

## Article

# Microwave and Ultrasound Assisted Rotary Drying of Carrot: Analysis of Process Kinetics and Energy Intensity

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**Abstract:** Convective drying is one of the most commonly employed preservation techniques for food. However, the use of high temperatures and extended drying times often leads to a reduction in product quality and increased energy consumption. To address these issues, hybrid processes combining convective drying with more efficient methods are frequently employed. This study investigates the convective rotary drying of carrot (cv. Nantes), assisted by microwaves and ultrasound, using a hybrid rotary dryer. In total, four distinct drying programs—comprising one convective and three hybrid approaches—were evaluated. The study assessed drying kinetics, energy consumption, and product quality. The use of ultrasound increased the drying rate by 13%, microwaves by 112%, and microwaves and ultrasound together by 140%. The use of microwaves reduced energy consumption by 30%, whereas ultrasound resulted in a slight increase. All processes resulted in a significant reduction in water activity. Ultrasound decreased the color difference index, while microwaves increased it compared to convective drying.

**Keywords:** color difference; drying constant; drying curves; drying rate; drying time; effective diffusion coefficient; mass transfer coefficient; specific energy consumption; temperature; water activity



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## 1. Introduction

One of the world's greatest challenges is the preservation of food. Drying is among the most common methods for preserving fruits and vegetables, effectively reducing moisture content and water activity—key factors in limiting natural decomposition processes. Drying foods limits bacterial and fungal decomposition, resulting in product stabilization [1]. However, most drying techniques involve prolonged heat application, which often compromises product quality and value. Factors like drying method, temperature, humidity, air flow rate, and additional heat sources such as microwave (MW), infrared (IF), or ultrasound (US) influence the extent of quality changes. Convective drying, a widely used method involving hot air, often requires high temperatures and extended durations, which trigger chemical and biochemical reactions that alter color, flavor, aroma, and nutritional properties [2–5]. Drying can also cause excessive shrinkage and/or shape deformation [6–8], making the product less appealing to consumers.

Another significant issue with drying is its high energy consumption. The energy needed to provide sufficient heat for evaporation makes drying one of the most energy-intensive unit operations. It is estimated that drying processes account for up to 25% of total industrial energy consumption [9,10]. Given the environmental and energy concerns, such as fossil fuel depletion and the need to reduce greenhouse gas emissions [11], reducing energy consumption in all industrial sectors, including those utilizing drying processes, is paramount. Therefore, ensuring good product quality while minimizing energy consumption remains a key challenge in drying operations.

One possibility for improving drying processes is the use of pretreatment. Examples of pretreatment methods include osmosis [11–14], ultrasound [15,16], or pulsed electric

field [12,17]. Another way to enhance drying processes is to use hybrid drying, which combines two or more techniques in a single process [18]. To accelerate the process, several methods are used in conjunction to supply additional energy to the process during drying. Such acceleration can result in reduced energy consumption and improved product quality. Plant materials are often dried using convection with the addition of microwaves [15,19–21], infrared [15,22,23], or ultrasound [20,24–26]. In most cases, the materials being dried in these processes are stationary, with exceptions being rotary convection–microwave and convection–infrared drying [15,19,22].

The aim of this work was to investigate the effect of the independent use of microwaves and ultrasound, as well as the simultaneous use of both energy sources, on rotary convective drying. Carrot root was chosen as the research material due to its high degree of hardness and inhomogeneous structure, making it particularly challenging to dry [27]. In total, four drying schedules were experimentally tested to determine the most effective process: convective–hot air drying (CV), convective drying assisted by ultrasound (CVUS), convective drying assisted by microwaves (CVMW), and convective drying assisted by both microwaves and ultrasound (CVMWUS). Each schedule was assessed in terms of drying kinetics, product quality, and energy consumption. The use of ultrasound increased the drying rate by 13%, microwaves by 112%, and both sources combined by as much as 140%. All processes resulted in a significant reduction in water activity, with the greatest reduction observed in the CVUS process. Ultrasound also led to a decrease in the color difference index ( $dE$ ), while microwaves significantly increased the value of this index. Additionally, the use of microwaves significantly reduced energy consumption, while ultrasound resulted in a slight increase in energy consumption.

## 2. Methodology of the Study

### 2.1. Material

Fresh carrots (*Daucus carota* cv. Nantes), bought at a local market, were used as the experimental material. Before processing, the material was stored in a refrigerator at 4 °C for at least 24 h. Next, three or four of the roots were washed, peeled, and cut into slices (5 mm thick) with the use of an industrial cutter, Hållde RG100 (Kista, Sweden). The prepared samples were divided into two parts. One part was used to measure moisture content, water activity, and color; the other was subjected to drying. The prepared batch of material, weighing approximately 200 g, was placed into the drum of the dryer and subjected to the drying process. The dryer was not preheated prior to the beginning of the drying process.

The initial moisture content of the material was determined using a Precisa XM120 moisture analyzer (Dietikon, Switzerland) and equaled  $86.63 \pm 1.73\%$  (wet basis).

### 2.2. Drying Procedure

The drying tests were conducted using a laboratory rotary hybrid dryer constructed by PROMIS-TECH (Wrocław, Poland), as shown schematically in Figure 1.

The dryer has two different techniques for drying: hot air-convective (CV) and microwave (MW). Convective drying utilizes air drawn in by a blower (Figure 1(1)) from the dryer's environment, which, after passing through a heater (5), is forced directly into the dryer drum (12). After passing through the drum, the moistened air leaves the dryer through the outlet duct (7b). Microwave drying is implemented using electromagnetic waves at 2.45 GHz, generated continuously by two water-cooled magnetrons (10), produced by Muegge (Reichelsheim, Germany). Additionally, each of the drying techniques may be supported by high-power ultrasound (US) generated by a transducer mounted on the side of the dryer (13) and delivered through the air directly to the material. In the experiment, the frequency of the acoustic waves was 26 kHz, and the maximum acoustic intensity reached 160 dB. The operation of the transducer is controlled by two of the airborne ultrasound system's (AUS) other units, specifically the controller (2) and the preamplifier (3). The system was developed and manufactured by Pusonics (Madrid, Spain).

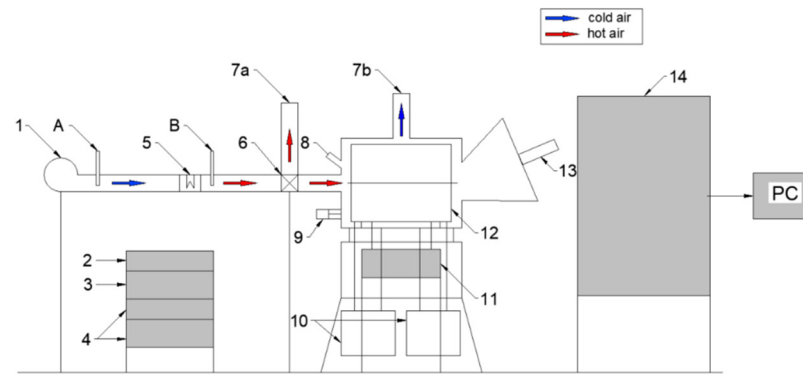


**Figure 1.** Scheme of the rotary hybrid dryer: 1—blower, 2—Airborne Ultrasound system (AUS) controller, 3—AUS amplifier, 4—microwave feeders, 5—heater, 6—pneumatic valve, 7a and 7b—air outlet, 8—pyrometer, 9—drum drive, 10—microwave generators, 11—balance, 12—rotating drum, 13—AUS transducer, 14—control unit, A—temperature and humidity sensor, B—temperature sensor.

