Bioactive Edible Coatings Based on CMC and Chokeberry Extract as a Strategy for Improving the Quality and Microbiological Safety of Freshly Cut Peppers During Short-Term Storage

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Article

Bioactive Edible Coatings Based on CMC and Chokeberry Extract as a Strategy for Improving the Quality and Microbiological Safety of Freshly Cut Peppers During Short-Term Storage

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Highlights

- Sanitization plus CMC was the most effective treatment for fresh-cut peppers.
- Chokeberry extract showed cultivar dependent effects on quality and sensory traits.
- Aronia based coatings did not consistently improve antimicrobial performance.
- Sensory acceptance depended more on aroma and flavor than on cultivar identity.

Abstract

The aim of this study was to evaluate whether edible coatings and plant derived extracts can help maintain the quality and microbiological safety of fresh-cut sweet peppers during short-term refrigerated storage. Two bell pepper cultivars, Sunny F_1 (yellow) and Yecla F_1 (red), were sliced and subjected to five treatments: water washing (control), washing with BioActiW 2000 Food sanitizer (BAW), BAW followed by carboxymethylcellulose (CMC) coating (BAW+CMC), CMC coating enriched with 3.5% alcoholic chokeberry pomace extract (CMC+AE), and soaking in 3.5% aqueous chokeberry pomace extract (AAE). Samples were stored at 5 °C for 7 days and evaluated for physicochemical analysis, microbiological contamination, postharvest quality, and sensory properties. The treatments influenced quality attributes in a cultivar dependent manner. All coating based treatments reduced polyphenol and L-ascorbic acid content relative to the control, although formulations containing chokeberry extract tended to limit these losses compared with BAW+CMC. Total sugar and carotenoid contents were not significantly affected. In both cultivars, BAW and BAW+CMC were the most effective treatments for reducing mesophilic bacteria and yeast counts, limiting softening, reducing weight loss, and maintaining marketable quality. By contrast, AAE applied without prior sanitization increased microbial counts in Sunny F_1, indicating that the extract alone was not sufficient to control native microflora. Sensory analysis showed clear cultivar specific responses: Sunny F_1 generally tolerated CMC+AE and BAW+CMC better, whereas Yecla F_1 was more sensitive to off-flavors associated with the chokeberry extract. PCA analysis indicated that smell and taste attributes were the main drivers of perceived quality. These results suggest that CMC based coatings can support fresh-cut pepper quality, but their practical value depends strongly on prior sanitization. The addition of chokeberry pomace extract may be beneficial for some quality traits, yet its overall effect depends on cultivar and treatment conditions, including extract concentration and pH.

Keywords: fresh-cut peppers; edible coatings; carboxymethylcellulose; chokeberry pomace extract; microbiological safety; sensory analysis; short-term storage

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1. Introduction

The demand for convenient, minimally processed food products has increased substantially in recent years, driving growth in the fresh-cut fruit and vegetable sector. However, minimal processing operations such as peeling, cutting, and slicing disrupt tissue integrity, accelerate physiological deterioration, and increase susceptibility to microbial contamination, thereby limiting product shelf life [1,2]. Postharvest losses of fresh produce remain a major global challenge, accounting for approximately 31% of total production [3]. For this reason, the development of effective and sustainable preservation strategies remains important.

Minimal processing induces wound related stress responses, including increased respiration, ethylene production, enzymatic browning, and accelerated oxidative degradation of bioactive compounds. Edible coatings may help mitigate some of these effects by modulating enzymatic activity, influencing the ascorbate glutathione system, and limiting reactive oxygen species accumulation [4,5]. In practice, however, their performance depends on coating composition, application conditions, and the characteristics of the raw material.

Edible coatings are widely investigated as an environmentally friendly approach to maintaining the quality of fresh and minimally processed produce [6–8]. These coatings can function as semipermeable barriers that reduce moisture loss, gas exchange, respiration rate, and oxidative reactions, thereby slowing senescence and quality deterioration [9–11]. Among coating materials, polysaccharide based systems are especially well studied because they are biodegradable and easy to form into films. Carboxymethylcellulose (CMC) has attracted attention because of its mechanical properties, availability, and compatibility with functional additives [12,13]. CMC based coatings have been used successfully on various fruits and vegetables, including tomatoes, goldenberries, and kiwifruit, where they helped maintain physicochemical quality and extend shelf life [14–16].

