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Impact of Protein- and Polysaccharide-Based Edible Coatings and Citric Acid as a Natural Antioxidant on the Quality Parameters, and Image Analysis, of Freeze-Dried *Jerusalem artichoke* (*Helianthus tuberosus*)

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Abstract

The aim of this study was to evaluate the effects of protein-based (zein) and polysaccharide-based (carboxymethylcellulose, CMC) edible coatings and citric acid (CA) applied prior to freeze-drying on the quality parameters of *Jerusalem artichoke* (*Helianthus tuberosus* L.) slices from 'Albik' and 'Rubik' cultivars. Freeze-drying increased inulin extraction efficiency (57–61 g 100 g^{-1} vs. 44–45 g 100 g^{-1} in fresh samples). In the 'Albik' cv., CMC and CA coatings significantly minimized L-ascorbic acid losses, with a 10–20% reduction vs. control. For the same cultivar, enhanced polyphenol retention was observed (up to 13%) when CA coating was applied, while the use of zein reduced vitamin C content in both cultivars. Sensory analysis (PCA, 92.4% variance) revealed that CMC improved appearance, texture, and overall acceptability, while zein imparted an off-taste, odor, and fragility. Image texture analysis showed elevated parameters (e.g., HMean) post freeze-drying, with CA inducing the greatest structural changes and zein yielding samples most similar to raw material. Machine learning classification (quadratic/linear SVM, 10-fold CV) achieved 91.5% ('Albik') and 81.9% ('Rubik') accuracy, perfectly distinguishing raw slices (100%). These findings demonstrate that CMC and CA coatings optimize bioactive retention, sensory quality, and textural differentiation in freeze-dried *Jerusalem artichoke*, supporting their application in functional food production.

Keywords: *Jerusalem artichoke*; edible coatings; freeze-drying; inulin content; sensory analysis

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Academic Editors: Oana Bianca Oprea and Ignat Tolstorebrov

Received: 31 December 2025
Revised: 8 February 2026
Accepted: 12 February 2026
Published: 15 February 2026

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1. Introduction

Jerusalem artichoke (*Helianthus tuberosus* L.), also known as tuberous sunflower, is a species belonging to the family *Asteraceae*. Native to North America, it is now cultivated worldwide, including in Poland, where it has been gaining increasing agronomic and nutritional importance in recent years [1]. This plant is characterized by a high tolerance to

adverse environmental conditions, ease of cultivation, and high fertility, which makes it an attractive raw material for agriculture, the food industry and the pharmaceutical industry [1,2].

Jerusalem artichoke tubers are a rich source of nutrients, including carbohydrates, fiber, and vitamins, as well as compounds with documented antioxidant properties (polyphenols) and numerous micro- and macroelements essential for human health [3–8]. The main polysaccharide found in *Jerusalem artichoke* is inulin, a polyfructose with a low glycemic index, documented prebiotic activity, and the ability to modulate the body's carbohydrate metabolism [9–14]. The biological activity of inulin derived from *Jerusalem artichoke* depends on its molecular structure and degree of polymerization, as described in the literature reviews [3,15]. Many studies confirm the supportive effect of inulin on the human immune system through its beneficial effect on the gut microbiota [16,17]. Therefore, *Jerusalem artichoke* tubers are a valuable ingredient in functional and dietary foods [9,18–22].

In recent years, there has been a rapid development in technologies based on edible coatings of biological origin. Edible coatings reduce water loss, oxidation processes, and the growth of microorganisms, as well as slow down aging processes, which results in extended shelf life and better preservation of the nutritional and sensory value of plant products [23–29].

Among protein coatings, zein is particularly noteworthy due to its hydrophobic nature and beneficial barrier properties against oxygen and water vapor in low-humidity conditions. Its mechanical and barrier properties can be further improved through composite modifications, such as the addition of bioactive compounds, lipids, and nanofillers, making zein a promising material for stabilizing many plant products [30,31]. Carboxymethylcellulose (CMC), a commonly used polysaccharide coating material, is characterized by high water solubility, high moisture binding capacity, the formation of flexible layers, and good adhesion to plant tissues. After application to raw plant materials, CMC forms a thin polymer coating that acts as a semipermeable barrier, limiting water loss and regulating gas exchange during processing and storage. These polymer coatings reduce the intensity of oxidation reactions, preserve color and aroma, and improve the structural integrity of plant tissues by reducing surface damage and excessive fragility [32,33]. Consequently, the use of CMC-based coatings before drying or during post-harvest storage contributes to improving the physicochemical stability and overall quality of plant-based products [34]. The use of citric acid lowers the pH of the raw material surface, which effectively reduces the activity of oxidative enzymes (e.g., polyphenol oxidase) responsible for enzymatic browning and oxidation of phenolic compounds [35]. The antioxidant effect of citric acid, resulting, among other things, from its ability to chelate metal ions and lower pH, promotes the stabilization of color, aroma, and sensory quality of plant raw materials during subsequent stages of processing, and also reduces the degradation of vitamins and other bioactive compounds [23].

Freeze-drying (sublimation drying) involves freezing crushed plant material and then subjecting it to sublimation under vacuum conditions, which causes it to change from a solid to a gaseous state. This process preserves the natural cellular structure and integrity of bioactive compounds through improved rehydration properties and minimal changes in the volume of raw materials [36]. Freeze-dried products can be used both as raw materials and as ready-made functional snacks. They are characterized by low water content, high microbiological stability, and good nutrient retention [6,16]. This method is particularly suitable for raw materials rich in thermolabile compounds, such as inulin, polyphenols, and vitamin C, which are abundant in *Jerusalem artichoke* [5]. However, despite its numerous advantages, freeze-drying also has certain limitations. The most commonly described problems include oxidation of oxygen sensitive components, color degradation, excessive porosity of the structure leading to increased hygroscopicity, and susceptibility of the product to mechanical damage and deterioration in quality during storage [19].

In this context, there is growing interest in the possibility of modifying the properties of raw materials prior to freeze-drying by applying edible protective coatings. Protein and polysaccharide coatings applied before freeze-drying have a significant impact on the drying process and the quality of the final product [37,38]. These effects result from the ability of the coating layer to regulate moisture and gas exchange during the freezing and sublimation process. These coatings act as protective barriers, limiting moisture loss and oxygen migration, which improves the structural integrity of the plant matrix and reduces the risk of collapse or cracking of the structure during freeze-drying. At the same time, the literature reports indicate that, after freeze-drying, edible coatings may partially lose their barrier properties due to the formation of a porous product structure, which emphasizes the importance of proper formulation and application methods [38].

The aim of the study was to evaluate the impact of edible coatings based on proteins (zein) and polysaccharides (carboxymethylcellulose (CMC)) and citric acid (CA), applied before freeze-drying, on the quality parameters (including the retention of bioactive compounds, sensory quality) and structural characteristics assessed by image analysis of freeze-dried slices of *Jerusalem artichoke* varieties 'Albik' and 'Rubik' (*Helianthus tuberosus* L.) compared with control samples without coatings.

Presumably, this conducted research will have a beneficial effect on the commercialization of freeze-dried *Jerusalem artichoke* slices as a functional raw material for the food and pharmaceutical industries, by obtaining a product with the appropriate texture, high retention of inulin (with prebiotic properties), phenolic compounds (with antioxidant properties), and stable color.

