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Hawthorn Drying: An Exploration of Ultrasound Treatment and Microwave–Hot Air Drying

Mohammad Kaveh [1,*], Małgorzata Nowacka [2,*], Esmail Khalife [3], Kamal Imanian [4], Yousef Abbaspour-Gilandeh [5], Maryam Sabouri [6] and Safoura Zadhossein [5]

1 Department of Petroleum Engineering, College of Engineering, Knowledge University, Erbil 44001, Iraq
2 Department of Food Engineering and Process Management, Institute of Food Sciences, Warsaw University of Life Sciences—SGGW, 02-776 Warsaw, Poland
3 Department of Civil Engineering, Cihan University-Erbil, Kurdistan Region, Erbil 44001, Iraq
4 Agricultural Engineering Research Department, West Azarbaijan Agricultural and Natural Resources Research and Education Center, Urmia 57169-63963, Iran
5 Department of Biosystems Engineering, College of Agriculture and Natural Resources, University of Mohaghegh Ardabili, Ardabil 56199-11376, Iran
6 Scientific Research Center, Erbil Polytechnic University, Erbil 44001, Iraq
* Correspondence: sirwan.kaweh@knu.edu.iq (M.K.); malgorzata_nowacka@sggw.edu.pl (M.N.)

Abstract: Drying is one of the methods used for preserving fruits and vegetables. However, due to the lengthy process and elevated temperature of convective drying, other pretreatment and drying methods are studied to shorten the drying time and obtain high-quality products. This study aimed to examine the effect of ultrasonic (US) pretreatment and microwave–hot air drying (MW–HA) on the drying time, specific energy (SEC), qualitative properties (e.g., color, shrinkage, and rehydration ratio), and bioactive compound properties (e.g., antioxidant activity, phenolic, and flavonoid contents) of hawthorn fruit. Experiments were performed using ultrasound pretreatment and a microwave dryer (microwave power: 180, 360, and 540 W) at air temperatures of 40, 55, and 70 °C. Drying of hawthorn lasts from 35 min for the ultrasound-treated sample (dried at 540 W and 70 °C) to 180 min (dried at 180 W and 40 °C without US treatment). The lowest amount of SEC (24.11 MJ/kg) was obtained using the US–MW–HA air drying method (dried at 540 W and 70 °C). The lowest values in total color change (13.37) and shrinkage (22.47%) were recorded for the sample dried with a MW power of 360 W and air temperature at 55 °C with US pretreatment prior to drying. Generally, the use of US and MW–HA air drying reduces the antioxidant activity (AC), total phenolic content (TPC), and total flavonoid content (TFC) during processing compared to fresh samples. The highest values for AA (28.01%), TPC (69.44 mg GAE/g d.m.), and TFC (64.38 mg QE/g) obtained at 360 W and 55 °C with US pretreatment for hawthorn fruit dried.

Keywords: hawthorn fruit; microwave drying; ultrasound treatment; specific energy; drying characteristics

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1. Introduction

Fruits and vegetables are potential sources of plant chemical compounds, especially phenolic compounds, which are actually bioactive compounds and natural antioxidants [1]. Hawthorn (*Crataegus pinnatifida*) belongs to the rose family, which is mostly distributed in the Northern Hemisphere and mainly in areas of China, Iran, Europe, and North America [2]. There are different types of ripe hawthorns, the color of the fully ripe fruit is yellow, red, dark red, and dark purple. It has high medicinal and nutritional value and is used to treat various human diseases, including heart diseases [3], high blood pressure, chest pain, and the hardening of the arteries [4,5]. The chemical compounds of hawthorn are flavonoids, terpenic acids, proanthospanins, and organic acids [6].

One of the most important processes to increase the shelf life of foods with high humidity is the drying process. The purpose of the drying process is to evaporate a certain amount of water in the product. Also, by using the drying process, access to dried food is easier and the storage time of food is increased [7]. The drying of solid materials takes place by the simultaneous transfer of mass and energy between a drying fluid and solid samples [8]. There are many common methods for drying, including solar [9], vacuum [10], hot air [11], freezing [12], etc. Most of these drying methods have high energy consumption and long drying time, which leads to the low quality of dried products under the mentioned methods. In recent studies, there have been significant advances in the use of new methods, which include microwave [13], infrared [14], ultrasound [15], pulsed electric field [16], blanching, and plasma [17]. These methods will increase the efficiency of the process and increase the quality of the final dried products. Some of these methods can be used as pretreatment or used in combination with common methods to reduce the initial humidity or change the texture of crops (in a way that shortens the drying time).

New technologies in the food industry always seek to produce high quality products with increased efficiency and reduced energy consumption. The use of ultrasound (US) waves is one of these new and non-thermal technologies that is used today as a pretreatment before the drying process [18]. Ultrasound consists of sound waves with a frequency beyond the range of human hearing. By adjusting the frequency and power, US can be used in many industrial applications, including food. The use of ultrasonic waves as a pretreatment is a suitable non-thermal method to increase productivity, and during the application of this process, the physicochemical and quality characteristics of the food are less damaged [19]. US pretreatment includes immersing the fruit in distilled water or hypertonic aqueous solution simultaneously with the application of ultrasound waves. US waves cause rapid alternating contractions and expansions (sponge effect) and maintain the moisture inside the capillary tubes by creating a difference in suction pressure of the capillary tube [15]. In addition, US creates cavitation (cavity) inside the food material, which may be useful for separating water [20]. Pretreatment with the help of US has been carried out before using different dryers. For example, Zhang et al. [21], Sledz et al. [22], and Dehghannya et al. [23] used US pretreatment before MW–HA dryer to study the TPC, TFC, color, energy, rehydration rate, and shrinkage for Chinese hickory, parsley leaves, and potato, respectively. Chouaibi et al. [24] used US bath pretreatment and then MW, infrared, freeze, and hot-air (HA) dryers to obtain the qualitative and bioactive properties of Tunisian eggplant. Rybak et al. [16] investigated the effect of thermal and non-thermal pretreatments on the quality and bioactive properties of red bell pepper in hot-air and MW–HA dryers.

In addition, most of the new methods produce better quality products compared to common drying methods such as hot-air, and also reduce the duration of the process and consume less energy. Meanwhile, the use of MWs in combination with other methods is an effective proposed method that will be discussed in this study. Among the methods combined with the MW method are hot-air [25], vacuum [26], infrared [27], electrohydrodynamic [28], and freeze drying [29], of which hot air is the most common. The combined method of MW and HA has been used to dry different agricultural products such as bitter melon [30], apple slices [31], edamame [32], onion [33], potato [23], and raspberries [34]. In general, it can be noted that microwaves cause heat in the material by moving water molecules, and due to the condensation of surface moisture, burns occur on the surface of the final product, which reduces its quality. However, in the combined method, air flow causes the evaporation of a part of the condensed moisture on the surface of the sample and prevents the loss of physical and chemical characteristics of the dried sample.

Therefore, due to the lack of studies in the field of drying hawthorn, in the present study, the effect of US pretreatment and MW–HA drying of hawthorn slices with the application of different parameters (MW power: 180, 360 and 540 W; air temperature: 40, 55, and 70 °C) were studied. Additionally, the kinetics of the drying process, drying time, specific energy consumption, product quality in terms of color, shrinkage, rehydration ratio, and bioactive properties including total phenol content, total flavonoids content as well as antioxidants were analyzed.

2. Materials and Methods

2.1. Material

Hawthorn samples prepared for drying experiments were obtained from a local garden located in Sardasht city in West Azerbaijan province and were kept in a cold room at a temperature of 4 ± 1 °C until the end of the experiments. In order to balance the temperature of the samples with the ambient temperature, the samples were transferred from the cold room to the laboratory about 60 min before the start of each experiment. To carry out this research, at first, hawthorn slices with a thickness of 4 mm were carefully cut by a sharp knife, and after weighing, they were quickly placed in the US bath machine. The used hawthorn slices had an average initial moisture content (MC) of 2.27 on a dry basis (d.b.). The MC of the samples was measured according to the AOAC method [35] by placing the samples (three samples of 30 g) in an oven (Memmert, UFB 500, Schwabach, Germany) and the temperature of 70 °C for 24 h until reaching a constant weight [5].

