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Effects of Polysaccharide-Based Edible Coatings on the Quality of Fresh-Cut Beetroot (*Beta vulgaris* L.) During Cold Storage

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Abstract: This study evaluated the effects of selected polysaccharide edible coatings (apple pectin and sodium alginate) on the quality characteristics of fresh-cut beetroot. The changes in texture (hardness), optical parameters such as colour and Hue angle, polyphenols, flavonoids, and red and yellow colourants during 4 weeks of refrigerated storage, as well as changes in microstructure, were examined. Self-standing coatings have also been prepared and characterised by continuous structure without pores, cracks, and high lightness. The obtained results for hardness showed reduced values during storage. Colour parameters (L^*, a^*, and b^*) and Hue angle remained mostly consistent, indicating the preservation of the desired colour, though slight changes were noted during storage. Lightness (parameter L^*) increased over time, suggesting changes in the beetroot surface. However, these changes were less pronounced in samples covered with coatings. The use of polysaccharide coatings and storage time positively impacted flavonoids in fresh-cut beetroots, except after 28 days when the lowest values for both parameters were observed. It can also be noted that the polyphenol content in coated samples decreased at a slower rate. Moreover, there was a significant decrease in the content of red and yellow colourants for both control and coated samples. However, greater changes were noted for samples treated with coatings. Scanning electron microscopy used at 0 and 28 days showed lower pores in beetroot tissue as a result of applied polysaccharide coatings, and refrigerated storage negatively affected the minimally processed beetroot surface. Nevertheless, minimally processed beetroots obtained with the treatment of polysaccharide coatings as mild technology showed modifications to the quality characteristics, which can find practical use in reducing the waste of fresh-cut vegetables during storage.

Keywords: edible coatings; beetroot; quality; colour; bioactive compounds

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1. Introduction

Consumers have an increasing demand for food that is both easy to prepare and readily available. This type of product includes minimally processed food, which undergoes technological processing to retain as much of its natural characteristics and biological value as possible [1]. For vegetables and fruits, these procedures involve sorting, washing, peeling, cutting, and removing inedible parts [2]. Physical, physicochemical, and biological methods preserve minimally processed food as non-thermal food processing methods [3,4]. One method to preserve products is food coating technology [5].

Edible coatings are made of edible of material as a thin layer used to create a protective barrier around a product, limiting biological and physicochemical changes [6]. Removing the coating from the product's surface is impossible without destroying it, which is advantageous since it can be washed easily. The coating process is most effectively applied to vegetables and fruits, which undergo many changes that reduce their quality during storage. Edible coatings can find application to whole or portioned raw materials [7,8]. These coatings play an essential role in limiting the biochemical and chemical changes that reduce the quality of vegetables during storage [9]. Coated products are characterised by an attractive appearance, gloss, and good quality, which are important to consumers. Additionally, they can play an antimicrobial role or have antioxidant properties by incorporating appropriate functional substances [10,11]. The coating materials used include polysaccharides (chitosan, starch, cellulose, and derivatives), proteins (milk proteins, soy proteins, gelatin, collagen), and fats (waxes, edible oils) [12,13]. The coating substance is usually an aqueous solution obtained using these materials. Single- or multi-component coatings are used [14]. Food products are typically coated using immersion, followed by surface drying. Polysaccharides or proteins provide mostly film-forming capacity, whereas lipids or fats, as hydrophobic substances, limit moisture migration [15,16].

Root vegetables, including beetroot, are often consumed as ingredients in soups, salads or other vegetable dishes. However, the disruption of plant tissue causes many quality changes that negatively affect quality [17]. Beetroot (*Beta vulgaris* L.) is one of Poland's most well-known and most commonly grown root vegetables. It is available on the market all year round [18,19]. In Europe, Poland is a leader in its cultivation. Beetroot is widely used in industry, e.g., for producing juices, red borscht, frozen food, canned food or beetroot [18,20]. It is also used as a natural food colouring instead of artificial colours [21]. Betalains, nitrogenous-coloured compounds, are found in cell juices and are highly soluble in water. They are strong antioxidants and have anti-inflammatory effects [19]. Beetroot is red due to the content of betacyanins, which belong to betalain pigments. Betacyanins (red) and betaxanthins (yellow) stand out among them. Among the betacyanins, betanin stands out. It constitutes 75%–95% of beetroot red pigments. The betaxanthins that occur in the most significant amounts in beetroot are vulgaxanthin I and vulgaxanthin II, in the amount of approx. 95% [18]. Beetroot is an important source of nutrients and has health-promoting properties [22]. Like any vegetable, it is composed of water in the largest amount (87.6%/100 g of edible parts). It contains vitamins A, B, and C, beta-carotene, folic and oxalic acids, fibre, and many microelements such as magnesium, potassium, iron, and zinc [21,23].

The edible coating can affect the preservation of the quality of vegetables by limiting negative quality changes, including colour, weight loss, and hardness [7]. Pectins are made of *D*-galacturonic acid polymers at various methyl esterification levels. Pectin films and coatings are obtained by evaporating water from pectin gel. Since it is easily soluble, it is used to package foods with low water content, such as instant coffee or food powders [24,25]. Therefore, pectins can be used in different applications for food, including minimally processed fruits or vegetables [26] or as a film-forming agent in sustainable packaging films containing fruit pomace [24]. Sucheta et al. [27] noted that quality attribute analysis showed a positive effect of edible coatings incorporated with beetroot powder on tomatoes. Alginate coatings are characterised by durability, transparency and gloss. Compared to whey, gelatin or starch, layers obtained based on sodium alginate have the lowest water vapour and oxygen permeability and good tensile strength. Sodium alginate films are soluble in acids, bases and water [28–30]. In addition, alginate coatings may be used for different food products, including application under a high-oxygen modified atmosphere [31].

Generally, edible coatings maintain quality and positively affect the shelf life of fresh or minimally processed products such as fruits and vegetables. Research data have shown that using a simple and environmentally friendly technology of protective edible coatings can retard fruit ripening and delay changes in quality attributes. Moreover, edible coatings could reduce food waste, a sustainable approach to mild processing in food preservation. Thus, this study aimed to evaluate the effect of apple pectin and sodium alginate-based edible coatings on selected quality characteristics of fresh-cut beetroots, including hardness, optical parameters, microstructure, the content of polyphenols, flavonoids, and pigments (red and yellow), during refrigerated storage.