2. Materials and Methods

2.1. Plant Material

The plant material used in this study consisted of *Jerusalem artichoke* tubers of the 'Albik' and 'Rubik' cultivars, originating from the collection of the Department of Plant Protect Against Pests of the National Institute of Horticultural Research, Skierniewice. Before further processing, the tubers were washed, peeled, and cut into 3 mm thick slices using a slicer (Robot Coupe CL 50, Montceau-les-Mines, France).

2.2. Experimental Organization

Three coating treatments were applied, consisting of *Jerusalem artichoke* slices immersed in zein, carboxymethylcellulose (CMC), and citric acid (CA) solutions (1.5% w/v) for 15 min. After immersion, samples were blotted on paper towels to remove excess surface moisture and left at room temperature for 1 h. The slices were then frozen at -28 ± 1 °C for 24 h in a Whirlpool freezer (Benton Harbor, MI, USA) and then freeze-dried.

A control treatment was also included, consisting of artichoke slices without edible coatings, subjected only to freeze-drying.

2.2.1. Methodology for Preparing an Edible Coating Solution

Zein Coating

For the protein-based coating, 73.2 g of zein (Pol-Aura, Olsztyn, Poland) was dissolved in 1.583 mL of an aqueous ethanol solution (60% v/v) at 50 °C using an electrically heated stirrer (Thermomix 31-1, Vorwerk Deutschland Stiftung & Co. KG, Berlin, Germany) and mixed at 400 rpm for 15 min.

CMC Coating

A medium-viscosity sodium carboxymethyl cellulose (CMC) salt (SIGMA-Aldrich, Poznań, Poland) was used to prepare the polysaccharide-based coating solution. The

formulation consisted of 30 g of CMC, 15 g of anhydrous glycerin as a plasticizer, 7.6 g of Tween 20 as an emulsifier, and 2 L of distilled water. CMC was dissolved in water at 50 °C using an electrically heated stirrer (Thermomix 31-1, Vorwerk Deutschland Stiftung & Co. KG, Berlin, Germany) at 400 rpm, and then heated to 80 °C and mixed at 400 rpm for an additional 30 min. Afterwards, anhydrous glycerin and Tween 20 were added, and the mixture was stirred for 2 min. Following this step, the solution was homogenized using a Heidolph Diax 600 homogenizer (Heidolph Instruments, Schwabach, Germany) at 13,500 rpm for 2 min.

Citric Acid (CA) Solution

A 1.5% (w/v) citric acid (CA) solution was prepared by dissolving 1.5 g of citric acid in 1 L of distilled water, followed by stirring until complete dissolution. The prepared slices were immersed in the CA solution for 15 min to ensure uniform surface coverage. After treatment, the slices were removed from the solution and gently blotted with paper towels to eliminate excess surface moisture. The samples were then left to equilibrate at room temperature for 1 h prior to further processing (e.g., freeze-drying).

2.2.2. Freeze-Drying Conditions for *Jerusalem artichoke* Slices

The frozen samples were dried in a laboratory freeze-dryer (LABCONCO, Kansas City, MO, USA). The slices were arranged on trays so that they did not touch one another. The temperature in the drying chamber was initially equal to 20 °C. Freeze-drying started once the condenser reached −55 °C. The process continued for 48 h, followed by a final 1 h stage performed at a shelf temperature of 25 °C. The terminal pressure in the chamber was 0.01 kPa. All freeze-drying procedures were carried out in two technological repetitions for independent biological batches. Once drying was completed, the *Jerusalem artichoke* slices were subjected to image analysis, sensory analysis, and then analysis of chemical properties. Each of the treatment combinations was prepared for both cultivars. The freeze-dried *Jerusalem artichoke* slices intended for chemical analysis were crushed in dry carbon dioxide to obtain a homogeneous powder and stored at −20 °C for no longer than 1 week until analysis.

2.3. Chemical Composition Analysis

2.3.1. Sugar Content

The analysis of sugars (sucrose, glucose, fructose) was determined by high-performance liquid chromatography Agilent 1200 HPLC system (Agilent Technologies, Waldbronn, Germany) equipped with a differential refractometric detector (RID) using an Aminex HPX-87C (300 mm × 7.5 mm) column (Bio-Rad Laboratories, Hercules, CA, USA) with a pre-column. The isocratic flow was 0.6 mL min^{-1}, column temperature was 80 °C and the mobile phase was 0.1 mM edetate calcium disodium (Ca-EDTA). *Jerusalem artichoke* was suspended in redistilled water, homogenized, and purified with a Waters SepPak PLUS C18 filter (Waters, Milford, MA, USA). The sugars were quantified by a calibration curve for sucrose, glucose and fructose (Merck Life Science, Poznan, Poland) and the results were expressed in 100 g^{-1} DW.

2.3.2. Inulin Content

The analysis of inulin was determined by the same analytical method as for sugars. The process for inulin extraction was as described by Brkljača et al. [39] with minor modifications. Briefly, powdered *Jerusalem artichoke* was suspended in redistilled water at 80 °C for 15 min (1 g in 15 mL). The supernatant was isolated after centrifugation (10,000 rpm, 6 min, 20 °C). Inulin was quantified by a calibration curve on the basis of chicory inulin (Merck Life Science, Poznan, Poland) and the results were expressed in g 100 g^{-1} DM.

2.3.3. Total Polyphenol Content

The total polyphenol content (TPC) was measured by a Folin–Ciocalteu method using gallic acid as a reference standard [40]. The powdered samples of *Jerusalem artichoke* were homogenized with 70% ethanol, and the homogenate was centrifuged for 10 min at 20,000 rpm. Then 0.4 mL of analyzed *Jerusalem artichoke* extracts was mixed with 1.6 mL of sodium carbonate solution (7.5%). Then, 2 mL of Folin–Ciocalteu phenol reagent was added and the mixture was shaken. The samples were incubated in the dark for 1 h at room temperature. The absorbance of the reaction mixture was measured using a UviLine 9400 spectrophotometer (SI Analytics, Hofheim am Taunus, Germany) at a wavelength of 750 nm and compared with the blank sample. The calibration curve was prepared using gallic acid and the total polyphenolic content was expressed as mg of gallic acid equivalent (GAE) (Sigma-Aldrich Chemie GmbH, Steinheim, Germany) in mg 100 g^{-1} DM of the analyzed slices of *Jerusalem artichoke* sample.

2.3.4. L-Ascorbic Acid Content

The L-ascorbic content of slices of *Jerusalem artichoke* was determined by high-performance liquid chromatography (Agilent Technologies, Waldbronn, Germany), equipped with a DAD detector. Separation was performed using a Supelco LC-18 column (250 mm × 4.6 mm; 5 µm) (Sigma-Aldrich Chemie GmbH, Darmstadt, Germany) with a pre-column. The determination was carried out at 30 °C using 1% phosphate-buffered solution KH_2PO_4, pH 2.5 (potassium phosphate, monobasic, JT Baker Chemicals, Phillipsburg, NJ, USA) as a mobile phase, and isocratic flow was 0.8 mL min^{-1}.

The detection was carried out at a wavelength of 244 nm. Sample preparation: the powdered samples of *Jerusalem artichoke* were dissolved in 6% HPO_3 (meta-phosphoric acid, Sigma-Aldrich Chemie GmbH, Steinheim, Germany), homogenized, and filtered. The content of L-ascorbic acid was quantified using a calibration curve for the L-ascorbic acid standard (Sigma-Aldrich Chemie GmbH, Steinheim, Germany). The results were expressed as mg·100 g^{-1} DM.