2.2. Processing: Ultrasound Treatment and Microwave—Hot Air Dryer (US–MW–HA)

Hawthorn samples were divided into two groups: (1) samples without US pretreatment; (2) samples with US pretreatment. To investigate the effect of using US pretreatment, an US bath Model Parsonic 7500S with a frequency of 28 kHz, power of 70 W, and a time period of 15 min was used. Before starting the drying process, the samples were treated with US waves under ambient temperature. After a certain period of time, the samples were taken out of the US bath and the excess moisture on the surface of the samples was dried with absorbent paper. Then the samples were placed in microwave–hot air dryer made at Mohaghegh Ardabili University, Ardebil, Iran [36]. About 30 min before the drying process started, the dryer was turned on. According to the specifications of each test, the MW power and air temperature inside the dryer were adjusted to the desired values (air temperature of 40, 55, and 70 °C and MW power of 180, 360, and 540 W) until the air temperature inside the dryer was stable. Samples were weighed every three minutes using a digital scale. The samples were dried from the initial MC of 2.27 d.b. until reaching the moisture content of 0.11 d.b. Drying experiments were performed in 3 replications, which resulted in a total of 54 variants of treatments.

The kinetics of the drying process were analyzed. Moisture ratio was calculated using Equation (1) where M_t is the MC on a dry basis at any time t (grams of water per gram of dry matter), M_0 is the initial MC on a dry basis and M_e is the equilibrium MC. M_e is neglected because it is insignificant compared to M_t and M_0 [25,37]:

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

2.3. Specific Energy Consumption (SEC)

2.3.1. Microwave Dryer

Energy consumption in the drying method using the MW method was obtained as follows [38]:

$$E_{mic} = P_{mic} t \tag{2}$$

where E_{mic} is SEC in MW (KJ), P_{mic} is the MW power (W), t is the drying time (s).

2.3.2. Hot-Air Dryer

SEC in the drying method using hot-air (HA) was calculated as follows [33]:

$$E_{con} = AV_a \rho_a \Delta H t \tag{3}$$

where E_{con} is the energy consumed in the HA dryer (KJ), A is the area of the sample container (m^2), V_a is the inlet air velocity (m/s), ρ_a is the air mass density (kg/m^3), ΔH is the air enthalpy (kJ/kg of dry air), and t is the time (min).

2.3.3. Ultrasound

Energy consumption in US pretreatment is calculated as follows [23]:

$$E_{US} = W \cdot V \cdot t \quad (4)$$

where E_{US}, W, and V are the energy used in US pretreatment (KJ), US volumetric power (W/L) and water volume (L), respectively, and t is the time (min).

2.3.4. US–MW–HA

The SEC in the combined MW–HA dryer with US pretreatment for drying hawthorn was calculated as follows [5]:

$$SEC = \frac{E_{mic} + E_{con} + E_{US}}{M_w} \quad (5)$$

where SEC is the specific energy consumption of the whole system (KJ/kg) and M_w is the amount of moisture removed from the sample (kg).

2.4. Proprties of the US–MW–HA Dried Hawthorn

2.4.1. Shrinkage Assessment

The amount of shrinkage of hawthorn samples was checked by measuring the volume change before and after drying. To measure the volume, the toluene displacement method was used according to the method of Dehghannya et al. [23]. Thus, shrinkage is defined as the percentage change in the volume of the processed sample compared to the raw sample (Equation (6)) [39]:

$$\%S = \frac{V_i - V_j}{V_j} \times 100 \quad (6)$$

where V_i is the volume of hawthorn samples before drying (g), V_j is the volume of hawthorn samples after drying (g), and $\%S$ is the shrinkage percentage.

2.4.2. Color of the Samples

Samples color was measured in L^*a^*b space. The color parameter L^* represents the lightness, a^* represents the redness/greenness and b^* represents the yellowness/blueness of the sample [10,40]. The color changes of dried hawthorn were measured using a colorimeter (HP-200, China). Then, the color changes of the dried product compared to the fresh product (ΔE) were calculated using Equation (7), [15].

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (7)$$

2.4.3. Rehydration Ratio

To calculate the RR parameter, dry samples were weighed and immersed in water with a temperature of 20 °C. Then, after 60 min [41], the samples were taken out of the water and weighed using a digital scale (AND, GF-6000, Japan), with an accuracy of ±0.01 g. All treatments were performed in three repetitions and their average was reported. The RR was calculated by Equation (8) [9]:

RR = (weight of dehydrated sample)/(drained weight of the rehydrated sample) (8)

2.4.4. Bioactive Compounds

Extract Preparation

To the 5 g of powdered dried samples, 100 mL of 80% methanol solution was added and shaken at room temperature for 24 h. Then, the supernatant of the centrifuged solutions was used to measure the total phenol content (TPC) and total flavonoid content (TFC) as well as antioxidant activity (AA).

Total Phenol Content (TPC)

The amount of TPC was determined by the Folin-Ciocalteu method described by Shahidi and Naczk, [42]. The amount of 1 mL of the extract of the sample was mixed with 2.5 mL of 10% Folin-Ciocalto solution and after 3 min, 2 mL of 7.5% sodium carbonate solution (75 g/L) was added into it. The samples were placed in the dark for 90 min, then the absorbance of the sample was read at 765 nm by a spectrophotometer (UV/Vis BIO-RAD-USA).

Total Flavonoid Content (TFC)

A 20 μL portion of the extract was mixed with 1 mL of distilled water and then 0.075 mL of sodium nitrite (5%) was added to it. After 5 min, 0.15 mL of $AlCl_3$ solution (10%) was added and after 6 min, 0.5 mL of NaOH (1 M) was added. The final volume of the solution was brought to 3 mL with distilled water. The absorbance of the resulting solution was immediately read at 510 nm by a spectrophotometer (UV/Vis BIO-RAD-USA).

Antioxidant Activity (AA)

The AA was measured using 2,2-diphenyl-1-picrylhydrazyl (DPPH). A 150 μL portion of the extract from hawthorn sample was completely mixed with 2 mL of 80% methanol and centrifuged for 10 min at a speed of 3500 rpm. Finally, its optical absorption intensity at the wavelength of 517 nm was read by a spectrophotometer (UV/Vis BIO-RAD-USA) and DPPH radical inhibitory capacity were calculated using Equation (9) [43]:

$$\%\mathrm{DPPH} = [(\mathrm{A}_0 - \mathrm{A}_i)/\mathrm{A}_0] \cdot 100 \tag{9}$$

where A_i is the absorption of the control sample and A_0 is the absorption of the tested sample read using a spectrophotometer.

2.5. Statistical Analysis

In order to investigate the effect of US, drying air temperature and microwave power on the properties of hawthorn samples (drying time, SEC, color, shrinkage, RR, TPC, TFC, and AA), a factorial experiment in the form of a completely randomized design with three replications was used. The independent variables included US time at one level of 15 min, drying air temperature at three levels of 40, 55, and 70 °C, and MW power of the dryer at three levels of 180, 360, and 540 W were used (Table 1). Analysis of variance and the presence of significant differences between treatments were performed using Duncan's multi-range test at the probability level of 5% ($p < 0.05$) using SPSS version 21 statistical software.

Table 1. Design of experiment properties.

Type of Experiment	Independent Variable	Level	Dependant Variable
Complete factorial design of experiments	Microwave Power	180 W 360 W 540 W	Drying time SEC Color
	Temperature	40 °C 55 °C 70 °C	Shrinkage RR TPC
	Ultrasound	15 min	TFC AA

3. Results and Discussion

3.1. Design of Experiments and Analysis

The aim of the investigation was to evaluate the effect of US pretreatment before drying hawthorn slices using a MW–HA dryer. Accordingly, a complete factorial design of experiments was conducted to judge the effect of US, drying air temperature, and MW power on drying time, SEC, total color change, shrinkage, RR, AA, TPC, and TFC was plotted. ANOVA results for the main effects and interaction of air temperature and MW power on the studied parameters are presented in Table 2.

Table 2. ANOVA analysis results of the drying time, color, energy, shrinkage, RR, TPC, TFC and AA at different MW power, temperature and MW power *temperature.