The research included four drying schemes. Each drying schedule was elaborated on the basis of the convective process (CV) supported by microwaves (MW) and/or ultrasound (US). The temperature and the velocity of the drying agent (air) was constant during the whole research process. The power of the microwave and ultrasonic enhancement was selected in accordance with the results of preliminary experiments. Each drying procedure was carried out in triplicate. Details about the drying conditions for the specified schedules of drying are given in Table 1.

**Table 1.** Drying procedures.

| No. | Acronym | Air Parameters |            |           | Radiation Power (W) |     |
|-----|---------|----------------|------------|-----------|---------------------|-----|
|     |         | T<br>(°C)      | v<br>(m/s) | RH<br>(%) | US                  | MW  |
| 1   | CV      | 60             | 0.2        | 7         | 0                   | 0   |
| 2   | CVUS    |                |            |           | 200                 | 0   |
| 3   | CVMW    |                |            |           | 0                   | 100 |
| 4   | CVMWUS  |                |            |           | 200                 | 100 |

T—air temperature, v—air velocity, RH—air relative humidity, US—ultrasound, MW—microwave.

The weight loss of the samples being dried was measured automatically throughout the whole operation at 5 min intervals using a laboratory balance (Figure 1(11)) model APP/25c (precision 0.01 g), produced by Radwag (Radom, Poland). To prevent any potential interference that might affect the accuracy of the mass measurement, the drum of the dryer was temporarily stopped, and the drying air was redirected through a pneumatic valve (6) to the outlet (7a), thus bypassing the chamber. The drying agent's parameters, such as temperature, velocity, and humidity, were also measured throughout the process using two sensors (A, B) models HD29371TC1.5 and HD4817ETC1.5 (precision 0.01 m/s, 0.1 °C, 0.01%), produced by DeltaOHM (Selvazzano Dentro, Italy). All measured data were collected by data acquisition software running on a personal computer (PC).

The temperature of the samples during drying was measured using two methods, depending on the process variant. In the convective and convective-ultrasound (CV, CVUS) processes, the temperature (T) was measured using a standalone HTDL-20 recorder produced by DWYER (Michigan City, IN, USA). Before the test, a single slice of carrot was impaled on the rigid external probe of the device and the whole was placed in the dryer with the other samples. After the drying process, the temperature recorded over time (at one-minute intervals) was read from the device. For the convective-microwave processes (CVMW, CVMWUS), the surface temperature (T\*) was measured using a model B1 infrared thermal camera made by FLIR (Wilsonville, OR, USA). At preset intervals (every 10 min), the drying process was paused in order to take a thermal image—a thermogram—of the

samples inside the dryer. The images were further analyzed using software provided by the camera manufacturer. The point with the highest temperature was marked on the images and its value was read.

### 2.3. Drying Kinetics and Energy Intensity

Drying kinetics were evaluated on the basis of drying curves, that is, changes in dimensionless moisture content over time, and changes in drying rate as a function of dimensionless moisture content. In addition, the average drying rate was also determined for each process.

By defining the dry basis moisture content as the ratio of the mass of moisture ( $m_w$ ) contained in the material to the mass of the dry phase ( $m_d$ ) [28]:

$$X = m_w / m_d, \quad (1)$$

the drying kinetics of samples could be assessed in terms of dimensionless moisture content ( $Y$ ) and drying rate ( $DR$ ) in accordance with the following equations [29]:

$$Y_i = \bar{X}(t_i) / X_0, \quad (2)$$

$$DR_i = -m_d(dX/dt) = -(dm_w/dt) = -(m(t_i) - m(t_{i-1})) / (t_i - t_{i-1}), \quad (3)$$

where  $\bar{X}(t_i)$  is the spatial average of the moisture content determined at time  $t_i$ ,  $X_0$  is the initial moisture content,  $dm_w$  is the weight loss of the sample, and  $dt$  is the time at which the weight loss  $dm_w$  occurred.

The mass of moisture  $m_w$  can be defined as the difference between the mass of the moist material  $m$  and the mass of the dry phase  $m_d$ . After substituting this difference into (1) the spatial average moisture content  $\bar{X}(t_i)$  (dry basis) at any  $i$ -th time of the process was calculated using the following formula [30]:

$$\bar{X}(t_i) = (m(t_i) - m_d) / m_d, \quad (4)$$

where  $m(t_i)$  is the sample mass measured at time  $t_i$ , and  $m_d$  is the dry matter determined using a Precisa XM120 moisture analyzer (Dietikon, Switzerland) with an accuracy of 0.01%.

The average drying rate for a given drying process was calculated using the following equation [30]:

$$DR_{av} = \Delta m / DT, \quad (5)$$

where  $\Delta m$  is the mass of moisture removed from the sample by drying, and  $DT$  is the total drying time.

The experimental data was also used to determine the drying constant,  $k$ ; mass transfer coefficient,  $\alpha$ ; and effective diffusion coefficient,  $D_{eff}$ . All these parameters could be determined from the drying rate curves [30]. Based on the experimental results, the values of the average moisture content  $(\bar{X})_i$  and the rate of moisture content change  $-(d\bar{X}/dt)_i$  were calculated in accordance with the following equations [30]:

$$(\bar{X})_i = (\bar{X}(t_i) + \bar{X}(t_{i-1})) / 2, \quad (6)$$

$$-(d\bar{X}/dt)_i = (\bar{X}(t_{i-1}) - \bar{X}(t_i)) / (t_i - t_{i-1}), \quad (7)$$

The rate of moisture content change  $-(d\bar{X}/dt)_i$  (7) was calculated as an average value for the time period  $(t_i - t_{i-1})$ . For consistency in kinetics modeling, material moisture content  $(\bar{X})_i$  (6) was also averaged over the same time period  $(t_i - t_{i-1})$ . Based on the linear approximation of the moisture content change over average moisture content, the drying constant,  $k$ , was determined to be the slope of approximation lines. The mass transfer,  $\alpha$ , and the effective diffusion coefficient,  $D_{eff}$ , were then calculated using the following formula [30]:

$$\alpha = kl, \quad (8)$$

$$D_{eff} = (4l^2k) / \pi^2, \quad (9)$$

where  $l$  is half of the sample's thickness.

Each drying schedule was also assessed in terms of energy intensity. The total electric energy consumed by the experimental setup during the drying tests was measured using an electricity meter. The resulting electricity consumption,  $EC$ , was then transformed through recalculation into specific energy consumption,  $SEC$ , that is, the amount of energy used to evaporate one kilogram of moisture according to the relationship:

$$SEC = (3.6 \cdot EC) / \Delta m, \quad (10)$$

The value thus determined enabled the energy consumption of each process to be compared.