2.4. Sensory Analysis

Quantitative description analysis (QDA), i.e., sensory profiling, was used for sensory evaluation, in accordance with the procedure set out in EN ISO 13299:2016 [41]. This method assumes that sensory quality consists of a number of characteristics (distinguishing features) that can be assessed individually in quantitative terms. The assessment was carried out in the sensory laboratory of the National Institute of Horticultural Research, which meets the requirements specified in the PN ISO 8589:2010 [42], in individual assessment boxes. The assessment was carried out by a team of 10 expert assessors with many years of experience in sensory assessments of vegetables, fruits, and spices, who regularly participate in studies conducted in accordance with the PN ISO 8586-1:1986 [43]. A list of aroma, color, texture, and taste quality attributes, developed during a dedicated panel session, was used and comprised eight quality descriptors. Eight slices of *Jerusalem artichoke* from each combination were placed in coded 250 mL plastic boxes, covered with lids, and submitted for evaluation. The samples were coded with random numbers and presented in a random order. In order to neutralize the taste, water at room temperature was served between samples. The intensity of each attribute was assessed on a monitor on a continuous graphic scale corresponding to 0–10 conventional units, with edge markings. For aroma and taste attributes, the markings ranged from imperceptible to very intense; color and texture attributes depended on the characteristic; overall quality assessment ranged from poor quality to very good. The assessment was carried out in two repetitions (sessions) using

ANALSENS ver. 6 to prepare the tests, record individual assessments, and statistically process the results.

2.5. Image Analysis

Both fresh and freeze-dried (without coating, with edible coating using zein, CMC, or citric acid) *Jerusalem artichoke* slices were scanned using a flatbed scanner (Epson Perfection, Epson, Suwa, Nagano, Japan) for extracting texture features. The imaging process was performed on a black background. Image acquisition was carried out in 50 repetitions for each combination. The exemplary images are presented in Figure 1. The resulting images were stored in BMP file format, enabling subsequent processing with MaZda software version 4.7 (Łódź University of Technology, Institute of Electronics, Łódź, Poland) [44–46]. The images were first converted to multiple color channels: R, G, B, L, a, b, X, Y, and Z. The black background facilitated segmenting the images based on brightness levels and isolating each *Jerusalem artichoke* slice as a distinct region of interest (ROI). For each ROI, 181 texture features were extracted across the nine color channels, employing methods such as the run length matrix, histogram analysis, co-occurrence matrix, gradient maps, Haar wavelet transforms, and autoregressive modeling, resulting in a total of 1.629 texture descriptors.

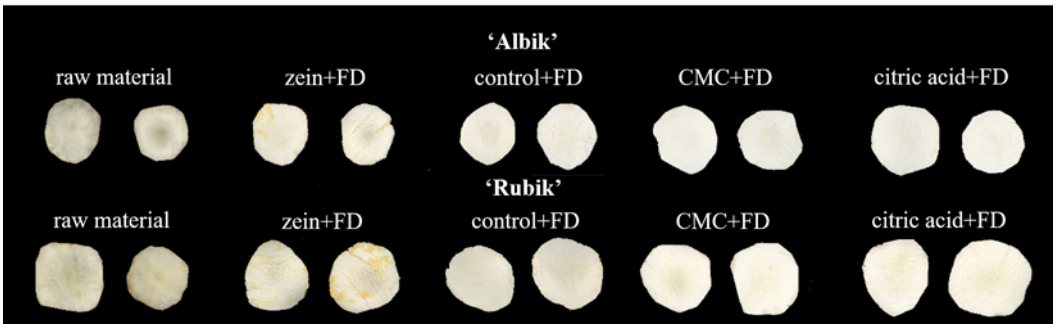

Figure 1. Exemplary images of *Jerusalem artichoke* slices of 'Albik' and 'Rubik' cultivars; control—without edible coating; zein, CMC, CA—treatment with edible coating solutions before freeze-drying (FD).

2.6. Statistical Analysis

2.6.1. Chemical Analysis

Statistical analysis of L-ascorbic acid and polyphenols was performed using STATISTICA v.13 software (StatSoft, Tulsa, OK, USA; Dell Inc., Round Rock, TX, USA) as a one-way analysis of variance for fresh tubers and *Jerusalem artichoke* slices treated with edible coatings, separately for each cultivar. Significant differences between means were determined at $p = 0.05$ based on Tukey's HSD test. Results are presented as means of two replicates.

2.6.2. Image Texture

Pairwise mean comparisons of image textures of *Jerusalem artichoke* samples were performed using STATISTICA 13.3 (TIBCO Software Inc., Palo Alto, CA, USA). The variance's homogeneity and distribution's normality were checked, and Tukey's test at a significance level of $p < 0.05$ was used for the analysis. Tukey's test was applied separately for textures RHMean, GHMean, BHMean, LHMean, aHMean, XHMean, YHMean, and ZHMean to compare differences between analyzed *Jerusalem artichoke* samples.

2.6.3. *Jerusalem artichoke* Slice Classification

Machine learning algorithms were applied to assess the impact of freeze-drying and edible coating on the image characteristics of *Jerusalem artichoke* slices. Separate

predictive models were created for 'Albik' and 'Rubik' cultivars. The models were built based on selected image textures. From an initial set of 1.629 texture attributes, feature selection was performed using the best-first algorithm. This stage was carried out to decrease the input data. Only selected image textures with the highest discriminative power were used in the subsequent stage to build discriminative models. Model development was carried out in MATLAB R2024a (MathWorks, Inc., Natick, MA, USA), employing a 10-fold cross-validation approach. Various classification algorithms were tested, including support vector machine (SVM), neural networks, naive Bayes, K-nearest neighbor (KNN), discriminant analysis, ensemble methods, and decision trees. The models achieving the highest classification accuracy were chosen for final analysis. Model evaluation included metrics, such as overall accuracy and confusion matrices.

2.6.4. Sensory Quality

Principal component analysis (PCA) was used for multidimensional analysis and visualization of the relationships between the sensory attributes evaluated and the samples tested. This method allows for a reduction in the number of variables while retaining as much of the total data variability as possible, which is particularly important in profile analysis (QDA) involving multiple sensory descriptors evaluated on the same scale. The analysis was performed on a correlation matrix, which allowed for the standardization of variables and a comparable assessment of the contribution of individual sensory attributes, regardless of their variance. PCA enabled the identification of the main directions of data variability and the assessment of the relationship between sensory attributes and the tested samples. The results were presented in the form of two-dimensional graphs (biplots), facilitating the interpretation of sensory profiles. The results of sensory evaluations were analyzed, taking into account the following factors of variability: evaluation sessions, evaluators, and tested samples. The calculations were performed using the STA-TISTICA 13 statistical package (Dell Inc., Round Rock, TX, USA).