Parameter	MW Power			Temperature			MW Power × Temperature			
	Sum of Squares	Mean Square	Sig.	Sum of Squares	Mean Square	Sig.	Sum of Squares	Mean Square	Sig.	C.V *
Drying time	24,033.333	12,016.667	0.000	52,533.333	10,506.667	0.000	466.667	46.667	0.278	5.544
SEC	6797.737	3398.868	0.000	5640.968	1128.193	0.000	570.659	57.066	0.000	4.705
Color	2918.686	1459.343	0.000	291.084570	58.216914	0.000	39.844	3.984	0.001	3.874
Shrinkage	1289.128	644.564	0.000	2649.188	529.838	0.000	38.928	3.893	0.123	3.675
RR	8.929	2.978	0.000	2.660	0.443	0.000	1.889	0.105	0.000	2.586
TPC	3451.115	1150.372	0.000	1234.116	205.686	0.000	588.697	32.705	0.000	2.061
TFC	4830.773	1610.257	0.000	1803.648	300.608	0.000	820.722	45.596	0.000	1.580
AA	7798.419	2599.473	0.000	3579.063	596.510	0.000	1308.834	72.713	0.000	1.519

* The coefficient of variation (CV) is a statistical measure of the relative dispersion of data points in a data series about the mean.

A significant correlation between the average parameters (drying time, SEC, color, shrinkage, RR, TPC, TFC, and AA) was observed at the level of 1%. In addition to the main effects, the results showed that the mutual effects of temperature and MW power, except for the drying time and shrinkage parameters, also caused a significant difference between the average parameters at the level of 1%.

3.2. Drying Time and Specific Energy Consumption

The effect of US pretreatment, drying air temperature and MW power on the drying time of hawthorn samples is presented in Figure 1. The drying process lasted between 35 and 180 min. The longest drying time (180 min) was obtained when drying (temperature of 40 °C and MW power of 180 W) without US pretreatment was applied, whereas the shortest drying time (35 min) was obtained when samples were subjected to US treatment and dried at a temperature of 70 °C and MW power of 540 W. Using ultrasound at the MW power of 360 W and a temperature of 70 °C reduced the drying time by 25%. This value was 12% at the MW power of 540 W and a temperature of 40 °C. The positive effect of US on reducing drying time during the process has been reported in many studies [21,23,28,44]. The use of US can improve water removal from hawthorn samples, especially during the fall rate period when water evaporation becomes more challenging. The use of ultrasound creates a sponge effect in the product, and also the sponge effect created by US causes the formation of micro-channels on the skin layer of the samples. In fact, US weakens the tight bond with of tissue and facilitates the outflow of water [45,46]. Also, the cavitation factor leads to the formation of high-intensity turbulence and causes the subsequent decrease in the resistance of the boundary layer [22].

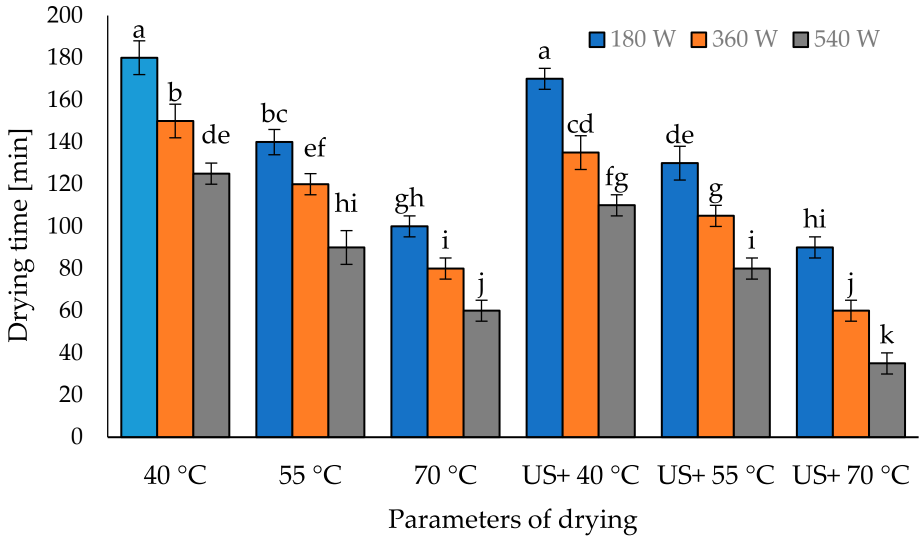

Figure 1. Drying time during different drying schemes. Data followed by different letters (a–k) in each column are significantly different at $p < 0.01$. Columns with the same letters are not significantly different.

Figure 1 shows that drying time decreased with increasing MW power. In the early stages of drying, the samples have high humidity and the use of microwave power causes molecules to be polarized, so the transfer of moisture to the surface of the product happens faster and the samples dry faster. The flow of water vapor from the inner parts to the surface of the product creates a porous structure, and as a result, the moisture evaporates faster, and finally the drying speed increases [23,47]. As it is evident in Figure 1, the increase in air temperature reduced the drying time. It is believed that the reason is the increase in the drying temperature increases the temperature of the drying product. After increasing the temperature of the product, a change in the latent heat of evaporation and an increase in the movement of water molecules in the product (substance) will occur due to the heat, and finally, the rate of evaporation and the rate of mass transfer in the drying substance will increase [48]. Similarly, other researchers also reported the simultaneous effect of increasing MW power and air temperature on reducing the drying time of agricultural products, including dragon fruit [47], white mushrooms [49] and carrot [50].

The drying process is known as one of the processes with high energy consumption [51]. Thus, in our study of hawthorn the specific energy consumption (SEC) was evaluated. The lowest amount of SEC was obtained under the conditions of 70 °C and 540 W of MW power with the use of US pretreatment. As seen in the results shown in Table 2, it was observed that the linear effect of the variables of air temperature, MW power, and the use of US as well as the interaction effect of air temperature and MW power on the SEC for drying were significant. Figure 2 shows the interaction effect of air temperature and MW power and US pretreatment on the SEC of drying hawthorn. As expected, with the increase in air temperature and MW power, the amount of SEC for drying decreased due to the reduction in drying time. Increasing MW power decreased the amount of energy consumed at all the tested treatments. However, increasing MW power had a greater effect on reducing drying energy than increasing air temperature. The SEC depends on various factors such as air temperature, air velocity, specific heat of air, and latent heat of water evaporation [52]. Increasing air temperature and MW power accelerates the evaporation of free water in the product, significantly reducing drying time and total energy consumption. [53]. Similar results were achieved by Szadzinska and Mierzwa [49] for mushrooms drying, Maftoonazad et al. [33] for onion drying, and Kaveh and Abbaspour- Gilandeh [36] for drying green peas.

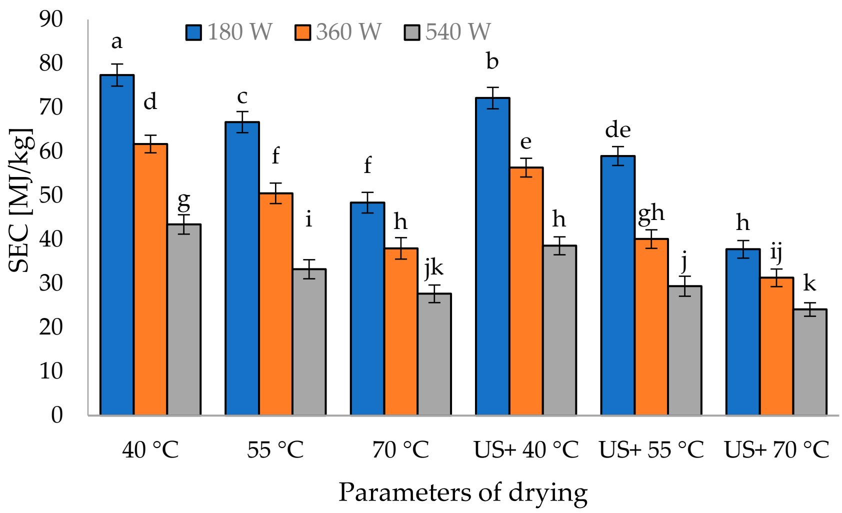

Figure 2. Specific energy consumption during different drying schemes. Data followed by different letters (a–k) in each column are significantly different at $p < 0.01$. Columns with the same letters are not significantly different.

Also, as seen in Figure 2, it can be noted that the use of US pretreatment has reduced the SEC. Products such as hawthorn form a hard surface layer when the moisture is removed from them, and then the moisture is removed from the product slowly. The application of US pretreatments reduces the formation of this hard surface layer, and as a result, the moisture removal from the surface of the product increases and the amount of SEC decreases [5,50]. The results obtained by Mirzaei-Baktash et al. [28] for button mushroom, Szadzińska et al. [54] for raspberries, and Mierzwa et al. [34] for raspberries, regarding the reduction in SEC when applying US pretreatment, are in line to the current research findings.

