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Article

Crunchiness of Osmotically Dehydrated Freeze-Dried Strawberries

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Abstract

Consumers expect snacks that are tasty, healthy, and crunchy. However, optimizing crunchiness using sensory methods is time-consuming and expensive. Therefore, this paper proposes a new approach to measuring instrumental crunchiness. Whole strawberries of the "Honeoya" variety were osmotic dehydrated in a solution of sucrose and chokeberry juice concentrate for 1, 2, and 3 hours before freeze-drying. Texture was measured using acoustic emission (AE) and a compression test. The crunchiness index was calculated taking into account the number of AE events and mechanical energy. The content of bioactive substances, water activity, and porosity of the freeze-dried products were also assessed. Freeze-dried fruits after dehydration in chokeberry juice concentrate were characterized by lower final water activity and higher content of bioactive substances, but their crunchiness was the lowest. The crunchiest, loudest, and least hard were freeze-dried strawberries, dehydrated in a sucrose solution. The tested freeze-dried strawberries differed in the range of sound frequencies generated, which indicates a different cracking mechanism.

Keywords: texture; fruit; acoustic properties; mechanical properties; polyphenols; anthocyanins

1. Introduction

Despite many consumer expectations regarding dry snacks, texture, next to taste, is the most important feature influencing acceptance [1]. Texture, like taste, encompasses features liked (crispness, crunchiness) and disliked by consumers (rubberiness, stickiness, hardness) [1–3]. Numerous researchers have demonstrated that crispness and crunchiness are complex concepts, combining a wide range of perceptions, such as crack characteristics, sound, density, and food geometry [1,4–7]. It has been proven that consumers have different understandings of the terms "crispy" and "crunchy," but the sound produced during chewing is important in both of these characteristics. According to consumer perceptions, the term "crunchy" referred to food a hard texture and generated a low-pitched sounds when chewed. High-frequency sounds, crackly and splitting, were used to describe the perception of "crispy". Consumers considered sound the most important characteristic for the perception of crispness/crunchiness, followed by food hardness [4,6,8,9]. Texture is most often assessed sensorially, but due to its high subjectivity, instrumental methods are constantly being improved to allow for quick, objective measurement [3,7], not only in laboratory settings but also in industrial settings. Instrumental texture testing has often been performed using mechanical, and in recent years also acoustic tests [7,10–12]. Due to the strong correlations between sensory properties and instrumental properties measured by deformation force and sounds, instrumental texture measurement has been found to be a good tool to mimic human chewing and texture perception [13–15].

Various methods are used to measure acoustic emissions generated during mechanical tests [3,7,16,17]. Sounds can be recorded using a microphone, vibration sensor, or piezoelectric sensor. When recording sound with a microphone, it is difficult to eliminate the acoustic background, i.e., sounds coming from the recording equipment, e.g., the noise of a computer fan, because the

microphone receives sounds passing through the air [11,16]. This means that the environment around the tested sample should be quiet. The use of a vibration sensor allows for the recording of vibrations generating sounds originating only from the deformed product [16,18]. This method has been successfully used to assess texture changes caused by increased moisture content in potato chips, cereal products and apple gels [16,17,19] and to predict the crispness of apples [18]. Therefore, in this study, it was assumed that instrumental (acoustic and mechanical) measurement of dried fruit texture could enable setting a standard of crispness to which newly developed snacks will be measured. This is particularly important when the product varies in shape, has a heterogeneous structure, or is porous, such as dried fruit, as these characteristics strongly influence the perception of texture. Although it was proven that the main factor affecting the textural properties of fruit and vegetable chips was their chemical composition, and the cell structure was a secondary factor [20].

Strawberries are valued for their flavor, low calories, and nutritional value. Water dominates the composition of these fruits (approximately 90%), with the amount varying slightly due to soil and climatic conditions in each harvest year. These fruits contain 7.2% total carbohydrates (including 1.4% sucrose), 0.7% protein, 0.4% fat, and 0.8% ash. They are also a source of dietary fiber (1.8–1.9%) and many vitamins such as ascorbic acid (C) on average 66.0 mg per 100 g, niacin (vitamin PP), riboflavin (B2), thiamine (B1) and vitamin B6, as well as minerals, primarily potassium, calcium, phosphorus, magnesium, sodium and iron, and in smaller amounts manganese, copper and zinc [21]. Strawberries are also rich in minerals as well as flavonoids and polyphenols compounds, many of which are natural antioxidants [22,23]. Salazar-Orbea et al. [24] identified 18 phenolic compounds in strawberries.