3. Results

3.1. Results of Chemical Analysis

3.1.1. Sugar Analysis

The fresh *Jerusalem artichoke* tubers of the 'Albik' and 'Rubik' cultivars, as well as freeze-dried slices (control and edible-coated) were analyzed for sugar and inulin content (Table 1), by means of HPLC-RID. The results showed interesting differences in the sugar and inulin content of freeze-dried slices, which were found to be statistically significant. The predominant sugar found was inulin, as widely reported in the literature. Inulin was found to be between 58% and 61% by dry weight in the freeze-dried samples, between 86% and 88% of total sugars. Levels were found to be slightly lower in the fresh samples—44% and 45% dry weight basis for 'Rubik' and 'Albik' cultivars, respectively. For the 'Rubik' cultivar, the differences in inulin concentrations across all samples were not found to be statistically significant. In this, we can surmise that the edible coatings and citric acid treatment had no impact on inulin content compared with the control. For the 'Albik' cultivar, the differences in inulin values were determined to be statistically significant only between the fresh sample and the freeze-dried samples. 'Albik' treated with citric acid was found to have the highest concentration of inulin (60.9 g 100 g^{-1}), while 'Albik' coated with zein was found to have the lowest content of inulin (57.5 g 100 g^{-1}), 94% of that of the citric acid treated group. Thus, the edible coatings in both 'Albik' and 'Rubik' cultivars had no impact on the inulin content of the freeze-dried samples.

Table 1. Sugar and inulin content of fresh and freeze-dried slices of *Jerusalem artichoke* (dry weight basis).

Sample	Sucrose g 100 g^{-1}	Glucose g 100 g^{-1}	Fructose g 100 g^{-1}	Total Sugars * g 100 g^{-1}	Inulin g 100 g^{-1}
'Albik' raw material	6.48 c ± 1.8	0.48 a ± 0.1	0.26 c ± 0.2	7.22 b ± 2.1	45.4 b ± 3.8
'Albik' control + FD	7.44 bc ± 0.6	-	0.60 b ± 0.1	8.04 ab ± 0.7	58.8 a ± 0.5
'Albik' CA + FD	7.75 abc ± 1.3	-	1.07 a ± 0.1	8.82 ab ± 1.4	60.9 a ± 0.3
'Albik' CMC + FD	9.33 a ± 1.3	-	0.69 b ± 0.1	10.02 a ± 1.2	59.3 a ± 0.6
'Albik' zein + FD	8.30 ab ± 1.0	-	0.95 a ± 0.1	9.26 a ± 0.8	57.5 a ± 1.4
'Rubik' raw material	8.71 b ± 1.5	0.50 a ± 0.3	0.71 d ± 0.1	9.91 b ± 1.2	44.4 a ± 0.3
'Rubik' control + FD	7.44 c ± 0.7	-	0.99 c ± 0.1	8.43 c ± 0.6	57.3 a ± 7.8
'Rubik' CA + FD	9.49 a ± 0.6	-	0.72 d ± 0.1	10.21 b ± 0.6	55.4 a ± 1.3
'Rubik' CMC + FD	9.76 a ± 0.8	-	1.20 a ± 0.1	10.96 a ± 0.6	55.6 a ± 0.2
'Rubik' zein + FD	8.97 b ± 0.9	-	1.04 b ± 0.1	10.01 b ± 0.8	51.0 a ± 0.8

a, b, c, d—the same letters in the columns mean no statistical differences between results for each cultivar (Tukey's test, ANOVA). *—sum of sucrose, glucose and fructose.

Among the mono- and disaccharides, sucrose was the predominant sugar in both cultivars, accounting for between 88 and 93% of total sugars and 11 and 13% of total sugars by dry weight basis. For both cultivars, the differences in sucrose content were found to be statistically significant. The 'Albik' freeze-dried samples and the fresh one were found to have the lowest concentration of sucrose (64.8 g kg^{-1} dry mass basis), while the CMC-coated sample was found to contain 93.3 g kg^{-1} by dry mass. Glucose was found in very small amounts (<0.1% of fresh weight), only in fresh, in good agreement with the literature [47].

Fructose was found in all samples and differences between the cultivar groups were found to be statistically significant. In all cases, amounts of fructose were found in small amounts (0.04–0.12% of total sugars), with a total percentage by dry weight basis of 0.3–1.2%. For the 'Albik' cultivar, the fresh material was found to have the lowest concentration of fructose (2.61 g kg^{-1}), while 'Albik' treated with citric acid (10.73 g kg^{-1}) and coated with zein (9.55 g kg^{-1}) were found to have the highest concentrations. The fresh tubers were also found to have the lowest fructose concentration in the 'Rubik' cultivar (7.09 g kg^{-1}), while 'Rubik' coated in CMC was found to have the highest concentration (12.00 g kg^{-1}).

3.1.2. Results L-Ascorbic Acid

There are no data in the literature regarding the effect of edible coatings on the retention of chemical components in freeze-dried *Jerusalem artichoke* slices. Our research showed that the *Jerusalem artichoke* cultivars studied differed significantly in the content of individual components depending on the coating used.

The results of L-ascorbic acid content in *Jerusalem artichoke* cultivars 'Albik' and 'Rubik' slices treated with edible coatings are shown in Figure 2. The average L-ascorbic acid content in the tested *Jerusalem artichoke* cultivars was: 11.7 mg·100 g^{-1} DM ('Albik'); 13.8 mg·100 g^{-1} DM ('Rubik'), respectively. After freeze-drying, a significant decrease in L-ascorbic acid content was observed in *Jerusalem artichoke* slices by approximately ~10% for the 'Albik' cultivar and ~20% for the 'Rubik' cultivar, compared with fresh material. In our study, treating *Jerusalem artichoke* slices with edible coatings (CMC) and CA had a positive effect on inhibiting the loss of L-ascorbic acid content after the freeze-drying process compared with slices in the control sample. The higher L-ascorbic acid content was observed in both cultivars, although, in the case of the 'Rubik' cultivar, these changes were not statistically significant. In these studies, the use of a protein coating (zein) on freeze-dried *Jerusalem artichoke* slices degraded the L-ascorbic acid content (Figure 2).

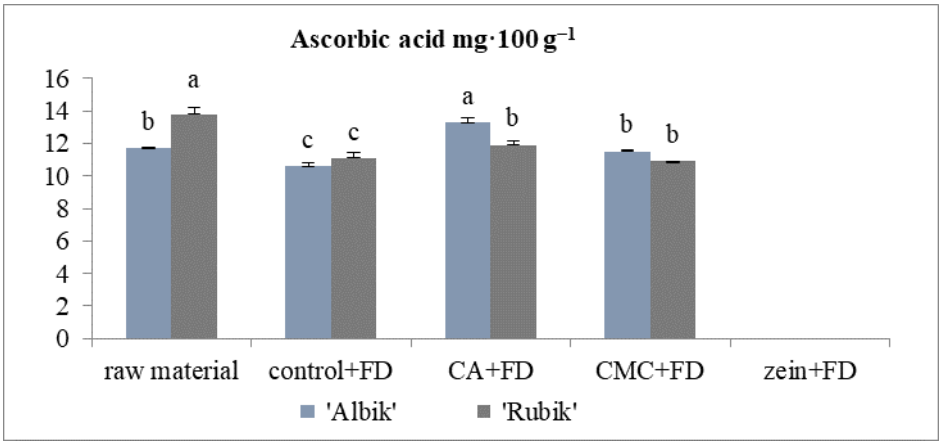

Figure 2. The content of L-ascorbic acid in *Jerusalem artichoke* slices depending on the type of coating used. Note: means in the column for each cultivar marked with the same letter are not different according to Tukey's HSD test (p = 0.05).