3.3. Effect of Drying on Physical Property Changes

3.3.1. Color

The results of investigating the effect of temperature, MW power and US on total color changes (ΔE), regarding fresh raw material, are shown in Figure 3. The results showed that the color parameter has the highest value when the highest temperature and the highest microwave power were used: at a temperature of 70 °C and a power of 540 W. On the other hand, application of US treatment before the drying results in a lower value of the ΔE. US treatment followed by drying at 70 °C and 540 W MW power resulted in a significant decrease in total color difference compared to drying at the same parameters without US treatment. This trend was also observed at other temperature and microwave power levels. Such changes can be connected to the shorter drying time of about 5–42%, when US was applied before drying. Compared to the other parameters, the best color (the lowest ΔE) was obtained for the sample subjected to US treatment and dried at a temperature of 55 °C with the MW power at 360 W. The higher MW power and air temperature showed the highest rate of total color changes. In this method, although the samples are placed inside the dryer for a short period of time, the temperature used for drying is so high that the non-enzymatic browning reaction is carried out with high intensity [48]. This reaction causes burns on the surface of the sample and increases the final color changes of the samples. As can be seen in Figure 3, with the increase in air temperature from 40 to 55 °C and MW power from 180 to 360 W, the overall color changes decreased. One of the reasons is the low temperature affects the properties of the food due to the prolonged drying time by creating free radicals and sonochemicals as a result of cavitation, and the color changes of hawthorn samples increase at low temperature [50,55]. In addition, by increasing the air temperature from 60 to 70 °C and MW power from 360 to 540 W, enzymatic reactions and non-enzymatic brown reactions can occur and result in higher values of total color change. This can be linked with the pigment decomposition which happens at high temperature [56]. Also, it can be seen that the use of US treatment in all drying conditions reduced the color changes. Similar results have been reported by other researchers for agricultural products such as hawthorn [50], sunflower [44], carrot [57], and raspberries [54].

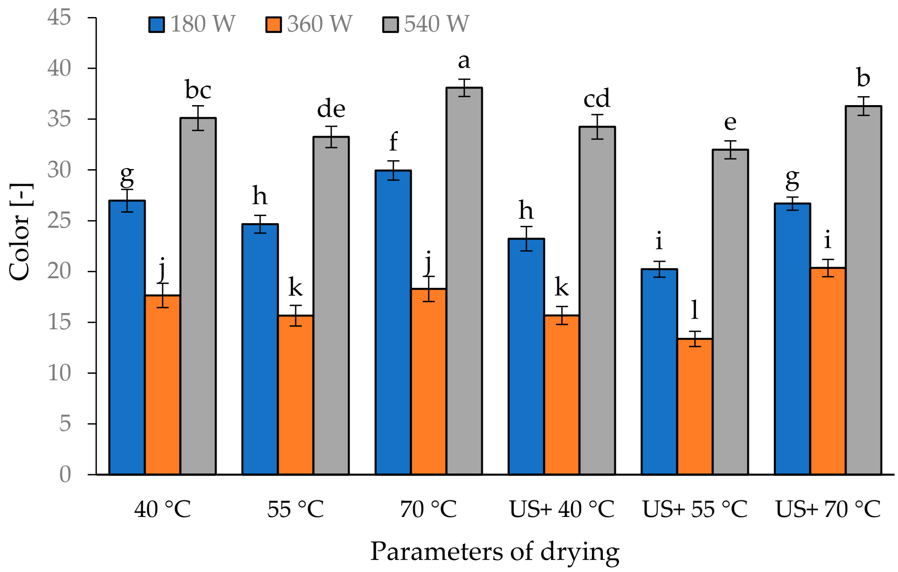

Figure 3. Effects of US pretreatment, MW power and air temperature during drying on total color difference (ΔE) in hawthorn. Data followed by different letters (a–l) in each column are significantly different at $p < 0.01$. Columns with the same letters are not significantly different.

3.3.2. Shrinkage

The application of microwave during drying results in porous plant material in comparison to traditional hot-air drying [58]. As the results in Table 2 show, the effect of MW power, air temperature and US on the amount of shrinkage was significant (0.01%), but the mutual effects on shrinkage were not significant (0.01%). The highest amount of shrinkage (57.69%) was obtained under drying conditions of air temperature of 70 °C, MW power 540 W, and without the application of US pretreatment. The lowest amount of shrinkage (22.47%) was obtained under the conditions of air temperature equal to 55 °C with the MW power of 360 W, and with the use of US pretreatment. As shown in Figure 4, by increasing the air temperature from 40 to 55 °C and MW power from 180 to 360 W, the shrinkage decreased. Due to the lengthening of the drying process, the volume of the product decreased significantly due to the creation of viscoelastic stresses in the pores, which leads to an increase in shrinkage [39]. In addition, shrinkage increased with increasing temperature from 55 to 70 °C and MW power from 360 to 540 W. This is due to the production of extensive internal heat, which accelerates the removal of water from the tissue in hawthorn samples at high power and temperature [50]. During the drying process, water removal from the tissue of the product by applying tension to its cell wall causes shrinkage. When the water in the intercellular wall of the product evaporates, air replaces it; as a result, the tissue is not able to maintain the structural network and the outer structure of the cell collapses and shrinkage results [32]. Joudi-Sarighayeh et al. [59] observed the amount of shrinkage in pumpkin slices dried by the MW/HA method. These results are in agreement with the findings of the studies reported by Bhat et al. [60], and Wang et al. [61].

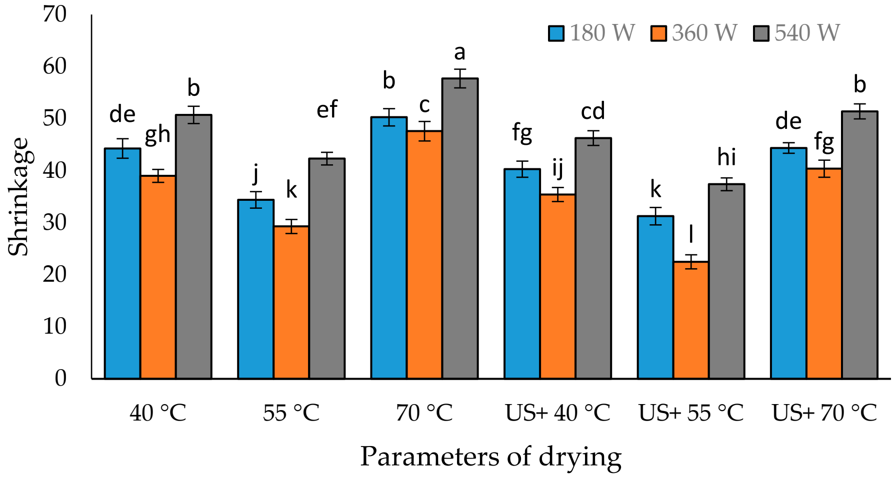

Figure 4. Effects of US pretreatment, MW power and air temperature during drying on shrinkage of hawthorn. Data followed by different letters (a–l) in each column are significantly different at $p < 0.01$. Columns with the same letters are not significantly different.

Also, the use of US pretreatment in all conditions of hawthorn drying reduced shrinkage compared to the methods of US-free pretreatment. During the drying process, the water leaving the cell causes an increase in the tension applied by the liquid on the cell wall. This increase in tension causes the fabric of the substance to shrink. Applying US pretreatment reduced the tension in the cell wall of the product [62]. Dehghannya et al. [50] showed that the use of US pretreatment reduces shrinkage for drying carrot in MW–CV. Jahanbakhshi et al. [63] also obtained similar results for drying nectarine in a hot air dryer under US pretreatment.

3.3.3. Rehydration Ratio (RR)

According to the results listed in Table 2, the independent effect of temperature, MW power, and the use of US pretreatment and the mutual effects of the desired parameters on the RR of dried hawthorn slices were significant at the probability level of 1%. As shown in Figure 5, the highest percentage of water reabsorption was observed in samples dried at 55 °C and MW power of 540 W with the use of US pretreatment. These results showed that a structure with less shrinkage has a higher water RR [30]. On the other hand, the lowest amount of RR was also observed in the samples without US pretreatment and at the MW power of 360 W dried at the temperature of 70 °C. This may be due to the changes in the structure or texture degradation of the samples during MW–HA air drying. Due to the increases in the internal temperature of the samples and the migration of sugars from the inside of the sample to the surface of the sample and because of the reduction of the pores during this drying stage, the RR decreased [64]. The results of Souza et al. [65] also showed that the RR of dried products was strongly dependent on the drying process, so that the carrots samples that were dried using higher MW powers had the lowest RR compared to other treatments. The results obtained in the present research are in agreement with the previous literature [59,66,67].