Due to seasonality, a large surplus of strawberries is inevitable, and their delicate texture and perishability necessitate their rapid preservation after harvest [25,26]. One of the many preservation methods is drying, which allows for the production of crispy snacks. The process should be carried out to ensure microbiological stability, preserve nutritional value, and the best possible quality characteristics, i.e., color, flavor, aroma, and crisp texture. Dried fruit contains concentrated nutrients, and even if they are partially degraded during drying, the product is still characterized by a content of bioactive compounds exceeding their level in raw tissues (per unit weight), which may make it a product with health-promoting properties [27–29]. In the process of drying strawberries and other soft fruits, it is tough to obtain high-quality dried fruit. Various drying techniques affect textural characteristics such as product hardness and crispness [30] and reduce the content of bioactive compounds [27,31,32]. One technique that largely preserves the properties of the raw material is freeze-drying [33,34]. This method is energy-intensive and expensive, but it produces a product with the texture desired by consumers, a lighter color than the raw material, and a higher nutritional value than when drying strawberries using other methods [27,30,35,36]. Freeze-dried fruits showed better retention of vitamin C, anthocyanins, phenols, and antioxidant capacity than those dried by hot-air drying and refractance window drying [31]. Freeze-dried strawberries retained better raw material properties including polyphenol content, compared to air-dried strawberries [30,37]. To ensure the desired nutritional and sensory value and shorten the drying time during freeze-drying, fruit pre-treatment with ultrasound [29,35,38–40] or high pressure [39,41], as well as osmotic dehydration in various solutions, e.g., fruit juice concentrates or fruit pomace extracts, is used. The use of osmotic dehydration in chokeberry juice concentrate causes an increase in the dry mass and total polyphenols content of the dehydrated apples and significantly reduces the water content [38], which improves the economics of the process freeze-drying. The process minimizes color changes, its effects on the composition and texture of the dehydrated fruit [42,43]. The addition of sugar protects anthocyanin pigments by inhibiting enzymatic degradation, enriching flavor, and preventing oxidation [44]. In particular, dehydration of fruit in fruit juice concentrate solutions may increase the content of bioactive compounds [38,45,46], which may be a natural antioxidant reducing the oxidation of nutrients [47]. Although the effect of temperature and time of osmotic dehydration of fruits in different solutions is well known [38,39,45], there is no information on the crunchiness of osmotically dehydrated strawberries before freeze-drying measured acoustically in combination with mechanical

properties and correlation with the content of bioactive substances. Literature reports indicate that acoustic parameters of food texture strongly correlate with sensory evaluation [2,12–14,28–30], and the sound produced during eating influences the perception of crisp/crunchy products [8,10]. Knowledge of crunchiness and bioactive compound content can contribute to developing optimal conditions for snack production. Therefore, it is necessary to evaluate the crunchiness of freeze-dried strawberries and analyze the correlation with the of bioactive compounds content. Objective measurement of crunchiness can be one of the parameters used to optimize the texture of dried fruits.

2. Materials and Methods

2.1. Osmotically Dehydrated and Freeze-Dried Strawberries

Whole strawberry fruits of the variety Honeoye were frozen at -40°C and stored at -20°C for 3 months. The strawberries were thawed in a microwave oven until a temperature of 25°C was reached. Then the fruits were dehydrated in osmotic solutions: sucrose ($60\pm 1\%$) and chokeberry juice concentrate ($60\pm 1^{\circ}\text{Brix}$) (Sokpol, Myszków, Poland). Chokeberry juice concentrate contained 60% carbohydrates, including 31% sugars. During osmotic dehydration, the ratio of material to solution was 1 to 4 (w/w,) the process at 30°C for 1, 2, and 3 hours was carried out, with constant mixing of the samples at a frequency of 1 Hz. Osmotically dehydrated fruit in chokeberry juice concentrate is shown in Figure S1. After dehydration, the strawberries were frozen at -45°C for 2 hours in a freezer (51.20 IRINOX SPA), and then freeze-dried in a device Alpha 1-4 LSC Plus Christ Company. Parameters of process drying were constant: pressure 63 Pa, safety pressure 137 Pa, temperature 30°C , and time 24 hours. Fruits after the freeze-drying process in a dark place at $20\pm 2^{\circ}\text{C}$ were stored until analysis. Freeze-dried, non-dehydrated material and osmotically dehydrated strawberries for 1h, 2h, and 3h in sucrose solution (samples code: sucrose 1h; sucrose 2h, sucrose 3h) and osmotically dehydrated in chokeberry juice concentrate (samples code: chokeberry 1h, chokeberry 2h, chokeberry 3h) were used for analysis.