2. Materials and Methods

2.1. Materials

The research material was the Red ball variety (8–10 cm in diameter) beetroot from the supplier F.H. Nowalijka (Piotrków Trybunalski, Poland), bought in the local supermarket 1–2 days after delivery. Low-methoxy apple pectin AMID AF 020–E with a degree of esterification (DE) of 27%–32% and a degree of amidation (DA) of 18%–23% was provided by Sovit J. Buczkowski Sp.J. (Warsaw, Poland), and sodium alginate was obtained from Merck Life Science Sp.z.o.o. (Warsaw, Poland). Glycerol (Avantor Performance Materials Poland S.A., Gliwice, Poland) was used as a plasticiser.

2.2. Coating Solutions

To prepare coating solutions, 1% (*w*/*w*) of apple pectin or sodium alginate was dissolved in distilled water during magnetic stirring (250 rpm). The mixtures were heated to 60 °C for 15 min; then, glycerol was added at 50% relative to the biopolymers (0.5 g). The coating solutions were cooled down and applied for beetroot coating. The density of the coating solutions was controlled and measured with a LabTH densimeter (Mettler Toledo, Columbus, OH, USA). The results were 1.0019 ± 0.0002 and 1.0045 ± 0.0001 g/cm^3 for apple pectin and sodium alginate, respectively.

2.3. Coating Preparation

The coating mixtures were poured onto Petri dishes in controlled volumes to provide a unified thickness of 60 ± 5 μm. The solutions were dried to constant moisture content at 50 °C for 6 h using the laboratory dryer model. The films were peeled off from the Petri dishes and stored before testing at 25 °C and a relative humidity of 50% in the climate chamber.

2.3.1. Coating Thickness

The thickness was evaluated using an electronic gauge, Pro Gage (Thwing-Albert Instrument Company, West Berlin, NJ, USA), with an accuracy of 1 μm.

2.3.2. UV Light Transmittance

The UV-VIS transmittance of the coatings was measured in the range of wavelengths 200–800 nm with an EVOLUTION 220 UV-Visible spectrometer (Thermo Electron Corporation, Waltham, MA, USA) using a magnetic film adapter and Thermo INSIGHT software (version 2.5).

2.3.3. Colour

The colour of the coatings was measured using the CIE *L*a*b** system with a CR-400 colorimeter (Konica Minolta, Tokyo, Japan). The results were recorded by SpectraMagic NK software (version 2.0). Ten repetitions were made for each type of film. The total colour dif-

ference (ΔE) as a distinction between the white background (L^* = 91.84, a^* = −0.59, b^* = 1.31) and the films was determined using the equation from the study of Sobral et al. [32]:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a*)^2 + (\Delta b*)^2} \quad (1)$$

2.3.4. Opacity

The opacity was determined with an EVOLUTION 220 UV-Visible spectrometer (Thermo Electron Corporation, Waltham, MA, USA) using a magnetic film adapter. Measurements were made at a visible light wavelength of 600 nm, repeated six times for each film type, and recorded by Thermo INSIGHT software.

2.3.5. Mechanical Properties

The tensile strength (TS) (as the mechanical resistance) and the elasticity (as elongation at break) (E) of the coatings were determined using a TA-Xt2i texture analyser (Stable Microsystems, Haslemere, UK) based on the standard ASTM D882 method (ASTM, 2002). Films of 100 × 25 mm were stretched at a rate of 1 mm/s until breakage, with an initial separation distance of 25 mm.

2.3.6. Contact Angle

The water contact angle was performed in six repetitions using the sessile drop technique (10 µL drop of distilled water at a speed of 10 µL/s) with an OCA 25 goniometer and SCA20_U software (version 5.0.37) (DataPhysics Instruments, Germany).

2.3.7. Water Vapour Permeability

A gravimetric method was used, based on the standard ASTM E96 method (ASTM, 2016), using Mater Cup FX-3180 equipment (Textest AG, Schwerzenbach, Switzerland). Three samples were cut from each film, and their thickness was measured. The samples were held between two rings on top of three glass cells containing distilled water, using a relative humidity gradient of 50 to 100%. With the apparatus, the water vapour transmission was determined using the mass change in the cup due to evaporation, the film's area, and the measurement time.

2.4. Vegetable Coating

The fresh beetroot was washed with tap water then dried using paper towels and cut crosswise into 1 cm slices using a laboratory slicer, the CL50 Version D (Robot Coupe, France). For analyses, beetroot slices were used (diameter of 2 cm). The selected locations were at a similar distance from the centre and root skin in to provide repeatable samples for experiments. The samples were coated by immersion in distilled water as control test (uncoated samples) or in coating solutions for coated samples. The immersion time was 2 min; then, all samples were drained on filter paper. All samples were sealed with air in PA/PE 70 T-flex 70 packaging bags, 70 µm thick, purchased from Pakmar (Warsaw, Poland), with 10 discs in each set, using a PP5.4 packing machine (Tepro S.A., Koszalin, Poland). The bags were made of barrier material, providing the vacuum-packed samples with conditions without access to oxygen, moisture, bacteria, and moulds. After packing, the samples were stored in a climate chamber of standardised conditions at 4 °C for 28 days with a high humidity of 80%. Figure 1 presents the coating process of beetroot slices. The beetroot samples were homogenised before the chemical experiments, and no preparation was made for physical analyses (colour, hardness and microstructure).

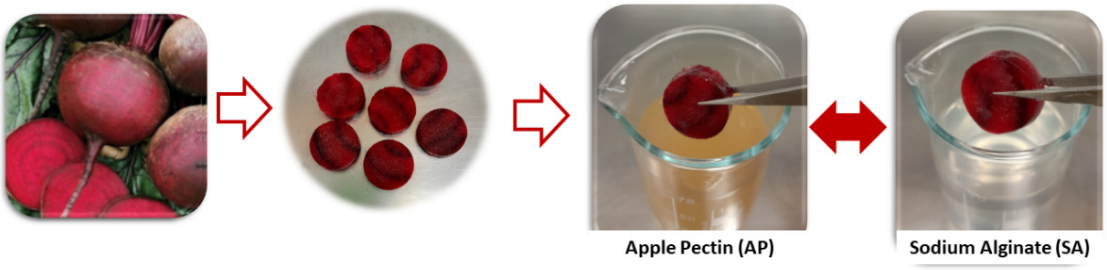


Figure 1. The coating process of beetroot slices with coating solutions based on apple pectin (AP) and sodium alginate (SA).