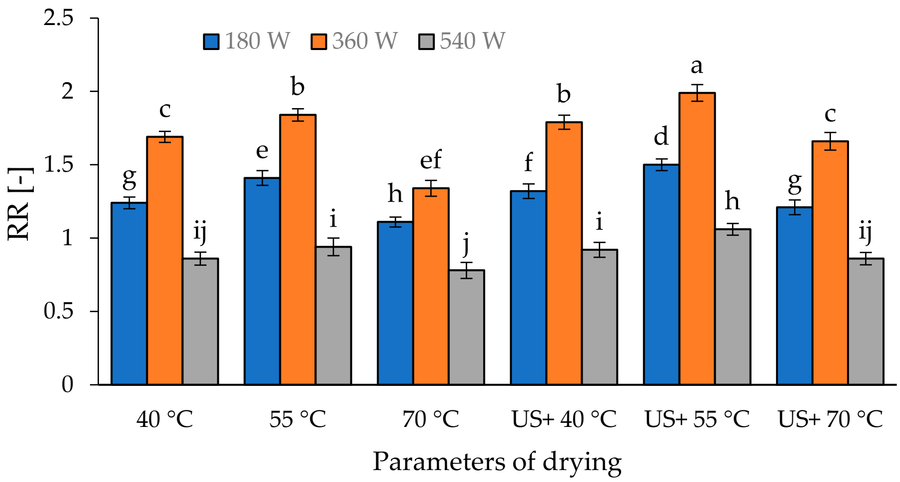

Figure 5. Effects of US pretreatment, MW power, and air temperature during drying on rehydration ratio (RR) in hawthorn. Data followed by different letters (a–j) in each column are significantly different at $p < 0.01$. Columns with the same letters are not significantly different.

Furthermore, the use of US pretreatment in all treatments improved the RR. The use of US can enlarge the capillaries and loosen the internal structure of the product by cavitation effect and mechanical effect, and this phenomenon is beneficial to improve the RR of the sample [68]. Tao et al. [69] also found that the use of US during the drying of white cabbage improved the RR of dried samples, which could be due to the microstructural changes produced by US during drying. Also, the study of Horuz et al. [70] proved that the use of US pretreatment before MW–HA drying can accelerate the RR process of dried tomato.

3.4. Effect of Drying on Chemical Property Changes

3.4.1. Total Phenol Content (TPC) and Total Flavonoid Content (TFC)

The content of bioactive compounds (TPC, TFC) of hawthorn slices before and after drying is presented in Figures 6 and 7. Hawthorn is a great source of TPC and TFC, but processing conditions such as exposure to heat, oxygen, and light can affect its preservation. After drying, TPC and TFC decreased significantly compared to the fresh slices. The results showed that the increase in temperature and MW power had an adverse effect on the TPC and TFC. In fact, the increase in MW power and temperature caused the TPC and TFC content to decrease compared to the fresh sample. On the other hand, using US pretreatment before drying at the temperatures at all three MW power levels did not have much effect on the TPC and TFC values. As shown in Figures 4 and 5, the TPC and TFC content at all the temperature levels was higher when the MW power of 360 W was used, regardless of the application of US pretreatment. The lowest content of the TPC and TFC is related to the treatment at the air temperature of 70 °C and microwave power at 540 W without US. The difference in the amount of TPC and TFC at different temperatures and MW powers of drying is mostly due to the duration of exposure of the samples to temperature [67]. Since polyphenols are destroyed during drying or are attached to other compounds (e.g., proteins), any drying can partially reduce the amount of TPC and TFC as a result [61]. Also, as the drying time increases, due to the increased exposure of TPC and TFC to heat; the destruction of these compounds increases and finally the amount of phenol decreases [71]. Since US pretreatment is a suitable non-thermal method to increase TPC and TFC, the use of this pretreatment before drying increases the TPC and TFC compared to non-pretreated samples [17]. This could be due to the fact US destroys the cell wall of the fruit and causes the release of TPC compounds, and this causes an increase in the amount of TPC and TFC [57]. A similar observation was highlighted in sonicated cranberries [72], carrots [57], and turmeric [73].

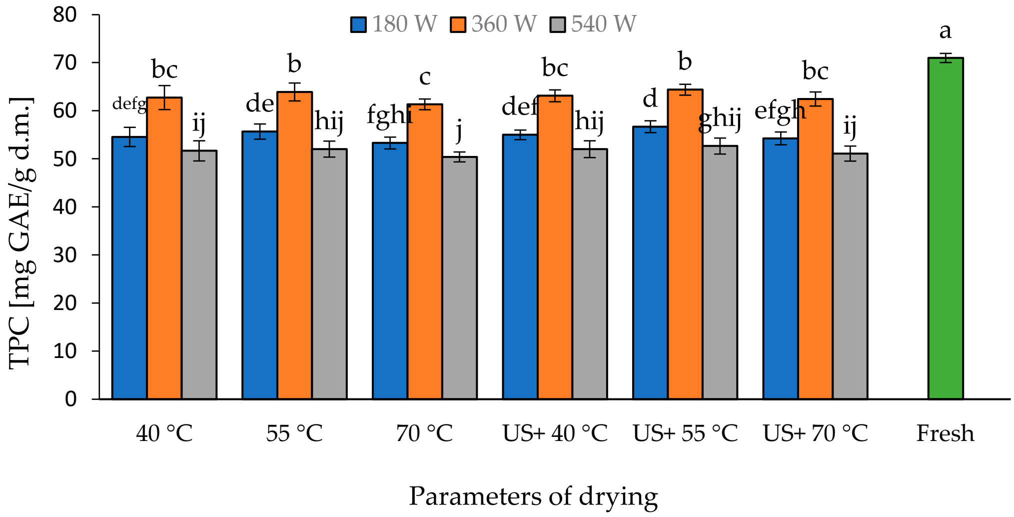

Figure 6. Effects of US pretreatment, MW power and air temperature during drying on total polyphenol content (TPC) in hawthorn. Data followed by different letters (a–j) in each column are significantly different at $p < 0.01$. Columns with the same letters are not significantly different.

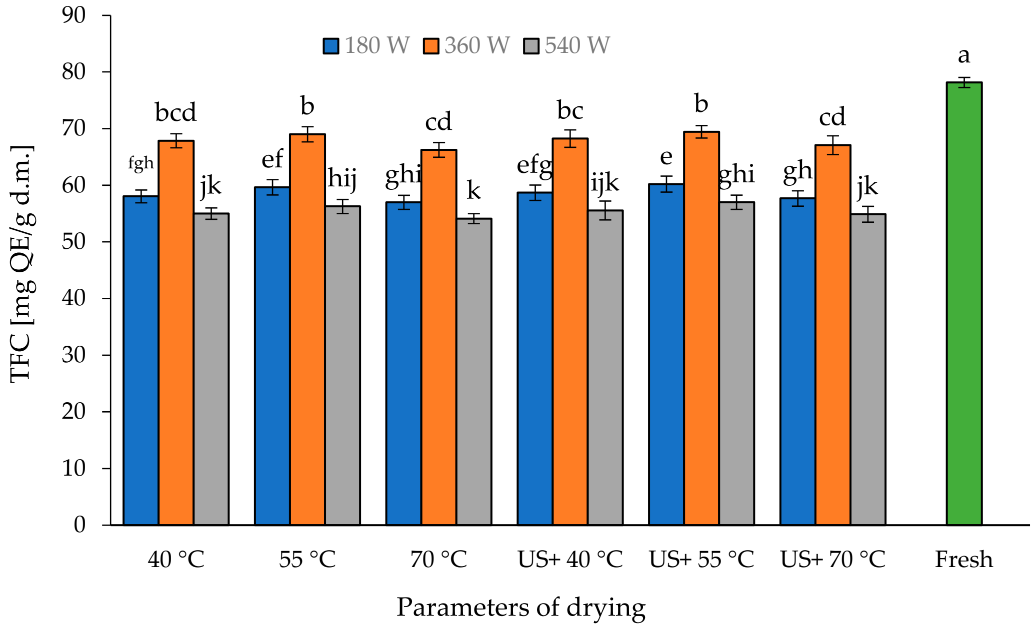

Figure 7. Effects of US pretreatment, MW power and air temperature during drying on total flavonoid content (TFC) in hawthorn. Data followed by different letters (a–k) in each column are significantly different at $p < 0.01$. Columns with the same letters are not significantly different.

