness of combined infrared and hot-air drying strategies for sweet potato. *J. Food Eng.* **2019**, *241*, 75–87. [CrossRef]
27. Kaveh, M.; Taghinezhad, E.; Aziz, M. Effects of physical and chemical pretreatments on drying and quality properties of blackberry (Rubus spp.) in hot air dryer. *Food Sci. Nutr.* **2020**, *8*, 3843–3856. [CrossRef]
28. Szadzinska, J.; Łechtańska, J.; Pashminehazar, R.; Kharaghani, A.; Tsotsas, E. Microwave- and ultrasound-assisted convective drying of raspberries: Drying kinetics and microstructural changes. *Dry. Technol.* **2019**, *37*, 1–12. [CrossRef]
29. Szadzinska, J.; Łechtanska, J.; Kowalski, S.J.; Stasiak, M. The effect of high power airborne ultrasound and microwaves on convective drying effectiveness and quality of green pepper. *Ultrason. Sonochem.* **2017**, *34*, 531–539. [CrossRef]
30. Dehghannya, J.; Kadkhodaei, S.; Heshmatia, M.K.; Ghanbarzadeh, B. Ultrasound-assisted intensification of a hybrid intermittent microwave—Hot air drying process of potato: Quality aspects and energy consumption. *Ultrasonic* **2019**, *96*, 104–122. [CrossRef]
31. Horuz, E.; Bozkurt, H.; Karatas, H.; Maskan, M. Effects of hybrid (microwave-convectional) and convectional drying on drying kinetics, total phenolics, antioxidant capacity, vitamin C, color and rehydration capacity of sour cherries. *Food Chem.* **2017**, *230*, 295–305. [CrossRef] [PubMed]
32. Schössler, K.; Jäger, H.; Knorr, D. Effect of continuous and intermittent ultrasound on drying time and effective diffusivity during convective drying of apple and red bell pepper. *J. Food Eng.* **2012**, *108*, 103–110. [CrossRef]
33. Da Silva, E.S.; Brandão, S.C.R.; Da Silva, A.L.; Da Silva, J.H.F.; Coêlho, A.C.D.; Azoubel, P.M. Ultrasound-assisted vacuum drying of nectarine. *J. Food Eng.* **2019**, *246*, 119–124. [CrossRef]
34. Kroehnke, J.; Szadzińska, J.; Stasiak, M.; Radziejewska-Kubzdela, E.; Biegańska-Marecik, R.; Musielak, G. Ultrasound- and microwave-assisted convective drying of carrots—Process kinetics and product's quality analysis. *Ultrason. Sonochem.* **2018**, *48*, 249–258. [CrossRef]
35. Cao, Y.; Tao, Y.; Zhu, X.; Han, Y.; Li, D.; Liu, C.; Liao, X.; Show, P.L. Effect of microwave and air-borne ultrasoundassisted air drying on drying kinetics and phytochemical properties of broccoli floret. *Dry. Technol.* **2019**, in press. [CrossRef]
36. Szadzinska, J.; Mierzwa, D.; Pawłowski, A.; Musielak, G.; Pashminehazar, R.; Kharaghani, A. Ultrasound- and microwave-assisted intermittent drying of red beetroot. *Dry. Technol.* **2020**, *38*, 93–107. [CrossRef]
37. Samani, B.H.; Gudarzi, H.; Rostami, S.; Lorigooini, Z.; Esmaeili, Z.; Jamshidi-kia, F. Development and optimization of the new ultrasonic-infrared-vacuum dryer in drying Kelussia odoratissima and its comparison with conventional methods. *Ind. Crop Prod.* **2018**, *123*, 46–54. [CrossRef]
38. Mierzwa, D.; Szadzińska, J.; Pawłowski, A.; Pashminehazar, R.; Kharaghani, A. Nonstationary convective drying of raspberries, assisted by microwaves and ultrasound. *Dry. Technol.* **2019**, *37*, 988–1001. [CrossRef]
39. Jambrak, A.R.; Mason, T.J.; Paniwnyk, L.; Lelas, V. Accelerated drying of button mushrooms, Brussels sprouts and cauliflower by applying power ultrasound and its rehydration properties. *J. Food. Eng.* **2007**, *81*, 88–97. [CrossRef]
40. Rashid, M.T.; Ma, H.; Jatoi, M.A.; El-Mesery, H.S.; Wali, A.; Ali, Z.; Sarpong, F. Effect of infrared drying with multifrequency ultrasound pretreatments on the stability of phytochemical properties, antioxidant potential, and textural quality of dried sweet potatoes. *J. Food Biochem.* **2019**, *43*, e12809. [CrossRef]
