fermentation

Article

Sustainable Production and Characteristics of Dried Fermented Vegetables

Emilia Janiszewska-Turak [1,*], Katarzyna Rybak [1], Katarzyna Pobiega [2], Anna Nikodem [3] and Anna Gramza-Michałowska [4,*]

1 Department of Food Engineering and Process Management, Institute of Food Sciences, Warsaw University of Life Sciences—SGGW, 02-787 Warsaw, Poland
2 Department of Food Biotechnology and Microbiology, Institute of Food Sciences, Warsaw University of Life Sciences—SGGW, 02-787 Warsaw, Poland
3 Department of Mechanics, Materials and Biomedical Engineering, Wroclaw University of Science and Technology, 7/9 Ignacego Łukasiewicza Street, 50-371 Wrocław, Poland
4 Department of Gastronomy Science and Functional Foods, Faculty of Food Science and Nutrition, Poznań University of Life Sciences, Wojska Polskiego 31, 60-624 Poznań, Poland
* Correspondence: emilia_janiszewska_turak@sggw.edu.pl (E.J.-T.); anna.gramza@up.poznan.pl (A.G.-M.); Tel.: +48-22-593-7366 (E.J.-T.); +48-61-848-7327 (A.G.-M.)

Abstract: The current fashion for healthy food and the increasing number of people with lactose intolerance make fermented vegetables increasingly important. On top of this, surpluses unused in the vegetable harvest can become a potential source of "green waste". The use of fermentation and freeze-drying can result in a valuable, sustainable product that can solve the problems of spoiled vegetables and the need for refrigerated storage. Therefore, this study aimed to obtain sustainable dried fermented vegetables and to compare their selected physical and structural properties. Beetroot, carrot, and red pepper were selected for this purpose. These vegetables were subjected to a spontaneous lactic fermentation process. After the process, the vegetables were freeze-dried, and their structure and selected properties (color, dry weight, and the number of lactic acid bacteria) were determined. Fermented vegetables were found to differ from their raw sources in structure and color, the main discrepancies being shown by the b* factor (yellow-blue). Root vegetables had smaller pores of structure in the freeze-dried samples than red peppers. The freeze-drying process did not affect the number of bacteria. It can be concluded that both the fermentation and the freeze-drying processes affected the structure of the selected vegetables. All tested vegetables can be fermented and freeze-dried without major changes in color and microbiological properties and can be used as a potential source of lactic acid bacteria and health-promoting pigments, e.g., in the form of chips. In addition, their shelf life is extended.

Keywords: beetroot; carrot; red bell pepper; lactic acid fermentation; scanning electron microscope; confocal scanning laser microscopy; microstructure

Citation: Janiszewska-Turak, E.; Rybak, K.; Pobiega, K.; Nikodem, A.; Gramza-Michałowska, A. Sustainable Production and Characteristics of Dried Fermented Vegetables. *Fermentation* **2022**, *8*, 659. https://doi.org/10.3390/fermentation8110659

Academic Editor: Diomi Mamma

Received: 15 October 2022
Accepted: 18 November 2022
Published: 21 November 2022

1. Introduction

Sustainable production, seen as a process aimed at using food ingredients in their entirety with minimal postproduction waste, is now becoming increasingly popular. Although modern technology is becoming helpful in reducing waste from households and restaurants, it is still a huge and financially costly problem for the food industry [1–4]. In landfills, food loss and waste that can be minimized to a large extent are vegetables and fruits called 'green waste', which are edible but do not meet the requirements of groceries in terms of color, the appearance of a uniform surface, or the calibrated shape and size [4–6].

Vegetables are raw materials subject to numerous treatments due to their seasonality. Raw and processed, they are rich in minerals and active ingredients [7,8]. In Poland, beetroot (*Beta vulgaris*), carrot (*Daucus carota),* and red bell pepper (*Capsicum annum* L.) are of great interest both to consumers and food companies.

Red beets and carrots are classified as root vegetables. Beetroot is a two-yearly vegetable plant with an edible, large, intensely red storage root and reddish leaves [9,10]. Other beet varieties are gaining in popularity, including white, yellow, red, and white. Carrots are most commonly orange in color but can also be found in other colors, such as purple, red, white, and yellow [11]. Both beetroot and carrots are high in water, approximately 87–88%; carbohydrates, approximately 9.5%; protein, 1–1.5%; and sugars, 5–7% [12,13].

Red pepper, on the other hand, is an edible fruit that belongs to the Solanaceae family, such as tomatoes. Analysis of red pepper composition revealed the presence of approximately 92% water, 6% carbohydrates, 1% protein, and 4% sugars [14].

Each of these vegetables has valuable active ingredients, such as betanin in red beet and carotenoids in carrots (mainly β-carotene) and peppers (carotenes and capsaicin) [9,15–17]. A common feature of these vegetables is their seasonality and instability. To extend their shelf life, they are often subjected to drying or freezing. However, to provide them with additional functional properties, a popular method in central and eastern Europe can be used, which is the pickling process involving lactic acid bacteria. The increase in popularity of this type of product may be related to the trend toward lactose-free probiotic foods [18–20].

The recent trend of reusing and reprocessing food has been revisited through the application of the recycling and fermentation process [21]. It can be observed that the fermentation of vegetables is currently a very attractive form of processing these raw materials, as vegetables are a source of essential nutrients, vitamins, minerals, antioxidants, and fiber, as well as sugar [22–24]. Lactic acid fermentation has been recognized for centuries as a safe food preservation method that requires minimal input. The lactic fermentation process is based on an anaerobic lactic fermentation process in which the sugars in the raw material are treated as a reaction substrate, and the preservative in the product is the lactic acid formed during fermentation. Lactic acid fermentation increases the bioavailability of nutrients and pigments, most likely by breaking down the cell walls of plant tissues.

The strains most commonly used in industry for dedicated plant fermentation are *Levilactobacillus brevis*, *Limosilactobacillus fermentum*, and *Lactiplantibacillus plantarum* [25–27]. The fermentation process, as a result of the production of lactic acid by lactic acid bacteria and the resulting reduction in pH, allows vegetables to be stored longer. Low pH inhibits the growth of bacterial spores during storage. As a result, food can be stored for many months with low temperatures and no UV radiation [28]. However, the need for specific storage conditions means that additional methods are being sought to process fermented products. One such method is the freeze-drying process, also known as low-temperature drying. It is a low-temperature dehydration process that involves freezing the product, lowering the pressure, and then removing the ice by sublimation. This process preserves the product with the structure of the raw material [29–31].

In addition, the fermentation process often improves the organoleptic properties of food, the digestibility of proteins and carbohydrates, and the bioavailability of vitamins and minerals [32]. Fermented vegetables benefit health by increasing immunity, mainly due to the increased availability of antioxidant components that support the elimination of harmful free radicals, which play a role in the formation of degenerative diseases. In addition, the lactic acid bacteria probiotics contained in fermented vegetables can help prevent certain diseases, such as cirrhosis [24,33].

The use of fermentation and freeze-drying can result in a valuable, sustainable product that can solve the problems of spoiled vegetables and the need for refrigerated storage. Therefore, this study aimed to obtain sustainable dried fermented vegetables and compare their selected physical and structural properties of fresh and freeze-dried fermented vegetables. Beetroot, carrot, and red pepper were selected for this purpose. The vegetables were subjected to the process of spontaneous fermentation of lactic acid. At the end of the process, the fermented and unfermented vegetables were freeze-dried, and their structure and selected physical properties (color and dry substance) were determined.

2. Materials and Methods

2.1. Materials

Beetroot (*Beta vulgaris*), carrot (*Daucus carota* L.), and red bell pepper (*Capsicum annum* L.) were purchased from a local market (Warsaw, Poland) and processed after buying.