3.1.3. Results of Phenolic Compounds

In our study, the content of phenolic compounds in fresh tubers of the tested cultivars 'Albik' and 'Rubik' was, respectively, 1003 mg·100 g^{-1} DM; 1177 mg·100 g^{-1} DM (Figure 3). After the freeze-drying process, a higher content of these compounds was observed by approximately ~13% ('Albik') and ~3.3% ('Rubik'). Treatment of *Jerusalem artichoke* slices of the 'Albik' cultivar with edible coatings (CMC, zein and CA) before freeze-drying resulted in an increase in the content of polyphenolic compounds. In the case of the 'Albik' cultivar, a significant increase in the content of these compounds was observed, in relation to fresh and freeze-dried *Jerusalem artichoke* slices. In the case of the 'Rubik' cultivar, a significant increase in the content of these compounds was observed only after treating *Jerusalem artichoke* slices with CA. The content of phenolic compounds in *Jerusalem artichoke* with CMC and zein coating was significantly lower than in the fresh material and the freeze-dried control sample.

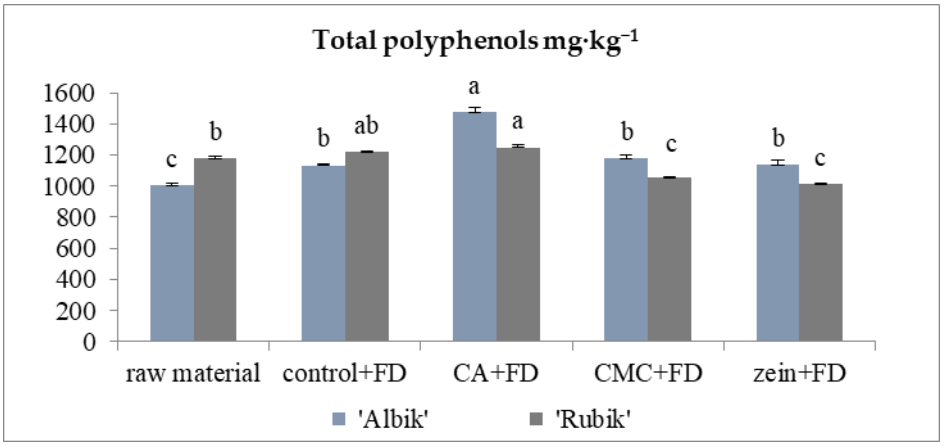

Figure 3. The total content of polyphenols in *Jerusalem artichoke* slices depending on the type of coating used. Note: means in the column for each cultivar marked with the same letter are not different according to Tukey's HSD test (p = 0.05).

3.1.4. Results of Sensory Analysis

To assess sensory differences among the samples, a principal component analysis (PCA) was performed. PCA is a dimensionality reduction method that transforms the original variables (sensory attributes) into new, uncorrelated variable principal components. This analysis enables the identification of key sensory attributes differentiating the

samples, as well as the grouping of samples based on similarities and differences in their sensory profiles.

The sensory space was defined by the first two principal components, which together explained 92.4% of the total variance, indicating that the projection retained nearly all relevant information. The diagram shows a scree plot obtained as a result of principal component analysis (PCA), which illustrates the contribution of individual components, explaining the total variability of the sensory data. The horizontal axis (X) shows successive principal components, while the vertical axis (Y) shows the percentage of variance explained by each of them (Figure 4).

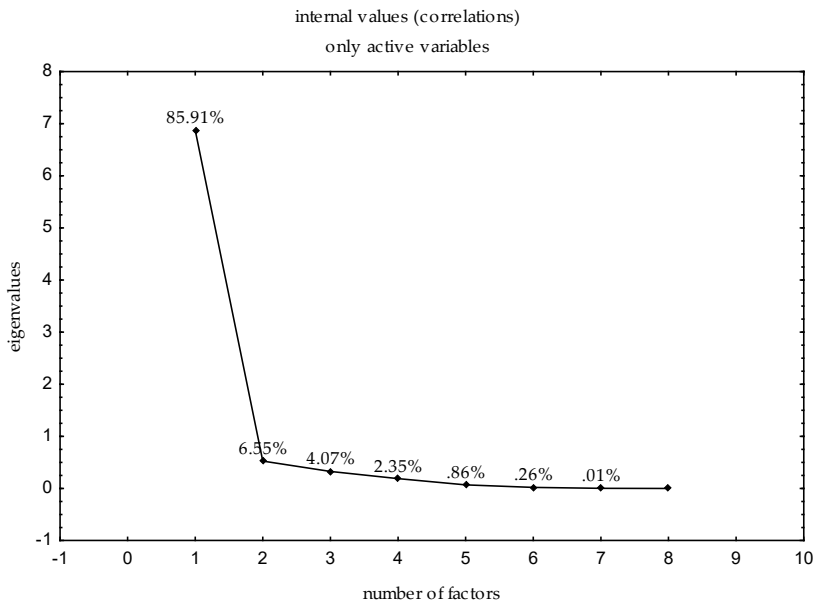

Figure 4. Screen diagram formed based on results of sensory evaluation of freeze-dried *Jerusalem artichoke*.

The analysis of the correlation between variables (quality descriptors) and factors confirms that the two-dimensional PCA space (PC1 and PC2) is sufficient to describe the sensory data. The first component is clearly dominant and accounts for most of the data variability. Very high positive loads are observed for characteristics such as external appearance (0.96), flesh texture (0.90), sweet taste (0.85), and overall quality (0.94). At the same time, high negative correlations occur for off-odor (−0.92), color (−0.98), fragility (−0.93), and off-taste (−0.93). This means that PC1 describes the overall sensory quality of the product, contrasting desirable characteristics (good appearance, proper texture, sweet taste, high overall quality) with undesirable characteristics (off-odor, off-taste, fragility, unacceptable color). This component can be interpreted as the main indicator of sensory acceptability. The second component shows a much smaller but still significant contribution explaining the variability. The highest positive loadings are for flesh texture (0.32), off-odor (0.31), and off-taste (0.29), while negative values are observed for sweet taste (−0.34) and fragility (−0.24). PC2 can be interpreted as a dimension that differentiates samples in terms of the balance between desirable sweetness and the presence of undesirable taste and odor sensations and textural characteristics. The remaining components contribute little information and are not critical for the interpretation of sensory analysis results (Table 2).

Table 2. Correlation coefficients between sensory quality descriptors and principal components (factors) obtained by principal component analysis (PCA) of freeze-dried *Jerusalem artichoke*.