Recent developments in edible coating technology have focused on the incorporation of natural bioactive compounds to enhance functionality [17–20]. Plant derived extracts rich in polyphenols may provide antioxidant and antimicrobial activity, making them attractive additives for active coating systems [21–23]. Chokeberry (*Aronia melanocarpa*) pomace, a by product of juice processing, is an abundant and underused source of phenolic compounds, including anthocyanins and proanthocyanidins [24]. Previous studies have shown that chokeberry derived extracts can improve the antioxidant properties of biopolymer films [25], and chokeberry based materials have been explored in active and smart packaging applications [26].

Studies in other food matrices also suggest that chokeberry extract may be useful in coating systems. Yang et al. [27] reported improved antioxidant stability and extended shelf life in coated pork, while Dyankova and Solak [28] found improved antioxidant activity, UV barrier properties, and mechanical performance in alginate/pectin films enriched with chokeberry extract. In addition, edible films combining chokeberry extracts with probiotics have shown antimicrobial effects against foodborne pathogens [29]. These findings support further evaluation of chokeberry pomace extracts as functional additives in active coating systems.

Sweet pepper (*Capsicum annuum* L.) is an economically important vegetable rich in vitamins, carotenoids, and phenolic compounds. Owing to its high water content, it is particularly susceptible to postharvest deterioration, including moisture loss, microbial spoilage, and texture degradation [30,31]. These problems become more pronounced in fresh-cut products, where tissue disruption accelerates quality loss. Although edible coating systems such as chitosan nanoparticles [32], gum Arabic based coatings enriched with plant extracts [33], and xanthan based antimicrobial coatings [34] have been studied in peppers, work on CMC based coatings enriched with polyphenol rich fruit pomace extracts for fresh-cut peppers remains limited.

The use of fruit pomace as a source of bioactive compounds for edible coatings is consistent with circular economy and waste valorization principles. Chokeberry pomace, generated in large quantities during juice production, represents an underexploited source of phenolic compounds that can be recovered using green extraction technologies and incorporated into functional coating formulations [35].

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Therefore, the aim of this study was to evaluate the effectiveness of CMC based edible coatings enriched with chokeberry (*Aronia melanocarpa*) pomace extract, combined with sanitization using BioActiW 2000 Food, in preserving the quality of fresh-cut sweet bell pepper (cv. Sunny F_1 and Yecla F_1) during refrigerated storage. The study examined the effects of the treatments on physicochemical, sensory, and microbiological attributes, as well as key postharvest quality parameters, including weight loss, tissue softening, and marketable value [36].

2. Materials and Methods

2.1. Plant Material

Two sweet pepper (*Capsicum annuum L.*) cultivars, Sunny F_1 (yellow fruit) and Yecla F_1 (red fruit), were used in the experiment. Fruits were obtained from a commercial producer (Agropaprix, Przystałowice Duże Kolonia, Poland) and cultivated under plastic tunnels. Prior to the experiment, the peppers were stored at 12°C and 90 - 95% relative humidity. Fruits were washed, air dried, and cut into strips (1.5 - 2 cm wide).

2.2. Organization of the Experiment

Immediately after cutting, the pepper samples were subjected to the following treatments:

- CTRL – washing with tap water
- BAW – washing with BioActiW 2000 Food
- BAW+CMC – sanitization followed by CMC coating
- CMC+AE – CMC coating enriched with 3.5% alcoholic chokeberry extract
- AAE – soaking in 3.5% aqueous chokeberry extract

After treatment, the samples were drained and air-dried for 30 min at room temperature. The experiment was arranged in a completely randomized design. Treated samples were packed into individual transparent polyethylene containers (GUILLIN W1/059C, 154 × 98 × 70 mm, 1.0 L, food-contact approved) sealed with perforated lids (GUILLIN W2/001) equipped with 77 holes to allow gas exchange. Four biological replicates were prepared for each cultivar × treatment combination, with one replicate consisting of five independent packages. Thus, 20 packages were prepared per cultivar and treatment combination (4 replicates × 5 packages). Packages within each treatment were stored separately and randomly positioned in the cold room to preserve replicate independence. Additional packages were prepared for microbiological, chemical, and sensory analyses.