#### 2.4. Quality of Products

The quality of the obtained products was evaluated on the basis of water activity and the color of the samples. Water activity ( $a_w$ ) was measured at room temperature ( $\sim 23^\circ\text{C}$ ) before and after drying experiments with a TESTO 650 multimeter (Testo, Titisee-Neustadt, Germany), equipped with a water activity measuring chamber. Prior to the measurement, approximately 5 g of ground sample was placed in a polystyrene container and subsequently inserted into a steel airtight measuring chamber. The measurement was conducted until a constant  $a_w$  value was reached, indicating no change at a value of 0.001 for a period of five minutes.

The color of the samples was measured using a CR400 colorimeter produced by Konica Minolta (Tokyo, Japan) and quantified in terms of the three-dimensional color space, CIELAB, where  $L^*$  represents brightness,  $a^*$  denotes the chromatic component of colors ranging from red to green, and  $b^*$  signifies the chromatic component of colors ranging from yellow to blue. Based on the measured values for the raw material (index  $_0$ ) and the dried sample (index  $_d$ ), the color difference index,  $dE$ , was determined according to the following equation [31]:

$$dE = \sqrt{(L_0^* - L_d^*)^2 + (a_0^* - a_d^*)^2 + (b_0^* - b_d^*)^2} \quad (11)$$

The experimental data were processed using OriginPro 2024b [32]. The data presented in Section 3, Results and Discussion, are means  $\pm$  standard deviations.

### 3. Results and Discussion

#### 3.1. The Kinetics and Energy Intensity of Drying

Figure 2a shows a graph demonstrating the dependence of dimensionless moisture content ( $Y$ ) on time ( $t$ ). Despite the variations in drying methods, the curve paths are very similar. The characteristic drying periods such as the constant drying-rate period and the falling drying-rate period cannot easily be distinguished, which is typical for biomaterials drying processes [9,33]. As expected, convective drying alone was the slowest among the methods tested. However, the application of microwaves (MW) or ultrasound (US) significantly reduced the drying time by increasing the rate of drying. Figure 2b illustrates the relationship between the drying rate ( $DR$ ) and dimensionless moisture content ( $Y$ ) during the process.

A comparative analysis of the drying rate curves reveals that the application of microwaves had a significantly greater impact than ultrasound (Figure 2b). The maximum drying rate for the microwave processes (CVMW and CVMWUS) reached a value above 0.03 g/s, while for the convective–ultrasound process (CVUS), the highest observed value was 0.02 g/s. The lowest drying rate was observed for the convection process (CV), with a maximum of approximately 0.015 g/s, which resulted in a prolonged drying time.

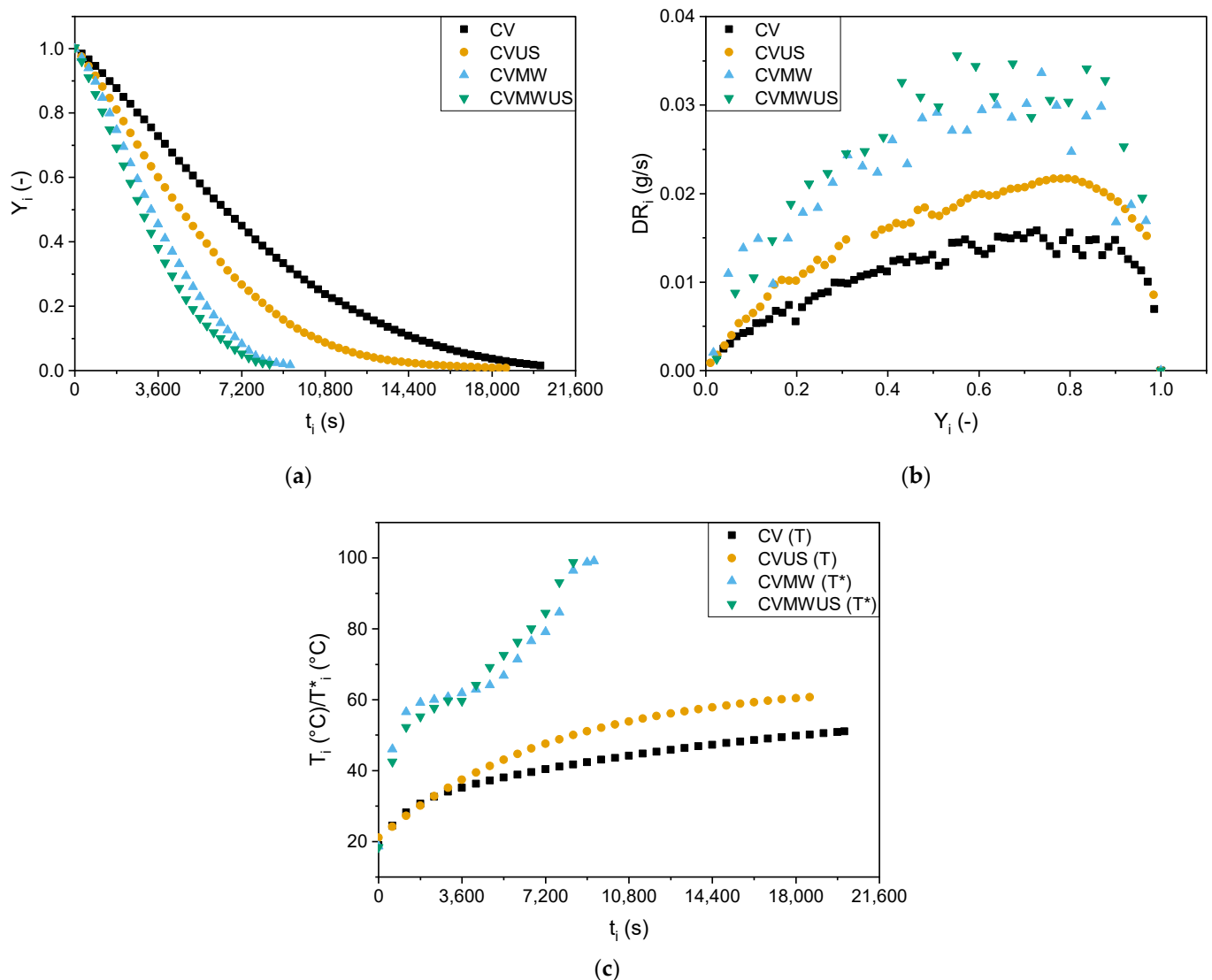


**Figure 2.** Evolution of dimensionless moisture content,  $Y_i$  (a); drying rate,  $DR_i$  (b); and temperature of the samples,  $T/T^*$  (c), for each process.

The shape of the drying rate curves exhibits a similar pattern across the different processes, which enables the essential drying periods to be identified. These include the initial stage, the constant drying rate period, and the falling drying rate period. The values of  $Y_i$  at which the transition between the drying periods occurs are slightly different for each process; however, some similarities can be observed between the CV and CVUS processes, as well as between the CVMW and CVMWUS processes.