3.4.2. Antioxidant Activity (AA)

The AA of hawthorn was evaluated using DPPH scavenging. According to Table 2, the effect of independent parameters (MW power and air temperature) and the mutual effect of MW power and air temperature on AA were significant at the 0.01% level. Regarding the AA, the results are similar to the TFC and TPC parameters; in other words, using air temperature and MW power had an adverse effect on the AA and decreased the AA of hawthorn compared to the fresh sample. However, the reduction rate was more significant compared to TFC and TPC. The decreasing trend in all temperature levels was more evident in the MW power of 540 W; therefore, the lowest value of the AA related to the treatment when 70 °C with the MW power of 540 W with and without US pretreatment was applied. On the other hand, the application of US pretreatment before drying in all three power levels and air temperatures did not have much effect on the AA. The results of the current research presented in Figure 8 show that the highest amount of AA was observed in the sample when US was applied before drying, with the use of the MW power of 360 W at a temperature of 55 °C. These four samples had a statistically significant difference at the level of 0.01% with other samples. The lowest amount of AA was obtained by samples dried at a temperature of 70 °C and MW power of 540 W ($p < 0.01\%$). In addition, these results could be related to the degradation of bioactive compounds such as TPC, TFC, and carotenoid due to higher thermal load [24,73]. US pretreatment may cause inhibition of cell respiration, inactivation of enzymes, and reduction in drying time, so the hawthorn slices retained more polyphenols and showed higher AA [28].

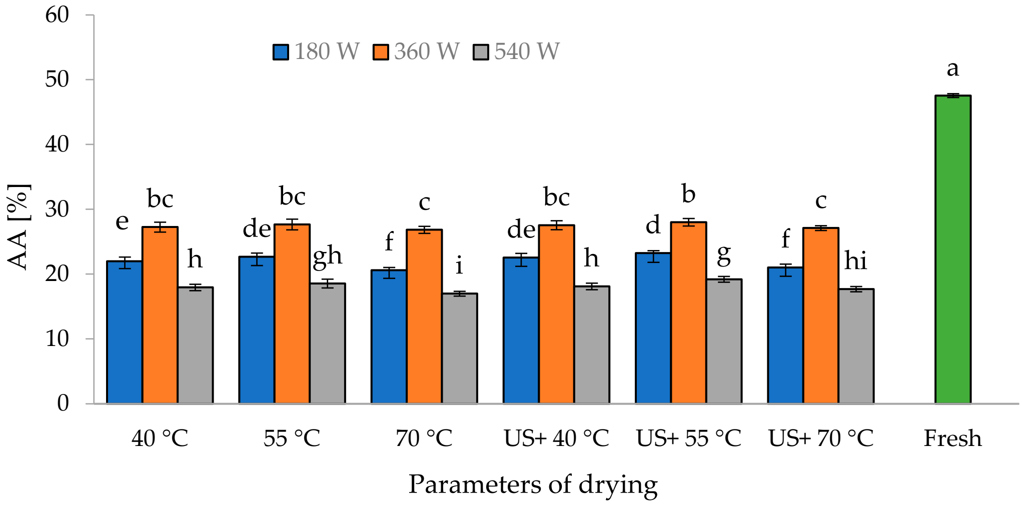

Figure 8. Effects of US pretreatment, MW power and air temperature during drying on antioxidant activity (AA) in hawthorn. Data followed by different letters (a–i) in each column are significantly different at $p < 0.01$. Columns with the same letters are not significantly different.

4. Conclusions

This research evaluated the effect of using US pretreatment and microwave–hot air (US–MW–HA) drying conditions on chosen physical and chemical properties of hawthorn pieces. The results indicated that US pretreatment could decrease drying time and specific energy consumption by enhancing moisture removal during the microwave–hot air drying process. Comparison between the use of US pretreatment and US-free pretreatment for drying time and specific energy consumption at the temperature of 70 °C and MW power of 540 W was reduced by 41.6% and 12.8%, respectively. However, it is important to evaluate the quality of the food product and the different parameters used for drying (temperature, microwave power) have an effect on the properties of plant tissue. Thus, results showed that the sample treated with US and dried at 60 °C and microwave power of 360 W had the highest RR amount (1.99) and the lowest amount of shrinkage and total color difference. Moreover, exposing raw material to the US pretreatment improves retention of total phenolic compounds, total flavonoids compounds and antioxidant activity due to the faster drying process. A microwave power level of 360 W and temperature of 55 °C with US pretreatment were the best drying conditions for hawthorn, which was characterized by the highest amount of bioactive compounds. Considering the medicinal value of hawthorn and also the use of this product in traditional medicine, it is necessary to conduct scientific studies in order to achieve the maximum quantitative and qualitative yield after harvesting by using the appropriate drying method. Thus, the use of US as a pretreatment technology resulted in better quality dried products than similar products without pretreatment.

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References

1. Belwal, T.; Cravotto, C.; Prieto, M.A.; Venskutonis, P.R.; Daglia, M.; Devkota, H.P.; Baldi, A.; Ezzat, S.M.; Gomez-Gomez, L.; Salama, M.M.; et al. Effects of different drying techniques on the quality and bioactive compounds of plant-based products: A critical review on current trends. *Dry. Technol.* **2022**, *40*, 1539–1561. [CrossRef]
2. Duan, X.; Liu, W.C.; Ren, G.Y.; Yang, X. Effects of different drying methods on the physical characteristics and flavor of dried hawthorns (*Crataegus* spp.). *Dry. Technol.* **2017**, *35*, 1412–1421. [CrossRef]
3. Li, J.; Li, Z.; Raghavan, G.S.V.; Song, F.; Song, C.; Liu, M.; Pei, Y.; Fu, W.; Ning, W. Fuzzy logic control of relative humidity in microwave drying of hawthorn. *J. Food Eng.* **2021**, *310*, 11070. [CrossRef]
4. Aral, S.; Bese, A.V. Convective drying of hawthorn fruit (*Crataegus* spp.): Effect of experimental parameters on drying kinetics, color, shrinkage, and rehydration capacity. *Food Chem.* **2016**, *210*, 577–584. [CrossRef] [PubMed]
5. Abbaspour-Gilandeh, Y.; Kaveh, M.; Fatemi, H.; Aziz, M. Combined hot air, microwave, and infrared drying of hawthorn fruit: Effects of ultrasonic pretreatment on drying time, energy, qualitative, and bioactive compounds' properties. *Foods* **2021**, *10*, 1006. [CrossRef] [PubMed]
6. Li, Y.; Wang, X.; Wu, Z.; Wan, N.; Yang, M. Dehydration of hawthorn fruit juices using ultrasound-assisted vacuum drying. *Ultrason. Sonochemistry* **2020**, *68*, 10521. [CrossRef]
7. Reis, F.R.; Marques, C.; de Moraes, A.C.S.; Masson, M.L. Trends in quality assessment and drying methods used for fruits and vegetables. *Food Control* **2022**, *142*, 10925.
8. Majumder, P.; Sinha, A.; Gupta, R.; Sablani, S.S. Drying of Selected Major Spices: Characteristics and Influencing Parameters, Drying Technologies, Quality Retention and Energy Saving, and Mathematical Models. *Food Bioprocess Technol.* **2021**, *14*, 1028–1054. [CrossRef]
9. Mohammed, H.H.; Tola, Y.B.; Taye, A.H.; Abdisa, Z.K. Effect of pretreatments and solar tunnel dryer zones on functional properties, proximate composition, and bioactive components of pumpkin (*Cucurbita maxima*) pulp powder. *Heliyon* **2022**, *8*, e10747. [CrossRef]
10. Zhou, Y.-H.; Pei, Y.-P.; Sutar, P.P.; Liu, D.-H.; Deng, L.-Z.; Duan, X.; Liu, Z.-L.; Xiao, H.-W. Pulsed vacuum drying of banana: Effects of ripeness on drying kinetics and physicochemical properties and related mechanism. *LWT Food Sci. Technol.* **2022**, *161*, 1133. [CrossRef]
11. Pei, Y.; Li, Z.; Song, C.; Li, J.; Xu, W.; Zhu, G. Analysis and modelling of temperature and moisture gradient for ginger slices in hot air drying. *J. Food Eng.* **2022**, *323*, 11100. [CrossRef]
12. Karwacka, M.; Ciurzyńska, A.; Galus, S.; Janowicz, M. Freeze-dried snacks obtained from frozen vegetable by-products and apple pomace—Selected properties, energy consumption and carbon footprint. *Innov. Food Sci. Emerg. Technol.* **2022**, *77*, 102949. [CrossRef]
13. Tepe, F.B.; Tepe, T.K.; Ekinci, A. Drying kinetics and energy efficiency of microwave-dried lemon slices. *Chem. Ind. Chem. Eng. Q.* **2022**, *28*, 297–304. [CrossRef]
14. Sadeghi, E.; Movagharnejad, K.; Asl, A.H. Parameters optimization and quality evaluation of mechanical properties of infrared radiation thin layer drying of pumpkin samples. *J. Food Process Eng.* **2019**, *43*, e13309. [CrossRef]
15. Dadan, M.; Nowacka, M. The assessment of the possibility of using ethanol and ultrasound to design the properties of dried carrot tissue. *Appl. Sci.* **2021**, *11*, 689. [CrossRef]
16. Rybak, K.; Wiktor, A.; Kaveh, M.; Dadan, M.; Witrowa-Rajchert, D.; Nowacka, M. Effect of thermal and non-thermal technologies on kinetics and the main quality parameters of red bell pepper dried with convective and microwave–convective methods. *Molecules* **2022**, *27*, 2164. [CrossRef]
17. Bao, T.; Hao, X.; Shishir, M.R.S.; Karim, N.; Chen, W. Green alternative methods for pretreatment of whole jujube before drying process. *J. Sci. Food Agric.* **2022**, *102*, 1030–1039. [CrossRef]