All samples were stored for 7 days at 5°C and 80% relative humidity under controlled refrigeration. Temperature and relative humidity were monitored throughout storage to confirm the stability and uniformity of the storage conditions.

2.3. Sanitization Procedure

BioActiW 2000 Food, based on hypochlorous acid (HOCl), was used as the sanitizing agent. A 5% (v/v) working solution was prepared according to the manufacturer's instructions. Pepper strips were immersed in the solution for 2 - 3 min, then drained and air-dried. If available, the manuscript should specify the actual HOCl concentration, the pH of the working solution, and the method used to confirm sanitization efficacy.

2.4. Preparation of Coatings

CMC Coating

A polysaccharide-based coating solution was formulated using medium viscosity sodium carboxymethyl cellulose (CMC) (Sigma, Poland) as the primary film forming agent. The composition of the solution comprised 30 g of CMC, 15 g of anhydrous glycerol serving as a plasticizer, 7.6 g of Tween 20 as a surfactant, and 2 L of distilled water. The CMC powder was gradually introduced into

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distilled water preheated to 50 °C and mixed under continuous agitation (400 rpm) using an electrically heated stirring device (Thermomix 31-1, Vorwerk Deutschland Stiftung & Co. KG, Berlin, Germany). Subsequently, the temperature was elevated to 80 °C, and the system was maintained under constant stirring for 30 min to ensure complete hydration and dissolution of the polymer. Following this step, glycerol and Tween 20 were added to the solution and mixed for 2 min to obtain a uniform dispersion. The final coating solution was then subjected to high-shear homogenization using a Diax 600 homogenizer (Heidolph Instruments, Germany) at 13,500 rpm for 2 min (Figure 1)

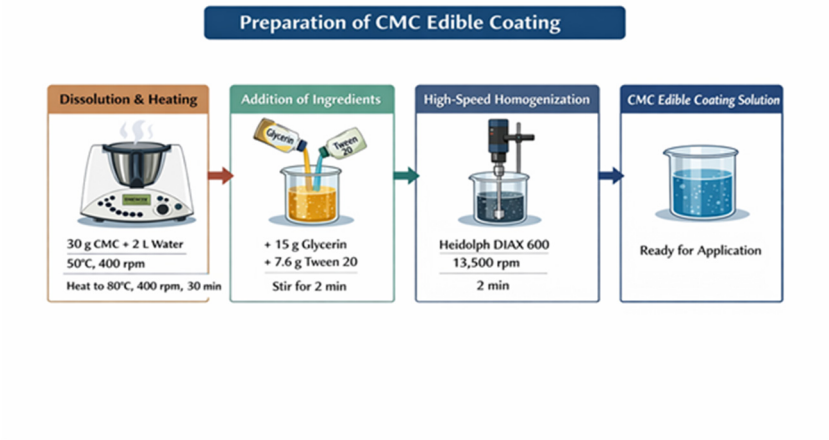

Figure 1. Polysaccharide based coating preparation scheme.

Methodology for Preparing Chokeberry Exstract

Anthocyanins were extracted from chokeberry pomace according to Dembczyński et al. [37], with slight modifications. Briefly, 1 g of pomace was suspended in 10 mL of 0.75% aqueous acetic acid, sonicated for 20 min at room temperature, and centrifuged at 10,000 rpm for 6 min. The supernatant was filtered and used as the stock aqueous chokeberry extract. No organic solvent was used in the final extract applied to the peppers.

CMC + Alcoholic Chokeberry Extract

For the CMC+AE treatment, the CMC coating solution was cooled to room temperature (~21°C) and enriched with chokeberry extract to obtain a final extract concentration of 3.5% (w/v). Specifically, 35 g of stock extract was added per 1 L of coating solution. The mixture was homogenized using a Heidolph Diax 600 homogenizer at 600 rpm for 30 s.