The initial stage of the process lasts from the beginning until a constant drying rate is reached. For the CV-CVUS pair of processes, this period lasted until the dimensionless moisture content reached  $Y_i \approx 0.89$ , while for the CVMW-CVMWUS pair, it lasted until  $Y_i \approx 0.87$ . In both instances, this occurred after approximately 1200 s of the process' duration. The relatively prolonged heating period observed in this study may be attributed to two factors: the larger sample batch size compared to other studies on hybrid drying and the initiation of drying on the cold dryer. In this approach, a portion of the heat energy supplied with the hot air was utilized for the heating of the dryer components. The process subsequently entered the constant drying rate period. In the case of the CV-CVUS pair of processes, this period lasted until the material reached a dimensionless moisture content of approximately 0.57, which occurred after approximately 5400 s of the convection (CV) process and 3900 s of the ultrasound-assisted process (CVUS). In the microwave-assisted processes

(CVMW, CVMWUS), the constant drying rate period ended at a dimensionless moisture content of 0.47, which was reached after approximately 3600 s, despite the variations in the types of processes. The condition for the end of the period of constant drying rate is the slowing down of the transport of moisture from the inside of the sample to its surface. In all the processes studied, the transport of moisture to the surface of the sample is caused by diffusion. When microwaves are used (CVMW, CVMWUS), the temperature of the samples is higher than in the other processes (CV, CVUS). This facilitates diffusion at lower moisture contents. In addition, internal heating of the material with microwaves causes an increase in moisture pressure, which in turn causes easier transport of moisture to the surface (pressure flow). For these two reasons, the period of constant drying rate is longer in the processes with microwaves (CVMW, CVMWUS) than in the processes without microwaves (CV, CVUS). Once the aforementioned moisture content—frequently designated as the critical moisture content—is surpassed, a falling drying rate period ensues, persisting until the end of the process.

By analyzing the temperature curves (Figure 2c), it can be seen that in the microwave-assisted processes (CVMW, CVMWUS) the temperature of the material increased much faster and reached a significantly higher value than for the convection (CV) or ultrasonic-assisted (CVUS) processes. This phenomenon is due to the effective interaction between the microwaves and the moist material being dried, and results in high drying rates and short processing times. The temperature curves also demonstrate the beneficial impact of ultrasound on heat transfer. The application of acoustic waves in the CVUS process resulted in a significantly enhanced heating rate when compared to the convection process (CV). This phenomenon may be attributed to ultrasound-induced effects at the material's surface, which result in a reduction of the boundary layer's thickness and thus enhances heat transfer efficiency and the absorption of ultrasonic energy [26].

An analysis of the shape of the temperature curves (Figure 2c) also reveals the similarity between the CV and CVUS processes, and between the CVMW and CVMWUS processes. In the case of convective (CV) and ultrasound-assisted convective (CVUS) drying, there are no evident characteristic periods, and the curves move asymptotically towards the temperature of the drying agent. For the microwave processes (CVMW and CVMWUS), three stages can be distinguished. During the first, there was intensive heating to a temperature of about 60 °C. This stage lasted about 1200 s and corresponds to the initial stage on the drying rate curves (Figure 2b). During the next stage, the temperature of the material was approximately constant (about 60 °C) and lasted up to 3600 s; this coincides with the constant drying rate period (Figure 2b). During the last stage, the temperature increased again to reach a value of about 100 °C at the end of the process. This period corresponds to a falling drying rate period.

Concerning the microwave processes, the intense heating during the initial stage was the result of effective absorption of microwave radiation by the very moist material. In this stage, intense moisture evaporation also began, leading to an increase in the drying rate (Figure 2b). The constant temperature of the material during the constant drying rate period (from 1200 s to 3600 s of the process) was due to the very intensive evaporation of moisture from the sample's surface. Because of this, convectively supplied and microwave-generated heat is used to evaporate moisture and does not heat up the material being dried. This phenomenon occurs only when there is enough moisture in the material, so that it can be transported efficiently to the surface/evaporation front, and that transport within the material does not limit the process rate. Given the constant value of the heat of vaporization, the rate of drying (evaporation) is thus primarily determined by the amount of energy applied per unit time. If drying is conducted under constant process conditions (i.e., constant air temperature and radiation power), it can be assumed that the amount of energy supplied to the surface of the material being dried is also constant. Consequently, the evaporation rate remains constant, resulting in a constant drying rate (Figure 2b) and also in almost constant temperature of material [34]. Once the moisture content of the material has decreased below a critical value, the effectiveness of the moisture transport

to the surface/evaporation front drops. The energy applied to the material is then used not only to evaporate the moisture but also to heat the material, resulting in a temperature increase (Figure 2c). As the drying rate during this period is determined primarily by the internal transport of moisture, the value of this parameter continues to decrease (Figure 2b) and falling drying rate period occurs.

The notable occurrence of a constant drying rate period may be somewhat unexpected. A review of the literature reveals numerous reports concerning materials of plant origin for which a constant drying rate period is not observed, and the entire drying process occurs during the period of falling drying rate [9]. However, some researchers have reported the presence of a constant drying rate period. Arslan et al. reported similar drying curves for carrot [35] and red pepper [36]. On the other hand, Abbaspour-Gilandeh et al. [15] did not observe a constant drying rate period during the drying of carrot using multiple techniques. The underlying reason behind this discrepancy remains unclear. May and Perré [33] hypothesized that this phenomenon may be linked to a variation in the mass exchange area resulting from material shrinkage during the drying process. However, determining exchange surface area is extremely difficult and requires advanced experimental techniques.

In Figure 3, the average drying rate,  $DR_{av}$ ; time,  $DT_{av}$ ; and specific energy consumption,  $SEC_{av}$ , for each particular drying process are presented.

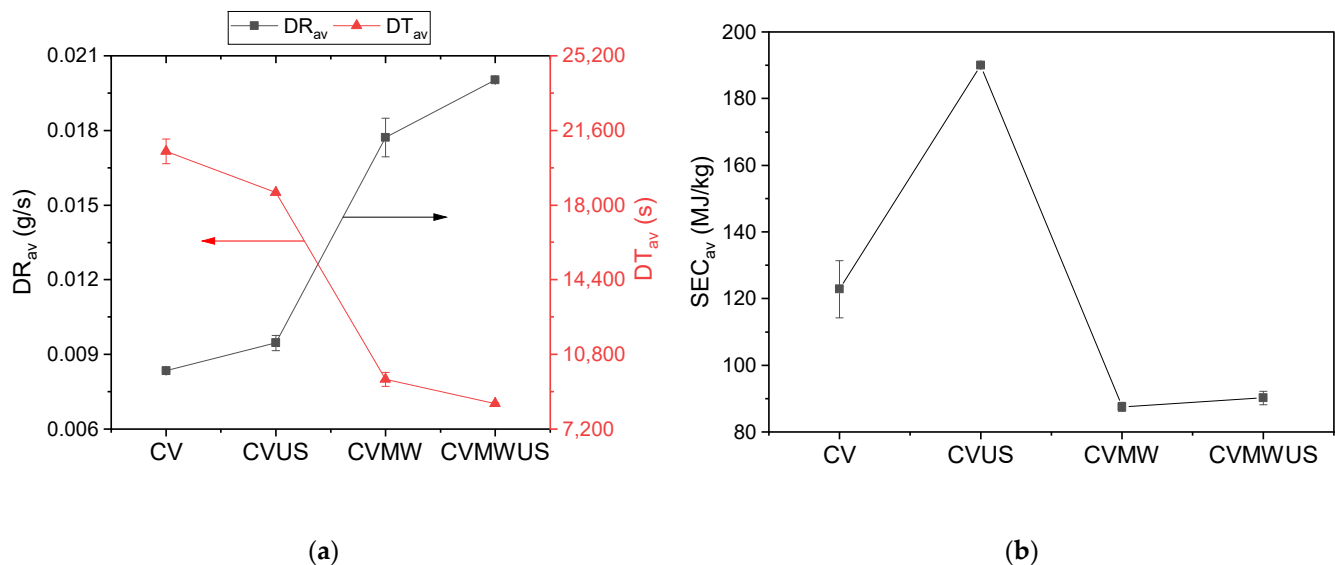


**Figure 3.** Average drying rate,  $DR_{av}$  and time,  $DT_{av}$  (a); and specific energy consumption,  $SEC_{av}$  (b) for each process.