18. Deng, Y.; Zhao, Y. Effects of pulsed-vacuum and ultrasound on the osmodehydration kinetics and microstructure of apples (Fuji). *J. Food Eng.* **2008**, *85*, 84–93. [CrossRef]
19. Awad, T.S.; Moharram, H.A.; Shaltout, O.E.; Asker, D.; Youssef, M.M. Applications of ultrasound in analysis, processing and quality control of food: A review. *Food Res. Int.* **2012**, *48*, 410–427. [CrossRef]
20. Rostamabadi, H.; Rohit, T.; Karaca, A.C.; Nowacka, M.; Colussi, R.; Frasson, S.F.; Aaliya, B.; Sunooj, K.V.; Falsafi, S.R. How non-thermal processing treatments affect physicochemical and structural attributes of tuber and root starches? *Trends Food Sci. Technol.* **2022**, *128*, 217–237. [CrossRef]
21. Zhang, J.; Li, M.; Ding, Z.; Wang, C.; Cheng, J. Evaluation of ultrasound-assisted microwave hot air convective drying Chinese hickory—Drying kinetics and product's quality properties. *J. Food Process Eng.* **2021**, *44*, e13842. [CrossRef]
22. Sledz, M.; Wiktor, A.; Rybak, K.; Nowacka, M.; Witrowa-Rajchert, D. The impact of ultrasound and steam blanching pre-treatments on the drying kinetics, energy consumption and selected properties of parsley leaves. *Appl. Acoust.* **2016**, *103*, 148–156. [CrossRef]
23. Dehghannya, J.; Kadkhodaei, S.; Heshmati, M.K.; Ghanbarzadeh, B. Ultrasound-assisted intensification of a hybrid intermittent microwave—Hot air drying process of potato: Quality aspects and energy consumption. *Ultrasonics* **2019**, *96*, 104–122. [CrossRef]
24. Chouaibi, M.; Snoussi, A.; Attouchi, S.; Ferrari, G. Influence of drying processes on bioactive compounds profiles, hydroxymethylfurfural, color parameters, and antioxidant activities of Tunisian eggplant (*Solanum melongena* L.). *J. Food Process. Preserv.* **2021**, *45*, e15460. [CrossRef]
25. Zeng, S.; Wang, B.; Lv, W.; Wu, Y. Effects of microwave power and hot air temperature on the physicochemical properties of dried ginger (*Zingiber officinale*) using microwave hot-air rolling drying. *Food Chem.* **2023**, *404*, 134741. [CrossRef] [PubMed]
26. Ando, Y.; Nei, D. Comparison of potato void structures dried by air-drying, freeze-drying, and microwave-vacuum-drying, and the physical properties of powders after grinding. *Food Bioprocess Technol.* **2023**, *16*, 447–458. [CrossRef]
27. Nanvakenari, S.; Movagharnejad, K.; Latifi, A. Modelling and experimental analysis of rice drying in new fluidized bed assisted hybrid infrared-microwave dryer. *Food Res. Int.* **2022**, *159*, 111617. [CrossRef]
28. Mirzaei-Baktash, H.; Hamdami, N.; Torabi, P.; Fallah-Joshaqani, S.; Dalvi-Isfahan, M. Impact of different pretreatments on drying kinetics and quality of button mushroom slices dried by hot-air or electrohydrodynamic drying. *LWT Food Sci. Technol.* **2022**, *155*, 112894. [CrossRef]
29. Li, L.; Zhang, M.; Wang, W. Ultrasound-assisted osmotic dehydration pretreatment before pulsed fluidized bed microwave freeze-drying (PFBMFD) of Chinese yam. *Food Biosci.* **2020**, *35*, 100548. [CrossRef]
30. Nguyen, T.-V.-L.; Nguyen, P.-B.-D.; Tran, T.T.V.; Tran, B.-L.; Huynh, T.-P. Low-temperature microwave-assisted drying of sliced bitter melon: Drying kinetics and rehydration characteristics. *J. Food Process Eng.* **2022**, *45*, e14177. [CrossRef]
31. Tepe, F.B. Impact of pretreatments and hybrid microwave assisting on drying characteristics and bioactive properties of apple slices. *J. Food Process. Preserv.* **2022**, *46*, e17067. [CrossRef]
32. An, N.; Sun, W.; Li, B.; Wang, Y.; Shang, N.; Lv, W.; Li, D.; Wang, L. Effect of different drying techniques on drying kinetics, nutritional components, antioxidant capacity, physical properties and microstructure of edamame. *Food Chem.* **2022**, *373*, 131412. [CrossRef]
33. Maftoonazad, N.; Dehghani, M.R.; Ramaswamy, H.S. Hybrid microwave-hot air tunnel drying of onion slices: Drying kinetics, energy efficiency, product rehydration, color, and flavor characteristics. *Dry. Technol.* **2022**, *40*, 966–986. [CrossRef]
34. 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]
35. AOAC. *Official Methods of Analysis*, 16th ed.; Association of Official Analytical Chemists: Washington, DC, USA, 2010.
36. Kaveh, M.; Abbaspour-Gilandeh, Y. Drying characteristics, specific energy consumption, qualitative properties, total phenol compounds, and antioxidant activity during hybrid hot air-microwave- rotary drum drying of green pea. *Iran. J. Chem. Chem. Eng.* **2022**, *40*, 655–672.
37. Sharifian, F.; Motlagh, A.M.; Nikbakht, A.M. Pulsed microwave drying kinetics of fig fruit (*Ficus carica* L.). *Aust. J. Crop Sci.* **2012**, *6*, 1441–1444.
38. Çetin, N.; Sağlam, C. Effects of ultrasound pre-treatment assisted drying methods on drying characteristics, physical and bioactive properties of windfall apples. *J. Sci. Food Agric.* **2022**, *103*, 534–547. [CrossRef]
39. Geng, Z.; Torki, M.; Kaveh, M.; Beigi, M.; Yang, X. Characteristics and multi-objective optimization of carrot dehydration in a hybrid infrared /hot air dryer. *LWT Food Sci. Technol.* **2022**, *172*, 114229. [CrossRef]
40. Sharifian, F.; Modarres-Motlagh, A.; Komarizade, M.H.; Nikbakht, A.M. Colour change analysis of fig fruit during microwave drying. *Int. J. Food Eng.* **2013**, *9*, 107–114. [CrossRef]
41. Wiktor, A.; Landfeld, A.; Matys, A.; Novotná, P.; Dadan, M.; Kováříková, E.; Nowacka, M.; Mulenko, M.; Witrowa-Rajchert, D.; Strohalm, J.; et al. Selected Quality Parameters of Air-Dried Apples Pretreated by High Pressure, Ultrasounds and Pulsed Electric Field—A Comparison Study. *Foods* **2021**, *10*, 1943. [CrossRef]
42. Shahidi, F.; Naczk, M. *Phenolics in Food and Nutraceuticals*; CRC Press: Boca Raton, FL, USA, 2004.
43. 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]
44. Dibagar, N.; Kowalski, S.J.; Chayjan, R.A.; Figiel, A. Accelerated convective drying of sunflower seeds by high-power ultrasound: Experimental assessment and optimization approach. *Food Bioprod. Process.* **2020**, *123*, 42–59. [CrossRef]