2.5. Dry Matter

The dry matter was evaluated in triplicate by drying samples in a laboratory dryer (SUP 65 WG, WAMED, Warsaw, Poland) at 105 °C for 24 h.

2.6. pH Value

The pH of the analysed homogenised beetroot samples was measured in triplicate at room temperature (23 ± 1 °C) using a pH meter Lab 850 (SHOTT AG, Mainz, Germany).

2.7. Hardness

The hardness of beetroot slices was measured in 8 replicates based on the method described in the previous study [33] with a 5 mm thick stylus and a TA-XT2i texturometer as the measuring table (Stable Micro Systems, Godalming, UK). The speed used was 1 mm/s. Texture Expert software (version 1.22) was used to determine the maximum force of hardness.

2.8. Colour

The colour was evaluated in 10 replications using a Minolta colourimeter Chroma Meter CR-5 (Minolta, Tokyo, Japan) in the CIE $L^*a^*b^*$ colour system. The colour changes were analysed using the L^* parameter as lightness, a^* as the share of red or green colour, and b^* as the share of yellow and blue, and the Hue colour tone angle was determined based on the parameters a^* and b^* [34].

2.9. Polyphenols

The total polyphenols in control and coated beetroot during storage was measured in 3 repetitions based on the Folin–Ciocalteu method described in our previous study.

2.10. Flavonoids

Flavonoids in control and coated beetroot during storage were determined in 3 replications based on the modified Lamaison method [35].

2.11. Betalains

The measurement of betalain compound content in beetroot was performed in triplicates based on the Nilsson method [36] and described also by Niemira and Galus [23]. Betalains were expressed as red and yellow pigments in mg of betanin/g d.m.

2.12. Microstructure

The observation of the microstructure of control and coated beetroot during storage was carried out with the scanning electron microscope FEI Quanta 200 (Brno, Czech Republic). Prior to the analysis, the beetroot was cut using a scalpel, and a sample size of 5 × 5 mm was used. No specific preparation of the materials was needed.

2.13. Statistical Analysis

Statistical analysis of the obtained results was performed using the Statistica 10.0 programme by one-way analysis of variance (ANOVA) with the Tukey post hoc test at a significance level of 0.05.

3. Results and Discussion

3.1. Coating Characterisation

The coating solutions were poured on solid support (Petri dishes) and dried to obtain self-standing edible coatings characterised by continuous structure, without pores or cracks. Both polysaccharides showed to be excellent coating materials for application to food products. Their thickness was 62.1–62.5 µm, similar to the films prepared from biopolymers, mostly from 50 to 200 µm. Figure 2 shows UV-VIS light spectra of coatings based on apple pectin and sodium alginate. It can be observed that both layers have no significant protection against visible light (400–700 nm). However, they showed UV light protection with the higher intensity for the apple pectin-based coating. This material had a yellowish character compared to the coating from sodium alginate, which was transparent without any colour. This protection against UV light shows the potential preventive effect of the analysed coatings on the reduction in product oxidation induced by UV light [37]. These findings align with the values of colour and opacity (Table 1).

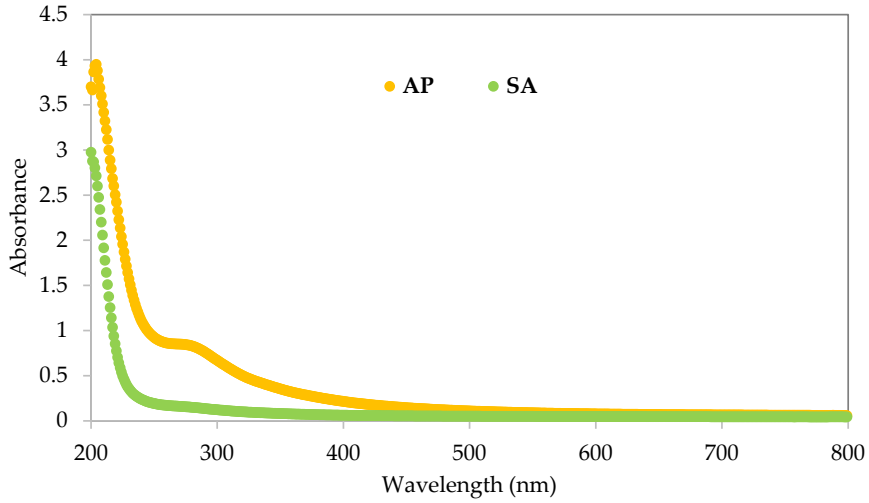


Figure 2. UV-VIS light spectra of films based on apple pectin (AP) and sodium alginate (SA).

The value of parameter L^* was lower for coating from apple pectin (85.96 ± 1.92) than for coating based on sodium alginate (89.32 ± 0.36). Parameters a^* and b^* were −0.16 ± 0.68 and 14.24 ± 3.71 for pectin formulation, while for the alginate layer, they were −0.52 ± 0.02 and 3.35 ± 0.51, respectively. In addition, the total colour difference (ΔE) was much higher for pectin coating (14.22 ± 4.17) than for alginate (3.25 ± 0.58). A similar correlation was observed for opacity. The values were 1.78 ± 0.23 and 0.88 ± 0.11 A/mm. Pectin-based coatings showed higher hydrophilic character, which was confirmed by a lower water contact angle (39.92 ± 2.73°) and higher water vapour permeability (5.84×10^{-10} ± 0.22 g/m·Pa·s) compared to sodium alginate coating (42.35 ± 4.97° and 5.16×10^{-10} ± 0.07 g/m·Pa·s). This is probably attributed to the softer structure due to the materials' origin and the compatibility with the plasticiser (glycerol). Pectin coatings were more elastic and showed lower mechanical resistance. These observations were confirmed by lower tensile strength (1.04 ± 0.14 MPa) and higher elongation at break (3.82 ± 0.63%) for pectin films compared to alginate (1.58 ± 0.18 MPa and 1.55 ± 0.21%).