2.2. Dry Matter, Water Activity and Density

The dry matter content was analyzed in freeze-dried, non-dehydrated and osmotically dehydrated strawberries; according to the methodology described by Kowalska et al. [45].

The water activity (aw) of dried strawberries was determined by an AquaLab instrument (Model CX-2, USA, DECAGON DEVICES. Inc., Pullman, WA, USA).

The particle density, apparent density and porosity was measured in 3 repetitions; according to the methodology describe by Marzec et al. [13].

2.3. Acoustic and Mechanical Properties

During the compression test, acoustic emission (AE) was being registered by the contact method using accelerometer type 4381 (Brüel&Kjær, Narum, Denmark). The accelerometer signal was amplified by 40 dB and digitized using card type 9112 (Adlink Technology Inc., Taipei, Taiwan) at a sampling rate of 44.1 kHz. The sound was analyzed in the frequency range of 1 to 16 kHz. A typical AE signal recording is a sinusoid. It appears as a sequence of pulses with variable amplitude in the time. Acoustic parameters can be determined time-domain. The AE event is a group of signals characterized by a damped sinusoid of over a period of time. The acoustic descriptors: energy of one acoustic event (a.u.), number of AE events, amplitude of sound (μV) were calculated using the Calculate_44kHz_auto program (Warsaw, Poland).

The compression test was used to investigate the mechanical properties of dried strawberries, in the Texture Analyzer TA-Hdplus (Stable Micro Systems, Godalming, Surrey, UK). The test speed was $0.5\text{ mm}\cdot\text{s}^{-1}$. The following mechanical parameters were calculated: compression force and mechanical energy (compression work). Compression work was calculated as the area under the compression curve of dried strawberries. Analysis was conducted with 15 replicates.

The crunchiness index was calculated as the product of the number of AE events and the mechanical energy recorded during sample compression [16].

2.4. Bioactive of Substance

The antioxidant properties of the tested non-dehydrated, dehydrated, and freeze-dried strawberries were expressed in terms of the content of total polyphenols, anthocyanins, and flavonoid phenolic compounds. Methanol extracts were prepared according to the methodology described in Kowalska et al. [45]. Total polyphenol content was determined spectrophotometrically using the Folin-Ciocalteu reagent. Absorbance was measured in a Helios γ ThermoSpectronic spectrophotometer at a wavelength of 750 nm. Total polyphenol content was calculated based on the determined standard curve equation, and the result was expressed as gallic acid (mg GAE/100 g d. m.).

The content of anthocyanins was expressed in terms of mg cyanidin-3-glucoside per g of dry matter content.

Flavonoid content was determined based on a quercetin standard calibration curve in the range of 0.075–0.200 mg/ml (Sigma-Aldrich, Steinheim, Germany). Absorbance was measured at 430 nm in a spectrophotometer (Thermo Spectronic Helios Gamma, Thermo Fischer Scientific, Waltham, MA, USA). Total flavonoid content was expressed as mg of quercetin equivalent per gram of dry matter content [45,46].

2.5. Statistical Analysis

The one-way ANOVA analysis was used to analyze significant differences in the obtained values. The significant differences between mean values were determined using Tukey's Multiple Range test at the significance level at $p < 0.05$. Principal Component Analysis (PCA) was performed. The STATISTICA software v. 13.3 (StatSoft Inc., Tulsa, OK, USA) was applied to statistical analysis of data. (StatSoft Inc., Tulsa, OK, USA)

3. Results and Discussion

3.1. Dry Matter Content, Water Activity and Density Results

The dry matter content of dehydrated fruit is important because it is closely related to the sugar content. Before drying, pre-dehydration of plant tissue in osmotic solutions such as sucrose or chokeberry juice concentrate affects the increase dry matter content [45]. It should also be noted that the fruits were thawed before osmotic dehydration. The freezing process influence in structure, which could have affected the in dry matter [48]. It should be emphasized that the strawberries were quickly frozen to reduce the drip loss [49]. After 1, 2 and 3 hours of osmotic dehydration in sucrose, significant increase in dry matter content was observed compared to non-dehydrated strawberries (Table 1). On the other hand, an increase in dry matter in strawberries osmo-dehydrated in chokeberry juice concentrate only after 2 and 3 hours was observed (Table 1)

Strawberries not osmotically dehydrated before freeze-drying had a water activity (a_w) of 0.275 (Table 1). The use of osmotic dehydration in sucrose solution before freeze-drying did not significantly affect water activity compared to non-dehydrated dried material. The use of chokeberry juice concentrate resulted in a statistically lower a_w regardless of the osmotic dehydration time. Water activity was approximately 0.190. Numerous studies have shown that freeze-drying fruit results in low water activity, which ensures microbiological stability during storage and product crispness/crunchiness [29,31,45]. According to Gautam et al. [50], the critical a_w required for microorganism growth is greater than 0.65.