2.2. Technological Treatment

2.2.1. Fermentation Process

The fermentation process was carried out according to the protocol [21]. Vegetables were washed, peeled, and sliced (slices 5 mm) and then placed into glass jars into which a 2% solution of NaCl in a proportion 1:1 w/w was added. The jars were closed to create anaerobic conditions. All experiments were left for 10 days. The pH in the jars after 10 days was 3.5 and was stable, which means that the fermentation process had ended [34,35]. After obtaining a stable pH level, the fermentation process was stopped by placing jars into the refrigerator for at least 12 h. All experiments were performed in duplicate.

2.2.2. Freeze-Drying

The vegetables were placed in a Petri dish and frozen at −40 °C (Shock Freezer HCM 51.20, Irinox, Treviso, Italy) for 5 h. Freeze-drying was carried out in an ALPHA 1–4 freeze-dryer (Christ, Osterode, Germany) for 24 h at a heating shelf temperature of 30 °C and a constant pressure of 63 Pa; safety pressure was set to 103 Pa. The experiments were carried out in duplicate.

2.3. Analytical Methods

2.3.1. Morphology of Freeze-Dried Vegetables

Scanning Electron Microscope

The morphology of dried vegetables was performed using a scanning electron microscope (SEM) Phenom (Hitachi High-Technologies Corporation, Tokyo, Japan) operated at an accelerating voltage of 10 kV. The vegetables were cut with a scalpel into 1 mm pieces, and the broken parts were blown off with compressed air from a compressor. Then, they were placed on a double sticky film on the microscope table and covered with gold. The images were taken using a built-in light-color optical navigation camera.

Confocal Scanning Laser Microscopy

Confocal scanning laser microscopy (CSLM) was used to observe the cellular structure of raw and fermented vegetables. Rectangular specimens (10 × 4 × 2 mm) were extracted from the produce. Each sample was placed on a glass slide and viewed using an FV3000 confocal imaging system (OLYMPUS, Tokyo, Japan) with a 10 × 3 NA dry objective lens. The observation was made with two different extractable wavelengths for the laser source. For beetroot, an excitation peak at 544 nm and an emission peak at 570 nm was taken; for carrot and red bell pepper, the excitation wavelength was 490 nm, and the emission was 525 nm.

Microtomography

To show whole sample analysis, microtomography was taken. The tests were carried out with the use of the 1172 SkySkan, Bruker® microtomograph, with the lamp parameters given in the table (Table 1). The difference in the values of the lamp settings parameters is due to the size of the object.

Table 1. Specimen registration parameters, 1172 SkyScan Bruker® X-ray microtomograph.

	Carrot	Red Bell Pepper	Beetroot
Image resolution	12 µm	12 µm	12.4 µm
Lamp voltage and amperage	49 kV/200 mA	49 kV/200 mA	59 kV/167 mA
Exposure time	615 ms	615 ms	615 ms
Filters		no additional filter	
Unit rotation angle	0.4°	0.4°	0.4°

Photo-Camera

The photos were taken with a Nikon D7000 digital camera (Nikon, Tokyo, Japan) with a 105 mm lens positioned at a distance of 50 cm in front of a sample (freeze-dried vegetables); the light source consisted of four fluorescent lamps reduced at an angle of 45, emitting daylight at a temperature of 6500 K. The photos were saved in JPG format.

Image Analysis

Changes in the structure of vegetables after freeze-drying were determined based on image analysis made with scanning electron microscope pictures. Graphic design and measurement of the projection area (mm^2) of the compartments identified as tissue cells were performed using the MultiScan v. 18.03 program (Computer Scanning System Company, Warsaw, Poland) according to the methodology presented by Janowicz and Lenart [36]. An area of 50% was calculated, which values indicate surfaces, obtained by 50% of tested areas.

2.3.2. Dry Matter

For dry matter determination, the gravimetric method was used. Approximately 1 g of vegetable (raw, fermented, and dried) was placed on a plate and dried using the vacuum drying method (Memmert VO400, Schwabach, Germany) under a pressure of 10 mPa at 75 °C for 24 h until constant weight, according to information from Rybak et al. [37]. Measurements were made in triplicate.

2.3.3. Color

Analysis of powder color was performed in CR-5 (Konica Minolta Sensing Inc., Osaka, Japan) in CIE L * a * b * system. The measurement parameters are as follows. Illuminant D65, angle 2°, and calibration with white color as presented by Janiszewska [38]. All measurements were made in five repetitions.

2.3.4. Determination of the Number of Lactic Acid Bacteria

The total count by pour plate method was used to enumerate viable cells. A total of 10 g of raw, fermented, or freeze-dried vegetable samples were serially diluted using sterile saline (0.85% NaCl, Biomaxima, Poland). The samples were streaked onto plates with Man Rogosa and Sharpe Agar (MRS, Biomaxima, Poland) agar and incubated at 28 °C ± 2 °C for 48 h ± 4 h. The number of colonies grown was counted (ProtoCOL 3—Automatic colony counting and zone measuring, Synbiosis, Frederick, MD, USA) and recorded as log CFU per g d.m. The samples were analyzed in triplicate.

2.4. Statistical Treatment

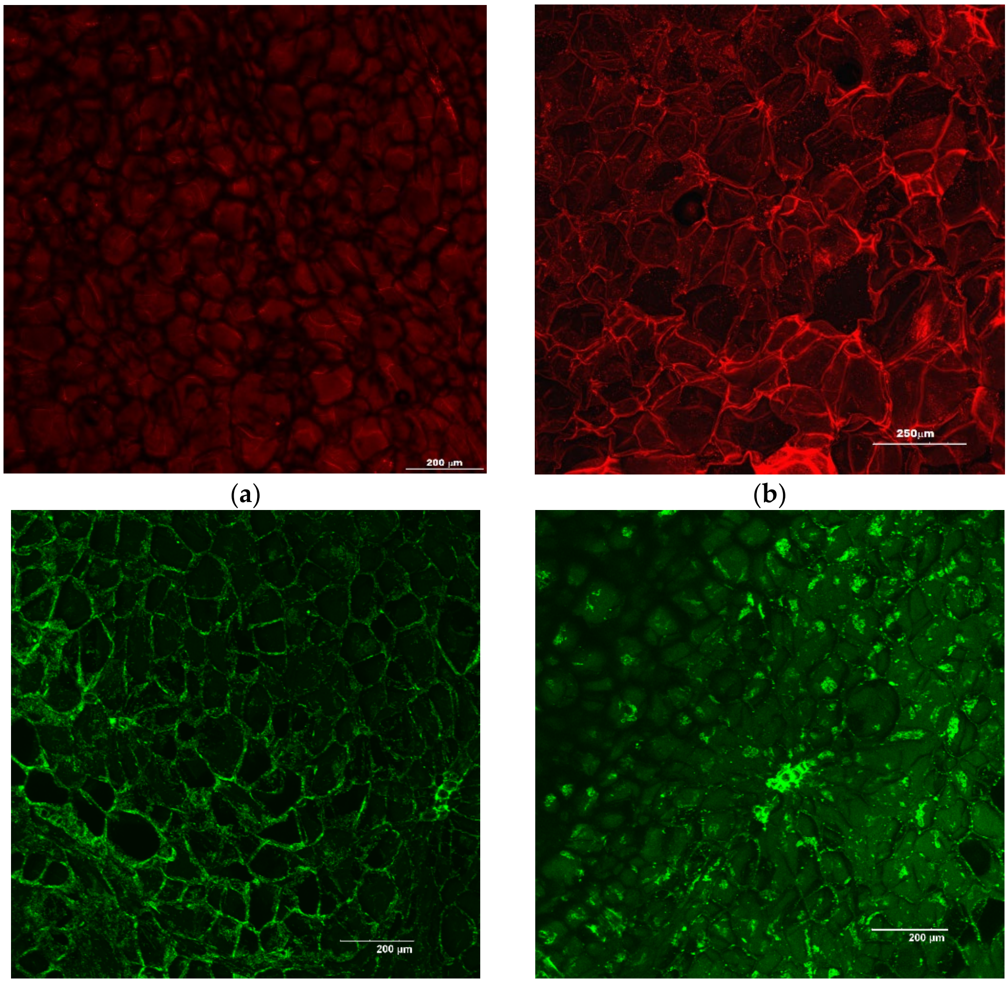
The results obtained were subjected to a statistical analysis using Statistica 13 software (StatSoft, Warsaw, Poland), using a one-way analysis of variance with the Tukey HSD test at a significance level of $\alpha = 0.05$. The other parameters were determined using Microsoft Office Professional Plus Excel 2019.