Table 1. Selected physical characteristics of films based on apple pectin (AP) and sodium alginate (SA).

Tested Feature	AP	SA
	Mean ± Standard Deviation	
Thickness (μm)	62.5 ± 5.0	61.2 ± 5.0
*L**	85.96 ± 1.92	89.32 ± 0.36
*a**	−0.16 ± 0.68	−0.52 ± 0.02
*b**	14.24 ± 3.71	3.35 ± 0.51
Total colour difference (Δ*E*)	14.22 ± 4.17	3.25 ± 0.58
Opacity (A/mm)	1.78 ± 0.23	0.88 ± 0.11
Tensile strength (MPa)	1.04 ± 0.14	1.58 ± 0.18
Elongation at break (%)	3.82 ± 0.63	1.55 ± 0.21
Water contact angle (°)	39.92 ± 2.73	42.35 ± 4.97
Water vapour permeability (10^{-10} g/m·Pa·s)	5.84 ± 0.22	5.16 ± 0.07

3.2. The Characteristics of the Raw Material

The most commonly eaten beets are red beets. Their nutritional and health properties have made them popular in the human diet for centuries. Scientific reports about many bioactive compounds could classify beetroot as a functional food [18,38]. Table 2 presents the characteristics of the beetroot regarding selected physical properties and nutritional values. The dry matter of analysed beetroot was 10.77 ± 0.25% and the pH was 5.75 ± 0.01, similar to other vegetables [39]. A high hardness of the beetroot was observed, 65.73 ± 4.78 N, which is similar to parsley root [33] and rather typical for fresh root vegetables. Many factors influence hardness, including cell wall composition and morphology (the presence of cellulose, hemicellulose, pectin, fat and protein), tissue type and turgor pressure. In fresh plant tissue, moisture helps maintain turgor pressure and, in conjunction with other factors, may determine the hardness of stored vegetables. It has been confirmed that high hardness is attributed to the moisture content, which is the highest for fresh vegetables but decreases during storage due to the mass loss [40,41]. The colour parameters obtained from the CIE *L***a***b** system were as follows: *L** 28.69 ± 1.66, indicating low lightness, typical for coloured products; *a** 25.78 ± 1.70; and *b** 5.89 ± 1.70. Parameter *a** being positive indicates colour leaning toward red; thus, high values are expected for beetroot [17,23,42]. Parameter *b** being positive indicates colour leaning toward yellow. The colour's Hue tone was 12.83 ± 3.25°, which showed a high degree of red colour. Beetroot consists of multiple biologically active phytochemicals, including polyphenols, flavonoids and betalains. All of them positively impact human health [43–45]. The content of polyphenols in beetroot was 9.13 mg gallic acid/g d.m., and flavonoids were 44.63 ± 0.31 mg of quercetin/g d.m. Red and yellow pigment contents in beetroot were 6.73 ± 0.35 and 5.29 ± 0.13 mg betanin/g d.m., respectively.

Generally, the genotype and cultivation techniques or location and differences in plant maturity may affect bioactive compound content. This was also observed in this study since the beetroot was of similar size, shape and colour but not uniform. Thus, differences in value between the sample and the days of storage were observed, especially in the content of bioactive compounds. In addition, some external factors, such as light or temperature combined with various nutrients in the soil, can also affect the presence of bioactive compounds in fresh vegetables [46]. Niemira and Galus [24], analysing crispbreads based on fresh red beetroot pomace, obtained polyphenols in dry snacks of approx. 8.20 mg chlorogenic acid/g d.m. and betalains in fresh beetroot pomace, as well as approx.

2.41 mg betanin/g d.m. and 1.22 vulgaxanthin/g d.m., confirming that waste material from this vegetable is rich in nutrients and can be a source of health benefits when used in different products, including vegetable snacks. In addition, the antioxidant activity and bioactive compounds of dried snacks based on beetroot pomace showed the potential of this vegetable in different applications, even after thermal processing. However, different methods can be used for analysis, and the origin of vegetables may also impact the content of bioactive compounds and the colour of fresh and processed vegetables [47]. Nevertheless, beetroot is a valuable vegetable, and the limited studies related to maintaining its quality attributes indicate the potential for using edible coatings as a mild processing method to protect its natural character.

Table 2. Characteristics of the raw material—beetroot.

Tested Feature	Mean ± Standard Deviation
Dry matter (%)	10.77 ± 0.25
pH	5.89 ± 0.01
Hardness (N)	65.73 ± 4.78
*L**	28.69 ± 1.66
*a**	25.78 ± 1.70
*b**	5.89 ± 1.64
Hue tone (°)	12.83 ± 3.25
Content of polyphenols (mg gallic acid/g d.m.)	9.13 ± 0.57
The content of flavonoids (mg quercetin/g d.m.)	44.63 ± 0.31
Red pigment content (mg betanin/g d.m.)	6.73 ± 0.35
Yellow pigment content (mg vulgaxanthin/g d.m.)	5.29 ± 0.13

3.3. The Effect of Polysaccharide Coatings on the Hardness of Fresh-Cut Beetroot

The texture and structure of food products are crucial as essential factor in the sensory evaluation of food quality. Both are important in the marketing of food products [48]. They also depend on the moisture content and processing conditions and may change during storage, especially in fresh vegetables, due to biological processes such as ripeness or respiration. During storage, the hardness of all samples decreased (Table 3). In the control samples, this was from about 59.2 to 45.4 N. Minor changes were observed in samples coated with apple pectin, from about 56.4 N in samples after their production to 50.3 N after storage for 28 days. However, no significant effect of coatings and their type on changes in hardness was observed up to 21 days of storage. Specific trends were observed related to the protection of beets against the loss of their hardness in coated samples, especially with a pectin coating. Compared to samples without a coating, in which the loss of hardness after 28 days of storage reached 23%, in samples with a pectin coating, the hardness decreased by about 11%, and with an alginate coating, this was by about 16%. This is likely attributed to the interaction between the coating material and the sample due to the trend towards equilibrium conditions, creating a specific headspace in the package during storage. However, the inside surface was limited to reduce the volume of headspace, thus minimising the release of juices or the migration of gases during storage. It can also be connected with the natural process of migration components, the coating formulation, the beetroot, and the mobility of ingredients in the vegetable matrix. This behaviour was also observed regarding the structure of the samples during storage (Figure 2). Differences in the hardness of root vegetables can be attributed to their anatomy, specifically the xylem, inner part, and phloem [49]. Changes in hardness during storage were observed for different vegetables, such as carrots [50] or parsley root [33].