	Correlation of Quality Descriptors with Variable Factors						
quality descriptors	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7
external appearance	0.96	0.25	0.02	0.02	−0.11	−0.10	−0.01
off-odor	−0.92	0.31	0.18	−0.08	0.15	−0.02	−0.01
color	−0.98	−0.05	0.11	−0.14	0.00	−0.03	0.01
flesh texture	0.90	0.32	0.24	−0.18	−0.03	0.03	0.01
fragility	−0.93	−0.24	0.02	−0.25	−0.12	−0.01	−0.01
sweet taste	0.85	−0.34	0.41	0.04	0.00	0.02	−0.01
off-taste	−0.93	0.29	0.07	0.13	−0.14	0.07	−0.01
overall quality	0.94	0.06	−0.23	−0.22	0.01	0.05	−0.01

Analysis of the PCA biplot for the sensory quality of *Jerusalem artichoke* samples showed that the application of edible coatings and citric acid had a greater influence on sample differentiation (distribution across all four quadrants) than cultivar differences. Overall quality was positively associated with texture-related descriptors, namely external appearance and flesh texture (vectors oriented in the same direction along PC1). Samples ('Albik' CMC + FD; 'Rubik' CMC + FD; 'Albik' control + FD and 'Rubik' control + FD) located near the vectors representing overall quality, sweet taste, flesh texture, and external appearance were characterized by the highest sensory quality. Freeze-dried *Jerusalem artichoke* samples coated with the polysaccharide CMC (both cultivars) exhibited a highly attractive appearance, delicate and crisp texture, and received the highest scores for overall quality compared with the other treatments. Descriptors located opposite the overall quality vector in the PCA space corresponded to color, fragility, and off-taste and off-odor. *Jerusalem artichoke* samples of both 'Albik' and 'Rubik' coated with zein solution clustered near these descriptors and showed the lowest sensory quality. Panelists reported an intense off-taste and off-odor in these samples, resulting from the zein coating, which retained a characteristic corn-like smell and taste. Freeze-dried zein-coated samples of both cultivars were a notably darker color and exhibited a very hard, cardboard like texture, markedly different from the CMC-treated and control samples (Figure 5).

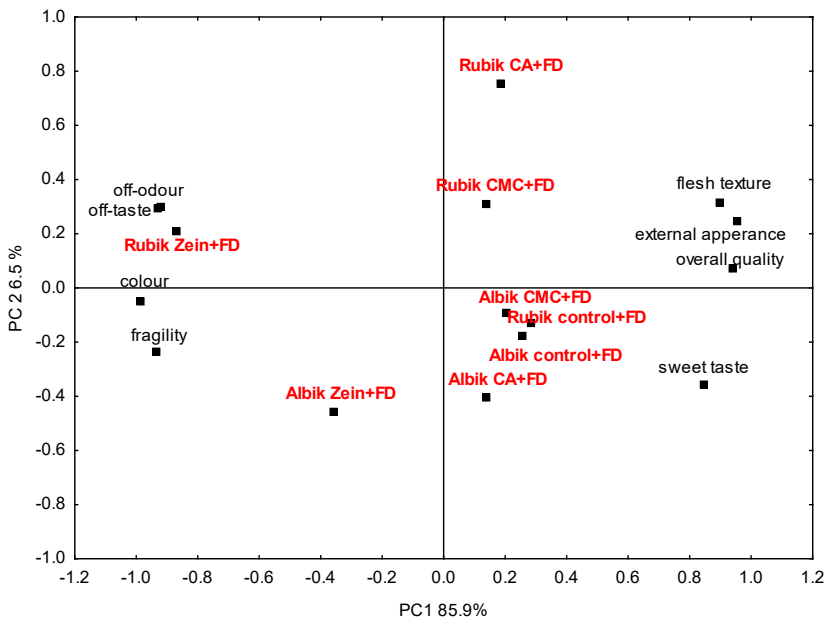

Figure 5. PCA biplot of similarities and differences in sensory profiles of freeze-dried *Jerusalem artichoke*.

3.1.5. Results of Image Texture Analysis

The means of selected image texture parameter HMean for different color channels extracted from different samples of the 'Albik' *Jerusalem artichoke*, including raw material and freeze-dried (FD) samples treated with various edible coatings, such as zein, CMC, and citric acid solutions, were compared (Table 3). The raw material was characterized by the statistically significantly lowest values of HMean texture across all analyzed channels. All texture parameter values were higher for freeze-dried samples compared with the raw sample and were different depending on edible coating, indicating changes in texture features due to the drying and pretreatment process. The freeze-dried sample with citric acid generally exhibited the highest texture values, suggesting that this treatment has the most significant effect on image texture.

Table 3. The mean values of selected image texture features of different *Jerusalem artichoke* slice samples of 'Albik' cultivar.

'Albik' Slices	Image Textures							
	RHMean	GHMean	BHMean	LHMean	aHMean	XHMean	YHMean	ZHMean
raw material	196.35 ± 8.93 a	191.99 ± 8.13 a	170.31 ± 7.67 a	204.88 ± 6.62 a	125.35 ± 0.17 a	126.69 ± 11.87 a	135.47 ± 12.50 a	108.91 ± 10.39 a
zein + FD	224.91 ± 11.70 b	216.84 ± 13.77 b	188.53 ± 26.20 b	224.60 ± 11.45 b	125.78 ± 0.38 b	169.55 ± 19.94 b	180.33 ± 20.70 b	141.37 ± 31.57 b
control + FD	229.81 ± 8.03 bc	225.67 ± 7.37 c	209.79 ± 7.22 c	231.64 ± 6.09 c	126.01 ± 0.14 c	183.24 ± 11.79 c	194.42 ± 12.32 b	169.44 ± 11.35 c
CMC + FD	232.67 ± 10.28 c	229.86 ± 8.93 c	217.11 ± 7.74 cd	234.85 ± 7.35 c	126.04 ± 0.17 c	191.14 ± 13.90 cd	202.69 ± 14.51 bd	182.02 ± 12.22 d
CA + FD	234.33 ± 9.48 c	231.25 ± 9.95 c	219.11 ± 11.48 d	235.99 ± 7.93 c	126.18 ± 0.14 d	193.98 ± 16.04 d	205.46 ± 16.90 d	185.64 ± 17.96 d

control—without edible coating; zein, CMC, CA—treatment with edible coating solutions before freeze-drying; FD—freeze-drying; a, b, c, d—the same letters in the columns mean no statistical differences between samples.

Table 4 summarizes the image texture means of the *Jerusalem artichoke* samples belonging to the cultivar 'Rubik'. Generally, freeze-dried samples, without and with edible coating, had higher values of texture parameters compared with the raw material. In most cases, differences were statistically significant. Only for the BHMean texture, 'Rubik' slices of raw material were in the same homogeneous group as slices treated with zein solution and freeze-dried. This suggests that freeze-drying, regardless of treatment, significantly affects the texture characteristics of *Jerusalem artichoke* slices. However, treatment with zein solution and freeze-drying resulted in obtaining the most similar samples to the raw material.

Table 4. The mean values of selected image textures of *Jerusalem artichoke* slice samples of 'Rubik' cultivar.

'Rubik' Slices	Image Textures							
	RHMean	GHMean	BHMean	LHMean	aHMean	XHMean	YHMean	ZHMean
raw material	188.40 ± 8.78 a	183.06 ± 7.80 a	157.24 ± 7.07 a	197.70 ± 6.37 a	125.14 ± 0.42 a	113.34 ± 10.70 a	121.54 ± 11.39 a	92.12 ± 8.77 a
zein + FD	210.83 ± 16.14 b	201.14 ± 17.48 b	165.38 ± 28.95 a	212.22 ± 14.47 b	125.47 ± 0.70 b	143.61 ± 25.15 b	153.25 ± 26.08 b	110.30 ± 32.96 b
control + FD	226.78 ± 14.02 c	221.23 ± 12.60 c	201.74 ± 11.14 b	228.20 ± 10.29 c	125.95 ± 0.27 c	175.74 ± 20.55 c	186.61 ± 21.50 c	156.52 ± 17.40 c
CMC + FD	237.71 ± 12.04 d	233.63 ± 10.88 d	217.87 ± 9.46 c	237.79 ± 8.86 d	126.00 ± 0.15 c	198.25 ± 18.01 d	210.31 ± 18.92 d	184.13 ± 15.55 d
CA + FD	239.02 ± 8.48 d	234.79 ± 8.15 d	218.88 ± 8.29 c	238.71 ± 6.65 d	126.03 ± 0.12 c	200.33 ± 13.50 d	212.47 ± 14.19 d	185.93 ± 13.21 d

a, b, c, d—the same letters in the columns mean no statistical differences between samples.

