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

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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 $7.12 \times 10^{-9}$ to $2.78 \times 10^{-8} \, \text{m}^2/\text{s}$. 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 cm²) 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 × 30 × 40 cm³ (Sharp R-196T, 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 × 70 × 50 cm³. 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.

| No | Acronym | Description | Air | Power (W) |
|----|---------|-------------|-----|-----------|
|    |         |             | T    | 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        | 450| 0   | 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]:

\[ MR = \frac{M_t - M_e}{M_b - M_e} \]  

(1)

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

\[ DR = \frac{M_t + \Delta t - M_t}{\Delta t} \]  

(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.). \( M_t + \Delta t \) is the moisture at \( t + \Delta t \) (g-water/g-dry-matter). \( \Delta t \) 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):

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

(3)

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

(4)
where $N$, $z$, $MR_{exp,i}$ and $MR_{pre,i}$ denote the number of observations, the number of the dryer constants, and the predicted and experimentally obtained $MR$ of the $i$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        | $MR = a \exp(-kt) + b \exp(-kt_l)$                                      | [4]        |
| Midilli et al.  | $MR = a \exp(-kt^n) + bt$                                               | [19]       |
| Logistic        | $MR = \frac{a}{(1 + t \exp(t_l))}$                                      | [20]       |

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

#### 2.4. Effective Moisture Diffusivity ($D_{\text{eff}}$)

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]:

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

where $D_{\text{eff}}$ 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 $D_{\text{eff}}$ [21]:

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

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

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

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]:

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

where $E_t$ is the energy consumption (kJ), $EU_{\text{ter}}$ 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), $\rho_a$ stands for air density (kg/m$^3$), $\Delta T$ is the temperature difference (°C), and $t$ is the drying time (min). Moreover, $EU_{\text{mech}}$ is the mechanical energy (kJ) and $\Delta P$ 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. $\cos \phi$ is the power factor and equals to 0.8. $K$ is the lamp power (W).

$$EU_{\text{ter}} = (A v \rho_a C_a \Delta T t)$$
\[ \text{EU}_{\text{mec}} = \Delta P M_{\text{air}} \ t \]  
\[ \text{EU}_{\text{ter}} = (A \ \rho_a \ C_a \ \Delta T \ t + K \ t) \]  
\[ \text{EU}_{\text{ter}} = (P \ t) \ 3600 \]  
\[ U_{IP} = U I \cos \phi \]  
\[ \text{EU}_{\text{ter}} = U_{IP} \ t \]

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

| Energy Consumption at Dryer | Reference |
|-----------------------------|-----------|
| \( E_t(\text{HD}) = \text{Equations (9) + (10)} \) | [10] |
| \( E_t(\text{MW}) = \text{Equation (12)} \) | [23] |
| \( E_t(\text{MW–HD}) = \text{Equations (9) + (10) + (12)} \) | [19] |
| \( E_t(\text{US+INF}) = \text{Equations (11) + (14)} \) | [24] |
| \( E_t(\text{US+INF–HD}) = \text{Equations (10) + (11) + (14)} \) | |
| \( E_t(\text{INF}) = \text{Equation (11)} \) | [25] |
| \( E_t(\text{INF–HD}) = \text{Equations (10) + (11)} \) | [26] |
| \( E_t(\text{US+HD}) = \text{Equations (9) + (10) + (14)} \) | [27] |
| \( E_t(\text{US+MW}) = \text{Equations (12) + (14)} \) | [28] |
| \( E_t(\text{US+MW–HD}) = \text{Equations (9) + (10) + (12) + (14)} \) | [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, \( \Delta E \) 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]:

\[ \Delta E = \sqrt{(L_0^* - L_i^*) + (a_0^* - a_i^*) + (b_0^* - b_i^*)} \]  
\[ 0 \text{ and } i \text{ subscripts stand for the fresh and dried samples, respectively.} \]

### 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]:

\[ \text{Shrinkage} = \frac{(\phi_i - \phi_f)}{\phi_i} \times 100 \]

In the above equation, \( \phi_f \) is the final volume (cm\(^3\)) after drying and \( \phi_i \) 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]:

\[
RR = \frac{W_r}{W_d}
\]  
(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].

| No | Drying Method | Drying Time (min) | Reduced Drying Time (%) | \(D_{ow} \text{ (m}^2\text{/s)}\) | SEC (MJ/kg) |
|----|---------------|-------------------|-------------------------|----------------------------|-------------|
| 1  | HD            | 190 ± 10g         | -                       | 7.12 \times 10^{-9}       | 297.29 ± 11.21 |
| 2  | INFD          | 145 ± 7e          | 23                      | 9.50 \times 10^{-9}       | 120.83 ± 9.22  |
| 3  | MWD           | 85 ± 5c           | 55                      | 1.79 \times 10^{-8}       | 42.5 ± 3.22  |
| 4  | INF–HD        | 135 ± 10d         | 28                      | 1.39 \times 10^{-8}       | 186.49 ± 10.99  |
| 5  | MW–HD         | 95 ± 6c           | 50                      | 1.43 \times 10^{-8}       | 164.47 ± 8.24  |
| 6  | US+HD         | 170 ± 9f          | 10                      | 8.28 \times 10^{-9}       | 265.99 ± 4.44  |
| 7  | US+INFD       | 130 ± 6d          | 31                      | 1.16 \times 10^{-8}       | 54.58 ± 3.75  |
| 8  | US+MWD        | 70 ± 3b           | 63                      | 2.09 \times 10^{-8}       | 23.75 ± 2.22  |
| 9  | US+INF–HD     | 60 ± 4b           | 68                      | 2.57 \times 10^{-8}       | 111.9 ± 6.31  |
| 10 | US+MW–HD      | 50 ± 2a           | 73                      | 2.78 \times 10^{-8}       | 103.23 ± 4.89  |

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.
while the lowest value was for the slowest method (i.e., HD), which is $7.12 \times 10^{-9}$
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.

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 *Keluissa 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 |
| 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 $2.78 \times 10^{-8}$ m$^2$/s; while the lowest value was for the slowest method (i.e., HD), which is $7.12 \times 10^{-9}$ 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 $1.01 \times 10^{-9}$ to $8.44 \times 10^{-9}$ m$^2$/s, while this range
was $8.11 \times 10^{-9} - 4.05 \times 10^{-8}$ 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 $3.42 \times 10^{-9}$ to $1.59 \times 10^{-8}$ 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 $1.77 \times 10^{-9}$ to $2.77 \times 10^{-9}$ 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 ($0.81 \times 10^{-8}$ m$^2$/s) and highest ($3.68 \times 10^{-8}$ 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 ($297.29 \pm 11.21$ 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 ($23.75 \pm 2.22$ 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 ($24.37 \pm 0.57$) 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, INF+HD, 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, INF+HD, MWD, INF+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).
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 broccoli 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 ($p < 0.05$).
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.

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