Table 3. The results of the hardness of control samples of fresh-cut beetroot and those coated with apple pectin (AP) and sodium alginate (SA) during storage.

Time (Days)	Hardness (N)		
	Type of Material		
	Control	AP	SA
0	$59.19 \pm 6.11^{b,AB}$	$56.38 \pm 5.77^{a,A}$	$56.43 \pm 9.26^{b,A}$
7	$58.62 \pm 3.21^{b,AB}$	$55.55 \pm 3.44^{a,A}$	$54.77 \pm 1.73^{b,A}$
14	$56.76 \pm 4.69^{b,A}$	$55.08 \pm 4.3^{a,A}$	$53.51 \pm 1.4^{ab,A}$
21	$53.65 \pm 4.9^{b,A}$	$54.75 \pm 5.2^{a,A}$	$52.58 \pm 0.9^{ab,A}$
28	$45.41 \pm 3.71^{a,A}$	$50.31 \pm 2.07^{a,B}$	$47.6 \pm 2.98^{a,AB}$

Mean values with standard deviations. Different superscript letters (^{a,b}) within the same column or (^{A,B}) within the lines indicate significant differences between the samples ($p < 0.05$).

3.4. The Effect of Polysaccharide Coatings on the Colour of Fresh-Cut Beetroot

Food colour, a physical property, is an important sensorial attribute that directly impacts food selection and acceptability [10]. Therefore, colour measurement is a basic factor that describes food products, especially those treated by different processing methods. Edible coating is a mild technology that often protects or maintains the food colour.

Regarding root vegetables, their consumption or processing is usually preceded by peeling, which causes injury to the natural skin layer and starts biological processes. Edible coatings, as a thin layer, can create a continuous layer that protects the surface against external conditions and creates a modified atmosphere around the sample [16,51]. This is due to the selective barrier properties against gases. For instance, the analysed coatings showed low water vapour permeability values of $5.84 \pm 0.22 \times 10^{-10}$ g/m·Pa·s and $5.16 \pm 0.07 \times 10^{-10}$ g/m·Pa·s for apple pectin and sodium alginate samples, respectively (Table 1). However, in the case of porous materials, such as beetroot, there is no equal effect in terms of barrier efficiency, probably due to the discontinuous structure. Table 4 presents the obtained values for the parameters of colour of control and coated fresh-cut beetroot. It can be observed that the analysed beetroot samples were characterised by increased lightness (parameter L^*) which ranged from 34.35 ± 0.96 to 42.26 ± 2.01 for control beetroot, as well as from 35.23 ± 1.27 to 38.74 ± 3.04 and from 34.96 ± 1.67 to 39.85 ± 1.48 for samples coated with apple pectin and sodium alginate, respectively. It can be noted that during storage (28 days), a statistically significant ($p < 0.05$) increase in lightness was observed compared to the initial time, whereas the most significant changes were observed for control samples, indicating that the applied coatings had a positive impact on beetroot colour. There was a slight difference between coating types. Thus, both played a role as agents stabilising the lightness of beetroot. This behaviour can be explained by the UV protection of coatings, especially based on apple pectin (Figure 1). Edible coatings probably minimised the migration of beetroot components and their oxidation on the surface. All samples were stored without access to light. However, the ageing processes occurred, making a lighter surface visible for uncoated samples.

In analysing the effect of storage time on changes in parameter a^* of beetroot samples, statistically significant differences ($p < 0.05$) were shown only between day 0 and after 21 days, but a tendency of lower values compared to the initial time (0 days) was observed (Table 4). The values changed from 17.27 ± 3.79 to 16.14 ± 2.97 for control samples, whereas for coated beetroot with apple pectin and sodium alginate, the values decreased from 18.65 ± 5.46 to 15.25 ± 2.09 and from 21.86 ± 3.96 to 14.58 ± 1.95, respectively. Parameter a^* is an important factor for beetroot since its positive values indicate colour leaning toward red, which is the desired colour of the samples. In our study, greater changes in this parameter were observed for the applied coatings, which can also be attributed to the

colour of the coatings. The previous works showed that they are transparent but provide some colour changes. The noted differences in parameter b^* over time were statistically significant ($p < 0.05$) in the control and coated beetroot samples (Table 4). The values were relatively low and varied between 3.92 ± 0.89 and 6.90 ± 1.29 for control samples after 7 and 28 days of storage. The values for coated samples were in this range. Furthermore, despite the lack of statistically significant differences, the same tendency towards higher values of parameter b^* was observed during storage of all samples. However, the highest increase was for control beetroot, and the lowest was for samples coated with sodium alginate. Thus, the coating type significantly affected the colour changes from blue to yellow (parameter b^*). The changes in the colour of the fresh-cut beetroot are probably related to the ageing of vegetables, migration of the components or the interactions between the sample and the coating, and degradation of the colourants (red and yellow pigments).

Table 4. Colour parameters (L^*, a^*, b^*) and Hue tone of control fresh-cut beetroot samples and those coated with apple pectin (AP) and sodium alginate (SA) during storage.