The average drying rate obtained during the hybrid processes was visibly higher compared to the convective process (Figure 3a). In the case of the fastest drying procedure (CVMWUS) the average drying rate increased by 140% compared to CV, while for other hybrid programs, namely ultrasound-assisted (CVUS) and microwave-assisted (CVMW) convective drying, the increase equaled 13% and 112%, respectively. These changes were reflected in the value of the average drying time, which exhibited reductions of 10%, 53%, and 59% for CVUS, CVMW, and CVMWUS, respectively (Table 2). A strong positive correlation (Pearson's  $r = 0.99$ ) was identified between the  $DR_{av}$  and  $DT_{av}$  values; a finding that is also evident in the graphical representation (Figure 3a).

**Table 2.** Relative change in average drying rates and specific energy consumption.

| Process | Relative Change |           |            |
|---------|-----------------|-----------|------------|
|         | $DR_{av}$       | $DT_{av}$ | $SEC_{av}$ |
| CV      | —               | —         | —          |
| CVUS    | 13%             | −10%      | 59%        |
| CVMW    | 112%            | −53%      | −30%       |
| CVMWUS  | 140%            | −59%      | −28%       |

On the basis of the obtained results, microwaves were found to be a more efficient enhancement agent compared to ultrasound; this follows from the different mechanisms of interaction they have with the material being dried. Microwaves heat the entire volume of the sample, thereby significantly intensifying the transport of moisture within the body (through the intensification of diffusion and evaporation). Furthermore, the application of MW radiation typically results in a reduction in the temperature gradient within the material, which additionally enhances the drying process (through the reduction of thermodiffusion) [34]. The obtained results are in good agreement with the reports of other authors. Abbaspour-Gilandeh et al. [15] also observed a 50% reduction in drying time for microwave-assisted hot air drying of carrot. Kroehnke et al. [37] noted a fivefold decrease in drying time during the microwave-assisted convective processing of this vegetable.

The influence of ultrasound on the material being dried is very limited and depends strictly on the acoustic impedance mismatch between the sample material and the surrounding air. Several authors have proposed different mechanisms for ultrasound interaction, for example, cavitation, the “sponge effect”, microstreaming, the formation of microchannels, disturbance in the boundary layer, etc. [26]. The proposed phenomena may accelerate the drying operation by reducing both the internal and external resistances. On the basis of the results obtained during the authors’ previous research [38,39], it can be stated that in the case of the presented drying system, ultrasound influences the kinetics of the process rather by reducing external resistance factors such as the laminar boundary layer. Due to the significant losses in ultrasound power/intensity that occur during the transfer of energy between the radiator plate and the material, only a small proportion of the acoustic energy is involved in accelerating the drying process. Nevertheless, the positive effect of the ultrasound assistance could be easily distinguished and is in agreement with the results presented by other researchers. Kroehnke et al. [37] noted a 20% reduction in processing time during the ultrasound-assisted convective drying of carrot.

An analysis of the specific energy consumption (SEC) (Figure 3b) reveals that the application of additional energy-consuming devices, in the form of microwave generators or ultrasound transducer, affects the energy intensity of the process in a different manner. In the case of the microwave processes (CVMW, CVMWUS), a notable enhancement of the drying rate—which also resulted in a considerable reduction in drying time—led to a reduction in the amount of energy required to evaporate a given mass of moisture. The  $SEC_{av}$  values for these processes were the lowest for all the schemes studied: 87 MJ/kg and 90 MJ/kg for CVMW and CVMWUS, respectively. This represents a respective 30% and 28% reduction compared to the convection CV process (Table 2). The ultrasound-assisted convective process (CVUS), despite an observable increase in drying rate and reduction in drying time, did not prove to be more energy efficient than the reference process. A notable increase (59%) in the value of specific energy consumption was observed for CVUS, reaching an approximate value of 190 MJ/kg.

The considerable increase in SEC for CVUS can be attributed to the higher instantaneous energy consumption (in comparison to CV) necessitated by the requirement to power the AUS ultrasound generation system. Despite the beneficial effects of acoustic waves on the drying rate and time, their effectiveness was insufficient to compensate for additional energy expenditure, leading to an increase in total energy consumption. This

phenomenon was previously reported by Kowalski et al. [38], Kroehnke et al. [37], and Kroehnke and Musielak [40].

In the case of the CVMW and CVMWUS processes, the instantaneous energy consumption was also higher. However, the kinetic benefits resulting from the use of microwave radiation (increased drying rate and reduced drying time) were substantial enough for compensate this additional energy expenditure and reduce overall energy consumption. The discrepancy between the *SEC* values for the ultrasound- and microwave-assisted processes may also be attributed to the differing energy efficiency of the generators and the varying attenuation coefficient of the radiation along the path from the generator/transducer. The energy efficiency of microwave-assisted processes was also confirmed in studies by Abbaspour-Gilandeh et al. [15] and Kroehnke et al. [37]. In both cases, the microwave-assisted drying of carrot was characterized by a lower energy consumption compared to the reference convective drying.

The experimental data was also used to determine the drying constant,  $k$ ; mass transfer coefficient,  $\alpha$ ; and effective diffusion coefficient,  $D_{eff}$ . Table 3 presents the values obtained for each process.

**Table 3.** Values for drying constant,  $k$ ; mass transfer,  $\alpha$ ; and effective diffusion coefficient,  $D_{eff}$ .

| Process | $k$ (1/s)                                     | $\alpha$ (m/s)                                | $D_{eff}$ (m <sup>2</sup> /s)                   | adj. R <sup>2</sup> (–) |
|---------|-----------------------------------------------|-----------------------------------------------|-------------------------------------------------|-------------------------|
| CV      | $1.75 \times 10^{-4} \pm 6.02 \times 10^{-6}$ | $4.39 \times 10^{-7} \pm 1.50 \times 10^{-8}$ | $4.44 \times 10^{-10} \pm 1.52 \times 10^{-11}$ | 0.9612                  |
| CVUS    | $2.17 \times 10^{-4} \pm 5.50 \times 10^{-6}$ | $5.43 \times 10^{-7} \pm 1.38 \times 10^{-8}$ | $5.50 \times 10^{-10} \pm 1.39 \times 10^{-11}$ | 0.9619                  |
| CVMW    | $3.29 \times 10^{-4} \pm 2.07 \times 10^{-5}$ | $8.23 \times 10^{-7} \pm 5.17 \times 10^{-8}$ | $8.34 \times 10^{-10} \pm 5.23 \times 10^{-11}$ | 0.9243                  |
| CVMWUS  | $4.59 \times 10^{-4} \pm 2.79 \times 10^{-5}$ | $1.15 \times 10^{-6} \pm 6.99 \times 10^{-8}$ | $1.16 \times 10^{-9} \pm 7.08 \times 10^{-11}$  | 0.9520                  |