3. Results and Discussion

3.1. Structure

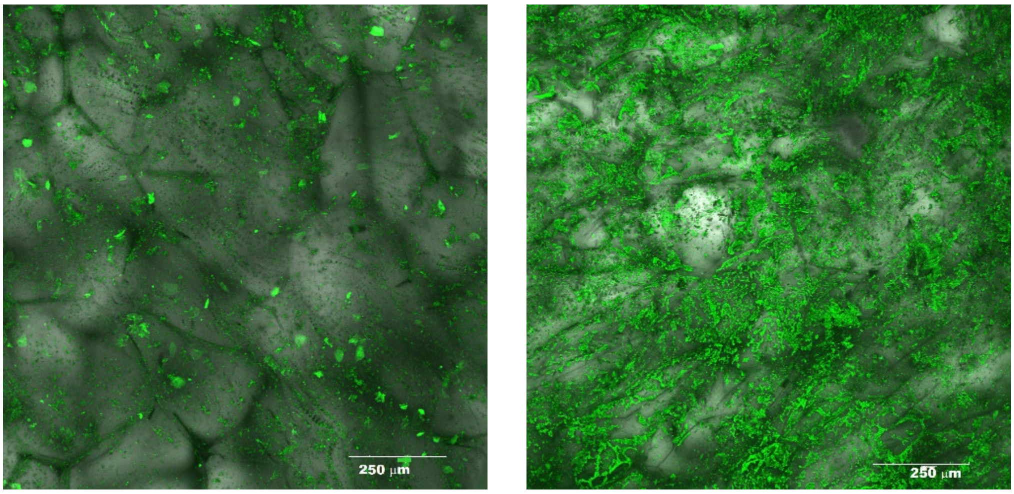
The analysis of the vegetable structure began with the determination of the structure of raw vegetables and those obtained immediately after the lactic fermentation process. A confocal microscope was used for this purpose. Due to the high content of pigments in vegetables (betalain, carotenoids), it was possible to observe the spatial structure without using markers (Figures 1 and S1 from supplementary file). However, the structure of dried vegetables is presented in the photos taken from the scanning microscope (sections of the outer wall and the cross-section of the dried tissue (Figure 2).

As a result of the fermentation process, independently from the fermented raw material, loosening of the cell wall structure and extraction of the pigment was observed in images from the confocal microscope (CLSM). The photos of nonfermented vegetables show the structure of the tissue; the areas between the adjacent parts of the tissue are separated by a visible barrier (the pigment in red beet and carrot is mainly located in the cell wall). On the other hand, after the fermentation of vegetables in a pickle containing table salt, leakage of pigment from the area of cell walls is observed, especially for red bell pepper (green color in Figure 2f).



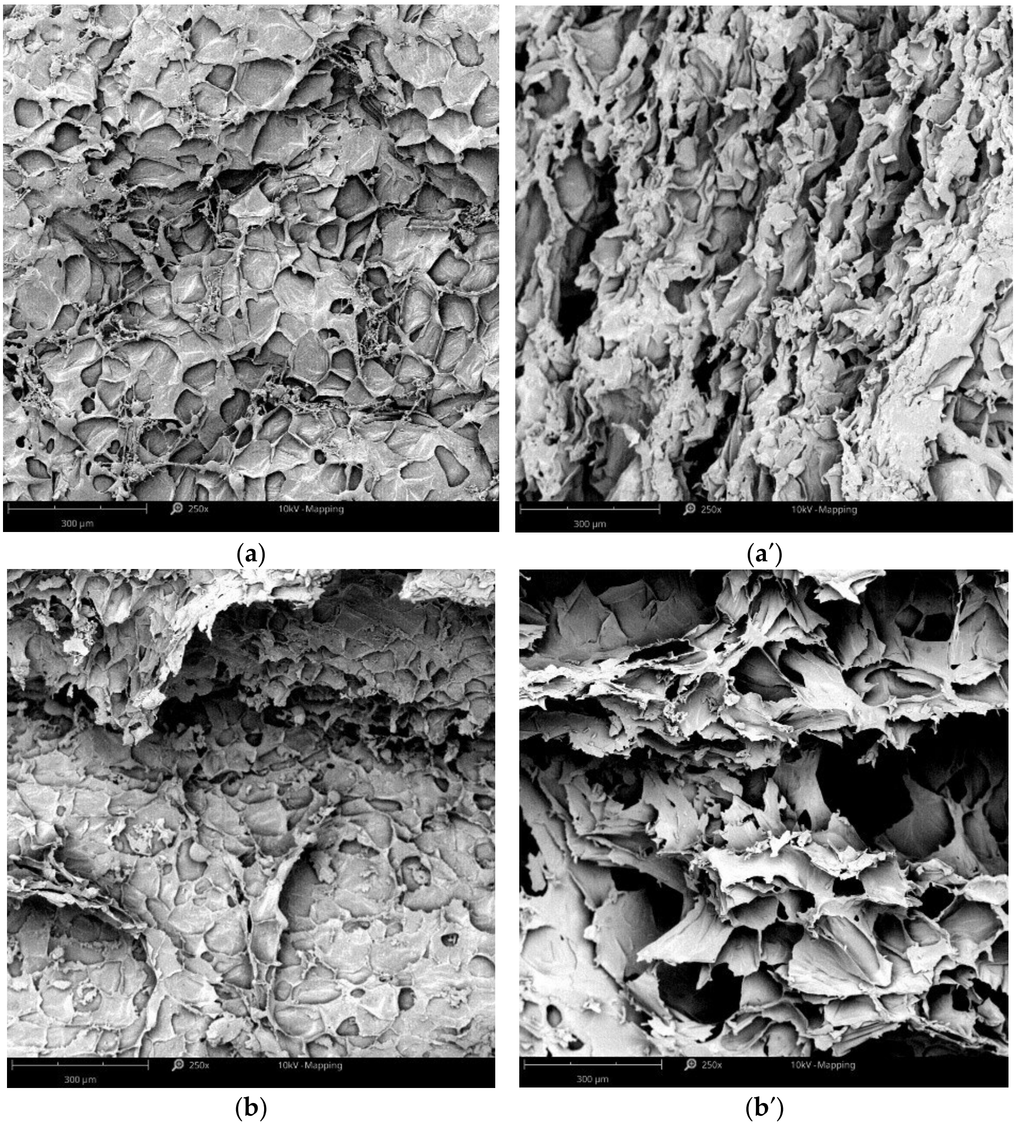
(**a**) (**b**) (**c**) (**d**)

Figure 1. *Cont.*



(**e**) (**f**)

Figure 1. Structure of raw and fermented vegetables (confocal microscope): (**a**) unfermented beetroot; (**b**) fermented beetroot; (**c**) unfermented carrot; (**d**) fermented carrot; (**e**) unfermented red bell pepper; (**f**) fermented red bell pepper.