Time (Days)	Type of Material		
	Control	AP	SA
L^*			
0	34.35 ± 0.96 ^{a,A}	35.23 ±1.27 ^{a,A}	34.96 ± 1.67 ^{a,A}
7	43.11 ± 1.39 ^{b,C}	38.32 ± 1.62 ^{bc,A}	40.72 ± 1.21 ^{b,B}
14	43.31 ± 2.10 ^{b,B}	40.81 ± 2.21 ^{c,A}	39.95 ± 2.21 ^{b,A}
21	43.36 ± 2.42 ^{b,B}	37.80 ± 2.56 ^{ab,A}	41.03 ± 1.32 ^{b,B}
28	42.26 ± 2.01 ^{b,B}	38.74 ± 3.04 ^{bc,A}	39.85 ± 1.48 ^{b,AB}
a^*			
0	17.27 ± 3.79 ^{bc,A}	18.65 ± 5.46 ^{a,A}	21.86 ± 3.96 ^{b,A}
7	15.06 ± 1.26 ^{ab,A}	16.98 ± 2.44 ^{a,AB}	17.93 ± 2.59 ^{a,B}
14	19.14 ± 2.17 ^{c,A}	18.34 ± 2.12 ^{a,A}	16.75 ± 3.40 ^{a,A}
21	13.63 ± 1.95 ^{a,A}	15.55 ± 2.55 ^{a,A}	18.08 ± 1.32 ^{a,B}
28	16.14 ± 2.97 ^{abc,A}	15.25 ± 2.09 ^{a,A}	14.58 ± 1.95 ^{a,A}
b^*			
0	3.92 ± 0.89 ^{a,A}	4.66 ± 1.13 ^{a,AB}	5.36 ± 1.18 ^{ab,B}
7	4.14 ± 1.34 ^{ab,A}	4.78 ± 1.97 ^{a,A}	5.98 ± 1.61 ^{ab,A}
14	4.82 ± 0.74 ^{ab,A}	4.55 ± 1.14 ^{a,A}	6.48 ± 0.84 ^{b,B}
21	5.49 ± 1.02 ^{b,B}	4.28 ± 1.15 ^{a,A}	4.78 ± 0.67 ^{a,AB}
28	6.90 ± 1.29 ^{c,A}	6.79 ± 1.20 ^{b,A}	5.55 ± 1.45 ^{ab,A}
Hue (°)			
28	13.25 ± 1.43 ^{a,A}	13.84 ± 2.05 ^{a,A}	15.08 ± 1.42 ^{a,A}
7	14.45 ± 2.00 ^{a,A}	15.19 ± 1.81 ^{a,AB}	16.50 ± 1.57 ^{ab,B}
14	18.89 ± 2.26 ^{b,A}	15.82 ± 4.40 ^{a,A}	18.21 ± 1.51 ^{ac,A}
21	19.78 ± 4.32 ^{b,A}	16.24 ± 3.62 ^{a,A}	19.67 ± 1.36 ^{c,A}
28	19.79 ± 2.95 ^{b,A}	20.20 ± 1.63 ^{b,A}	18.20 ± 1.97 ^{ac,A}

Mean values with standard deviations. Different superscript letters ($^{a–c}$) within the same column or ($^{A–C}$) within the lines indicate significant differences between the samples ($p < 0.05$).

Hue values were in the red range on the colour wheel and increased from 13.25 to 19.79° for control samples, from 13.84 to 20.20 for samples coated with apple pectin-based solutions and from 15.08 to 18.20 for samples coated with the formulation based on sodium alginate (Table 4). The smallest changes were observed for samples coated with alginate coatings, probably due to the transparency and the smaller effect on colour changes during storage. However, the significant increase observed for control samples was at a higher rate

than other samples, which was clearly observed after 14 days of storage (18.89 in relation to 15.82 and 18.21 for pectin and alginate coatings, respectively).

3.5. The Effect of Polysaccharide Coatings on the Polyphenol Content in Fresh-Cut Beetroot

Polyphenols show biological activity in beetroot. It was noted that different factors, such as the cultivation stage, may influence their concentration. The polyphenol content in control and coated fresh-cut beetroot is presented in Table 5. A significant reduction in polyphenol content ($p < 0.05$) was observed for all analysed samples. Its content was approx. 22–24 mg gallic acid/g d.m. for the fresh samples and was reduced to 2.05 ± 0.28 mg gallic acid/g d.m. for control samples after 28 days of storage. It can be noted that the polyphenol content in coated samples with apple pectin and sodium alginate coatings decreased at a lower rate. Those tendencies correlate with the results for lightness (parameter L^*), where smaller changes in colour were observed for the coated sample compared to the control (Table 4). After 28 days of storage, the polyphenol content in beetroot coated with sodium alginate coatings was statistically different ($p < 0.05$), and more than 2 times higher (4.80 ± 1.14 mg gallic acid/g d.m.), whereas for the sample coated with apple pectin, it was almost 4 times higher (7.65 ± 1.72 mg gallic acid/g d.m.). Therefore, polysaccharide coatings composed of apple pectin and sodium alginate applied to fresh-cut beetroot significantly impacted the maintenance of polyphenols. This is probably due to the protective effect and the selected barrier properties of formulations that affected more compact structures and avoided the degradation of bioactive compounds. Vegetables are generally a good source of bioactive compounds, such as phenols and flavonoids, which act as antioxidants to reduce the risk of diseases like cancer and have protective effects on cardiovascular health. These bioactive compounds exert various beneficial effects due to their antioxidant and anti-inflammatory properties [52,53]. The content of these compounds usually decreases with storage time due to the vegetable's metabolic rate and treatment methods, such as drying.

Table 5. Polyphenols in control fresh-cut beetroot samples and those coated with apple pectin (AP) and sodium alginate (SA) during storage.

Time (Days)	Polyphenols (mg Gallic Acid/g d.m.)		
	Type of Material		
	Control	AP	SA
0	22.39 ± 2.11 ^{d,A}	23.86 ± 0.10 ^{d,A}	23.83 ± 0.37 ^{d,A}
7	18.86 ± 0.29 ^{c,A}	23.92 ± 0.18 ^{d,C}	20.68 ± 0.90 ^{c,B}
14	17.51 ± 0.94 ^{c,AB}	19.58 ± 2.42 ^{c,B}	14.21 ± 2.05 ^{b,A}
21	10.78 ± 1.19 ^{b,A}	13.95 ± 0.52 ^{b,B}	13.44 ± 0.38 ^{b,B}
28	2.05 ± 0.28 ^{a,A}	7.65 ± 1.72 ^{a,B}	4.80 ± 1.14 ^{a,AB}

Mean values with standard deviations. Different superscript letters ($^{a–d}$) within the same column or ($^{A–C}$) within the lines indicate significant differences between the samples ($p < 0.05$).