Aqueous Chokeberry Extract

For the AAE treatment, a 3.5% (w/v) aqueous chokeberry extract was prepared by diluting the stock extract with distilled water and used directly as the treatment solution.

The concentration of chokeberry extract (3.5%) was selected based on literature data indicating that plant derived bioactive compounds are most effective in edible coatings within the range of 3 - 5%. Lower concentrations (<3%) are often insufficient to provide significant antimicrobial activity, while higher concentrations (>5 - 7%) may negatively affect the structural integrity, homogeneity, and mechanical properties of the coating matrix. Previous studies have demonstrated that the incorporation of plant extracts at approximately 3 - 5% provides an optimal balance between bioactivity and film forming properties [38,39]. Moreover, phenolic compounds present in chokeberry extract may interact with the CMC matrix, and excessive concentrations can destabilize the polymer network or limit the release of active compounds. Therefore, the selected 3.5% concentration represents a compromise ensuring sufficient biological activity while maintaining

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appropriate physicochemical properties of the coating. Additionally, the selected concentration was consistent with preliminary trials and aimed to avoid potential prooxidant or structural destabilization effects observed at higher phenolic loadings.

2.5. Storage Experiment and Quality Assessment

After 7 days of storage at 5°C and 80% relative humidity, the storage quality of the sliced peppers was assessed. Marketable value and softening were evaluated using a 9 - point rating scale commonly used in storage studies of fresh-cut products, including those by Stommel et al. [40], Zdulski et al. [41], and Grzegorzewska and Machlańska [42], who applied subjective assessment of visual quality in stored pepper slices. The following assessments were conducted in the storage experiment: market value, softening. Weight loss was expressed as the percentage difference between the initial mass and the mass after storage, relative to the initial mass of the sample.The assessment of marketable value was conducted using a conventional 9 - 1 rating scale, in which: 9 indicated excellent quality (as after cutting), 7 - good quality (slight defects, slightly lowering the quality), 5 - sufficient (light and medium defects - lower limit of marketability), 3 - fair (limit of usability), 1 - poor quality (unacceptable product). Pepper fruit softening was evaluated using a 9 - 1 visual scale based on tissue turgor and softening symptoms. The scale ranged from 9 (very firm, freshly harvested tissue) to 1 (extremely soft, decayed tissue), with 5 defined as the limit of marketability and 3 as the limit of edibility. Weight loss was determined as the percentage difference between the initial mass and the mass after the storage period, relative to the initial mass of the product.

2.6. Chemical Analysis

All chemical and microbiological analyses were conducted following the application of the edible coatings and subsequent short-term storage under controlled conditions, with all samples stored for 7 days at 5°C.

2.6.1. Analysis of Dry Matter Content

Dry matter was determined by the weight drying method in accordance with PN-90/A-75101/03 [43]. The pepper fruits were dried at 70°C under vacuum (3 kPa) to constant weight. The results are expressed in %.

2.6.2. Analysis of Total Sugar Content

Total sugar content was determined by high-performance liquid chromatography (Agilent 1200 HPLC system, equipped with a differential refractometer detector), using Aminex HPX-87C (300 mm × 7.5 mm) with a precolumn according to norm PN-EN 12630:2002 procedures [44]. Elution conditions were as follows: flow 0.6 ml min^{-1}, temperature 80 ◦C, mobile phase - edetate calcium disodium (Ca-EDTA, Sigma-Aldrich Chemie GmbH, Steinheim, Germany). Samples of peppers for sugar determinations were dissolved in redistilled water, homogenized, and purified on a Waters SepPak PLUS C18 filter (Waters, Milford, MA, USA). The sugars were quantified based on a calibration curve for sucrose, glucose, and fructose(Sigma-Aldrich Chemie GmbH, Steinheim, Germany), and the results were expressed as g·100 g^{-1} FM.