Image textures were used to develop models to classify *Jerusalem artichoke* slices belonging to raw material, the freeze-dried sample without coating, and freeze-dried samples treated previously with zein, CMC (carboxymethylcellulose), or citric acid edible coating solutions. For the 'Albik' cultivar, the most successful model was built using the quadratic SVM algorithm. It classified slice samples with an average accuracy reaching 91.5% (Figure 6). Slices of raw material were completely different in the selected image textures used to build a model and were distinguished from other samples with 100.0% accuracy. The lowest accuracy of 81.4% was obtained for the sample prepared using edible coating—CMC combined with freeze-drying.

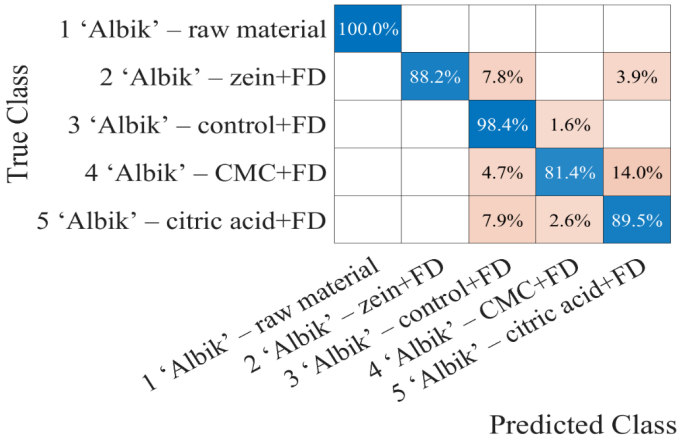

Figure 6. Confusion matrix of the classification of *Jerusalem artichoke* slice samples of 'Albik' cultivar based on selected image textures using quadratic SVM algorithm; control—without edible coating; zein, CMC, citric acid—treatment with edible coating solutions before freeze-drying; FD—freeze-drying; blue mark—correctly classified cases, orange mark—incorrectly classified cases.

In the case of 'Rubik' *Jerusalem artichoke*, the average accuracy of the classification of slice samples was up to 81.9% for a model built using the linear SVM algorithm (Figure 7). *Jerusalem artichoke* raw slices were distinguished from all freeze-dried samples, without and with edible coating, with an accuracy of 100%, whereas samples treated with citric acid and CMC and then freeze-dried were classified with very low accuracies, 55.4% and 64.7%, respectively. These samples were also the most similar to each other, which was reflected in the highest percentages of misclassified cases.

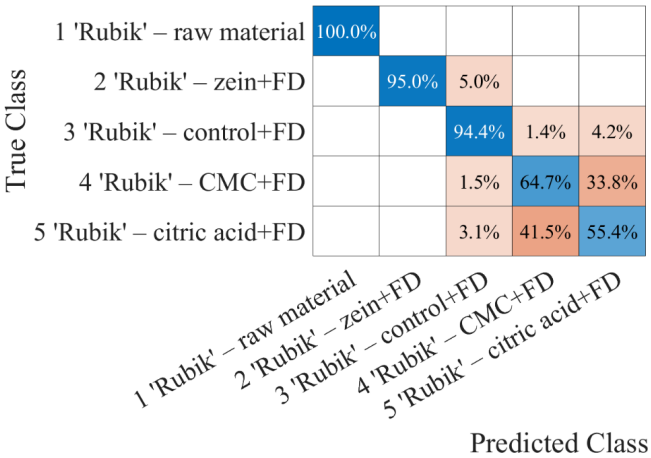

Figure 7. Confusion matrix of the classification of 'Rubik' *Jerusalem artichoke* slices using a model built based on selected image textures using linear SVM algorithm; control—without edible coating; zein, CMC, citric acid—treatment with edible coating solutions before freeze-drying; FD—freeze-drying; blue mark—correctly classified cases, orange mark—incorrectly classified cases.

4. Discussion

The obtained results revealed an interesting difference in inulin content between the fresh samples and the freeze-dried samples. Fresh samples in both 'Rubik' and 'Albik' cultivars were lower in inulin than the freeze-dried samples (23% lower for both cultivars before freeze-drying compared with the corresponding freeze-dried control). The results show that the extraction of inulin after freeze-drying treatment is higher than that of fresh material. Our values (Table 1) of 44–45 g 100 g^{-1} DM and 58–61% g 100 g^{-1} DM inulin content for fresh and freeze-drying samples, respectively, are both higher than those reported by others in the literature [48,49]. However, in both cases, the samples had different drying protocols to ours (oven dried at 80 °C for 24 h [48] and 60 °C for 12 h [49]). It has been shown that inulin is thermally unstable via glycosidic hydrolysis [50], and it is supposed that the process of lyophilization eliminates the thermal glycosidic hydrolysis of inulin, resulting in higher levels of inulin compared with the thermally dried samples. Brkljača et al. 2014 [39] reported an inulin content between 8 and 13% by fresh weight basis (12 accessions) using the direct detection of inulin by HPLC, utilizing light scattering detection, and Matias et al. 2011 [47] reported an inulin content of 14–17% by fresh weight basis (cultivar undisclosed), utilizing LC-MS. These analytical methodologies are very close to ours, and the analyses were performed on fresh tubers that were not exposed to a drying step. Our values are in very good agreement with those of Brkljača et al. [39] and Matias et al. [47]. Given the good agreement in inulin content between our analysis and that of Brkljača et al. [39] and Matias et al. [47], these correlations may add weight to the hypothesis that drying by lyophilization may cause less degradation of inulin than at elevated temperatures. It should be emphasized that the application of coatings had no significant effect on the inulin content in freeze-dried *Jerusalem artichoke* slices.

Compared to Danilchenko et al. [51], who found a sucrose content at 5% (cultivar Swojecki), and Matias et al. [47], who found a sucrose content at 1% (cultivar undisclosed) by fresh mass basis, our results of 1.6–2.1% are comparable.

Leroy et al. [52] found fructose at a 0.1% dry weight basis, comparable to our values of 0.3–1.2%, while Matias et al. [47] found fructose at 0.9% fresh weight basis, comparable to our values of 0.1–0.3%.

The content of antioxidant compounds, such as vitamin C and polyphenols, in plant materials is desirable because products containing them can be considered health-promoting. The content of vitamin C and phenolic compounds in *Jerusalem artichoke* tubers varies and depends on the variety, stage of maturity, agrotechnical and climatic conditions, and storage [48,53–55]. The obtained results, especially those regarding the increase in polyphenolic compound content in *Jerusalem artichoke* slices after freeze-drying, are not easy to explain and therefore require further research. Changes in the content of chemical components may be related to complex physicochemical and biological reactions that occur during the freeze-drying process Maillard reaction products may have formed during freeze-drying, potentially leading to an overestimated phenolic compound content using the Folin–Ciocalteu method. These changes may also be caused by changes in the volume of the freeze-dried material and a decrease due to the loss of osmotic pressure caused by the evaporation of internal moisture, which was also observed in our study. Furthermore, tissue shrinkage also occurs in plant material, which is associated with the loss of vacuolar pressure and cell wall damage, which can lead to changes in the texture of plant products and changes in nutrient content [56,57].