41. Motevali, A.; Zabihnia, F. Effect of the different pre-treatments thermal, pulse, chemical and mechanical on the external mass transfer coefficient changes, moisture diffusion coefficient and activation energy. *J. Res. Innov. Food Sci. Technol.* **2017**, *6*, 221–320. (In Farsi)
42. Faruq, A.A.; Zhang, M.; Fan, D. Modeling the dehydration and analysis of dielectric properties of ultrasound and microwave combined vacuum frying apple slices. *Dry. Technol.* **2019**, *37*, 409–423. [CrossRef]
43. Behera, G.; Sutar, P.P. Effect of convective, infrared and microwave heating on drying rates, mass transfer characteristics, milling quality and microstructure of steam gelatinized Paddy. *J. Food Process. Eng.* **2018**, *41*, e12900. [CrossRef]
44. Łechtanska, J.M.; Szadzinska, J.; Kowalski, S.J. Microwave- and infrared-assisted convective drying of green pepper: Quality and energy considerations. *Chem. Eng. Process.* **2015**, *98*, 155–164. [CrossRef]

45. Wang, Q.; Li, S.; Han, X.; Ni, Y.; Zhao, D.; Hao, J. Quality evaluation and drying kinetics of shitake mushrooms dried by hot air, infrared and intermittent microwave–assisted drying methods. *LWT* **2019**, *107*, 236–242. [CrossRef]
46. Zielinska, M.; Zielinska, D.; Markowski, M. The effect of microwave-vacuum pretreatment on the drying kinetics, color and the content of bioactive compounds in osmo-microwave-vacuum dried cranberries (Vaccinium macrocarpon). *Food Bioprocess Technol.* **2018**, *11*, 585–602. [CrossRef]
47. Jiang, N.; Zhang, Z.; Li, D.; Liu, C.; Zhang, M.; Liu, C.; Wang, D.; Niu, L. Evaluation of freeze drying combined with microwave vacuum drying for functional okra snacks: Antioxidant properties, sensory quality, and energy consumption. *LWT* **2017**, *82*, 216–226. [CrossRef]
48. Aydogdu, A.; Sumnu, G.; Sahin, S. Effects of microwave-infrared combination drying on quality of eggplants. *Food Bioprocess Technol.* **2015**, *8*, 1198–1210. [CrossRef]
49. Ashtiani, S.H.M.; Sturm, B.; Nasirahmadi, A. Effects of hot-air and hybrid hot air-microwave drying on drying kinetics and textural quality of nectarine slices. *Heat Mass Transfer* **2018**, *54*, 915–927. [CrossRef]
50. Ricce, C.; Rojas, M.L.; Miano, A.C.; Siche, R.; Augusto, P.E.D. Ultrasound pre-treatment enhances the carrot drying and rehydration. *Food Res. Int.* **2016**, *89*, 701–708. [CrossRef]
51. Doymaz, I. Air-drying characteristics of tomatoes. *J. Food Eng.* **2008**, *78*, 1291–1297. [CrossRef]
52. Wiktor, A.; Witrowa-Rajchert, D. Drying kinetics and quality of carrots subjected to microwave-assisted drying preceded by combined pulsed electric field and ultrasound treatment. *Dry. Technol.* **2020**, *38*, 176–188. [CrossRef]
53. Liu, Y.; Zeng, Y.; Wang, Q.; Sun, C.; Xi, H. Drying characteristics, microstructure, glass transition temperature, and quality of ultrasound-strengthened hot air drying on pear slices. *J. Food Process. Preserv.* **2019**, *43*, e13899. [CrossRef]
54. Wang, J.; Xiao, H.-W.; Ye, J.-H.; Wang, J.; Raghavan, V. Ultrasound pretreatment to enhance drying kinetics of kiwifruit (Actinidia deliciosa) slices: Pros and Cons. *Food Bioprocess Technol.* **2019**, *12*, 865–876. [CrossRef]
55. Jia, Y.; Khalifa, I.; Hu, L.; Zhu, W.; Li, J.; Li, K.; Li, C. Influence of three different drying techniques on persimmon chips' characteristics: A comparison study among hot-air, combined hot-air-microwave, and vacuum-freeze drying techniques. *Food Bioprod. Process.* **2019**, *118*, 67–76. [CrossRef]
56. Roknul, A.S.M.; Zhang, M.; Mujumdar, A.S.; Wang, Y. A comparative study of four drying methods on drying time and quality characteristics of stem lettuce slices (*Lactuca sativa* L.). *Dry. Technol.* **2014**, *32*, 657–666. [CrossRef]