45. Huang, Y.; Zhang, M.; Mujumdar, A.S.; Luo, Z.; Fang, Z. Dehydrated fruits and vegetables using low temperature drying technologies and their application in functional beverages: A review. *Dry. Technol.* 2022, *in press*. [CrossRef]
46. Dehsheikh, F.N.; Dinani, S.T. Coating pretreatment of banana slices using carboxymethyl cellulose in an ultrasonic system before convective drying. *Ultrason. Sonochemistry* **2019**, *52*, 401–413. [CrossRef]
47. Raj, G.V.S.B.; Dash, K.K. Effect of intermittent microwave convective drying on physicochemical properties of dragon fruit. *Food Sci. Biotechnol.* **2022**, *31*, 549–560. [CrossRef]
48. 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]
49. Szadzinska, J.; Mierzwa, D. The influence of hybrid drying (microwave-convective) on drying kinetics and quality of white mushrooms. *Chem. Eng. Process. Process Intensif.* **2021**, *16*, 108532. [CrossRef]
50. Dehghannya, J.; Seyed-Tabatabaei, S.-R.; Heshmati, M.K.; Ghanbarzadeh, B. Influence of three stage ultrasound—Intermittent microwave—Hot air drying of carrot on physical properties and energy consumption. *Heat Mass Transf.* **2021**, *57*, 1893–1907. [CrossRef]
51. Witrowa-Rajchert, D.; Wiktor, A.; Sledz, M.; Nowacka, M. Selected emerging technologies to enhance the drying process: A review. *Dry. Technol.* **2014**, *32*, 1386–1396. [CrossRef]
52. Motevali, A.; Minaei, S.; Banakar, A.; Ghobadian, B.; Khoshtaghaza, M.H. Comparison of energy parameters in various dryers. *Energy Convers. Manag.* **2014**, *87*, 711–725. [CrossRef]
53. Kaveh, M.; Abbaspour-Gilandeh, Y.; Nowacka, M. Comparison of different drying techniques and their carbon emissions in green peas. *Chem. Eng. Process. Process Intensif.* **2021**, *160*, 108274. [CrossRef]
54. Szadzińska, J.; Łechtańska, J.; Pashminehazar, R.; Kharaghani, A.; Tsotsas, E. Microwave- and ultrasound-assisted convective drying of raspberries: Drying kinetics and microstructural changes. *Dry. Technol.* **2019**, *37*, 1–12. [CrossRef]
55. İlter, I.; Akyıl, S.; Devseren, E.; Okut, D.; Koç, M.; Ertekin, F.K. Microwave and hot air drying of garlic puree: Drying kinetics and quality characteristics. *Heat Mass Transf.* **2018**, *54*, 2101–2112. [CrossRef]
56. Zeng, Y.; Liu, Y.; Zhang, J.; Xi, H.; Duan, X. Effects of far-infrared radiation temperature on drying characteristics, water status, microstructure and quality of kiwifruit slices. *J. Food Meas. Charact.* **2019**, *13*, 3086–3096. [CrossRef]
57. 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. Sonochemistry* **2018**, *48*, 249–258. [CrossRef]
58. Witrowa-Rajchert, D.; Rzaca, M. Effect of drying method on the microstructure and physical properties of dried apples. *Dry. Technol.* **2009**, *27*, 903–909. [CrossRef]
59. Joudi-Sarighayeh, F.; Abbaspour-Gilandeh, Y.; Kaveh, M.; Hernández-Hernández, J.L. The optimization of the physical–thermal and bioactive properties of pumpkin slices dried in a hybrid microwave– convective dryer using the response surface method. *Agronomy* **2022**, *12*, 2291. [CrossRef]
60. Bhat, T.A.; Hussain, S.Z.; Wani, S.M.; Rather, M.A.; Reshi, M.; Naseer, B.; Qadri, T.; Khalil, A. The impact of different drying methods on antioxidant activity, polyphenols, vitamin C and rehydration characteristics of Kiwifruit. *Food Biosci.* **2022**, *48*, 101821. [CrossRef]
61. Wang, Y.; Li, X.; Chen, X.; Li, B.; Mao, X.; Miao, J.; Zhao, C.; Huang, L.; Gao, W. Effects of hot air and microwave-assisted *48*drying on drying kinetics, physicochemical properties, and energy consumption of chrysanthemum. *Chem. Eng. Process. Process Intensif.* **2018**, *129*, 84–94. [CrossRef]
62. Gharkhloo, Z.R.; Sharifian, F.; Rahimi, A.; Yamchi, A.A. Influence of high wave sound pretreatment on drying quality parameters of Echinacea root with infrared drying. *J. Sci. Food Agric.* **2022**, *102*, 2153–2164. [CrossRef]
63. Jahanbakhshi, A.; Yeganeh, R.; Momeny, M. Influence of ultrasound pre-treatment and temperature on the quality and thermodynamic properties in the drying process of nectarine slices in a hot air dryer. *J. Food Process. Preserv.* **2020**, *44*, e14818. [CrossRef]
64. Çetin, N. Comparative assessment of energy analysis, drying kinetics, and biochemical composition of tomato waste under different drying conditions. *Sci. Hortic.* **2022**, *305*, 111405. [CrossRef]
65. Souza, A.U.; Correa, J.L.G.; Tanikawa, D.H.; Abrahao, F.R.; Junqueira, J.R.J.; Jimenez, E.C. Hybrid microwave-hot air drying of the osmotically treated carrots. *LWT Food Sci. Technol.* **2022**, *156*, 113046. [CrossRef]
66. Darıcı, M.; Süfer, O.; Simsek, M. Determination of microwave drying and rehydration kinetics of green peppers with the bioactive and textural properties. *J. Food Process Eng.* **2021**, *44*, e13755. [CrossRef]
67. Zahoor, I.; Khan, M.A. Microwave assisted fluidized bed drying of red bell pepper: Drying kinetics and optimization of process conditions using statistical models and response surface methodology. *Sci. Hortic.* **2021**, *286*, 11020. [CrossRef]
68. Song, Y.; Tao, Y.; Zhu, X.; Han, Y.; Show, P.L.; Song, C.; Zaid, H.F.M. Ultrasound-Enhanced Hot Air Drying of Germinated Highland Barley Seeds: Drying Characteristics, Microstructure, and Bioactive Profile. *Agri Eng.* **2019**, *1*, 496–510. [CrossRef]
69. Tao, Y.; Han, M.; Gao, X.; Han, Y.; Show, P.-L.; Liu, C.; Ye, X.; Xie, G. Applications of water blanching, surface contacting ultrasound-assisted air drying, and their combination for dehydration of white cabbage: Drying mechanism, bioactive profile, color and rehydration property. *Ultrason. Sonochemistry* **2019**, *53*, 192–201. [CrossRef]
70. Horuz, E.; Jaafar, H.J.; Maskan, M. Ultrasonication as pretreatment for drying of tomato slices in a hot air–microwave hybrid oven. *Dry. Technol.* **2017**, *35*, 849–859. [CrossRef]

71. Li, M.; Wang, B.; Wang, Y.; Liu, J.; Zhang, M. Evaluation of the uniformity, quality and energy cost of four types of vegetables and fruits after pilot-scale pulse-spouted bed microwave (915 MHz) freeze-drying. *Dry. Technol.* **2023**, *41*, 290–370. [CrossRef]
72. Zhou, Y.-H.; Staniszewska, I.; Liu, Z.-L.; Zielinska, D.; Xiao, H.-W.; Pan, Z.; Nowak, K.W.; Zielinska, M. Microwave-vacuum-assisted drying of pretreated cranberries: Drying kinetics, bioactive compounds and antioxidant activity. *LWT Food Sci. Technol.* **2021**, *146*, 111464. [CrossRef]
73. An, N.; Shang, N.; Lv, W.; Li, D.; Wang, L.; Wang, Y. Effects of carboxymethyl cellulose/pectin coating combined with ultrasound pretreatment before drying on quality of turmeric (*Curcuma longa* L.). *Int. J. Biol. Macromol.* **2022**, *202*, 354–365. [CrossRef] [PubMed]