2.6.3. Analysis of L-Ascorbic Acid Content

The L-ascorbic acid content was determined by high-performance liquid chromatography (HPLC) using an Agilent system (Agilent Technologies, Waldbronn, Germany) equipped with a diode array detector (DAD). Chromatographic Separation was performed using a Supelco LC-18 column (250 mm × 4.6 mm; 5 µm) (Sigma-Aldrich Chemie GmbH, Darmstadt, Germany) with a precolumn according to IFU procedures; 1% phosphate-buffered solution KH_2PO_4, pH 2.5 (potassium phosphate, monobasic, JT Baker Chemicals, Phillipsburg, NJ, USA), was used as the mobile phase. The isocratic flow was 0.8 mL min^{-1}, with a temperature of 30 °C. The detection of L-ascorbic acid

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was based on the absorbance at 244 nm. Prior to analysis, pepper samples were homogenized and extracted in 6% HPO_3 (meta-phosphoric acid, Sigma-Aldrich Chemie GmbH, Steinheim, Germany), and subsequently filtered. Quantification was based on an calibration curve prepared using an L-ascorbic acid standard (Sigma-Aldrich Chemie GmbH, Steinheim, Germany). The results were expressed as mg·100g^{-1} FM.

2.6.4. Analysis of Total Polyphenol Content

The total polyphenol content (TPC) was determined using a spectrophotometric method according to Tsao and Yang [45]. Samples were first ground and homogenized, then centrifuged at 20,000 rpm for 10 minutes. An aliquot of 0.4 ml of the diluted phenolic extract was mixed with 1.6 ml of 7.5% sodium carbonate solution (Chempur, Piekary Śląskie, Poland). Subsequently, 2 mL of Folin-Ciocalteu reagent (Sigma-Aldrich Chemie GmbH, Darmstadt, Germany) was added, and the mixture was thoroughly shaken. The samples were incubated in the dark for 30 min at room temperature. The absorbance was then measured using a UviLine 9400 spectrophotometer (SI Analytics, Hofheim am Taunus, Germany) at a wavelength of 750 nm and compared to the blank sample. The total polyphenols content was expressed as milligrams of gallic acid equivalents (mg GAE) (Sigma-Aldrich Chemie GmbH, Steinheim, Germany) per kilogram of sample (mg · kg^{-1} FM).

2.6.5. Analysis of Total Carotenoids Content

Total carotenoids content was determined according to the method described by Bohoyo-Gil et al. [46]. Briefly, 5 g of fresh pepper fruit sample was weighed and homogenized in a hexane: acetone mixture (6:4, v/v) (JT Baker Chemicals, Phillipsburg, NJ, USA) with the addition of magnesium carbonate (Chempur, Piekary Śląskie, Poland). The homogenate was filtered under reduced pressure using a Büchner funnel. The filtrate was then transferred to a separatory funnel containing water and thoroughly mixed. After phase separation, the aqueous-acetone phase was discarded. The washing step was repeated until complete removal of acetone from the lower phase was achieved. The hexane fraction containing carotenoids was dried over anhydrous sodium sulfate (Chempur, Piekary Śląskie, Poland) and evaporated to dryness under vacuum at 40°C. The residue was re-dissolved in a mixture of acetonitrile: methanol:ethyl acetate (55:25:20, v/v/v) (JT Baker Chemicals, Phillipsburg, NJ, USA) supplemented with 0.1% BHT (Butylated hydroxytoluene, Merck KGaA, Darmstadt, Germany) and 1 ml TEA (Triethanolamine Avantor, Gliwice, Poland), followed by the addition of hexane (JT Baker Chemicals, Phillipsburg, NJ, USA). The extract was filtered through a 0.45 µm PTFE filter into amber vials prior to analysis. The total carotenoids analysis was performed using high-performance liquid chromatography (HPLC). Separation was carried out on a Kinetex C18 column (250 × 4.6 mm; 5 µm) using an Agilent 1200 HPLC system (Agilent Technologies, Waldbronn, Germany) equipped with a diode array detector (DAD). The chromatographic conditions were as follows: 0.7 ml min^{-1}, temperature 28°C, mobile phase: acetonitrile, ethyl acetate, methanol + 1 ml TEA + 1 g BHT in gradient flow. The detection of carotenoids was based on the absorbance at 450 nm. The quantification of carotenoids was carried out using a calibration curve prepared with a β-carotene standard (Sigma-Aldrich, Germany). The results were expressed as mg·kg^{-1} fresh mass (FM).