The particle density of the dried material differed significantly. However, the apparent density was significantly lower only in strawberries that were not osmotically dehydrated. This resulted in differences in the porosity of the dried fruit (Table 1). After 3 hours of osmotic dehydration in both

solutions, the samples had porosity lower by 10 percentage points compared to the non-dehydrated samples.

During the osmotic dehydration of plant materials, sucrose and other sugars present in the solutions migrate into the material, and water is transferred from the material into the solution [45]. Therefore, the longer the dehydration time, the greater the amount of osmotic substance that can be absorbed by the strawberries, which results in an increase in the density and reduction in porosity of the dried product.

Table 1. Dry matter content, water activity and density analysis of freeze-dried strawberries. (Each value is presented as mean ± SD).

Code of samples	Dry matter content (g/ 100 g)	Water activity (-)	Particle density (g / cm³)	Apparent density (g / cm³)	Porosity (-)
Non-dehydrated	87.20 ± 0.15 ^a	0.275 ± 0.013 ^b	0.163± 0.001 ^a	1.228 ± 0.117 ^a	0.87 ± 0.01 ^c
Sucrose 1h	90.96 ± 0.27 ^b	0.261 ± 0.013 ^b	0.199 ± 0.000 ^b	1.368 ± 0.015 ^b	0.85 ± 0.01 ^c
Sucrose 2h	91.74 ± 3.38 ^b	0.298 ± 0.016 ^b	0.239 ± 0.000 ^c	1.383 ± 0.007 ^b	0.82 ± 0.01 ^b
Sucrose 3h	94.50 ± 0.36 ^c	0.284 ± 0.018 ^b	0.329 ± 0.000 ^g	1.405 ± 0.008 ^b	0.77 ± 0.00 ^a
Chokeberry juice 1h	89.03 ± 1.58 ^b	0.177 ± 0.005 ^a	0.241 ± 0.000 ^d	1.378 ± 0.035 ^b	0.82 ± 0.00 ^b
Chokeberry juice 2h	89.02 ± 1.51 ^b	0.185 ± 0.027 ^a	0.256 ± 0.001 ^e	1.423 ± 0.048 ^b	0.82 ± 0.00 ^b
Chokeberry juice 3h	94.83 ± 1.43 ^c	0.191 ± 0.001 ^a	0.319 ± 0.000 ^f	1.414 ± 0.008 ^b	0.77 ± 0.00 ^a

The values with the same letter in the column did not differ significantly at $\alpha < 0.05$.

3.2. Crunchiness of Freeze-Dried Strawberries

Acoustic emission (AE) is the phenomenon of the generation and propagation of elastic waves in solid materials and liquids. Materials in which AE signals are generated are characterized by a heterogeneous distribution of internal energy, resulting from manufacturing technology or operating under various conditions [16,17]. Sounds generated by dry products during deformation are closely related to their cellular structure. The tissue of freeze-dried fruit consists of air-filled cells [17]. During a compression test, the source of the generated sound is the rupturing of the cell walls. The loudness of such a sound results from the disruption of the cell walls, which is a factor determining the sound amplitude. Dried products with strong acoustic emission ("loud") are characterized by high crunchiness and low hardness [13].

The acoustic texture parameters (energy of acoustic event, number of AE events, amplitude of sound) and mechanical parameters (force, work) determined during the compression test are presented in Table 2.

Table 2. Acoustic and mechanical parameters analysis of freeze-dried strawberries. (Each value is presented as mean ± SD).

