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Article

Chosen Biochemical and Physical Properties of Beetroot Treated with Ultrasound and Dried with Infrared–Hot Air Method

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Featured Application: A widely used method of food preservation is drying. Unfortunately, apart from the increase in the durability of the raw material and the decrease in its weight and volume, there are also negative changes related to its physical, chemical, and sensory properties. To reduce some unfavorable effects of the drying process, pretreatment can be used. Ultrasonic waves applied before drying in most cases positively affect the changes in food, obtaining high-quality products with changed physical properties. Additionally, ultrasounds have a positive impact on the efficiency of the technological process based on heat and mass transfer, reducing its duration, which results in lower production costs. Therefore, pretreatment using ultrasound is a promising alternative to the thermal pretreatment of raw materials.

Abstract: Beetroots are sources of bioactive compounds and valued pigments such as betalains. The purpose of this study was to determine the influence of ultrasound pretreatment on the beetroot infrared–hot air drying process and the functional properties of the obtained product. In this study, there were two used frequencies—21 and 35 kHz—and three different periods of time—10, 20, and 30 min. Since beetroots are usually subjected to thermal treatment, another aim was to examine the influence of blanching and soaking on the beetroot tissue properties in order to compare traditional and ultrasound-treated methods. As a result of this study, it was found that ultrasound pretreatment changed the dry matter content, water activity, thickness of the tissue, total color difference, and contents of betanin pigments in the beetroot. It was revealed that the drying process is shorter after ultrasound pretreatment using a 21 kHz frequency. Drying tissue exposed to ultrasounds showed a significant increase in the L* parameter; however, the decrease in the a* parameter was caused by a reduced content of betalain pigments. Taking into consideration parameters important from a technological point of view, it was found that the best condition for beetroot pretreatment is 20 min treatment, regardless of the frequency used.

Keywords: color; betalain content; structure; rehydration ratio; hygroscopic properties; blanching

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1. Introduction

Beetroot is one of the most nutrient-rich vegetables and is botanically classified as an herbaceous biennial with a wide variety of bulb colors ranging from yellow to red. Beetroot contains a number of compounds and minerals that have a beneficial effect on the human body. It is characterized by a high content of folic acid, the content of which in 100 g of raw material covers as much as 20% of the recommended daily intake. Folate has a positive effect on the nervous system and brain and prevents ischemic heart diseases. In addition, this vegetable has a high content of fibrous substances and sugars with a moderate caloric value. Additionally, it has been shown that beetroot has a high content of minerals, e.g., calcium, sodium, iron, magnesium, and potassium, which restore the acid–base balance in the body [1,2]. Moreover, it is characterized by a high betaine content, thanks to which its root has an intense red color, and in the human body, it serves as a natural antioxidant. Additionally, betaine is a compound that combats high levels of homocysteine—an amino acid that is a factor in the development of atherosclerosis, heart and brain diseases, and thrombotic lesions. This vegetable contains approximately 750 μg of betaine/g of fresh material [3–5]. Another group of compounds found in beetroot are saponins, which have a positive effect on the digestive system, accelerate the digestion of fats, and have diuretic and anti-inflammatory properties [6].

The basic task of all pretreatments is to properly prepare the raw material for adequate processing while maintaining its nutritional value and taste as best as possible. Pretreatments often also contribute to extending the shelf life of finished products. Preparing the raw material before pretreatment is intended to minimize unfavorable changes occurring during the actual processes. Moreover, by manipulating the process parameters themselves, it is possible to increase the efficiency of the process and obtain a product attractive to a potential consumer [7–9]. In addition, pretreatment reduces the level of hazardous chemicals accumulated in raw materials, resulting from excessive soil fertilization and environmental pollution. When selecting the pretreatment used before the drying process, an important element is the final properties that the product will have. Dried products should have the ability to rehydrate. This process is used in semi-finished products used for production and processing, as well as in finished products treated as convenience foods. Dried food can be stored for a long time without significant qualitative or quantitative losses. After hydration, it is an addition to various types of dishes. To obtain a finished product with the required quality parameters, various types of preliminary treatments and various processing parameters are analyzed [7,10].

Blanching causes the loosening of the tissue, partial destruction of the microflora, removal of gases from the intercellular spaces contained in the material, and inactivation of enzymes, primarily polyphenol oxidase, responsible for the darkening of the raw material, and also limits the fibrosis of the raw material and preserves the color of the product. The blanching process, despite its positive impact on specific parameters, has a negative impact on the overall quality of the product. It reduces the content of valuable nutrients. Additionally, this process requires high energy inputs and a large amount of water, which creates the problem of generating excessive amounts of wastewater. The effectiveness of blanching performed in industrial conditions is measured by a negative result of a qualitative test for peroxidase activity [11–13].

Ultrasound is increasingly used in the food industry to speed up unit operations. This process affects physical, chemical, and biological changes in raw materials [14]. Ultrasonic waves can be propagated through liquids, solids, and gases. In the food industry, high-power, low-frequency ultrasonic waves (20–100 kHz) are used for liquid products to cause the cavitation effect. This phenomenon is the result of the explosion of gas bubbles caused by a sudden change in pressure and temperature. In the places where the cavitation bubbles collide and the wave is generated after the implosion, mechanical forces are generated, causing irreversible cell damage, which is used to inactivate microorganisms and facilitate the release of cell contents into the environment [15]. In solid products, ultrasound causes the so-called "sponge effect". It involves a series of rapid contractions and expansions of the raw material tissue. The forces resulting from this mechanism may be greater than the surface tension keeping water inside the capillaries. The described effect results in the formation of microscopic channels in the porous material, thanks to which water is easier to remove from the raw material. The use of ultrasound before the process increases water diffusion during the drying or osmotic dehydration process. This shortens the process time and, consequently, reduces production costs [16,17].

Soaking is used as a pretreatment often combined with blanching or ultrasonication. This is a process that strongly influences the aesthetic, physicochemical, and nutritional properties of the final product after processing. Soaking removes water-soluble components such as sugars and some organic acids by leaching [18,19].

Infrared drying uses thermal energy from heated surfaces using radiated energy. Thermal radiation penetrates to a small depth, heating the product mainly on the surface; therefore, this drying is used to support convective drying in order to accelerate it. It was found that the infrared–convective drying time of selected plant raw materials was shorter by approximately 50% than the convection drying time. An increase in the power of the infrared radiation source and a reduction in the distance between the dried material and the lamps shorten the process time and reduce energy costs [20–22]. Despite the many advantages of the drying process, it is worth remembering that food is a material sensitive to high temperatures. Drying leads to changes in plant tissue caused by chemical reactions, e.g., oxidation, non-enzymatic browning, and changes in mechanical properties caused by material shrinkage. Therefore, it is particularly important to select appropriate drying parameters, the aim of which is to obtain a product with the best possible quality parameters and to reduce the operating costs of this energy-intensive process. In order to minimize unfavorable changes occurring in dried raw materials and reduce energy consumption, several methods are increasingly used simultaneously [23].

Thus, the aim of this work was to study the influence of pretreatment using ultrasound on the kinetics of the infrared–hot air drying process of beetroot and its properties, such as betalain content, color, texture and microstructure, rehydration ratio, and hygroscopic properties. Also, the effect of blanching and soaking was evaluated since the blanching process is usually used for beetroot processing, whereas soaking was used to compare it with ultrasound treatment due to it being conducted in water surroundings.

2. Materials and Methods

2.1. Material

The research material consisted of red beetroots (*Beta vulgaris* L.) of the Boro F1 variety, purchased in a local store (Warsaw). The raw material was preserved under refrigerated conditions (5–8 °C, RH 90%). Prior to experimentation, the beetroots were allowed to reach equilibrium at ambient temperature and were cut into slices 5 ± 1 mm thick and 30 ± 1 mm in diameter using the Robot Coupe CL 50 automatic slicer (RobotCoupe, Montceau-en-Bourgogne, France).