The values for all determined parameters corroborate the hypothesis that ultrasonic and microwave assistance has a favorable impact on convective drying kinetics. For the hybrid processes, the drying constant, mass transfer, and effective diffusion coefficient are markedly higher than for the convective process. There is also a clear distinction between acoustic waves and microwave radiation. In the case of the latter, the observed values are higher than in the case of ultrasound, which confirms the fact that it has a more effective influence on mass transfer processes. Arslan et al. [35] and Abbaspour-Gilandeh et al. [15] also observed significant increases in the effective diffusion coefficient for the microwave drying of carrot. On the other hand, Kroehnke et al. [37] noted an increase in the convective mass transfer coefficient with an increase in the power of the ultrasound enhancement. It can therefore be stated that the intensification of mass exchange is less pronounced for ultrasound than for microwaves, yet it is discernible and has a beneficial impact on convective drying kinetics. In turn, the values of the adjusted coefficient of determination (adj. R<sup>2</sup>) confirm that there is close convergence between the experimental curve and the linear approximation (Table 3).

### 3.2. Assessment of Product Quality

The water activity ( $a_w$ ) of a food product is a crucial factor in determining its shelf life. A low  $a_w$  inhibits the growth of pathogenic microorganisms, such as fungi, yeasts, and molds, and prevents unfavorable biochemical reactions, including enzymatic and non-enzymatic processes, and oxidation. It is generally accepted that microbial activity ceases below an  $a_w$  value of 0.6, while the most unfavorable biochemical reactions are maximally inhibited for an  $a_w$  below 0.4 [41]. Figure 4 depicts the mean water activity values for each dried sample and the raw material.

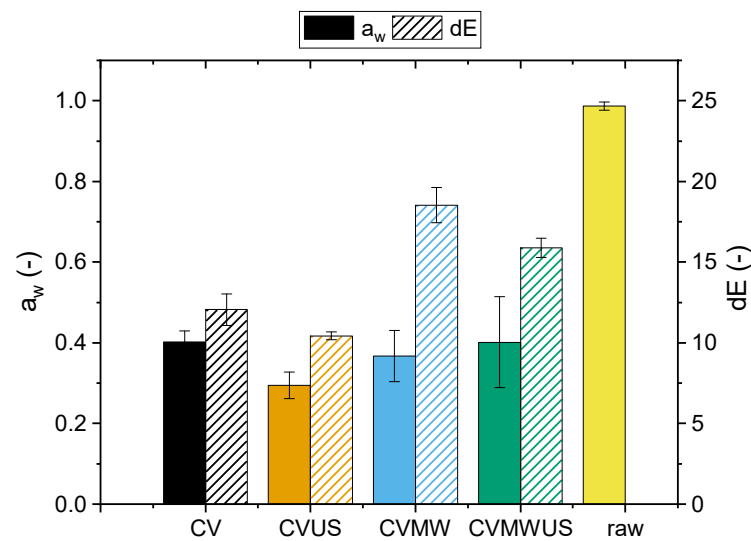


**Figure 4.** Average water activity,  $a_w$ , and color difference index,  $dE$ , for each process.

From an analysis of the results, we can conclude that the safety and microbiological stability of the material were ensured, as the results for the obtained (dried) products were characterized by a water activity ( $a_w$ ) value below 0.4. Differences between the particular drying procedures were negligible and did not affect the shelf-life of the material.

The color of the samples is also a significant quality parameter. It is primarily responsible for determining the sensory properties of the product and indicating the so-called palatability. Additionally, color can indirectly indicate the safety of a product or the changes that occur in it, such as the color change in fruit during the ripening process. It must be acknowledged, however, that color perception is highly subjective, and the evaluation of products will invariably depend on the observer's preferences. Consequently, instrumental color measurement was introduced as a means of objectively determining changes in color relative to the raw material. Figure 4 illustrates the color differences ( $dE$ ) for dried samples in relation to the raw material. It is assumed that a value above 4 units represents a perceptible difference in color as discerned by an average observer.

As can be observed in Figure 4, all the dried products exhibited a color that was discernibly distinct from that of the raw material, as indicated by color difference index values exceeding 4 units. The application of microwaves in microwave-assisted convective drying (CVMW and CVMWUS) resulted in the most detrimental impact on product quality. The color difference index ( $dE$ ) was, for these processes, visibly greater in comparison to the solely convective (CV) or ultrasound-assisted convective processes (CVUS) (Figure 4). Thus it turned out that the very significant achievements made in the drying kinetics led to the opposite results regarding the quality of the products. This is often observed in drying processes, for example, as found by Mierzwa and Szadzińska [39].

The color loss that occurs during microwave drying is usually caused by the high temperatures to which the products are exposed. Figure 5 shows thermal images specifically of samples taken at the 140th minute of the CVMW and CVMWUS drying processes. The maximum material temperature recorded in the image is approximately 98 °C, indicating a considerable degree of overheating in the material. Such elevated temperatures give rise to a number of detrimental changes, which, among other parameters, impact the color. These changes are attributed to both biochemical processes and thermal decomposition [42]. The rapid increase in temperature of the material being microwave-dried can be attributed to the inhomogeneity of the microwave field and changes occurring in the material. In the former, localized overheating of the material, known as “hot spots”, results in substantial qualitative alterations at these locations. To address this phenomenon, advanced microwave chamber designs are employed, and the dried material's movement is maintained through the microwave field (transmission belt, rotating pan, drum, etc.) [43].

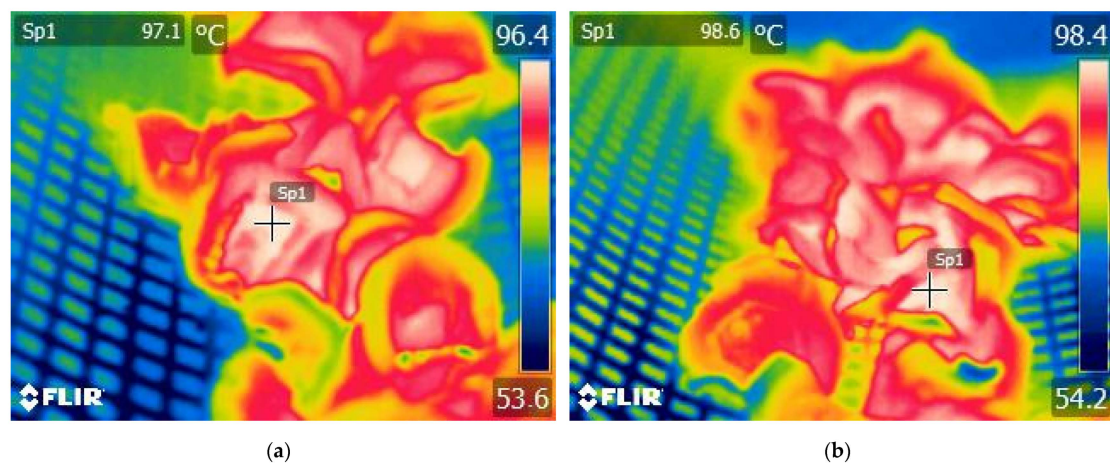


**Figure 5.** Exemplary thermograms of samples dried in microwave-assisted processes: (a) CVMW and (b) CVMWUS at 140th minute of the processes.