(**a**) (**a′**)

(**b**) (**b′**)

Figure 2. *Cont.*

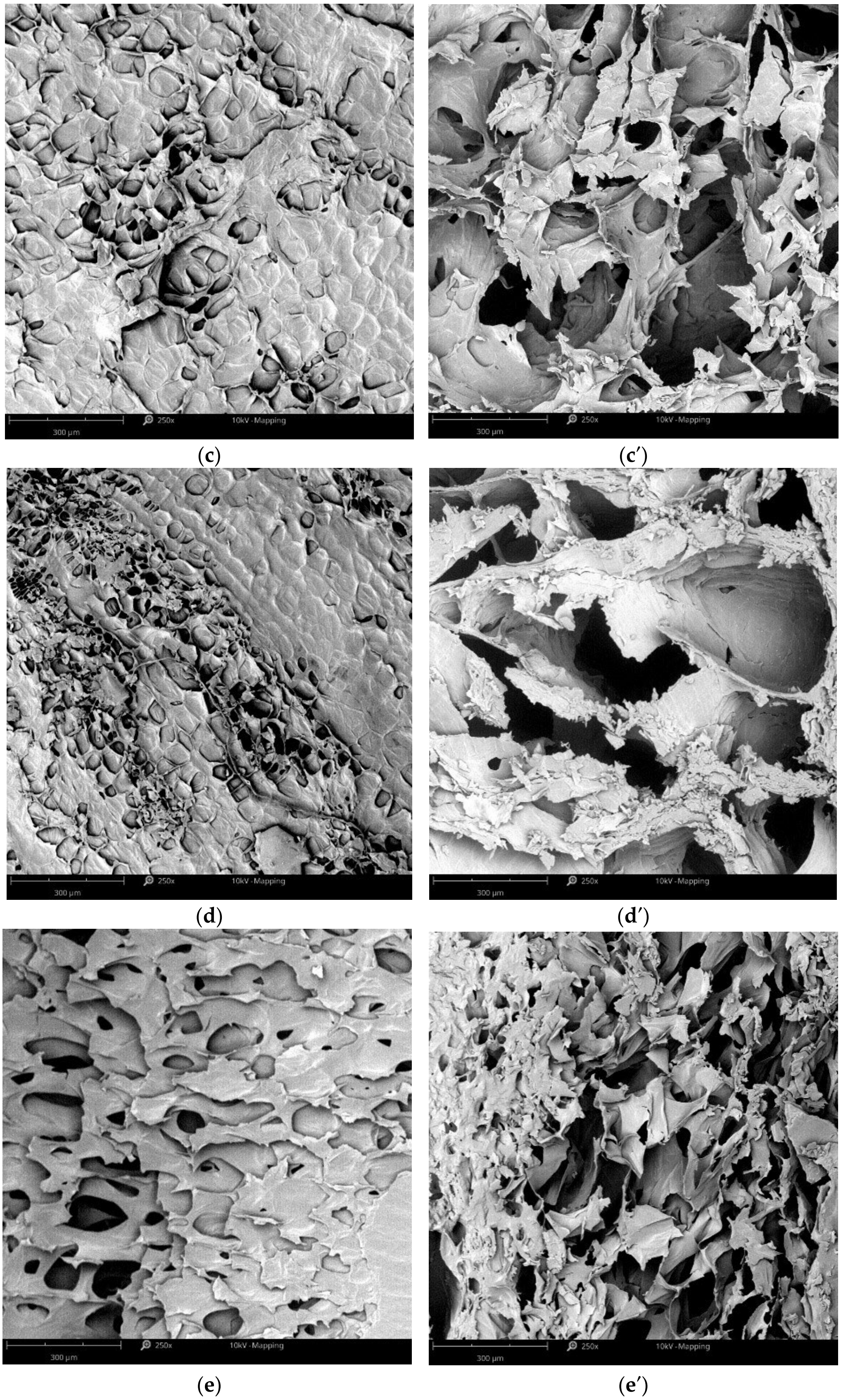
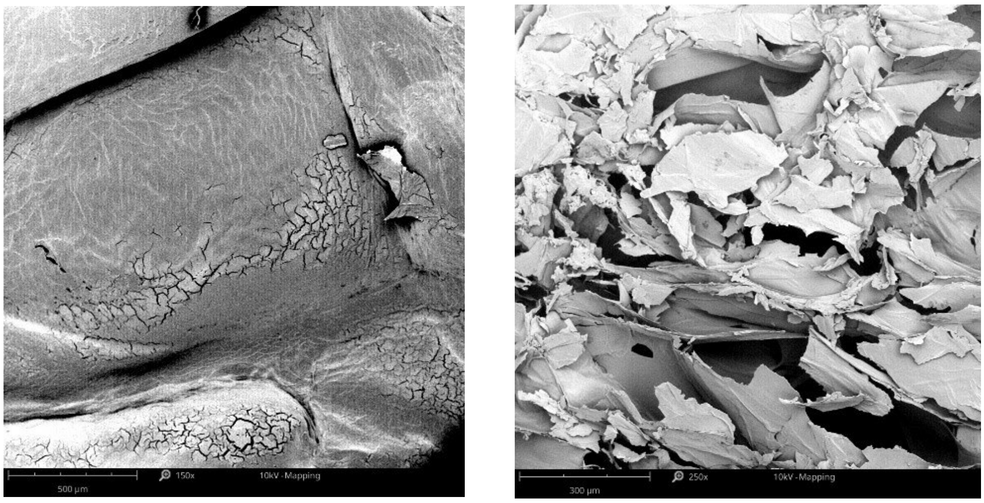


Figure 2. *Cont*.



(**f**) (**f′**)

Figure 2. Structure of freeze-dried unfermented and fermented vegetables (scanning electron microscope) Pictures without **′** at the letter show a view of the side surface of the slice; Pictures with **′** at the letter are a top view of the slice. (**a**) unfermented beetroot; (**b**) fermented beetroot; (**c**) unfermented carrot; (**d**) fermented carrot; (**e**) unfermented red bell pepper; (**f**) fermented red bell pepper.

Moreover, the size of tissue cells differed after the fermentation process compared to those before the process. This may be due to salt water migration into the vegetable tissues (Figure 1). Similar relationships and shapes were visible for carrot tissue after thermal treatment by Alvarez et al. [39]. The size of the enlarged empty spaces of tissues after the fermentation process was also visible in the droughts obtained after the freeze-drying process (Figures 2–4). The outer surface (skin part of the vegetable) of the dried vegetable was more compact, with no marked open pores (Figure 2a–f). In red bell peppers, an almost smooth outer surface was visible, which is related to the presence of an impermeable water and air-waxy cuticula layer on the surface of the red bell pepper (Figure 2e,f).

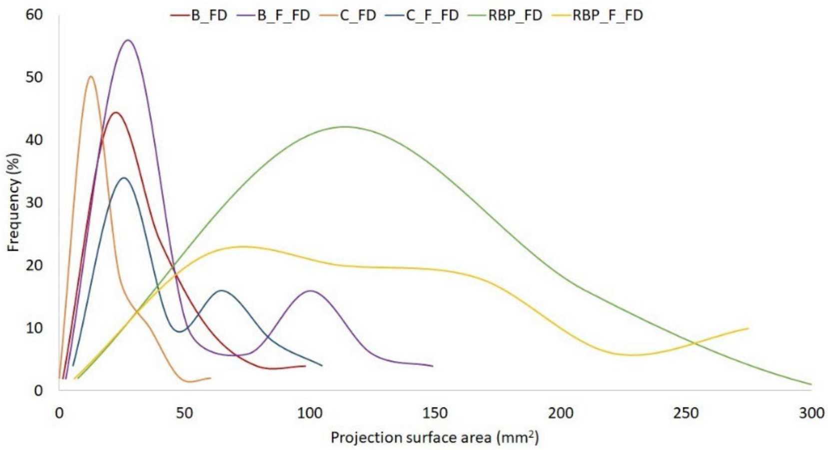


Figure 3. Distribution of the vegetable projection surface area dependent on the vegetable type and fermentation process, B—beetroot, C—carrot, RBP—red bell pepper; FD—freeze dried, F—fermented.

The interior of the vegetables, regardless of their type, shows open pores of various sizes. After the fermentation process, they are larger compared to the raw material. The highest difference before and after fermentation was observed for carrot samples (Figure 2c′,d′). The projection surface area was confirmed in the calculation tests performed in the graphical program (Figure 3, Table 2).