2.2. Technological Processing

2.2.1. Pretreatments

Blanching, soaking, and ultrasound were used as pretreatments. In all treatments, the material-to-water ratio was constant and amounted to 1:4 [24]. The experiments were performed in two repetitions for each pretreatment.

Blanching

Conventional heat treatment was conducted by immersing the material in a container with tap water at a temperature of 90 °C. After 3 min, the material was placed on a sieve and cooled for 15 s in a stream of cold water [25]. A paper towel was used to remove excess water from the beets. However, blanching caused weight loss, which was related to the transfer of water-soluble ingredients to the medium in which the process took place. The weight loss during blanching was statistically significant ($p < 0.05$) and amounted to 7.5% in relation to the material not subjected to pretreatment.

Soaking

Soaking was performed in distilled water at room temperature (21 ± 1 °C) for durations of 10, 20, and 30 min. After the process, the material was dried on filter paper. This process was performed to compare it with the effect of ultrasound treatment, which was also conducted in water surroundings. The use of soaking caused an increase in weight in samples due to the penetration of water into the raw material. It was observed that in the case of soaked tissue, with increasing soaking time, there was a smaller increase in weight.

Ultrasound Treatment

Sonication was conducted using a laboratory ultrasonic bath (MKD-3, MKD Ultrasonics, Stary Konik, Poland) operating at 180 W and a frequency of 21 kHz and 35 kHz, whereas the ultrasound intensity amounted to 3 and 4 W/cm^2, respectively [26]. The treatment durations were 10, 20, and 30 min. Following the procedure, the research material was dried on tissue paper.

The experiments were performed in two repetitions. During processing, alterations in sample mass and the temperature of the medium were assessed.

Ultrasound treatment was carried out at a room temperature of 21 ± 1 °C. While generating ultrasonic waves, the temperature of the medium in which the samples were immersed increased. When using ultrasound at a frequency of 21 kHz, there was a slight increase in water temperature, independent of the process duration, ranging from 1 to 1.75 °C, and these changes were statistically insignificant ($p > 0.05$). However, during pretreatment using ultrasound at a frequency of 35 kHz, there was a significant increase in temperature until 7 °C. As the duration of the exposure to ultrasonic waves with a frequency of 35 kHz increased, the temperature of the medium in which the samples were immersed increased. Similar results were obtained by Jambrak et al. [27], who exposed mushrooms, Brussels sprouts, and cauliflower to ultrasound at a frequency of 40 kHz. An increase in the temperature of the medium by 1 °C was observed for a 3 min process and by 4 °C for a 10 min treatment of plant tissue with ultrasound.

The use of ultrasound treatment in an aqueous medium resulted in an increase in the samples' weight due to the penetration of water into the raw material and the loss of water-soluble components as well as the ultrasound mechanism such as the sponge effect [28]. When using ultrasound at a frequency of 21 kHz for 10, 20 and 30 min, there was an increase in the mass of 5.88, 7.46, and 7.95%, respectively. Slightly higher values of mass gain were recorded for samples exposed to ultrasound at a frequency of 35 kHz. For samples treated for 10, 20, and 30 min, the mass increased by 6.7, 7.7, and 8.2%, respectively, compared to the material not subjected to pretreatment. There was no observed significant effect of the ultrasound frequency or duration of ultrasound treatment. Similar relationships were observed by Fernandes et al. [29], who treated melon tissue with ultrasound at a frequency of 25 kHz for 20 min, noting an increase in the weight of the raw material by 8.7%.

2.2.2. Infrared–Hot Air Drying (IR-HA)

The drying procedure was conducted in a custom-designed laboratory convection dryer (WULS) equipped with infrared lamps positioned 30 cm away from the samples. The material was arranged in a single layer parallel to the airflow. Drying was carried out at an air temperature of 70 °C, with an airflow velocity of 1.5 m/s. Throughout the process, the fluctuation in the mass of the raw material was monitored at one-minute intervals using the POMIAR program, connected to a microprocessor scale (±0.1 g). Drying was stopped after reaching a constant weight of the dried material. The samples were stored in barrier packaging made of BOPA/PE 1540FF foil (Pakmar, Warsaw, Poland). The process was carried out in duplicate for each processing.

Drying curves were developed as functions of dimensionless water content (MR) plotted against time. In accordance with the method presented by Tylewicz et al. [30], the relative moisture ratio was computed using the following formula:

$$\mathrm{MR} = u/u_0, \tag{1}$$

where u represents the water content during the drying process (kg water/kg dry matter (d.m.)), and u_0 is the initial water content (kg water/kg d.m.).

2.3. Physical and Biochemical Analysis

2.3.1. Dry Matter Content and Water Activity

The dry matter content was determined by weight under the official AOAC method [31]. The crushed material was dried at 70 °C for 24 h. The water activity (a_w) was measured using a hygrometer (AquaLab CX-2, Decagon Devices, Pullman, WA, USA) at room temperature (25 °C). The determinations were performed in three repetitions.

2.3.2. Density and Shrinkage

The displacement method with n-heptane was used to determine the density of slices in fresh material and after drying [32]. The measurements were made in three repetitions. Two weighed slices of the sample were placed in a 25 cm^3 cylinder and poured with organic reagent from a 25 cm^3 burette, and the volume of n-heptane remaining in the burette corresponded to the volume of two slices of the material. The shrinkage was estimated by measuring the volume of the beetroot slices before (V_0) and after the drying (V_d) process:

$$S = 100\% \ (1 - (Vd/V_0)) \tag{2}$$

The density was calculated according to the following equation:

$$\varrho = m/(25 - V) \tag{3}$$

where m—sample mass; V—amount of toluene in the cylinder.

2.3.3. Texture Analysis

The analysis of mechanical properties was conducted using a TA-TX2 texture analyzer (Stable Micro Systems Ltd., Surrey, UK) equipped with a 25 kg load cell. The experiment employed a cutting blade measuring 62 mm in length, 24 mm in width, and 0.5 mm in thickness [33]. The test aimed to fully cut slices of dried beetroot with a head velocity of 1.0 mm/s and a force of 15 N. Cutting was started with a resistance of 0.1 N. The movement of the cutting element took place inside a metal base with a slot. For the test, 20 slices of randomly selected material were utilized. The cutting work was calculated as the area under the curve showing changes in force (N) as a function of head displacement (mm) to achieve the maximum force.

2.3.4. Color Measurement

The color was measured in reflected light using a CR-300 chromometer (Konica Minolta, Osaka, Japan). The device was calibrated against standard colors in the CIE L*a*b* system. The measurement was made with CIE Standard Illuminant C, d:0° (diffuse illumination/0° viewing angle), CIE: 2° Standard Observer, and the measurement area was 8 mm. The results were presented as the brightness (L*), green/red index (a*), blue/yellow index (b*), and the total color difference (ΔE). The assay was performed in at least ten repetitions for randomly selected slices.

Images of the surface of the dried beetroot were captured using a Nikon D7000 digital camera (Nikon, Tokyo, Japan).

2.3.5. Betalain Content

The betalain content in the raw material and after pretreatments was determined using the spectrophotometric method according to [34]. A total of 0.5 g of the crushed sample was extracted with 50 mL of phosphate buffer at pH 6.5 on a Vortex shaker (20 min, 2000 rpm). The solution was centrifuged, and the absorbance was measured in a Spectronic 200 spectrophotometer (Thermo Fisher Scientific Inc., Waltham, MA, USA) at 476, 538, and 600 nm, against the buffer solution. The assay was performed three times. The quantitative content of red dyes was expressed as mg of betanins in 100 g of dry matter; the content of yellow dyes was expressed as mg of vulgaxanthin in 100 g of dry matter of the sample.