For the chemical analysis, pepper fruits were finely sliced and frozen at −20 °C and then ground in dry ice. The following chemical analyses of fruits of the pepper were carried out.

2.7. Microbiological Analyses

Polish standard methodologies were used to conduct microbiological analyses of pepper samples. Plant material (25 g) with peptone water (225 ml) was transferred into sterile stomacher filter bags 400 ml. The samples were homogenized in a stomacher BagMixer® 400P (8 stroke/s, 10 min). The serial dilution method and inoculation of selective media were used to determine the abundance and enumeration following microorganisms: aerobic mesophilic bacteria (plate count agar - PCA), yeasts and moulds (yeast extract glucose chloramphenicol agar - YGC). All used media

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were purchased from the Merck company (Germany). The obtained results were expressed as colony-forming units per gram of plant material (cfu g^{-1}). Each analysis was performed in three independent laboratory replicates. The data were transformed to logarithm (log_{10} cfu g^{-1}) for statistical analysis.

Microbiological analyses for the AAE treatment in the Yecla F_1 cultivar were not conducted due to insufficient sample material obtained after processing and coating application, and thus this variant was excluded from further microbiological evaluation.

2.8. Sensory Analysis

The sensory properties of the coated bell pepper slices were assessed by means of Quantitative Descriptive Analysis (QDA), following the procedural requirements of EN ISO 13299:2016 (Sensory analysis Methodology General guidance for establishing a sensory profile, 2016) [47]. This profiling method relies on the principle that overall sensory quality can be resolved into discrete attributes, each amenable to independent quantitative evaluation. All sessions were held in the sensory laboratory of the National Institute of Horticultural Research, which is fitted with individual evaluation booths meeting the specifications of PN ISO 8589:2010 (General Guidance on the Design of Sensory Analysis Laboratories, 2010) [48]. Assessments were carried out by a panel of 10 trained experts, all of whom had long standing experience in the sensory evaluation of vegetables, fruits, and spices. Prior to the main evaluation, a dedicated panel session was convened to define 14 quality descriptors spanning four attribute categories: smell, color, texture, and taste. Three slices of bell pepper from each cultivar and treatment combination were placed in 250 mL plastic containers equipped with lids and identified with randomly assigned numerical codes. Samples were presented to panelists in a randomized sequence to minimize order effects, and room temperature water was offered between evaluations for palate neutralization. Panelists rated the intensity of each descriptor on a continuous, unstructured line scale displayed on a monitor, anchored at 0 and 10 conventional units. The endpoints were labeled imperceptible and very intense for aroma and taste descriptors, while attribute specific anchors were used for color and texture; overall quality was bounded by poor quality and very good. Each evaluation was replicated across two independent sessions. Test design, individual score recording, and statistical processing were managed using ANALSENS ver. 6 software.

3. Statistical Analysis

The results of the chemical, microbiological, and postharvest quality analyses were statistically evaluated using STATISTICA v.13 (StatSoft, Tulsa, OK, USA; Dell Inc., Round Rock, TX, USA). Analyses were conducted separately for each variety using one-way analysis of variance (ANOVA). The results of chemical and microbiological analyses are presented as mean values from three replicates. Chemical analyses, microbiological, sensory, and postharvest quality analyses of coating treated samples were performed after storage. The significance of differences between means was assessed at a significance level of $\alpha = 0.05$, using Tukey's (HSD) test.