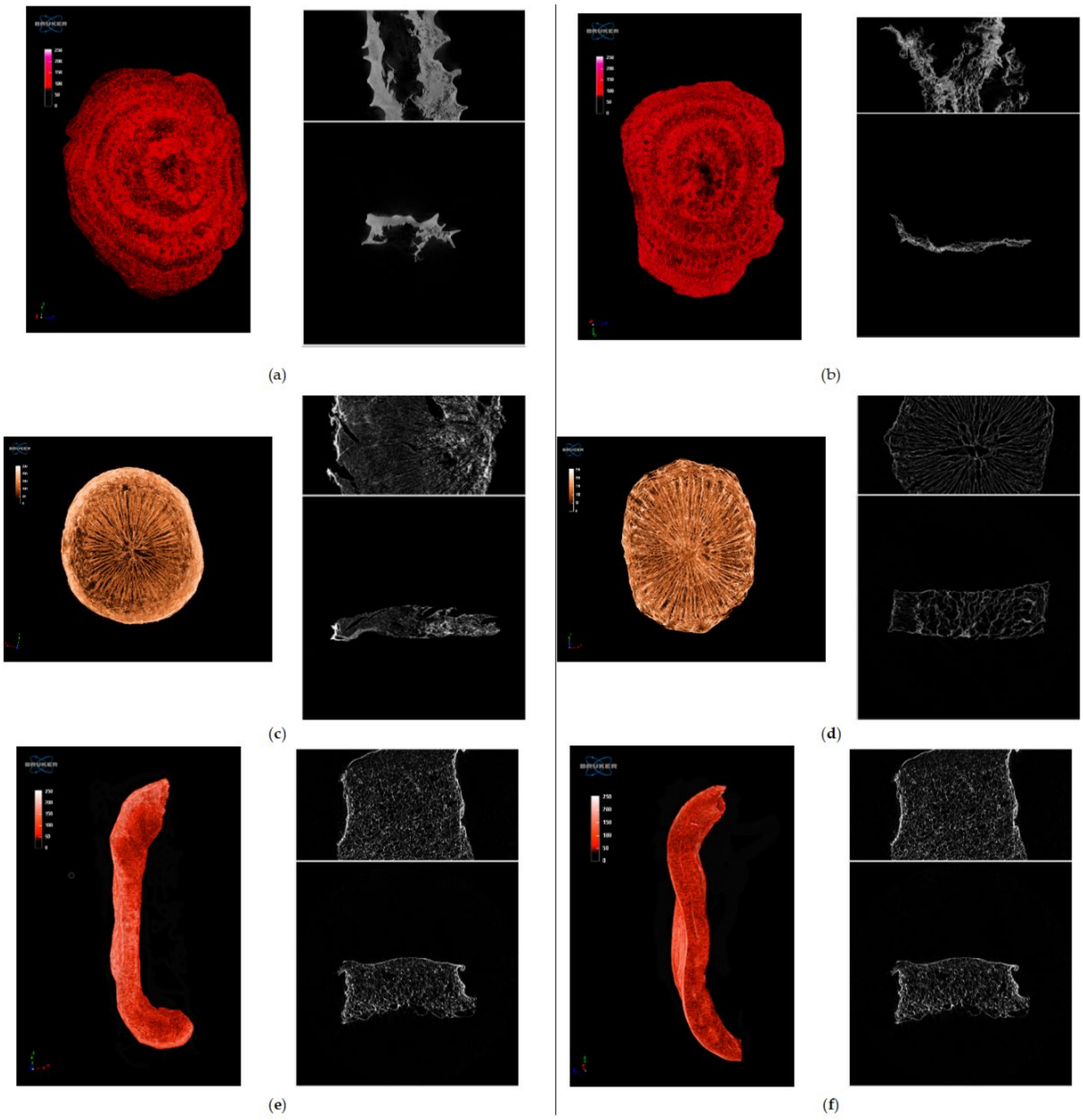


Figure 4. Structure of freeze-dried unfermented and fermented vegetables (Microtomography) (**a**) unfermented beetroot; (**b**) fermented beetroot; (**c**) unfermented carrot; (**d**) fermented carrot; (**e**) unfermented red bell pepper; (**f**) fermented red bell pepper.

All fermented and unfermented vegetables obtained as a result of freeze-drying had a similar internal structure (Figures 2 and 4). They were all very porous, and damage to the structure was observed when breaking a slice of the tested vegetable. When cutting with a scalpel for examination under a scanning microscope, it was found that red pepper was characterized by the most fragile structure, and the dried beetroots were the hardest. This observation was confirmed by analysis of the projection surface area calculated from an SEM image and a histogram constructed from 100 pores (Figure 3).

Structural results related to the distribution of pores in the vegetable tissue and the distribution of pigments after fermentation allowed for predictions related to the tested vegetables. The analysis of vegetables not preserved by freeze-drying showed that the vegetables obtained by fermentation could be unstable if stored outside the brine, and the dye released after fermentation from the tissue cells would quickly degrade due to the availability of oxygen and light. However, the removal of the dye from the tissue walls could also be considered an advantage, as upon consumption, the dye, having antioxidant properties, would be more readily available to the consumer.

Table 2. Selected physical properties of raw and freeze-dried vegetables.

Vegetable Type	Dry Matter (%)	Color Coefficients			Projection Surface Area 50% (mm^2)
		L *	a *	b *	
Beetroot (B)	18.5 ± 0.2 ^{b}	18.52 ± 0.13 ^{ab}	2.09 ± 0.12 ^{a}	0.47 ± 0.05 ^{b}	-
Fermented Beetroot (F_B)	15.2 ± 0.3 ^{a}	16.28 ± 2.26 ^{a}	15.02 ± 1.30 ^{b}	2.03 ± 0.44 ^{b}	-
Freeze-dried Beetroot (B_FD)	97.9 ± 0.4 ^{c}	22.09 ± 0.05 ^{bc}	22.92 ± 1.09 ^{c}	1.48 ± 0.09 ^{b}	20.5 ± 1.2 ^{a}
Freeze-dried Fermented Beetroot (F_B_FD)	97.7 ± 0.1 ^{c}	26.27 ± 2.83 ^{c}	20.93 ± 1.68 ^{c}	−10.29 ± 1.45 ^{a}	24.3 ± 1.8 ^{a}
Carrot (C)	17.4 ± 0.2 ^{b}	55.73 ± 0.79 ^{b}	19.15 ± 1.80 ^{a}	28.57 ± 0.80 ^{a}	-
Fermented Carrot (F_C)	13.2 ± 0.4 ^{a}	47.82 ± 0.08 ^{a}	22.84 ± 0.23 ^{b}	35.83 ± 0.19 ^{b}	-
Freeze-dried Carrot (C_FD)	96.6 ± 0.4 ^{c}	65.43 ± 1.17 ^{c}	20.15 ± 1.89 ^{ab}	35.60 ± 1.91 ^{b}	39.3 ± 2.5 ^{a}
Freeze-dried Fermented Carrot (F_C_FD)	96.3 ± 0.3 ^{c}	68.31 ± 2.68 ^{c}	17.77 ± 0.38 ^{a}	33.44 ± 0.24 ^{b}	105.8 ± 4.1 ^{b}
Red Bell Pepper (RBP)	13.6 ± 0.3 ^{b}	24.65 ± 1.53 ^{a}	27.46 ± 2.72 ^{a}	20.15 ± 3.45 ^{a}	-
Fermented Red Bell Pepper (F_RBP)	10.4 ± 0.1 ^{a}	27.93 ± 0.12 ^{a}	25.64 ± 0.10 ^{a}	16.97 ± 0.18 ^{a}	-
Freeze-dried Red Bell Pepper (RBP_FD)	98.4 ± 0.4 ^{c}	54.08 ± 1.72 ^{b}	29.43 ± 1.59 ^{a}	35.35 ± 0.55 ^{b}	10.1 ± 2.4 ^{a}
Freeze-dried Fermented Red Bell Pepper (F_RBP_FD)	98.6 ± 0.4 ^{c}	50.80 ± 2.24 ^{b}	33.90 ± 9.44 ^{a}	32.17 ± 1.80 ^{b}	76.6 ± 6.6 ^{b}

* ^{a}, ^{b}, ^{c}, and specific letters: different indexes for each vegetable type and each column mean statistically significant differences for given values at the level of $p < 0.05$.