The content of red and yellow pigments was calculated according to the following formulas:

$$\text{Red pigments} = \text{DF} \cdot 1.095\ (\text{A}_{538} - \text{A}_{600})/(\text{m} \cdot \text{DM} \cdot 1120), \tag{4}$$

$$\text{Yellow pigments} = \text{DF} \cdot (\text{A}_{475} - \text{A}_{538} + 0.677 \cdot 1.095\ (\text{A}_{538} - \text{A}_{600})/(\text{m} \cdot \text{DM} \cdot 750), \tag{5}$$

where DF—dilution factor; 1.095—absorption coefficient at λ = 538 nm; m—sample mass; DM—dry matter content; 1120—absorbance at 538 nm of a 1% betanin solution in a 1 cm cuvette; 0.677—absorption coefficient at λ = 476 nm; 750—absorbance at 476 nm of a 1% betanin solution in a 1 cm cuvette.

2.3.6. Rehydration Ratio and Hygroscopic Properties

Rehydration was conducted at a temperature of 20 °C. The dried material, previously weighed, was submerged in 100 mL of distilled water for 180 min. After the process, the samples were removed from the water using a sieve, carefully dried with filter paper, and then reweighed, and the dry matter content was determined [35]. The assays were performed in triplicate.

For hygroscopic properties' measurement, the material of known mass was placed in a desiccator over supersaturated sodium chloride (RH = 75%). The process was carried out at a temperature of 25 °C. After 72 h, the samples were reweighed. The assays were performed in triplicate.

2.3.7. Microstructure

From the central part of the sample, a 2 mm thick strip was cut out with a razor blade and attached to conductive carbon tape. The sample was sputtered with a 5 nm layer of gold using an auto sputter coater (Cressington 108auto, Watford, UK) and analyzed using a scanning electron microscope (TM 3000, Hitachi, Tokyo, Japan) at 100 magnification and 10 kV voltage.

2.4. Statistical Analysis

Statistical analysis included a one-way analysis of variance (ANOVA), while homogeneous groups were determined with Duncan's test (significance level of α = 0.05). In order to examine the influence of two factors, e.g., the frequency and duration of ultrasound exposure, on the tested properties of beetroot, a two-way analysis of variance was performed. Data were analyzed using the STATISTICA program (TIBCO company software, version 13, Palo Alto, CA, USA).

3. Results and Discussion

3.1. Drying Kinetics

The most common and efficient method for the evaluation of the effect of various pretreatment techniques on the course of processing is the determination of the process kinetics. For processes based on mass transfer, e.g., drying, it would be tracking changes in mass that depicts the amount of water evaporating from the material tissue [36]. The drying kinetics shown in Figure 1 were calculated specifically to present the progression of water removal from the material tissue within the IR-HA time. The MR expresses the quantity of water in the material, starting from 1, which presents the total amount of water, which decreases until the equilibrium moisture content. The drying kinetics obtained in this study are divided into three groups. Figure 1a shows the impact of conventional (control) treatment methods on IR-HA drying. Figure 1b,c present how US pretreatment affected water removal from the beetroot slices compared to the untreated sample, respectively for the frequency of 21 kHz and 35 kHz. Drying times, expressing the time that the material needed to reach the equilibrium moisture content of 0.09 g H_2O/g d.m. determined for each variant, are also included in the figure (next to the legends of the figures, marked with a gray color). As can be seen, although the statistical analysis did not recognize any significant differences between drying times, the tendency of blanching and soaking to prolong dehydration by up to 13% was observed. Regardless of the applied parameters, US pretreatment did not significantly affect either kinetics or drying time. For the majority of US-treated variants, the values varied from 129 to 132 min. Such results indicate that there was a reduction in drying time by 3–5%, however it cannot be considered impactful. The exception was noted for the sample subjected to US at 35 kHz for 20 min, for which the drying time was 141 min, which was 4% longer than it was for the untreated beetroot. Rashid et al. [37] reported that US pretreatment (20, 40, or 60 kHz) did not affect the catalytic IR drying time of sweet potato slices at 70 °C, but there was a correlation between drying time and US frequency in drying at 60 and 80 °C. The greatest reduction was observed after 30 min of pretreatment at 40 kHz. Nevertheless, IR-HA is more effective in terms of mass transfer and less harmful to the quality attributes of the dried material than traditional convective drying due to the heating mechanism that allows for quick water removal, thus a remarkably shorter exposition to elevated temperature [38,39].

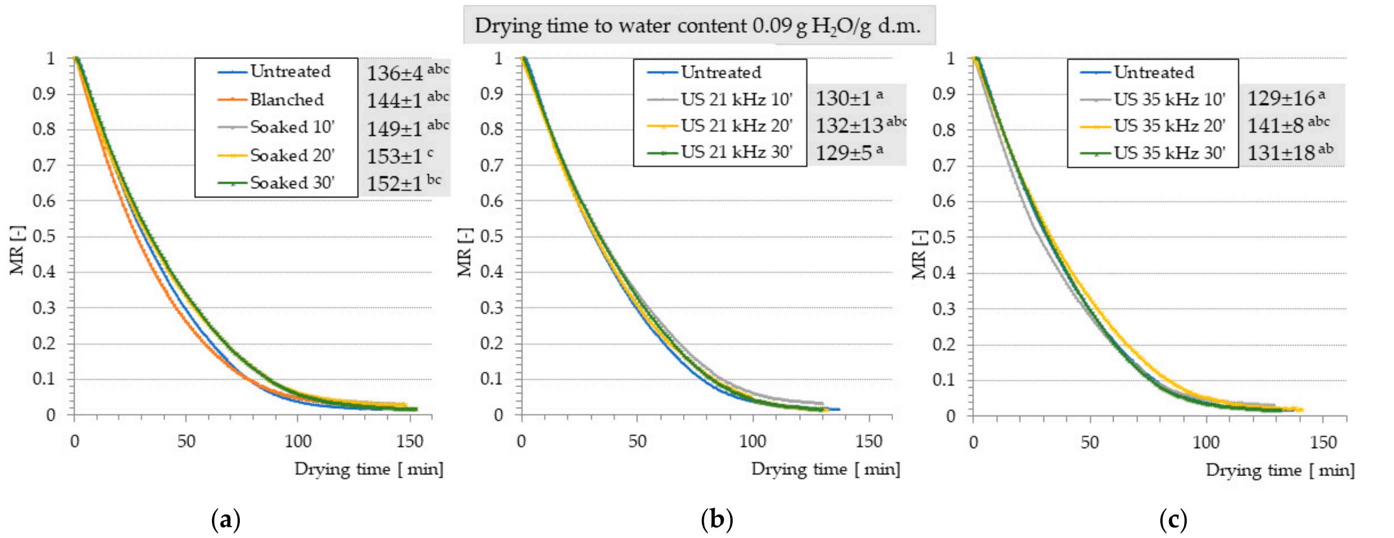

Figure 1. Drying kinetics of beetroot subjected to pretreatment: (**a**) untreated, blanched, and soaked, (**b**) ultrasound at a frequency of 21 kHz, and (**c**) ultrasound at a frequency of 35 kHz; a–c—letters next to the drying time are homogeneous groups; different letters indicate statistical significance ($p < 0.05$).

3.2. Dry Matter, Water Activity, and Tissue Density Changes after Pretreatments and Drying

The applied pretreatments utilized led to a mass alteration, which correlated with changes in the dry matter content of the material (Table 1). Initially, fresh beetroot exhibited a dry matter content of 14.9%. Traditional blanching and soaking methods induced weight losses of approximately 14% and 12–16.6%, respectively. These losses were attributed to the removal of dry substance components, including water-soluble betalain dyes, during the processes [40,41]. Tissue subjected to ultrasound at a frequency of 21 kHz for durations of 10 and 30 min showed no statistically significant difference in dry matter content compared to untreated tissue. A slightly statistically significant decrease was observed in samples treated with ultrasound for 20 min at 21 kHz frequency. The most significant decrease occurred in samples exposed to ultrasound at a frequency of 35 kHz for 30 min, resulting in a reduction in dry matter content by 17.5% compared to untreated samples. However, the duration of ultrasound exposure and the applied frequency showed no significant effect on changes in the dry matter content of the material. Dried beetroot obtained through convective drying supported by infrared radiation, when untreated, exhibited a dry matter content of 92.0%. The pretreated dried material was characterized by similar or slightly higher dry matter content in the range of 92.9–95.5%. Statistically, neither the duration nor the frequency of ultrasound operation exhibited a significant impact on the dry substance content in dried fruit.