The storage time did not affect the changes in the polyphenol content of samples coated with apple pectin until day 14. However, after 7 days, other samples observed a significant reduction in polyphenol content. Nevertheless, after 21 days of storage, around 50% of polyphenols remained in all samples. A similar decreasing tendency in the total content of polyphenols was observed for fresh-cut parsley roots during four weeks of storage using coatings based on chitosan and citric acid formulation [54] or whey protein-based coatings incorporated with jojoba oil [33]. Pen and Jiang [55] reported an opposite tendency by applying chitosan coating on chestnut fruit over two weeks. The authors explained this

phenomenon (higher values in polyphenol content) as likely being due to inhibiting the enzyme, which may affect the regulation of the phenolic compound biosynthetic pathway.

3.6. The Effect of Polysaccharide Coatings on the Flavonoid Content in Fresh-Cut Beetroot

The content of flavonoids in the analysed fresh-cut beetroot is presented in Table 6.

Table 6. Flavonoids in control fresh-cut beetroot samples and those coated with apple pectin (AP) and sodium alginate (SA) during storage.

Time (Days)	Flavonoids (mg Quercetin/g d.m.)		
	Type of Material		
	Uncoated	AP	SA
0	$48.86 \pm 0.07^{e,C}$	$44.43 \pm 0.26^{d,A}$	$45.91 \pm 0.20^{d,B}$
7	$35.47 \pm 0.20^{d,A}$	$49.27 \pm 0.14^{e,C}$	$44.79 \pm 0.33^{c,B}$
14	$32.53 \pm 0.20^{a,A}$	$35.95 \pm 0.19^{b,C}$	$33.16 \pm 0.07^{a,B}$
21	$33.35 \pm 0.13^{b,A}$	$33.69 \pm 0.40^{a,A}$	$37.45 \pm 0.07^{b,B}$
28	$34.39 \pm 0.13^{c,A}$	$42.47 \pm 0.19^{c,B}$	$44.62 \pm 0.20^{c,C}$

Mean values with standard deviations. Different superscript letters ($^{a–e}$) within the same column or ($^{A–C}$) within the lines indicate significant differences between the samples ($p < 0.05$).

The values varied between approx. 44 and 50 mg quercetin/g d.m. at day 0, followed by a significant ($p < 0.05$) decrease of about 33–37 mg quercetin/g d.m. after 21 days of storage, and then an increase to the values similar to those before storage. A higher increase was observed for coated samples, indicating that polysaccharide coatings could be attributed to the metabolic changes resulting in such increased values. The statistical analysis showed a significant effect of storage time on changes in flavonoid content in the tested beetroot. In analysing the data presented in Table 6, it was shown that using edible coatings made of apple pectin and sodium alginate limits the degradation of flavonoids in beetroot slices. This behaviour can be attributed to the selective barrier against gases (Table 1). The coated samples retained more flavonoids than the control ones, which suggests that edible coatings were also a source of those bioactive compounds. The flavonoid content for individual coatings differed significantly ($p < 0.05$). Similar results were observed for carrot slices coated with chitosan [54] or parsley root slices coated with protein-based coatings [33]. The authors showed higher flavonoid content values than the control sample during storage. The greatest differences in flavonoid content between the control and coated samples were observed after 4 weeks of storage. However, others [56] observed a decrease in the flavonoid content in slices of parsley root coated with chitosan after 2 weeks of storage, and then, the content increased after 2 weeks.

3.7. The Effect of Polysaccharide Coatings on the Betalain Content in Fresh-Cut Beetroot

Betalains are the pigments that give beetroot its red or yellow colour [19,23]. They are one of the characteristic features of beetroot and can be, for example, betacyanins (e.g., betanin, betanidin, and isobetanin) and betaxanthins (vulgaxanthin I and dopamine–betaxanthin) [17]. The content of betalains in the analysed control and coated beetroot is presented in Table 7. Red pigment content was 4.00–4.75 mg betanin/g d.m. at day 0 and 2.72–4.17 mg betanin/g d.m. after 28 days of storage. Coated samples had a lower content of red pigments, probably due to the coating process and the miscibility of pigments on the surface with coating solutions. It can be observed that both red and yellow pigments were significantly reduced during the 28 days of storage ($p < 0.05$). The highest reduction was observed after 7 days compared to samples at day 0, and the values in the following days were similar. This observation suggests that the migration of betalains to the coating solution occurred when samples were immersed to create integral layers on

the vegetable surfaces. However, much lower values were noted on days 7 and 14, but higher on days 21 and 28. The differences may be connected with the nature of the samples, which were from multiple tubers with differences in concentrations of betalains. The results can also be correlated with the changes in colour (Table 4). However, the red pigment content was reduced by approx. 50%, suggesting that the cutting and coating process significantly impacted the betalain amount in beetroot. Moreover, the humid conditions inside the packaging could facilitate the migration or degradation of betalains from the vegetable matrix.

Table 7. Betalains in control fresh-cut beetroot samples and those coated with apple pectin (AP) and sodium alginate (SA) coatings during storage.

Time (Days)	Type of Material		
	Control	**AP**	**SA**
	Red Pigments (mg betanin/g d.m.)		
0	$4.75 \pm 0.05^{d,C}$	$4.21 \pm 0.06^{d,B}$	$4.00 \pm 0.06^{d,A}$
7	$2.44 \pm 0.07^{a,B}$	$2.08 \pm 0.02^{a,A}$	$2.74 \pm 0.05^{c,C}$
14	$2.22 \pm 0.21^{a,A}$	$2.20 \pm 0.03^{a,A}$	$1.90 \pm 0.08^{a,A}$
21	$3.51 \pm 0.03^{b,C}$	$3.40 \pm 0.06^{b,B}$	$2.41 \pm 0.01^{b,A}$
28	$4.17 \pm 0.01^{c,C}$	$3.68 \pm 0.16^{c,B}$	$2.72 \pm 0.01^{c,A}$
	Yellow Pigments (mg vulgaxanthin/g d.m.)		
0	$3.77 \pm 0.03^{c,C}$	$3.49 \pm 0.04^{c,B}$	$3.26 \pm 0.11^{c,A}$
7	$2.24 \pm 0.07^{a,A}$	$2.13 \pm 0.02^{a,A}$	$2.68 \pm 0.05^{b,B}$
14	$2.16 \pm 0.16^{a,B}$	$2.18 \pm 0.02^{a,B}$	$1.86 \pm 0.06^{a,A}$
21	$3.41 \pm 0.03^{b,C}$	$3.19 \pm 0.06^{b,B}$	$2.56 \pm 0.01^{b,A}$
28	$3.91 \pm 0.01^{c,C}$	$3.45 \pm 0.14^{c,B}$	$2.70 \pm 0.01^{b,A}$

Mean values with standard deviations. Different superscript letters ($^{a–d}$) within the same column or ($^{A–C}$) within the lines indicate significant differences between the samples ($p < 0.05$).