Dried fermented vegetables, in turn, are very fragile due to the presence of large air spaces in the tissue, which can be detrimental to the storage or transport of the dried pieces. Pickled dried vegetables can be used as snacks or, after grinding, the powder can be used to increase the health value of products, as an additive containing lactic acid bacteria, as a dye due to the foreignness of dyes having a color effect, and as a substance having an antioxidant effect.

There were no visible differences in the color and shape of the analyzed freeze-dried fermented and nonfermented samples (Figures 4 and 5), which is confirmed by the color test results (Table 1). Microtomography analysis of vegetables can show the 3D structure of the entire analyzed sample. Rybak et al. [29] observed similar results for microtomography of freeze-dried red bell pepper, Bialik et al. [40] for kiwi berry, and Ropelewska et al. [30] for beetroot raw and fermented.

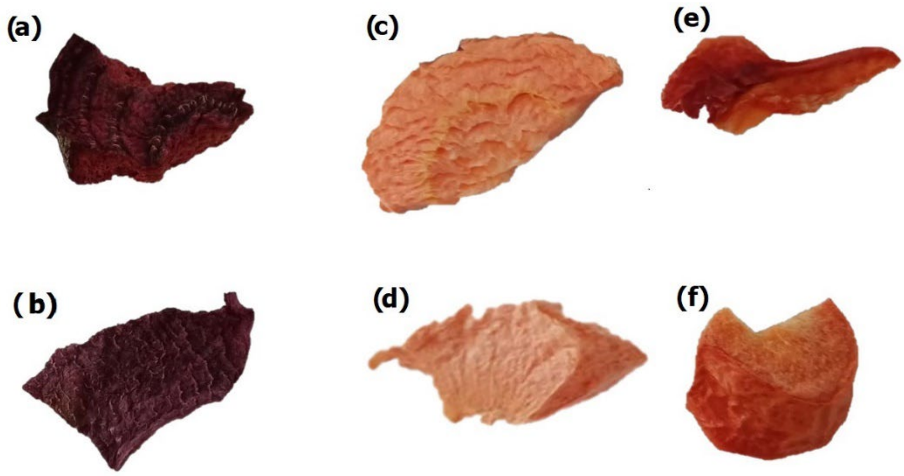


Figure 5. Structure of freeze-dried nonfermented and fermented vegetables (photo camera) (**a**) unfermented beetroot; (**b**) fermented beetroot; (**c**) unfermented carrot; (**d**) fermented carrot; (**e**) unfermented red bell pepper; (**f**) fermented red bell pepper.

3.2. Physical Properties

The physical properties that the potential customer pays attention to are mainly the color of the product and its size. For vegetables, including dried ones, it is extremely important. The color is influenced by the pigments contained in the raw material, as well as its structure and water content (Table 2).

Each of the vegetables tested had different colors and amounts of dry matter (Table 2). The dry substance for each of the vegetables was similar. The highest amount of dry matter was observed in beetroot samples, and the lowest was in red bell pepper. After the fermentation process, the dry matter content decreased, and thus the water content in vegetables increased, regardless of the type of vegetable. This phenomenon is related to the fermentation process in which slices of vegetables are kept in salty water for the fermentation time (for beetroots and carrots from 7–14 days, shorter for red bell peppers) [30,41,42], which causes water to seep into the vegetable [18,43].

Each of the vegetables analyzed had a different color; the beetroot was characterized by a purple-red color which is related to the betaxanthins (yellow-orange, mainly vulgaxanthin-I) and betacyanins (red-violet, main betanin), after the fermentation process it turned into a more purple color. Betalains are water-soluble and stable in the pH range of 3–6; however, some chemical changes at higher temperatures could be observed. This can be related to the stability of these pigments; yellow betaxanthins are more stable than red-violet betacyanins [10,44,45]. However, some betalains can pass from the beet tissue to the brine because they are water-soluble pigments.

Carrots can be characterized by a yellow-orange color, and red bell peppers are red (skin) and orange (upper layer below the skin). Carotenoids, here, β-carotene and capsaicin, are water-insoluble pigments that are kept more in the tissue, and no water-colored brine was observed, which can be the reason for the more stable color of the carrot tissue during the fermentation process.

After the freeze-drying process, the dry matter content increased, which is related to the removal of water in the sublimation process during the freeze-drying process. In connection with this death, the obtained vegetable droughts also became darker. In the case of red beet, a color shift toward a darker blue was observed, in combination with the position of the a* coefficient to more purple. Apart from the change in the brightness parameter for the carrots, no changes were obtained in the values of the other factors determining the color of the product. This may indicate good color retention of this vegetable and, at the same time, low degradation of dyes during the freeze-drying process.

The greatest changes in the color index for red beet and pepper affected the b* factor (green-blue), which may indicate a change in the consumer's perception of this color.

Studies have confirmed that the pigments from beetroot, such as betaxanthins and betacyanins, as well as the carotenoids from carrots and red peppers, change color under the influence of the fermentation process. It should therefore be recognized that fermentation or drying processes carried out in an inappropriate manner can result in significant losses of the visual characteristics of colored vegetables.

3.3. Microbiology

Beetroot, carrot, and red bell peppers were fermented naturally for 10 days. Raw vegetables and fermented vegetables were freeze-dried. The count of lactic acid bacteria in the tested samples is shown in Table 3. LAB count of LAB was observed in the vegetables before fermentation at the level of 2–3 log CFU/g. A similar count of LAB was observed after the freeze-drying of raw vegetables, as indicated by the lack of influence of the freeze-drying process on the content of lactic acid bacteria in the samples. After fermentation, a greater count of LAB was observed for red bell pepper than for beetroot and carrot. Furthermore, in the case of fermented vegetables, there was no effect of freeze-drying on LAB count.

Table 3. Lactic acid bacteria in vegetables.

Vegetable Type	Beetroot	Carrot CFU/g $_{d.m.}$	Red Bell Pepper
Unfermented	2.09 ± 0.12 [a]	2.98 ± 0.05 [b]	2.24 ± 0.18 [a]
Fermented	7.62 ± 0.03 [b]	7.13 ± 0.06 [c]	8.25 ± 0.03 [c]
Unfermented freeze-dried	2.42 ± 0.17 [a]	2.14 ± 0.11 [a]	2.03 ± 0.11 [a]
Fermented freeze-dried	7.57 ± 0.06 [b]	7.66 ± 0.08 [d]	7.48 ± 0.29 [b]

[a], [b], [c] and specific letters—different indexes for each column mean statistically significant differences for given values at the level of $p < 0.05$.

Ropelewska et al. [30] showed that the use of natural fermentation in the case of popular vegetables, such as beetroot, is preferable for sensory reasons to fermentation with the use of starter cultures. Studies of fermented pomace showed that the use of freeze-drying to preserve the fermented product reduces the LAB count by approximately 3–4 log cycles [21]. On the other hand, other studies have shown that the freeze-drying of fermented juices does not affect the LAB count [27], which confirms the previous research by Barbu et al. [46]. It has been shown that freeze-dried carrot fermented juices exhibit greater stability than spray drying over a one-month storage period, confirming the benefits of lyophilization to extend the shelf life of fermented products [47]. Moreover, the use of fermentation prevents the growth of the *Enterobacteriaceae* family in the products, in particular, from *Salmonella* spp. [48].