Table 1. Basic physical properties after pretreatments (blanching, soaking, ultrasound) and after infrared–hot air drying.

Sample	After Pretreatments			After Pretreatments and Drying			
	Dry Matter Content [%]	Water Activity a_w [-]	Density [g/cm^3]	Dry Matter Content [%]	Water Activity a_w [-]	Density [g/cm^3]	Shrinkage [%]
Untreated	14.85 ± 0.1 d *	0.997 ± 0.001 b	0.993 ± 0.007 c	92.0 ± 1.4 b	0.377 ± 0.008 bc	1.386 ± 0.182 bc	83.5 ± 0.1 cd
Blanched	12.77 ± 0.16 abc	0.992 ± 0.002 a	0.984 ± 0.011 abc	92.9 ± 0.4 b	0.374 ± 0.005 c	1.007 ± 0.084 ab	81.0 ±0.1 b
Soaked 10′	12.87 ± 0.07 abc	0.991 ± 0.001 a	0.954 ± 0.004 ab	93.3 ± 0.4 a	0.379 ± 0.003 bc	0.971 ± 0.082 a	81.6 ± 0.2 b
Soaked 20′	12.43 ± 0.015 a	0.991 ± 0.001 a	0.978 ± 0.003 abc	93.6 ± 0.4 a	0.333 ± 0.001 abc	1.204 ± 0.128 bc	84.0 ± 0.1 cd
Soaked 30′	13.06 ± 0.01 bc	0.991 ± 0.001 a	0.919 ± 0.006 a	93.7 ± 0.1 a	0.361 ± 0.012 abc	1.134 ± 0.014 bc	83.7 ± 0.2 cd
US 21 kHz 10′	13.95 ± 0.42 d	0.993 ± 0.001 a	0.977 ± 0.009 bc	93.5 ± 0.6 b	0.377 ± 0.005 bc	1.062 ± 0.101 c	81.7 ± 0.3 b
US 21 kHz 20′	13.26 ± 0.53 c	0.994 ± 0.001 a	0.986 ± 0.013 bc	94.6 ± 0.6 b	0.328 ± 0.0017 abc	1.017 ± 0.195 bc	82.9 ± 0.1 c
US 21 kHz 30′	14.06 ± 0.06 d	0.993 ± 0.001 a	0.989 ± 0.013 bc	93.7 ± 0.3 b	0.349 ± 0.014 abc	0.995 ± 0.225 bc	75.3 ± 1.5 a
US 35 kHz 10′	12.50 ± 0.28 ab	0.993 ± 0.001 a	0.949 ± 0.009 abc	94.1 ± 0.3 a	0.319 ± 0.012 ab	1.030 ± 0.108 bc	83.2 ± 0.1 c
US 35 kHz 20′	12.56 ± 0.15 ab	0.991 ± 0.001 a	0.970 ± 0.014 abc	93.8 ± 0.9 a	0.319 ± 0.020 ab	1.032 ± 0.147 bc	84.5 ± 0.1 de
US 35 kHz 30′	12.25 ± 0.42 a	0.992 ± 0.001 a	0.981 ± 0.011 c	95.5 ± 0.4 a	0.294 ± 0.005 a	1.057 ± 0.095 bc	85.3 ± 0.1 e

* a–e—homogeneous groups are presented next to mean values (mean ± standard deviation) as different letters within the same column, which indicate statistical significance ($p < 0.05$).

Raw beets exhibited a high water activity of 0.997, leading to the low microbiological durability of the material [42]. Following pretreatment, there was no statistically significant decrease in water activity, and this decrease did not significantly impact product durability. The water activity of dried beetroot ranged from 0.294 to 0.377, a range that inhibits the growth of microorganisms. Pretreatment had a positive effect on reducing water activity slightly, with significant reductions observed in samples exposed to ultrasound at a frequency of 35 kHz for 30 min. Similar results for dried beetroots were obtained by Ciurzyńska et al. [43].

Apparent density is a parameter that reflects changes in the mass of the sample relative to its volume. The preliminary treatments resulted in a reduction in this parameter for the material slices. Except for soaking, other preliminary processes did not cause statistically significant changes in this parameter compared to the raw material. Soaking for 10 min decreased the material density by 4.3%, while extending the soaking time to 30 min led to a 7.5% decrease compared to the untreated material. Furthermore, as the ultrasonic exposure time increased, the reduction in density became less noticeable compared to the untreated raw material. However, statistical analysis did not reveal a significant effect of processing time and the applied ultrasound frequency on changes in the density of the raw material exposed to ultrasound.

The drying process resulted in an increase in the density of the beetroot material. Significant differences were observed in the density of the material depending on the type of pretreatment applied to the beet. Beetroot soaked for 10 min exhibited the lowest apparent density. For ultrasound treatments at a frequency of 21 kHz, the apparent density decreased with increasing treatment duration, while for ultrasound treatments at a frequency of 35 kHz, the relationship was reversed. None of these relationships were observed in soaked samples. During drying, tissue shrinkage occurred, leading to a decrease in the specific surface area of the sample, an increase in apparent density, and a decrease in porosity. Blanching resulted in a minor reduction in material shrinkage, approximately 3 percentage points compared to untreated tissue. However, an increase in pretreatment duration generally led to increased tissue shrinkage, except for ultrasound treatment at a frequency of 21 kHz. In this case, material exposed to ultrasound at a frequency of 21 kHz for 30 min exhibited the lowest shrinkage at 75.3 ± 1.5%. Additionally, there was no significant effect of ultrasound time and frequency on material shrinkage.

3.3. Texture Changes after Pretreatments

Texture is an important quality determinant of the product. Studying this parameter leads to a better understanding of changes occurring in raw materials subjected to technological processes. In Figure 2, the changes in texture are expressed as the maximum force and the work necessary to cut a slice of raw beetroot and subjected to various types of pretreatments. The results showed that the type of used pretreatment had a significant impact on the maximum cutting force and the work needed to cut a beetroot slice. To cut the raw beetroot, a force of 94.7 ± 14.9 N was used (Figure 2a), and the work performed was 169.2 ± 38.3 mJ (Figure 2b). In most cases, samples subjected to pretreatments required comparable or greater force and cutting work than untreated beetroot. The literature indicates that ultrasound has the potential to protect the cell wall due to enhancing the stability of cell wall polysaccharides, according to the inhibition of the activity of cell wall decomposition enzymes. This processing helps with delaying fruit softening and extending the storage period of fruits and vegetables [44]. A similar effect was obtained by Day et al. [45] for carrots. After ultrasound pretreatment at 60 °C for 10 min, they noticed a higher mechanical strength of the carrot cell wall structure compared to blanching, especially when combined with the addition of 0.5% $CaCl_2$ during pretreatment. Plant cell wall tissues treated with ultrasound demonstrate higher elasticity than those treated with low temperature and prolonged blanching. Thus, in our study, blanched beetroot was characterized by a significantly lower maximum cutting force (58%) compared to unprocessed tissue. Therefore, the blanched beetroot was characterized by equally low work required to cut the slice, amounting to 70.7 ± 50.3 mJ. This was probably related to tissue changes that influenced the mechanical properties of the tissue [46].