The highest increase in values was observed for control samples. All changes were statistically significant ($p < 0.05$). Similar tendencies were observed for yellow pigments. This phenomenon can be attributed to different mechanisms occurring during storage. In addition, slices were procured from various beetroot parts, which probably impacted their concentrations.

3.8. The Effect of Polysaccharide Coatings on the Microstructure of Fresh-Cut Beetroot

Food processing and preservation processes affect the structure of food products. Different postharvest processing technologies and storage conditions may affect both the structural integrity of the cell of vegetable tissue and the biochemical composition of the cell wall. In general, a plant tissue is a group of cells with a common function or structure that affects the product's sensory attributes. The microstructure of the control and coated beetroot slices was observed after the coating process and after 28 days of refrigerated storage (approx. 4 °C). The photographs are presented in Figure 3.

It was noticed that immediately after coating the raw material, the pores were characterised by a similar shape and arrangement, and most of the pores were open, in contrast to the uncoated control sample. The coating material, sodium alginate and pectin, was largely located inside the pores of the tissue. After 28 days of storage, surface drying was observed. The use of edible coatings contributed to limiting the drying process of the beetroot surface and closing the pores. The structure was similar between samples, indicating that the coating did not significantly affect their structure. Nevertheless, due to enzymatic degradation, there is often a loss of texture and integrity in fresh tissue products, such as fruits or vegetables, which decreases consumer acceptability. Moreover, the softening of tissue observed in the tested beetroot as decreased hardness (Table 2) can also be related

to enzyme activity. However, this minimal water loss was related only to the inner layer of the packaging since the wet surface of the material was observed. Our previous study reported similar observations for fresh-cut parsley root coated with whey protein-based coatings enhanced with jojoba oil [33]. However, another study showed that freeze-dried carrots were characterised by uneven surface coverage with empty areas of cells [33].

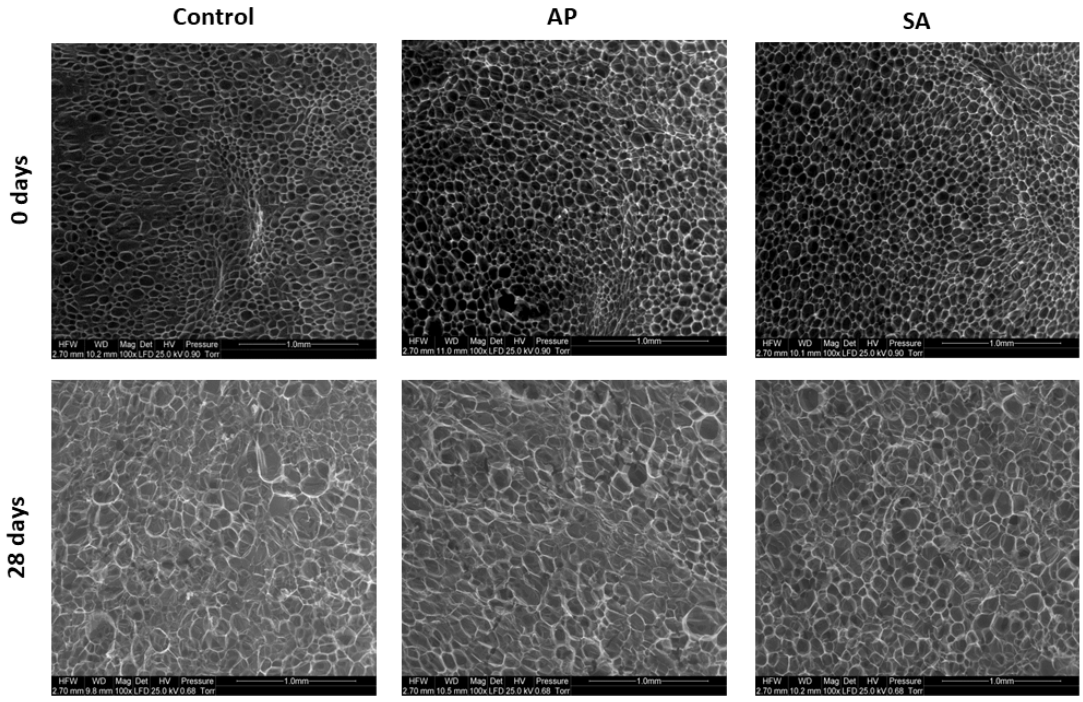


Figure 3. Scanning electron micrographs of control and coated beetroot slices with apple pectin (AP) and sodium alginate (SA) at 0 and 28 days of storage (magnification: 100×).

4. Conclusions

Apple pectin and sodium alginate-based edible coatings were chosen and used to preserve the minimally processed beetroot through the immersion technique during 28 days of refrigerated storage (4 °C). These formulations showed continuous structure, without pores and cracks, and were characterised by transparency. Both control and coated samples were characterised by changes in colour over storage time. The colour parameters (L^*, a^*, and b^*) and Hue angle were mainly at a similar level, indicating the maintenance of colour. However, differences in values were observed during storage, especially for lightness (parameter L^*), but also for the values of parameters b^* and h, which increased over time, while the values of a^* decreased during storage. Beetroot slices coated with apple pectin and alginate coatings showed maintained hardness, while control samples were characterised by decreasing hardness during storage. Polysaccharide coatings and extended storage time positively impacted the flavonoid content in fresh-cut beetroots. There was also a significant reduction in the content of red and yellow pigments for both control and coated samples. The microstructure analysis showed fewer pores in tissue due to the protective effect of coatings. The storage negatively affected the quality of the fresh-cut beetroot surface, and the drying effect was also observed. Thus, the minimally processed, fresh-cut beetroot presented in this study, obtained with the application of polysaccharide coatings, showed modifications to the quality characteristics. The obtained results and observations are a good direction for designing protective coatings for fresh-cut beetroot, which can improve sensory attributes and reduce the waste of fresh-cut vegetables during storage.

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