4. Conclusions

Research confirmed that beetroot pigments, e.g., betaxanthins and betacyanins, as well as carrots and red bell peppers, e.g., carotenoids, which are abundant in β-carotene and capsaicin, change their color due to the fermentation process. Therefore, it should be considered that processing, including inadequate fermentation and drying, can cause significant losses in the nutritional value and the visual characteristics of colored vegetables. There are many applications for pickled dried vegetables. They could be used as snacks or for increasing the health value of numerous instant products when pulverized, therefore benefiting the probiotic and antioxidant properties of the final product.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/fermentation8110659/s1, Figure S1: Figure S1. Structure of raw and fermented vegetables (confocal microscope): (a) fermented beetroot; (b) fermented carrot; (c) fermented red bell pepper.

Author Contributions: Conceptualization, E.J.-T. and A.N.; methodology, E.J.-T., K.R., K.P. and A.N.; validation, E.J.-T., K.R., K.P., A.N. and A.G.-M.; formal analysis, E.J.-T., K.R., K.P. and A.N.; investigation E.J.-T., K.R., K.P. and A.N.; resources, E.J.-T., K.R., K.P. and A.N.; data curation, E.J.-T., K.R., K.P. and A.N.; writing—original draft preparation, E.J.-T., K.R., K.P., A.N. and A.G.-M.; writing—review and editing, E.J.-T., K.R., K.P., A.N. and A.G.-M.; visualization, E.J.-T. and A.N.; supervision, E.J.-T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data available from the corresponding author.

Acknowledgments: Research equipment was purchased as part of the "Food and Nutrition Centre—modernisation of the WULS campus to create a Food and Nutrition Research and Development Centre (CŻiŻ)" co-financed by the European Union from the European Regional Development Fund under the Regional Operational Programme of the Mazowieckie Voivodeship for 2014–2020 (Project No. RPMA.01.01.00-14-8276/17).

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

References

1. Schanes, K.; Dobernig, K.; Gözet, B. Food waste matters-A systematic review of household food waste practices and their policy implications. *J. Clean. Prod.* **2018**, *182*, 978–991. [CrossRef]
2. Liegeard, J.; Manning, L. Use of intelligent applications to reduce household food waste. *Crit. Rev. Food Sci. Nutr.* **2020**, *60*, 1048–1061. [CrossRef] [PubMed]
3. Arnold, M.; Rajagukguk, Y.V.; Sidor, A.; Kulczyński, B.; Brzozowska, A.; Suliburska, J.; Wawrzyniak, N.; Gramza-Michałowska, A. Innovative Application of Chicken Eggshell Calcium to Improve the Functional Value of Gingerbread. *Int. J. Environ. Res. Public Health* **2022**, *19*, 4195. [CrossRef] [PubMed]
4. Jungowska, J.; Kulczyński, B.; Sidor, A.; Gramza-Michałowska, A. Assessment of factors affecting the amount of food waste in households run by polish women aware of well-being. *Sustainability* **2021**, *13*, 976. [CrossRef]
5. Loebnitz, N.; Schuitema, G.; Grunert, K.G. Who buys oddly shaped food and why? Impacts of food shape abnormality and organic labeling on purchase intentions. *Psychol. Mark.* **2015**, *32*, 408–421. [CrossRef]
6. Makhal, A.; Robertson, K.; Thyne, M.; Mirosa, M. Normalising the "ugly" to reduce food waste: Exploring the socialisations that form appearance preferences for fresh fruits and vegetables. *J. Consum. Behav.* **2021**, *20*, 1025–1039. [CrossRef]
7. Neri-Numa, I.A.; Arruda, H.S.; Geraldi, M.V.; Maróstica Júnior, M.R.; Pastore, G.M. Natural prebiotic carbohydrates, carotenoids and flavonoids as ingredients in food systems. *Curr. Opin. Food Sci.* **2020**, *33*, 98–107. [CrossRef]
8. Różyło, R. Recent trends in methods used to obtain natural food colorants by freeze-drying. *Trends Food Sci. Technol.* **2020**, *102*, 39–50. [CrossRef]
9. Fu, Y.; Shi, J.; Xie, S.Y.; Zhang, T.Y.; Soladoye, O.P.; Aluko, R.E. Red Beetroot Betalains: Perspectives on Extraction, Processing, and Potential Health Benefits. *J. Agric. Food Chem.* **2020**, *68*, 11595–11611. [CrossRef]
10. Hadipour, E.; Taleghani, A.; Tayarani-Najaran, N.; Tayarani-Najaran, Z. Biological effects of red beetroot and betalains: A review. *Phytother. Res.* **2020**, *34*, 1847–1867. [CrossRef]
11. Nagraj, G.S.; Jaiswal, S.; Harper, N.; Jaiswal, A.K. Carrot. In *Nutritional Composition and Antioxidant Properties of Fruits and Vegetables*; Academic Press: Cambridge, MA, USA, 2020; pp. 323–337.
12. USDA1. Beet Raw, FDC ID: 169145. Available online: https://fdc.nal.usda.gov/fdc-app.html#/food-details/169145/nutrients (accessed on 25 April 2022).
13. USDA3. Carrots Raw FDC ID: 170393. Available online: https://fdc.nal.usda.gov/fdc-app.html#/food-details/170393/nutrients (accessed on 25 April 2022).
14. USDA2. Peppers, Sweet, Red, Raw FDC ID: 170108. Available online: https://fdc.nal.usda.gov/fdc-app.html#/food-details/170108/nutrients (accessed on 25 April 2022).
15. Petito, N.D.L.; Devens, J.M.; Falcão, D.Q.; Dantas, F.M.L.; Passos, T.S.; Araujo, K.G.d.L. Nanoencapsulation of Red Bell Pepper Carotenoids: Comparison of Encapsulating Agents in an Emulsion Based System. *Colorants* **2022**, *1*, 132–148. [CrossRef]
16. Marlina, D.; Novita, M.; Karwur, F.F.; Rodonuwu, F.S. Recent Development of Carotenoids Encapsulation Technology. In Proceedings of the International Conference on Research: Implementation and Education of Mathematics and Sciences, Yogyakarta, Indonesia, 18–20 May 2014.
17. Zeece, M. Chapter Eight—Food colorants. In *Introduction to the Chemistry of Food*; Zeece, M., Ed.; Academic Press: Cambridge, MA, USA, 2020; pp. 313–344.
18. Jackson, R.S. Chapter 7—Fermentation. In *Wine Science*, 5th ed.; Jackson, R.S., Ed.; Academic Press: Cambridge, MA, USA, 2020; pp. 461–572.
19. Gänzle, M.G. Food fermentations for improved digestibility of plant foods—An essential ex situ digestion step in agricultural societies? *Curr. Opin. Food Sci.* **2020**, *32*, 124–132. [CrossRef]
20. Xiang, H.; Sun-Waterhouse, D.; Waterhouse, G.I.N.; Cui, C.; Ruan, Z. Fermentation-enabled wellness foods: A fresh perspective. *Food Sci. Hum. Wellness* **2019**, *8*, 203–243. [CrossRef]
21. Janiszewska-Turak, E.; Kołakowska, W.; Pobiega, K.; Gramza-Michałowska, A. Influence of Drying Type of Selected Fermented Vegetables Pomace on the Natural Colorants and Concentration of Lactic Acid Bacteria. *Appl. Sci.* **2021**, *11*, 7864. [CrossRef]
22. Mustafa, S.M.; Chua, L.S. 13—Green Technological Fermentation for Probioticated Beverages for Health Enhancement. In *Biotechnological Progress and Beverage Consumption*; Grumezescu, A.M., Holban, A.M., Eds.; Academic Press: Cambridge, MA, USA, 2020; pp. 407–434.
23. Agriopoulou, S.; Stamatelopoulou, E.; Sachadyn-Król, M.; Varzakas, T. Lactic acid bacteria as antibacterial agents to extend the shelf life of fresh and minimally processed fruits and vegetables: Quality and safety aspects. *Microorganisms* **2020**, *8*, 952. [CrossRef]
24. Swain, M.R.; Anandharaj, M.; Ray, R.C.; Parveen Rani, R. Fermented fruits and vegetables of Asia: A potential source of probiotics. *Biotechnol. Res. Int.* **2014**, *2014*, 250424. [CrossRef]
25. Khubber, S.; Marti-Quijal, F.J.; Tomasevic, I.; Remize, F.; Barba, F.J. Lactic acid fermentation as a useful strategy to recover antimicrobial and antioxidant compounds from food and by-products. *Curr. Opin. Food Sci.* **2022**, *43*, 189–198. [CrossRef]
26. Bontsidis, C.; Mallouchos, A.; Terpou, A.; Nikolaou, A.; Batra, G.; Mantzourani, I.; Alexopoulos, A.; Plessas, S. Microbiological and Chemical Properties of Chokeberry Juice Fermented by Novel Lactic Acid Bacteria with Potential Probiotic Properties during Fermentation at 4 degrees C for 4 Weeks. *Foods* **2021**, *10*, 768. [CrossRef]