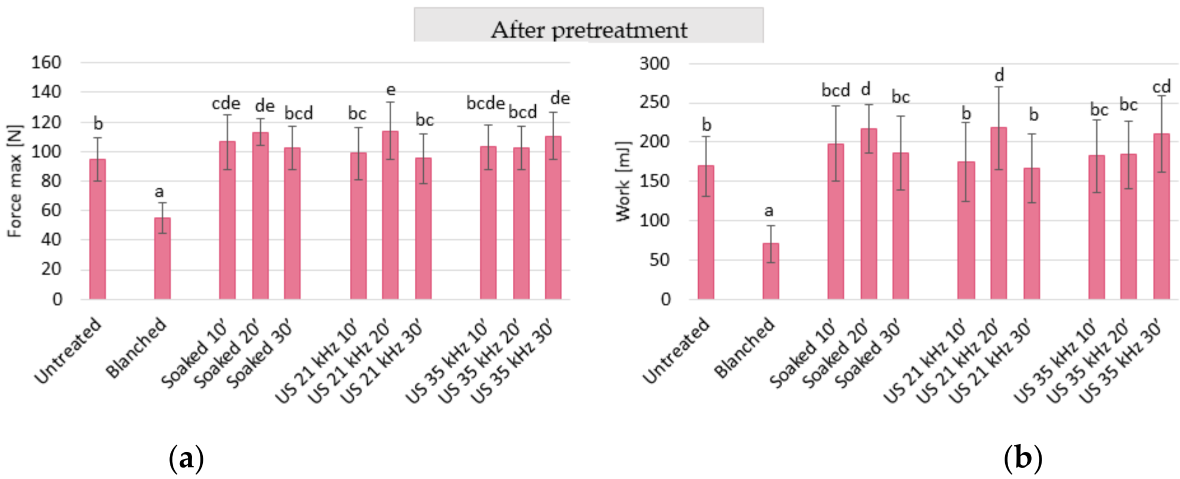

Figure 2. The maximum force (**a**) and the work (**b**) necessary to cut a slice of raw beetroot and beetroot subjected to various types of pretreatments, a–e—homogeneous groups are presented above the column; different letters indicate statistical significance ($p < 0.05$).

The highest results of the maximum force needed to cut the patch and the cutting work were obtained for tissue exposed to ultrasound at a frequency of 21 kHz for 20 min, obtaining values of 114.0 ± 21 N and 217.8 ± 53.0 mJ, respectively. Comparable results were also obtained for tissue soaked for 20 min, obtaining values of 113.0 ± 9.1 N and 217.2 ± 30.6 mJ, respectively, which may indicate that the duration of ultrasound operation and its frequency are not important when assessing the textural properties of beetroot.

3.4. Color Changes after Pretreatments and Drying

Color is an important attribute of a food product that serves to assess its quality and gain consumer preference. Subjecting fruits and vegetables to heat treatments may lead to the non-enzymatic browning and destruction of the pigment. These phenomena can result in color changes in dried tissues [47]. Pei et al. [48] stated that the use of an appropriate US pretreatment duration could not only accelerate the drying process but also effectively reduce color change.

The raw beetroot was characterized by the value of the L* parameter amounted to 29.3 ± 1.5 (Figure 3a). Samples subjected to US, with parameters other than 35 kHz and 20 min, had a statistically significant increase in the L* parameter, compared to the untreated tissue. However, no significant effect of the time and frequency of US pretreatment used on the brightness of the beetroot tissue was noted. Soaking for 10 min also increased the brightness of the beetroot, while blanching as well as soaking for longer than 10 min did not significantly change the value of this parameter. Other researchers also observed that beetroot samples (juice and pomace) after 10 or 15 min of US pretreatment were lighter than untreated samples, while samples after thermal steam pretreatment for 10 or 15 min did not differ significantly from the untreated samples [49].

The drying process increased the brightness of the dried materials (Figure 3b). A similar effect was obtained by Gokhale and Lele [50] for the beetroot dried with hot air drying, where the lightness of the beet increased throughout the entire drying duration. Meanwhile, Liu et al. [51] stated that the brightness increases according to the increase in hot air drying temperatures. The lowest growth of the L* parameter was recorded for the untreated and blanched samples, amounting to 1.1 and 1.9, respectively. In the other variants for soaked and US-treated, the growth ranged from 5 to 11. The tissues treated with US were significantly brighter, compared to the untreated one, which is visible also in the macroscopic photographs of beetroot dried with the infrared–hot air method presented in Figure 4. Furthermore, it was found that there was an increase in the L* parameter as the time of ultrasonic treatment increased. An increase in the brightness of dried materials could be a result of the leakage of soluble solids, including betalain pigments, during pretreatment processes from the beetroot tissue to the water [52]. When a pretreatment of at least 10 min was used, the values of the L* parameter were noticeably greater as the leakage lasted longer. Additionally, the changes in brightness may be related to the leakage of pigments from the tissue. However, the colorimeter measures only surface color and does not assess the actual pigment content [50]. In addition, the higher values of the L* parameter in the dried fruit may have been due to the method of measuring, in which radiation reflected from the sample is recorded. In the undried beetroot samples, the water content was higher, so that part of the radiation was absorbed, and a smaller amount was reflected from the surface and measured by the device [53]. Similar results were obtained in the study of Fijałkowska et al. [52], in which pretreatment in the form of blanching did not affect the lightness of dried beetroot, whereas US pretreatment resulted in an increase in brightness by over 50% in relation to dried material without any pretreatments.

The value of the a* parameter, which accounts for the proportion of the green (−) and red (+) color, for the raw tissue was 18.7 ± 2.2 (Figure 3c). As a result of blanching, the value of the a* parameter decreased statistically significantly by 30% to a value of 13.1. This could be related to the temperature sensitivity of the red pigment as betacyanin [50]. Similarly, soaking for longer than 10 min resulted in a statistically significant decrease in the a* value, which could be related to a significant leaching of betalain pigments due to betalains being water-soluble pigments [50]. In the case of ultrasound-treated tissue, the changes in the a* parameter were not statistically significant.