Code of samples	Energy of acoustic event (j.u.)	Number of AE event	Amplitude of sound (µV)	Force (N)	Work (mJ)	Crunchiness index
Non-dehydrated	2610.83 ±	2626 ± 563 ^b	497.14 ±	70.51 ± 16.44 ^b	285.17 ±	9.21 ± 1.97 ^{bc}
	581.86 ^b		51.66 ^{cd}		73.14 ^c	
Sucrose 1h	1827.13 ±	1678 ± 263 ^{ab}	451.75 ±	38.58 ± 5.54 ^{ab}	155.28 ±	10.80 ± 1.70 ^c
	182.23 ^a		35.16 ^{bc}		29.83 ^{ab}	
Sucrose 2h	3931.55 ± 293.53 ^c	8727 ± 695 ^c	551.36 ±	28.88 ± 4.79 ^a	120.53 ±	72.12 ± 5.75 ^e
			21.45 ^d		32.91 ^a	

Sucrose 3h	3420.86 ± 628.17 ^c	8618 ± 502 ^c	542.29 ± 28.90 ^d	52.79 ± 20.08 ^{ab}	197.23 ± 54.91 ^{abc}	38.70 ± 15.00 ^d
Chokeberry juice 1h	1420.33 ± 150.03 ^a	1907 ± 923 ^{ab}	409.75 ± 45.92 ^{ab}	130.02 ± 45.51 ^c	475.25 ± 110.23 ^d	5.25 ± 2.24 ^{ab}
Chokeberry juice 2h	1599.25 ± 205.42 ^a	1759 ± 693 ^{ab}	423.50 ± 47.72 ^{ab}	150.53 ± 24.75 ^{ab}	261.04 ± 108.52 ^{bc}	6.74 ± 2.66 ^{ab}
Chokeberry juice 3h	1514.00 ± 169.23 ^a	1471 ± 655 ^a	389.89 ± 25.70 ^a	187.53 ± 67.19 ^d	426.83 ± 156.63 ^d	3.44 ± 1.53 ^a

The values with the same letter in the column did not differ significantly at $\alpha < 0.05$.

Knowing that the freezing process causes damage to the tissue structure and that cell juice leaks out during thawing, we assumed that this would affect the texture and the resulting snacks would not be "loud" and therefore crunchy. As it turned out, freeze-drying preceded by osmotic dehydration, but only in sucrose solution for 2 and 3 hours, allowed obtaining snacks that generated the highest number of AE events, with the highest energy of acoustic event and amplitude of sound (Table 2). The values of acoustic parameters were significantly higher than the non-osmotically dehydrated sample that was not thawed before drying. According to literature data, the structure, including the porosity of the material, is primarily responsible for acoustic emission [14,17]. In our study, strawberries osmotically dehydrated in chokeberry juice concentrate had significantly lower porosity compared to non-osmotically dehydrated strawberries and similar porosity to samples osmo-dehydrated in sucrose solution. It was likely the chemical composition that determined the acoustic properties of the tested samples. Acoustic emission also depends on the mechanical properties of the material and defects present in the sample caused by the technological process. However, it was most likely the chemical composition that determined the acoustic properties of the tested samples. Despite retaining porosity, the content of organic acids in the chokeberry juice concentrate may have weakened the structure of the freeze-dried strawberries, resulting in weaker AE. Li et al. [20] studied the effect of chemical composition and structure on the texture of various dried fruits; they demonstrated that texture depends on chemical composition, while structure is of secondary importance for texture. Pre-dehydration in sucrose resulted in reduced compression force and work compared to non-dehydrated strawberries. Osmotic dehydration of fruit in chokeberry juice concentrate, combined with and extending the dehydration time from 1 hour to 3 hours, increased the force and work compression of the samples. Some textural properties of our osmotically dehydrated strawberries were consistent with those previously reported, while others were inconsistent. These differences may be due to various samples, preparation conditions, and the type of mechanical test used. Piotrowski et al. [30] demonstrated that the compressive strength of whole strawberries dried by vacuum, convection, and freeze-drying was a consequence of the structure of materials. The porosity and total surface area of air cells in the freeze-drying fruit structure influence on the acoustic and mechanical properties [10].

Alonzo-Macias et al. [51] considered the total number of force peaks recorded during the puncture test of dried strawberries to be one of the main and important parameters identifying crunchiness. Our previous research shows that, among acoustic parameters, the number of AE events strongly correlated with sensory assessment. Zdunek et al. [18] tested fresh apples and also indicated that the number of AE events was related to sensory characteristics. In our opinion, the crunchiness of dried fruits should be considered as mechanical and acoustic properties, as these properties are important for perception, because consumers perceive mechanical characteristics and hear sounds. Hence, we determined the crunchiness index as the product of the generated number of AE events and the work compression. Earlier the crunchiness index was determined for crackers, which well described the change in texture was described well, depending on the water content [16]. Strawberries osmo-dehydrated in a sucrose solution before freeze-drying had a significantly higher crunchiness index than those dehydrated in chokeberry juice concentrate (Table 2).