27. Janiszewska-Turak, E.; Walczak, M.; Rybak, K.; Pobiega, K.; Gniewosz, M.; Woźniak, Ł.; Witrowa-Rajchert, D. Influence of Fermentation Beetroot Juice Process on the Physico-Chemical Properties of Spray Dried Powder. *Molecules* **2022**, *27*, 1008. [CrossRef]
28. Behera, S.S.; El Sheikha, A.F.; Hammami, R.; Kumar, A. Traditionally fermented pickles: How the microbial diversity associated with their nutritional and health benefits? *J. Funct. Foods* **2020**, *70*, 103971. [CrossRef]
29. Rybak, K.; Wiktor, A.; Witrowa-Rajchert, D.; Parniakov, O.; Nowacka, M. The quality of red bell pepper subjected to freeze-drying preceded by traditional and novel pretreatment. *Foods* **2021**, *10*, 226. [CrossRef] [PubMed]
30. Ropelewska, E.; Wrzodak, A.; Sabanci, K.; Aslan, M.F. Effect of lacto-fermentation and freeze-drying on the quality of beetroot evaluated using machine vision and sensory analysis. *Eur. Food Res. Technol.* **2021**, *248*, 153–161. [CrossRef]
31. Rajagukguk, Y.V.; Arnold, M.; Sidor, A.; Kulczyński, B.; Brzozowska, A.; Schmidt, M.; Gramza-Michałowska, A. Antioxidant Activity, Probiotic Survivability, and Sensory Properties of a Phenolic-Rich Pulse Snack Bar Enriched with Lactiplantibacillus plantarum. *Foods* **2022**, *11*, 309. [CrossRef] [PubMed]
32. Hwang, J.; Kim, J.-C.; Moon, H.; Yang, J.-Y.; Kim, M. Determination of sodium contents in traditional fermented foods in Korea. *J. Food Compos. Anal.* **2017**, *56*, 110–114. [CrossRef]
33. Garcia, C.; Remize, F. Lactic acid fermentation of fruit and vegetable juices and smoothies: Innovation and health aspects. In *Lactic Acid Bacteria in Food Biotechnology*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 27–46.
34. Niakousari, M.; Razmjooei, M.; Nejadmansouri, M.; Barba, F.J.; Marszałek, K.; Koubaa, M. Current Developments in Industrial Fermentation Processes. In *Fermentation Processes: Emerging and Conventional Technologies*; Koubaa, M., Barba, F.J., Roohinejad, S., Eds.; Wiley: New York, NY, USA, 2021; pp. 23–96.
35. Marszałek, K.; Woźniak, Ł.; Wiktor, A.; Szczepańska, J.; Skąpska, S.; Witrowa-Rajchert, D.; Saraiva, J.A.; Lorenzo, J.M.; Barba, F.J. Emerging Technologies and Their Mechanism of Action on Fermentation. In *Fermentation Processes: Emerging and Conventional Technologies*; Koubaa, M., Barba, F.J., Roohinejad, S., Eds.; Wiley: New York, NY, USA, 2021; pp. 117–144.
36. Janowicz, M.; Lenart, A. Selected physical properties of convection dried apples after HHP treatment. *LWT-Food Sci. Technol.* **2015**, *63*, 828–836. [CrossRef]
37. Rybak, K.; Parniakov, O.; Samborska, K.; Wiktor, A.; Witrowa-Rajchert, D.; Nowacka, M. Energy and quality aspects of freeze-drying preceded by traditional and novel pre-treatment methods as exemplified by red bell pepper. *Sustainability* **2021**, *13*, 2035. [CrossRef]
38. Janiszewska, E. Microencapsulated beetroot juice as a potential source of betalain. *Powder Technol.* **2014**, *264*, 190–196. [CrossRef]
39. Alvarez, M.D.; Saunders, D.; Vincent, J.; Jeronimidis, G. An engineering method to evaluate the crisp texture of fruit and vegetables. *J. Texture Stud.* **2000**, *31*, 457–473. [CrossRef]
40. Bialik, M.; Wiktor, A.; Witrowa-Rajchert, D.; Samborska, K.; Gondek, E.; Findura, P. Osmotic dehydration and freezing pre-treatment for vacuum dried of kiwiberry: Drying kinetics and microstructural changes. *Int. Agrophys.* **2020**, *34*, 265–272. [CrossRef]
41. Di Cagno, R.; Surico, R.F.; Minervini, G.; De Angelis, M.; Rizzello, C.G.; Gobbetti, M. Use of autochthonous starters to ferment red and yellow peppers (*Capsicum annum* L.) to be stored at room temperature. *Int. J. Food Microbiol.* **2009**, *130*, 108–116. [CrossRef]
42. Di Cagno, R.; Surico, R.F.; Siragusa, S.; De Angelis, M.; Paradiso, A.; Minervini, F.; De Gara, L.; Gobbetti, M. Selection and use of autochthonous mixed starter for lactic acid fermentation of carrots, French beans or marrows. *Int. J. Food Microbiol.* **2008**, *127*, 220–228. [CrossRef] [PubMed]
43. Koubaa, M. Introduction to Conventional Fermentation Processes. In *Fermentation Processes: Emerging and Conventional Technologies*; Koubaa, M., Barba, F.J., Roohinejad, S., Eds.; Wiley: New York, NY, USA, 2021; pp. 1–21.
44. Czapski, J. The effect of heating conditions on losses and regeneration of betacyanins. *Z. Für Lebensm. Unters. Und Forsch.* **1985**, *180*, 21–25. [CrossRef]
45. Lombardelli, C.; Benucci, I.; Mazzocchi, C.; Esti, M. Betalain Extracts from Beetroot as Food Colorants: Effect of Temperature and UV-Light on Storability. *Plant Foods Hum. Nutr.* **2021**, *76*, 347–353. [CrossRef] [PubMed]
46. Barbu, V.; Cotârleț, M.; Bolea, C.A.; Cantaragiu, A.; Andronoiu, D.G.; Bahrim, G.E.; Enachi, E. Three Types of Beetroot Products Enriched with Lactic Acid Bacteria. *Foods* **2020**, *9*, 786. [CrossRef] [PubMed]
47. Rishabh, D.; Athira, A.; Preetha, R.; Nagamaniammai, G. Freeze dried probiotic carrot juice powder for better storage stability of probiotic. *J. Food Sci. Technol.* **2021**, 1–9. [CrossRef]
48. Li, Y.; Ten, M.M.Z.; Zwe, Y.H.; Li, D. *Lactiplantibacillus plantarum* 299v as starter culture suppresses Enterobacteriaceae more efficiently than spontaneous fermentation of carrots. *Food Microbiol.* **2022**, *103*, 103952. [CrossRef]