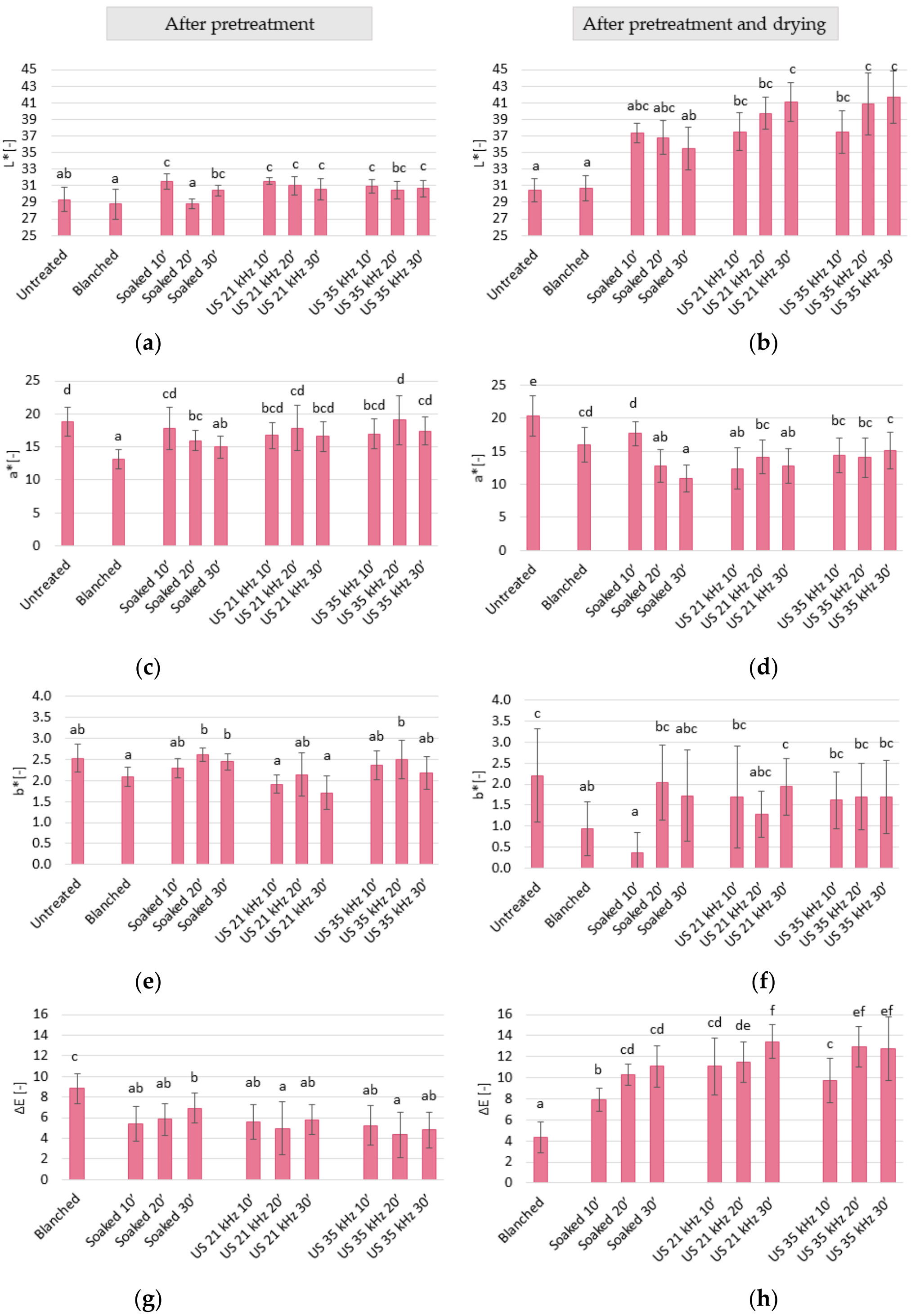

Figure 3. Color parameters: L*—brightness (**a**), a*—red color (**c**), and b*—yellow color (**e**) of untreated, blanched, soaked, and ultrasound-treated raw beetroot and subjected to various types of pretreatments, and L*—brightness (**b**), a*—red color (**d**), and b*—yellow color (**f**) of untreated, blanched, soaked, and ultrasound-treated after drying with infrared–hot air method; total color change (ΔE) in comparison to raw beetroot after pretreatments (**g**) and after pretreatments and drying (**h**); a–f—homogeneous groups are presented above column; different letters indicate statistical significance ($p < 0.05$).

Figure 4. Macroscopic photographs of untreated, blanched, soaked, and ultrasound-treated beetroot dried with infrared–hot air method.

After the drying process, the value of the a* parameter increased to 20.3 ± 3.1 (Figure 3d). It was observed that, regardless of the method used, pretreatment significantly reduced the value of the a* parameter in relation to the sample subjected only to drying. In addition, when soaking and US treatment were applied, the value of the a* parameter decreased after drying, compared to pretreated samples before drying. The decrease in the proportion of the red color in the material may be related to the leaching of dyes during pretreatment or their increased oxidation during the drying process.

Changes in the value of the parameter b*, describing the yellow (+) and blue (−) color, are shown in Figure 3e (after pretreatment). The value of parameter b* for raw beetroot tissue was 2.5 ± 0.3. After pretreatment, the b* parameter changed statistically significantly only after soaking for 20 or 30 min and US treatment at 35 kHz for 20 min. The drying process reduced the value of the b* parameter to 2.2 ± 1.1 (Figure 3f). Both blanching and soaking for 10 min resulted in a statistically significant decrease in the value of the b* parameter. As Gokhale and Lele [50] stated, the red pigment of betalains converts to yellow during thermal treatment due to thermochemical reactions. The values of the b* parameter for the other samples in our study were not statistically significantly different from those for the dried sample without pretreatment. In particular, there was no significant effect of the applied frequency or duration of ultrasound on the values of parameter b*.

The total color difference (ΔE) takes into account all the above-mentioned color parameters and represents the color difference between the pretreated samples with the raw material (Figure 3g) and between the pretreated and dried samples with the dried material without pretreatments (Figure 3h). All pretreated samples had a total color difference value above 4, indicating a clear difference between those samples and the raw beetroot. The largest value of ΔE was recorded for blanched beetroot and was 8.8 ± 1.4.

Also, after drying, all pretreated samples differed from the only dried sample (ΔE above 5). In turn, after drying, the blanched sample showed the smallest ΔE among all samples, and it amounted to 5.3 ± 1.4. The materials subjected to US and drying showed a total color difference ranging from 9.8 ± 2.1 to 12.9 ± 1.9, whereas the soaked and dried samples, from 10.3 ± 1.0 to 11.1 ± 2.0. High values of ΔE after soaking and

US pretreatments may arise from the higher values of lightness and lower values of parameter a* that illustrates the redness of samples. Bozkir et al. [54], who studied the effect of US and osmotic dehydration pretreatments of the quality of dried persimmon, also observed that the lightness of dried samples pretreated with US was mainly higher than only dried samples, whereas the values of parameters a* and b* decreased and did not differ significantly, respectively. Consequently, ΔE for samples pretreated for 20 and 30 min increased. Lechtanska et al. [55] noted that the intensity of the color change in green pepper was dependent mainly on the duration of drying, during which they are exposed to a high temperature. In our study, none of the pretreatments caused a significant shortening of drying whilst they altered the beetroot structure resulting in the intensification of color changes during drying (Figure 4).

3.5. Betalain Content Changes after Pretreatments and Drying

An important indicator of the quality of products derived from beetroot is the content of betalain pigments that are responsible for the reddish-purple color of the vegetable and are its essential bioactive component. Betalain pigments are divided into betanin and vulgaxanthin, which are red and yellow pigments, respectively [56]. Betalains are water-soluble compounds that are sensitive to light and elevated temperature. Therefore, by analyzing the content of betalain pigments, it can assess the degradation resulting from technological processing. Moreover, beetroot extract is a food coloring additive with the symbol E162 and is often used for instant drinks, cakes, or meat products [57].

The quantity of red and yellow betalain content in raw beetroot is presented in Figure 5a,c, respectively. The content of betalain pigments in raw material was 899.2 mg betanin and 668.7 mg vulgaxanthin per 100 g d.m. In the case of fresh material, the application of each form of pretreatment tested in this study caused some variation in the betanin content. However, soaking and US treatment at both 21 and 35 kHz that were carried on for 20 min resulted in a significant increase in this value (15, 18, and 68%). Red colorant content in other samples varied (from −23 to +4%), but it did not differ in comparison to the untreated sample. In the case of vulgaxanthin content, blanched, soaked for 10 min, and US-treated at 21 kHz for 10 min and at 35 kHz for 30 min samples were characterized by a significantly lower quantity of the compound by up to 10%. There was also an increasing tendency in vulgaxanthin content noticed for the same samples subjected to 20 min long treatments, regardless of the type of treatment used. Usually, higher frequencies make the compression and rarefaction cycle more difficult, making it more difficult to induce cavitation bubble growth due to the shorter time intervals. Conversely, lower frequencies may influence the formation of transient cavitation bubbles [58,59]. However, in our study, such a trend was not observed. Such observations might have been a consequence of technological treatment, but the diversity of the biological material could be a reasonable explanation as well [60]. Especially considering that ultrasounds are commonly used to improve the extraction yield of bioactive compounds, among others, reduction in betalain content in the US-treated material is therefore expected due to losses during the treatment [61]. Janiszewska et al. [49] found no significant impact of either steaming or sonication times on red and yellow pigments in freeze-dried beetroot juice and pomace. However, in that study, the reduction in betalain content after pretreatment was associated with a temperature increase in the steaming and washing out of the water-soluble dyes.