Additionally, changes in moisture content can also result in the material overheating. This is due to the fact that the moisture affects the dielectric properties of the material, namely, its capacity to absorb and reflect microwaves. When the material contains a substantial amount of moisture and the radiation power is properly adjusted, microwaves can effectively evaporate moisture without causing a sudden increase in the material's temperature. However, as the moisture content decreases during the drying process, the ability of the material to absorb microwaves changes. This can lead to a significant increase in the temperature of the material and unfavorable changes in its color. Therefore, it is very important to regulate the microwave power and exposure time, especially towards the end of the process. An alternative solution is the periodic application of microwaves (intermittent microwave drying) and the introduction of a so-called “relaxation period”, during which the temperature and humidity gradients will be equalized. This non-stationary hybrid drying is a promising technology that allows operational time to be reduced while maintaining high product quality, including color [35,39,44].

The beneficial impact of ultrasound on product color (Figure 4, CVUS) can be attributed to its non-thermal nature. Although ultrasound application accelerated heating of the material (compared to CV), unlike microwave radiation, it did not result in overheating effects (Figure 2c). Consequently, the initial color of the samples was preserved more effectively, and the majority of observed changes can be attributed to the temperature of the drying agent (air) and the high oxygen content in the atmosphere. These findings align well with those reported by Kroehnke et al. [37].

#### 4. Conclusions

The application of microwaves and/or ultrasound during the convective drying of carrots positively influenced the drying kinetics. The hybrid processes exhibited higher drying rates, resulting in shorter drying times. Among these methods, microwaves were more effective than ultrasound across all evaluated aspects, including drying rate, time, effective diffusion coefficient, and drying constant.

Microwave-assisted drying significantly improved energy efficiency by reducing drying time, leading to lower energy consumption per unit mass of moisture evaporated. In contrast, ultrasound-assisted drying showed higher specific energy consumption compared to conventional convective drying, attributed to its lower drying intensification efficiency and higher instantaneous energy use.

A negative impact of constant microwave irradiation on the color of the product was also observed. In contrast, non-thermal ultrasound waves were found to have minimal impact on the color of the material, thus acting as a quality promoter. All dried products exhibited low water activity, ensuring their safety and microbiological stability. Further

research is necessary to investigate the influence of MW and US enhancement as a function of applied power.

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## References

1. Jayaraman, K.S.; Das Gupta, D.K. Drying of Fruits and Vegetables. In *Handbook of Industrial Drying*; Mujumdar, A.S., Ed.; CRC Press: Boca Raton, FL, USA, 2014; pp. 611–636, ISBN 978-1-4665-9665-8.
2. Bonazzi, C.; Dumoulin, E. Quality Changes in Food Materials as Influenced by Drying Processes. In *Modern Drying Technology, Volume 3: Product Quality and Formulation*; Wiley-VCH Verlag GmbH & Co. KGaA: Weinheim, Germany, 2011; Volume 3, pp. 1–20, ISBN 978-3-527-63166-7.
3. Krokida, M.K.; Tsami, E.; Maroulis, Z.B. Kinetics on Color Changes During Drying of Some Fruits and Vegetables. *Dry. Technol.* **1998**, *16*, 667–685. [[CrossRef](#)]
4. Markowski, M.; Stankiewicz, I.; Zapotoczny, P.; Borowska, J. Effect of Variety on Drying Characteristics and Selected Quality Attributes of Dried Carrots. *Dry. Technol.* **2006**, *24*, 1011–1018. [[CrossRef](#)]
5. Santos, P.H.S.; Silva, M.A. Retention of Vitamin C in Drying Processes of Fruits and Vegetables—A Review. *Dry. Technol.* **2008**, *26*, 1421–1437. [[CrossRef](#)]
6. Ramos, I.N.; Brandão, T.R.S.; Silva, C.L.M. Structural Changes During Air Drying of Fruits and Vegetables. *Food Sci. Technol. Int.* **2003**, *9*, 201–206. [[CrossRef](#)]
7. Ratti, C. Shrinkage during Drying of Foodstuffs. *J. Food Eng.* **1994**, *23*, 91–105. [[CrossRef](#)]
8. Zogzas, N.P.; Maroulis, Z.B.; Marinou-Kouris, D. Densities, Shrinkage and Porosity of Some Vegetables During Air Drying. *Dry. Technol.* **1994**, *12*, 1653–1666. [[CrossRef](#)]
9. Jangam, S.V.; Mujumdar, A.S. Basic Concepts and Definitions. In *Drying of Foods, Vegetables and Fruits*; Jangam, S.V., Law, C.L., Mujumdar, A.S., Eds.; Singapore, 2010; Volume 1, pp. 1–30, ISBN 978-981-08-6759-1. Available online: <https://arunmujumdar.com/wp-content/uploads/2020/03/Drying-of-Foods-Vegetables-and-Fruits-Volume-1.pdf> (accessed on 15 November 2024).
10. Strumiło, C.; Jones, P.L.; Żyła, R. Energy Aspects in Drying. In *Handbook of Industrial Drying*; Mujumdar, A.S., Ed.; CRC Press: Boca Raton, FL, USA, 2014; pp. 1077–1100, ISBN 978-1-4665-9665-8.
11. Grabowski, S.; Marcotte, M.; Poirier, M.; Kudra, T. Drying Characteristics of Osmotically Pretreated Cranberries—Energy and Quality Aspects. *Dry. Technol.* **2002**, *20*, 1989–2004. [[CrossRef](#)]
12. Amami, E.; Khezami, L.; Vorobiev, E.; Kechaou, N. Effect of Pulsed Electric Field and Osmotic Dehydration Pretreatment on the Convective Drying of Carrot Tissue. *Dry. Technol.* **2008**, *26*, 231–238. [[CrossRef](#)]
13. Lenart, A.; Lewicki, A. Kinetics of Osmotic Dehydration of Plant Tissue. In *Drying '87*; Mujumdar, A.S., Ed.; Hemisphere Publisher: New York, NY, USA, 1987; pp. 239–248.
14. Wang, R.; Zhang, M.; Mujumdar, A.S. Effect of Osmotic Dehydration on Microwave Freeze-Drying Characteristics and Quality of Potato Chips. *Dry. Technol.* **2010**, *28*, 798–806. [[CrossRef](#)]
15. Abbaspour-Gilandeh, Y.; Kaveh, M.; Aziz, M. Ultrasonic-Microwave and Infrared Assisted Convective Drying of Carrot: Drying Kinetic, Quality and Energy Consumption. *Appl. Sci.* **2020**, *10*, 6309. [[CrossRef](#)]
16. Rawson, A.; Tiwari, B.K.; Tuohy, M.G.; O'Donnell, C.P.; Brunton, N. Effect of Ultrasound and Blanching Pretreatments on Polyacetylene and Carotenoid Content of Hot Air and Freeze Dried Carrot Discs. *Ultrason. Sonochem.* **2011**, *18*, 1172–1179. [[CrossRef](#)] [[PubMed](#)]
17. Ade-Omowaye, B.I.O.; Angersbach, A.; Taiwo, K.A.; Knorr, D. Use of Pulsed Electric Field Pre-Treatment to Improve Dehydration Characteristics of Plant Based Foods. *Trends Food Sci. Technol.* **2001**, *12*, 285–295. [[CrossRef](#)]
18. Kudra, T.; Mujumdar, A.S. Classification and Selection Criteria: Conventional versus Novel Technologies. In *Advanced Drying Technologies*; CRC Press: Boca Raton, FL, USA, 2009; ISBN 978-0-429-15075-3.