Dacremont [52] demonstrated that food crispness/crunchiness can be distinguished based on the frequency of instrumentally recorded sounds. Although no significant correlation was observed between the low-frequency range and sensory crispness for puffed-grain food, it was found that acoustic features extracted from the natural low-frequency range showed a significantly better correlation with sensory crispness [53]. In connection with the above the frequencies of generated sound in the human audible range were also analyzed, and the results are presented in acoustograms (Figure 1).

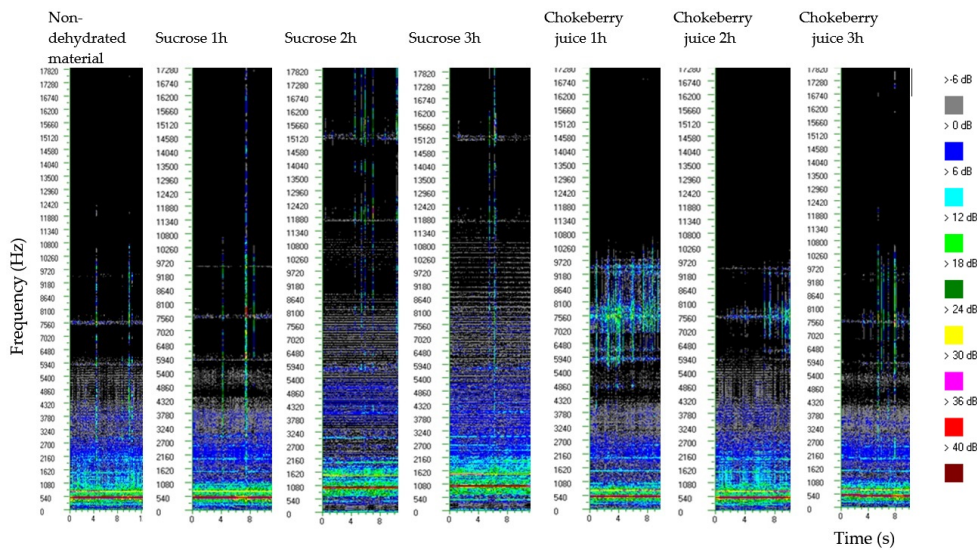


Figure 1. Acoustic activity of strawberries dried by freeze-drying, not dehydrated and osmotically dehydrated in sucrose and chokeberry juice concentrate for 1 h, 2 h and 3 h.

A acoustograms showing the frequency characteristic of materials, the X-axis represents the actual measurement time of the sound generated by the compressed sample, the Y-axis represents the sound frequency, and the colors indicate the sound intensity [13]. The freeze-dried strawberry types tested differed in terms of acoustic activity non-dehydrated and osmo-dehydrated in chokeberry juice concentrate, did not generate high-frequency sounds above 10 kHz. However, osmo-dehydration in sucrose solution resulted in a material that generated low- and high-frequency sounds (Figure 1). A detection of dominant sound frequency bands in the frequency characteristics indicates the complexity and diversity of the cracking mechanism of freeze-dried strawberries. The generated sounds originated from the breakdown and microdislocation of the structure. Cracking of pore walls caused displacements and generated low-frequency sounds. However, structural densification, destruction of substructures, and dislocations of macromolecules in the samples could be responsible for the generation of high-frequency sound, exceeding 10 kHz.

3.3. Bioactive Substans Results

The osmotic dehydration and the type of osmotic substance used before freeze-drying influenced the content of bioactive compounds in the final products (Table 3). Non-dehydrated strawberries had the lowest phenolic content (1975 mg GAE/100 g d.m) (Table 3). In contrast, the highest content of the determined compounds, ranging from 4664.58 mg GAE/100 g d.m. in samples dehydrated for 1 hour to 5000.80 mg GAE/100 g d.m. after 3 hours of dehydration, was found in strawberries dehydrated in chokeberry juice concentrate. The obtained results confirm the validity of using chokeberry juice concentrate as an osmotic medium, as well as the effect of dehydration time on total phenolic content. Removing water during dehydration increases the concentration of compounds in the food matrix, and conducting the process at low temperatures protects labile phenolic compounds [54].

The anthocyanins are characterized by low thermal stability, which leads to their degradation during drying. Therefore, the content of these compounds in dried fruits such as blueberries, raspberries, and cherries is lower compared to fresh fruits [54–56]. However, the freeze-drying process takes place at low temperature and under vacuum conditions, therefore it does not lead to significant thermal and oxidative degradation of anthocyanin [54]. Furthermore, the obtained results confirmed the beneficial effect of osmotic dehydration on anthocyanin content, regardless of the osmotic solution used (Table 3). Strawberries dehydrated in sucrose before freeze-drying had the highest anthocyanin content. In turn, the lower pH of the chokeberry juice concentrate likely influenced the anthocyanin content, which ranged from approximately 74 to approximately 200 mg c3g/100g. It should be noted that thermal processes, including various drying methods, are the main factor influencing anthocyanin content [10].