IR-HA drying contributed to a remarkable loss in red (Figure 5b) and yellow (Figure 5d) betalain content. Betanin retention in dried beetroot slices was in the range of 49–74% in relation to the initial content in the pretreated material before dehydration. The highest retention was observed in variants that contained notably more dye before drying. The dried control sample contained 377 mg betanin/100 g d.m., which indicates a degradation of 58% of red dye due to IR-HA drying. In samples treated with 10 min soaking, and 21 and 35 kHz US, a 50, 50, and 42% decrease was observed, respectively, compared to the material before drying. The highest decrease in red dye content was obtained for tissue treated for 20 min with 21 and 30 min with 35 kHz ultrasound (a decrease of about 69%). In the case of yellow pigments, the raw tissue was characterized by its content of 668.7 mg vulgaxanthin/100 g d.m., while after the drying process, the content of this parameter decreased significantly, reaching a value of 334.2 mg vulgaxanthin/100 g d.m. for dried tissue without pretreatment. The use of blanching as a pretreatment resulted in the greatest loss of yellow pigments in the beet at 58%, relative to the raw tissue. Tissue treated with 35 kHz ultrasound for 30 min had an equally low vulgaxanthin content (54% loss relative to raw tissue). After drying, the sample soaked for 20 min was characterized by the highest yellow pigment content, with a yellow pigment content of 494.4 mg vulgaxanthin/100 g d.m. However, that was the material in which yellow dye degradation was found to be the greatest, compared to undried. Overall, the highest vulgaxanthin retention (69–74%) was found in dried beetroot that was subjected to 10 min pretreatment, regardless of the technique used. Such a negative outcome most likely was a consequence of the temperature elevation in the material during drying, which resulted in the degradation of the betalain content. It has been established that both betanin and vulgaxanthin are very sensitive to thermal treatment [34].

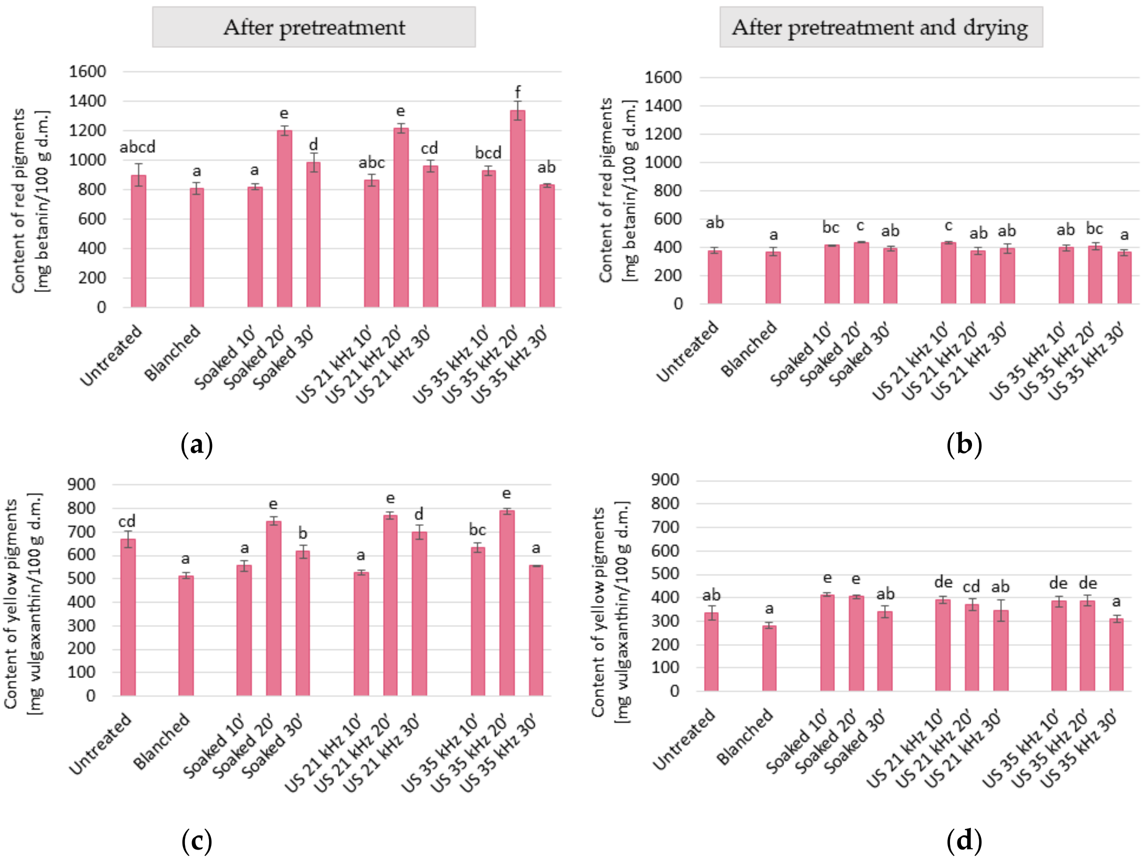

Figure 5. Content of red (**a**) and yellow (**c**) pigments in raw beetroot and beetroot subjected to various types of pretreatments; content of red (**b**) and yellow (**d**) pigments in raw beetroot and beetroot subjected to various types of pretreatments, a–f—homogeneous groups are presented above the column; different letters indicate statistical significance ($p < 0.05$).

In general, a two-way analysis of variance found no significant effect of the duration and frequency of ultrasonic treatment on betalain content in samples before and after drying. Previously, the effect of the US pretreatment frequency on phytochemical compounds in IR-dried sweet potatoes showed that the highest retention was noted after subjecting the material to 40 kHz for 30 min [37]. They also established that both the US frequency and drying temperature have a crucial effect on the quality of the obtained product, which was the opposite compared to our results.

3.6. Rehydration Ratio and Hygroscopic Changes after Pretreatments and Drying

Rehydration determines the material's ability to absorb water [62]. Table 2 contains the rehydration ratio (RR) values obtained after 3 h of analysis by the reference sample (untreated) and beetroots subjected to blanching, soaking, and ultrasound treatment prior to infrared–hot air drying. Among all analyzed samples, only the US 35 kHz 20′ sample exhibited a significantly higher RR (by 20.4%) than the untreated sample. The sorption mechanism depends not only on the physical properties of a given material. Its chemical composition also has a significant impact on this parameter [63]. Perhaps ultrasonic treatment with the following process parameters, a frequency equal to 35 kHz and treatment time equal to 20 min, led to significant changes in the treated tissue at the chemical level, beneficial from the perspective of rebinding water. Despite the lack of statistically significant differences, samples that were blanched and soaked before drying had slightly higher RR values than the untreated sample (RR values rose in line with extending the soaking time). A similar tendency—an increase in RR with the extension of immersion duration—was observed after treating beetroots with ultrasound with a frequency of 21 kHz. The improvement in the hydration properties of these samples could result from the leaching of some soluble solids [64] and from opening the structure of the material [65].

Table 2. Rehydration ratio (RR) after 3 h of rehydration process and hygroscopic properties expressed as water content after 72 h over NaCl solution [g H_2O/g d.m.] of untreated dried beetroot and that subjected to pretreatments (blanching, soaking, ultrasound) and infrared–hot air drying.

Sample	RR after 3 h [-]	Water Content after 72 h over the NaCl Solution [g H_2O/g d.m.]
Untreated	4.89 ± 0.28 ab *	0.23 ± 0.03 b
Blanched	5.05 ± 0.43 abc	0.21 ± 0.03 b
Soaked 10′	5.11 ± 0.10 abc	0.17 ± 0.01 a
Soaked 20′	5.17 ± 0.44 abc	0.19 ± 0.01 b
Soaked 30′	5.19 ± 0.11 abc	0.18 ± 0.01 b
US 21 kHz 10′	4.68 ± 0.17 a	0.21 ± 0.03 b
US 21 kHz 20′	4.80 ± 0.66 ab	0.19 ± 0.01 b
US 21 kHz 30′	5.31 ± 0.21 abc	0.19 ± 0.01 b
US 35 kHz 10′	5.30 ± 0.53 abc	0.28 ± 0.01 c
US 35 kHz 20′	5.89 ± 0.26 c	0.25 ± 0.05 b
US 35 kHz 30′	5.65 ± 0.61 bc	0.21 ± 0.01 b

* a–c—homogeneous groups are presented next to mean values (mean ± standard deviation) as different letters within the same column, which indicate statistical significance ($p < 0.05$).