The obtained results showed that the coatings used had a significant effect on the ascorbic acid (Figure 2) and total polyphenol content (Figure 3) of freeze-dried *Jerusalem artichoke* slices. The treatment of *Jerusalem artichoke* slices with citric acid (CA) had the greatest effect on the preservation of L-ascorbic acid and total polyphenols. Applying a

citric acid coating immediately after peeling or cutting can stabilize L-ascorbic acid content, may contribute to its stabilization in the plant material, and protect against degradation, as observed in our studies. Although citric acid is not an antioxidant, its presence in the environment helps preserve other antioxidants, including ascorbic acid. Citric acid also inhibits enzymes that degrade vitamin C and may reduce browning reactions associated with vitamin C loss [58]. It also has chelating properties that limit the oxidation process leading to vitamin C degradation [59]. Furthermore, citric acid lowers environmental pH, cell membrane permeability, and disrupts transport, anion accumulation, or lowers internal cellular pH [60]. Research by Marghmaleki et al. 2021 [59] showed that fruits coated with citric acid retain higher levels of vitamin C for longer periods compared with uncoated controls, extending shelf life. In turn, a CMC coating helps preserve vitamin C by creating a barrier that reduces exposure to oxygen, slowing the oxidation and degradation of ascorbic acid. It may also limit the weight loss of plant material and inhibit enzymes that contribute to the loss of this nutrient. When combined with other compounds, such as citric acid, calcium chloride, or ascorbic acid, its ability to preserve vitamin C is further enhanced [61,62], as observed in studies by Saba and Sogvar [61]. This is probably why, in our study, the better preservation of L-ascorbic acid was observed after the application of a citric acid and CMC coating. The higher content of total polyphenols after the application of citric acid coating to plant material may be related to their better availability from fruits and vegetables by supporting their solubility and preventing their degradation [63], which was also observed in our studies. Furthermore, citric acid may aid in their preservation by inhibiting the action of certain enzymes, such as polyphenol oxidase, thereby increasing their total content. It also acts as an antioxidant synergist and protects polyphenols from oxidation. Citric acid can stabilize the polyphenol content in plant material, even when combined with other methods or coatings, and may lead to increased antioxidant activity in the final product [63–65].

According to the literature, principal component analysis is a commonly used technique to reduce the dimensions of complex sensory data and facilitate the interpretation of the relationship between organoleptic characteristics and the technologies used [66].

The results of the PCA analysis (Figure 5) confirm that the use of edible coatings (CMC and zein) and CA prior to freeze-drying had a significant effect on the sensory profile of *Jerusalem artichoke* samples. Polysaccharide and protein coatings are currently an important area of scientific research as an effective strategy for reducing transpiration, slowing down oxidation processes and stabilizing the surface of plant raw materials during the drying process. The latest scientific publications show that properly designed biopolymer coatings can improve bioactive ingredients retention (e.g., vitamins and phenolic compounds), reduce discoloration and have a positive effect on the sensory parameters of products subjected to freeze-drying [67,68]. In the case of *Jerusalem artichoke* (*Helianthus tuberosus* L.), coatings based on carboxymethylcellulose (CMC) and corn protein (zein) have a functionally justified application. CMC, as a hydrophilic biopolymer with good film-forming properties, forms semipermeable films that directly limit the process of transpiration from the surface of plant tissue, facilitate the control of gas exchange, which translates into a reduction in weight loss, and prevents color changes during the freeze-drying process [69]. Studies conducted on apple slices and other plant materials have shown that CMC-based coatings can modify the drying kinetics and color parameters of the product [70]. Some studies reported only a slight effect on selected sensory characteristics, such as texture, while other studies indicated a reduction in color changes, especially in the case of prior osmotic treatment [69,70]. In summary, CMC forms hydrophilic coatings, which may affect the rehydration process and the final texture of the product after freeze-drying. However, the scale of these effects is strongly dependent on the thickness of the coating, its homogeneity

and the specific interactions between the biopolymer and the structural properties of the raw material [70]. Zein, on the other hand, thanks to its relative hydrophobicity and good ability to form continuous films, reduces the penetration of oxygen and water vapor, helping to protect the structure of plant tissue and reducing the intensity of oxidative processes after drying [71]. In this study, *Jerusalem artichokes* coated with zein were characterized by a high intensity of flavor and aroma that was not very acceptable to the sensory panel. These results are consistent with reports in the literature [72], emphasizing that certain components of edible coatings can affect the aroma and flavor profile not only of plant products but also of meat, leading to modifications in aroma intensity or the appearance of unacceptable foreign odors. The mechanism of these changes may be related, among other things, to the volatile properties of the coating components, their ability to bind or release aromatic compounds, and possible chemical reactions occurring on the surface of the raw material during drying [72].

5. Conclusions

This study provides a comprehensive evaluation of the effects of edible coatings such as zein, carboxymethylcellulose (CMC), and citric acid (CA) on the quality of freeze-dried *Jerusalem artichoke* (*Helianthus tuberosus* L.) slices from 'Albik' and 'Rubik' cultivars. Freeze-drying enhanced inulin extraction efficiency compared with fresh samples, exceeding values reported for thermal drying and highlighting its advantage as a dehydration method. CMC and CA coatings effectively minimized L-ascorbic acid losses, improved polyphenol retention, and enhanced sensory attributes such as texture, appearance, and overall acceptability, demonstrating strong potential for practical application in functional food production. Zein preserved structural features similar to raw material but negatively affected sensory quality, limiting its practical use. Image texture analysis revealed elevated HMean values in coated samples, with CA inducing the most pronounced structural changes. Machine learning classification (SVM) accurately distinguished raw and treated samples (91.5% for 'Albik', 81.9% for 'Rubik'), highlighting the discriminative impact of coatings. These findings indicate that polysaccharide- and acid-based solutions, when combined with freeze-drying, optimize bioactive compound preservation, sensory quality, and product differentiation, supporting their application in high-value, health-promoting food products.

Author Contributions: Conceptualization, A.W.; methodology, A.W., J.S.-G., E.R., N.J.D., J.A.Z. and M.M.-F.; software, A.W., J.S.-G., E.R., N.J.D., J.A.Z. and M.M.-F.; validation, A.W., J.S.-G., E.R., N.J.D. and M.M.-F.; formal analysis, A.W., J.S.-G., E.R. and N.J.D.; investigation, A.W., J.S.-G., E.R., N.J.D., J.A.Z. and M.M.-F.; resources, M.S., A.S.H. and A.S.; data curation, A.W., J.S.-G., E.R. and N.J.D.; writing—original draft preparation, A.W., J.S.-G., E.R., N.J.D. and J.A.Z.; writing—review and editing, A.W., J.S.-G., E.R., N.J.D., J.A.Z. and M.M.-F.; visualization, A.W., J.S.-G., E.R., N.J.D., J.A.Z. and M.M.-F.; supervision, A.W. and M.M.-F.; project administration, A.W.; funding acquisition, M.M.-F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Polish Ministry of Science and Higher Education, grant number 5.9.22 "The use of edible coatings and nanoemulsions to maintain quality and microbiological purity and extend the shelf life of whole and cut fruit and vegetables".

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data supporting the results presented in this publication are available upon request from the corresponding author.

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

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