Overall, osmotic treatment positively affected the flavonoid content in freeze-dried strawberries (Table 3). The lowest flavonoid content was determined in control samples and in samples osmotically dehydrated in sucrose solution for 1 hour. In the remaining dehydrated samples, the determined flavonoid content was at a similar level, ranging from approximately 15 to 17 mg quercetin/g d.m. A decrease in the content of the determined compounds was observed after 3 h of dehydration, which could be caused by mass exchange and transfer of water-soluble flavonoids to the dehydrating solution.

In summary, studies show that osmotic dehydration prior to strawberry freeze-drying increases the content of bioactive compounds, and the content of phenolic compounds depends on the dehydration solution used [45,46]. The osmotic dehydration process in chokeberry juice concentrate increased the polyphenol content and antioxidant potential of carrots and zucchini [55]. A significant factor influencing the content of phenolic compounds is the drying technique used, including temperature and process time [34,55–59]. Samoticha et al. [55] found that various drying methods led to the loss of polyphenols and anthocyanins, with the lowest anthocyanin losses, approximately 43%, occurring after freeze-drying of chokeberry fruits. In turn, Mendelowa et al. [56] showed that drying of chokeberry fruits with hot air and infrared led to a loss of polyphenols content compared to fresh material, by 45% and 41%, respectively; the content of anthocyanin pigments also decreased by 67% and 55%. Similarly, Akcicek et al. [54] confirmed the degradation of phenolic compounds during drying of blueberries by various methods, except freeze-drying, which caused an increase in the polyphenol content from 1423.31 mg GAE/100 g d.m. in fresh fruits to 1662.83 mg GAE/100 g d.m. in freeze-dried products. However, it should be remembered that processing is not the only factor influencing the content of bioactive compounds. According to Bojarska et al. [60], of the 11 varieties tested, fresh strawberries of the "Honeoya" variety were characterized by a high content of total polyphenols (5870 mg/100 g dry weight), but the lowest oxidative capacity of 44.8%. The varying content of bioactive compounds in fruit varieties results from differences in genotypes and environmental conditions [54,60].

Table 3. The total phenolic, anthocyanin and flavonoid content in freeze-dried strawberries. (Each value is presented as mean ± SD).

Code of samples	Total phenolic (mg acid GAE / 100g d.m.)	Anthocyanin (mg c3g/100g)	Flavonoid (mg quercetin / g d.m.)
Non-dehydrated material	1975.17 ± 35.32 ^a	130.23 ± 14.18 ^b	10.03 ± 0.78 ^a
Sucrose 1h	2581.30 ± 22.58 ^{ab}	139.00 ± 1 97 ^b	8.13 ± 0.18 ^a
Sucrose 2h	2669.40 ± 581.94 ^{ab}	173.32 ± 5.71 ^{cd}	16.24 ± 1.20 ^c
Sucrose 3h	3076.14 ± 271.14 ^b	208.95 ± 2.47 ^e	15.91 ± 0.18 ^c
Chokeberry juice 1h	4661.58 ± 32.14 ^c	74.13 ± 5.47 ^a	16.29 ± 0.39 ^c
Chokeberry juice 2h	4878.52 ± 287.06 ^c	152.06 ± 7.09 ^{bc}	17.03 ± 0.94 ^c

Chokeberry juice 3h	5000.80 ± 72.01 ^c	200.34 ± 3.35 ^{de}	15.14 ± 0.00 ^c
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The values with the same letter in the column did not differ significantly at $\alpha < 0.05$.