Using hygroscopic properties, it is possible to assess the ability of a given material to adsorb water vapor [36]. Most of the obtained dried beetroots did not differ from each other in terms of hygroscopicity (Table 2). In relation to the reference sample (untreated), only the Soaked 10′ and US 35 kHz 10′ samples exhibited statistically significant differences in water content after spending 72 h over the NaCl solution. Their values were 26.1% lower and 21.7% higher than the untreated sample, respectively. As mentioned above, sorption processes (adsorption, absorption, desorption) depend on various factors—those related to the material are both physical (the characteristics of the material surface, its porosity, occurrence of drying shrinkage, etc.) and chemical (chemical composition) [63,66,67]. As shown in Figure 1, the US 35 kHz 10′ sample was one of the samples whose drying time was the shortest, which could prevent negative material changes from the stability point of view.

3.7. Microstructure Changes after Pretreatments and Drying

During the technological process of drying, the water content decreases, resulting in the stiffening and shrinkage of the material [68]. Figure 6 shows photos of the morphological structure of dried beetroot tissue, unsubjected and subjected to various types of pretreatment. Dried beet tissue was characterized by a compact structure, low porosity, and high shrinkage (Table 1). Generally, no differences were observed in the structure of the untreated beet tissue and that treated with soaking before drying, and the effect of ultrasound at 21 and 35 kHz did not differ from the beetroot tissue not subjected to pretreatment. Similarly, Umaña et al. [69] observed a minor effect of ultrasound treatment for beetroot. They explain that beetroots with lower porosity and smaller cells are less prone to acoustic energy-induced cell wall damage in comparison to samples with larger cells and medium porosity like apples. Also, in the case of eggplant, which is the most porous material among apples, beetroot, and eggplant, ultrasound application did not significantly alter cell size in comparison to the untreated sample. As a consequence, Umaña et al. [69] stated that the effects of ultrasound vary across materials with differing initial characteristics, e.g., porosities and cell sizes.

Due to the cavitation, sponge effect, and accompanying phenomena, the ultrasound treatment of the plant tissue usually results in structural alterations. For example, ultrasound application significantly increased the cross-sectional areas of convectively dried apple tissue cells, particularly with longer sonication times [70]. Prolonged sonication causes further damage to the tissue, resulting in the formation of empty areas [26]. Other researchers have observed a similar effect during the sonication of pineapple [71], melon [72], and berries [73]. In our study, the lack of an effect on the beetroot tissue could also be related to the further drying process, which leads to shrinkage, affecting the final characteristics of the cells in the dried tissue.

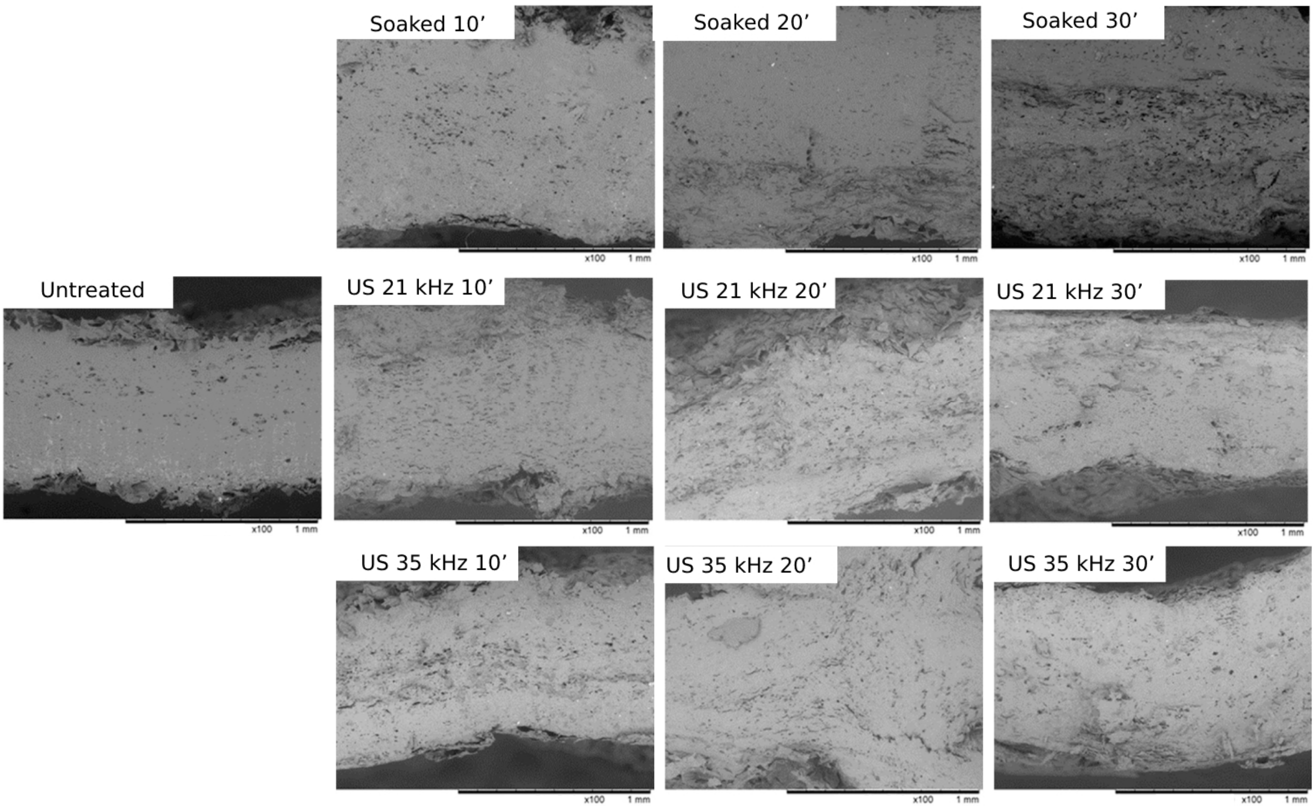

Figure 6. Microstructure of untreated, soaked, and ultrasound-treated beetroot dried with infrared–hot air method (100× magnification).

4. Conclusions

This study examined the influence of different pretreatment methods on fresh beetroot before infrared–hot air drying, as well as the chosen properties of the dried product. Blanching, ultrasound (at 21 and 35 kHz), and soaking pretreatment significantly altered beetroot tissue properties, reducing dry matter content, water activity, and apparent tissue density compared to raw tissue, probable due to water entrance or soluble ingredient loss. Ultrasound and soaking lightened tissue color, possibly by leaching betalain pigments, though some longer treatments increased pigment content. The mechanical properties of ultrasound-treated and soaked tissue resembled raw tissue, while blanched tissue showed the poorest characteristics due to high processing temperatures.

A high-frequency ultrasound of 21 kHz shortened the drying time by 2.9–4.8%, while varied effects were observed at 35 kHz. However, soaked or blanched tissue exhibited longer drying times compared to the untreated material. Dried tissue demonstrated high dry matter content (>90%) and low water activity (0.294–0.377) assuring microbiological safety. Furthermore, minimal changes in apparent density were confirmed by microstructure analysis. Longer ultrasound treatment at 21 kHz reduced apparent density, while the opposite trend was observed at 35 kHz. Tissue shrinkage increased with prolonged pretreatment, except for ultrasound at 21 kHz. Also, ultrasound pretreatment slightly enhanced rehydration, increasing mass gain. However, a significant hygroscopicity increase was observed in raw material pretreated with ultrasound at 35 kHz for 10 min, whereas other samples were characterized by a decrease in hygroscopicity, in comparison to the untreated sample. Ultrasound-treated dried fruit showed an increased L* color parameter, while a decreased a* parameter indicated betalain pigment loss, responsible for the raw material's color.

Ultrasound causes the "sponge effect" as well as cavitation, which affect plant tissue. However, several parameters of ultrasound treatment influence the final effect, thus the optimal parameters for the material should be chosen. Thus, the optimal pretreatment parameters for beetroot were determined as ultrasound conducted for 20 min, regardless of the used frequency. Overall, ultrasound pretreatment positively impacted some quality parameters, suggesting further research to establish the optimal process parameters for beetroot production.

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