19. Kaveh, M.; Abbaspour-Gilandeh, Y.; Nowacka, M. Optimisation of Microwave-Rotary Drying Process and Quality Parameters of Terebinth. *Biosyst. Eng.* **2021**, *208*, 113–130. [\[CrossRef\]](#)
20. Szadzińska, J.; Łechtańska, 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. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Zhang, M.; Jiang, H.; Lim, R.X. Recent Developments in Microwave-Assisted Drying of Vegetables, Fruits, and Aquatic Products—Drying Kinetics and Quality Considerations. *Dry. Technol.* **2010**, *28*, 1307–1316. [\[CrossRef\]](#)
22. 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. [\[CrossRef\]](#)
23. Łechtańska, J.M.; Szadzińska, J.; Kowalski, S.J. Microwave- and Infrared-Assisted Convective Drying of Green Pepper: Quality and Energy Considerations. *Chem. Eng. Process. Process Intensif.* **2015**, *98*, 155–164. [\[CrossRef\]](#)
24. Gamboa-Santos, J.; Montilla, A.; Cárcel, J.A.; Villamiel, M.; García-Pérez, J.V. Air-Borne Ultrasound Application in the Convective Drying of Strawberry. *J. Food Eng.* **2014**, *128*, 132–139. [\[CrossRef\]](#)
25. 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. [\[CrossRef\]](#)
26. Musielak, G.; Mierzwa, D.; Kroehnke, J. Food Drying Enhancement by Ultrasound—A Review. *Trends Food Sci. Technol.* **2016**, *56*, 126–141. [\[CrossRef\]](#)
27. de la Fuente-Blanco, S.; Riera-Franco de Sarabia, E.; Acosta-Aparicio, V.M.; Blanco-Blanco, A.; Gallego-Juárez, J.A. Food Drying Process by Power Ultrasound. *Ultrasonics* **2006**, *44*, e523–e527. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Mujumdar, A.S. Principles, Classification, and Selection of Dryers. In *Handbook of Industrial Drying*, 4th ed.; Mujumdar, A.S., Ed.; CRC Press: Boca Raton, FL, USA, 2014; pp. 3–30, ISBN 978-1-4665-9665-8.
29. Cui, Z.-W.; Xu, S.-Y.; Sun, D.-W. Microwave–Vacuum Drying Kinetics of Carrot Slices. *J. Food Eng.* **2004**, *65*, 157–164. [\[CrossRef\]](#)
30. Szadzińska, J.; Mierzwa, D.; Musielak, G. Ultrasound-Assisted Convective Drying of White Mushrooms (*Agaricus bisporus*). *Chem. Eng. Process.—Process Intensif.* **2022**, *172*, 108803. [\[CrossRef\]](#)
31. Pathare, P.B.; Opara, U.L.; Al-Said, F.A.J. Colour Measurement and Analysis in Fresh and Processed Foods: A Review. *Food Bioprocess Technol.* **2013**, *6*, 36–60. [\[CrossRef\]](#)
32. *Origin(Pro)*; OriginLab Corporation: Northampton, MA, USA, 2024.
33. May, B.K.; Perré, P. The Importance of Considering Exchange Surface Area Reduction to Exhibit a Constant Drying Flux Period in Foodstuffs. *J. Food Eng.* **2002**, *54*, 271–282. [\[CrossRef\]](#)
34. Wang, Y.; Zhang, M.; Mujumdar, A.S. Microwave-Assisted Drying of Foods—Equipment, Process and Product Quality. In *Modern Drying Technology, Volume 5: Process Intensification*; Tsotsas, E., Mujumdar, A.S., Eds.; Wiley-VCH Verlag GmbH & Co. KGaA: Weinheim, Germany, 2014; Volume 5, pp. 279–315, ISBN 978-3-527-63172-8.
35. Arslan, A.; Soysal, Y.; Keskin, M. Comparative Investigation of Drying and Quality Characteristics of Organic and Conventional Black Carrots Dried by Intermittent Microwave and Hot Air. *Tekirdağ Ziraat Fakültesi Derg.* **2023**, *20*, 591–604. [\[CrossRef\]](#)
36. Arslan, A.; Soysal, Y.; Keskin, M. Comparing Hot Air Drying Kinetics and Color Quality of Organic and Conventional Sweet Red Peppers. *Mustafa Kemal Üniversitesi Tarım Bilim. Derg.* **2020**, *25*, 271–283. [\[CrossRef\]](#)
37. 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. [\[CrossRef\]](#)
38. Kowalski, S.J.; Mierzwa, D.; Stasiak, M. Ultrasound-Assisted Convective Drying of Apples at Different Process Conditions. *Dry. Technol.* **2017**, *35*, 939–947. [\[CrossRef\]](#)
39. Mierzwa, D.; Szadzińska, J. The Microwave-Assisted Convective Drying of Kale (*Brassica oleracea* L. Var. *Sabellica* L.) Using Continuous and Changeable Power Radiation. *J. Food Process Eng.* **2019**, *42*, e13004. [\[CrossRef\]](#)
40. Kroehnke, J.; Musielak, G. Ultrasound-Assisted Drying of Apples—Process Kinetics, Energy Consumption, and Product Quality. *Dry. Technol.* **2024**, *42*, 1757–1765. [\[CrossRef\]](#)
41. Pittia, P.; Antonello, P. Chapter 2—Safety by Control of Water Activity: Drying, Smoking, and Salt or Sugar Addition. In *Regulating Safety of Traditional and Ethnic Foods*; Prakash, V., Martín-Belloso, O., Keener, L., Astley, S., Braun, S., McMahon, H., Lelieveld, H., Eds.; Academic Press: San Diego, CA, USA, 2016; pp. 7–28, ISBN 978-0-12-800605-4.
42. Pham, N.D.; Karim, M.A. Investigation of Nutritional Quality Evolution of Papaya during Intermittent Microwave Convective Drying. *Dry. Technol.* **2022**, *40*, 3694–3707. [\[CrossRef\]](#)
43. Bae, S.-H.; Jeong, M.-G.; Kim, J.-H.; Lee, W.-S. A Continuous Power-Controlled Microwave Belt Drier Improving Heating Uniformity. *IEEE Microw. Wirel. Compon. Lett.* **2017**, *27*, 527–529. [\[CrossRef\]](#)
44. 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. [\[CrossRef\]](#)

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