3.4. A Comprehensive Description of the Texture of Osmotically Dehydrated and Freeze-Dried Strawberries

To visually present the correlations between acoustic, mechanical, and bioactive properties, as well as porosity, water activity, and dry matter content, and the freeze-dried strawberry samples, principal component analysis (PCA) was performed. The first two principal components (PCs) explained 83.3% of the variance in all measured parameters, PC1 and PC2 explain 55.7% and 27.6%, respectively. PC1 was formed by textural parameters (acoustic and mechanical), crunchiness index, water activity and total polyphenol content. PC2 consisted of porosity, dry matter, and bioactive compounds (anthocyanins, flavonoids). On the right side of the diagram (green loop in Figure 2), samples dehydrated in sucrose solution for 2 and 3 hours had low hardness, strong acoustic emission and crunchiness, and lower total polyphenol content, but higher anthocyanin content and oxidative capacity. The osmotically dehydrated strawberry samples in chokeberry juice concentrate were located next to each other on the left side of the PCA diagram (blue loop in Figure 2), indicating they were similar. They were characterized by the highest hardness, low crunchiness, and weak acoustic emission, but had the highest total polyphenol content. Non-dehydrated strawberries and those dehydrated in sucrose solution for 1 hour formed a separate group in the PCA diagram (red loop in Figure 2), they had optimal texture, but the lowest content of bioactive compounds. A table of correlations between the analyzed parameters is provided in the supplements (Table S2). Significant negative correlations were found between water activity (a_w) and force (-0.909), work compression (-0.807), as well as positive correlations between a_w and energy of acoustic event (0.878); a_w and amplitude of the sound (0.932), and negative a_w and total polyphenol content (-0.917). Amplitude of the sound also correlated negatively with total polyphenol content (-0.779). Dry matter correlated with porosity (-0.756) and anthocyanins (0.902). No correlation was observed between the crunchiness index and the content of bioactive compounds. These relationships confirm that low water activity contributes to a greater loss of bioactive compounds and sounds amplifies. These results are consistent with those available in the literature. Low humidity during the drying banana leads to the degradation of bioactive compounds [61].

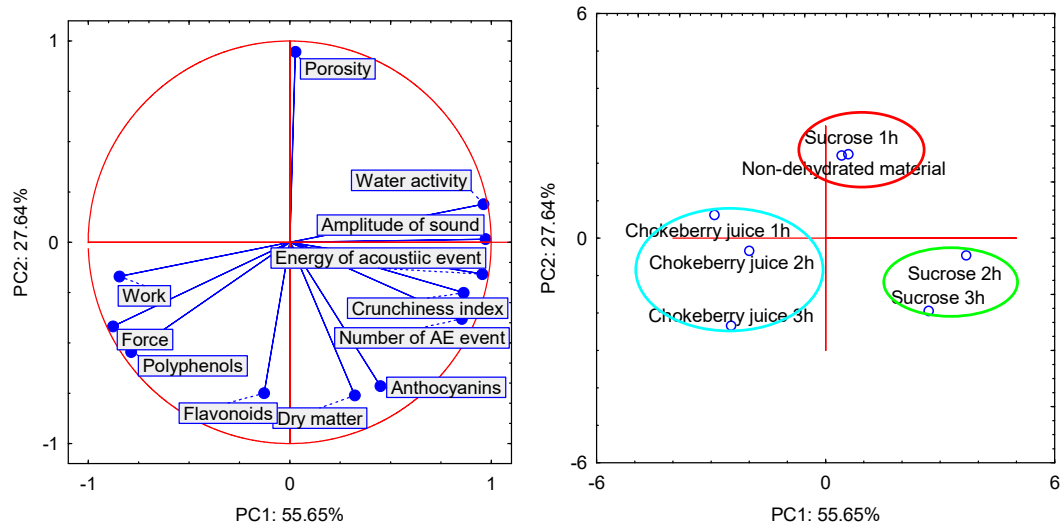


Figure 2. PCA diagram.

4. Conclusions

In this study, we instrumentally examined the crunchiness and content of polyphenols, anthocyanins, and flavonoids in freeze-dried strawberries that had been osmotically dehydrated in a solution of sucrose and chokeberry juice concentrate. The texture of the final products varied. Osmotic dehydration in sucrose solution preceding freeze-drying improved texture; the crunchiness index was the highest, and the samples were the loudest (highest energy, number of EA events, and sound amplitude), but the content of total phenolics was lower compared to fruits dehydrated in chokeberry juice concentrate. Preceding freeze-drying with osmotic dehydration in chokeberry juice concentrate produced snacks with low crunchiness, a hard texture, and a high content of bioactive compounds. The study suggests that instrumental assessment of crunchiness and the proposed crunchiness index can be used to objectively assess the texture of dried fruits. Freeze-dried strawberries, non-dehydrated and osmotically dehydrated in chokeberry juice concentrate, generated sounds at frequencies between 0.5 and 10 kHz. However, fruits osmotically dehydrated in sucrose solution generated sounds across the entire frequency range (0.5-16 kHz). The results indicate the influence of the osmotic pre-dehydration conditions on a different cracking mechanism. Therefore, research focusing on a detailed analysis of the structure and general chemical composition is necessary.

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