Sensory Analysis

To explore the multivariate structure of the sensory data and to visualize the associations among the evaluated attributes and the pepper samples, *Principal Component Analysis* (PCA) was applied. PCA reduces the dimensionality of complex datasets while preserving the maximum proportion of the original variance a feature that is especially valuable when numerous descriptors are assessed on a common scale, as is the case in *Quantitative Descriptive Analysis* (QDA) profiling. The computation was based on the correlation matrix, thereby standardizing all variables and ensuring that the contribution of each sensory attribute was weighted independently of its individual variance. Through this approach, the principal directions of variability within the dataset were identified, and the interrelationships between sensory descriptors and the analyzed samples were characterized. Outcomes were visualized as two-dimensional biplots to aid the interpretation of sensory profiles.

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Sources of variability considered in the analysis included evaluation session, individual assessor, and sample identity. All computations were carried out using the STATISTICA v. 13 (StatSoft, Tulsa, OK, USA; Dell Inc., Round Rock, TX, USA). software package (Dell Inc.).

4. Results

4.1. Chemical Analysis

The results of the chemical analyses of pepper fruits from the Yecla F_1 and Sunny F_1 cultivars subjected to the different treatments (CTRL, BAW, BAW+CMC, CMC+AE, and AAE) and short-term storage are presented in Table 1.

Table 1. Effect of edible coating treatments on the content of L-ascorbic acid, total polyphenols, total carotenoids, total sugars (mean values ± standard deviations) of fresh-cut pepper (Yecla F_1 and Sunny F_1) stored at 5 ◦C for 7 days.

Cultivar	Treatments	Dry Matter %	Total sugars g·100g^{-1} FM	L-ascorbic acid mg·100 g^{-1} FM	Total polyphenols mg·kg^{-1} FM	Total carotenoids mg·kg^{-1} FM
Yecla F_1	CTRL	8.95 ±0.07a	5.38 ±0.08 a	184.3 ±1.17 a	1006 ±1.74 a	52.1 ± 2.98a
	BAW	8.60 ±0.00 b	5.24 ±0.01 a	152.6 ±1.17 b	871.4 ±4.09 b	52.4 ±1.31 a
	BAW+CMC	8.60 ±0.00 b	5.24 ±0.02 a	144.1 ±0.49 c	812.9 ±6.68 c	56.7 ±0.85 a
	AAE	8.95 ±0.07 a	5.35 ±0.05 a	153.3 ±1.76 b	867.2 ±5.36 b	59.3 ±1.36 a
	CMC+AE	8.90 ±0.00 a	5.48 ±0.02 a	155.8 ±3.42 b	856.5 ±2.66 b	54.8 ±3.17 a
Sunny F_1	CTRL	8.45 ±0.07 b	5.01 ±0.07 a	190.8 ± 4.59 a	773.7 ±1.94 a	10.6 ±0.49 a
	BAW	8.70 ±0.11 ab	5.37 ±0.02 a	189.6 ±2.63 a	739.1 ±6.85 b	12.0 ±0.85 a
	BAW+CMC	8.80 ±0.00 a	5.25 ±0.03 a	172.8 ±3.51 b	717.1 ±1.13 c	12.2 ±0.73 a
	AAE	8.80 ±0.00 a	5.32 ±0.07 a	186.1 ±3.03 a	728.6 ±5.87 bc	12.6 ±1.86 a
	CMC+AE	8.70 ±0.00 ab	5.34 ±0.02 a	179.1 ±1.95 ab	729.1 ±2.56 bc	10.2 ±0.89 a

4.1.1. Dry Matter Content

The dry matter content was comparable in both cultivars; however, Yecla F_1 showed slightly higher values (8.60 - 8.95%) than Sunny F_1 (8.45 - 8.80%). In both cultivars, the effect of the applied coatings on this parameter was limited. In Yecla F_1, a significant decrease in dry matter content was observed following the application of BAW and BAW+CMC coatings, whereas in Sunny F_1, a slight but significant increase was noted after treatment with BAW+CMC and AAE (Table 1). Overall, the minor changes indicate that the coatings had only a limited effect on the water balance of the pepper fruits.

4.1.2. Total Sugar Content

Total sugar content was relatively uniform across cultivars and treatments. In Yecla F_1, it ranged from 5.24 to 5.48 g·100 g^{-1} FM, while in Sunny F_1 it ranged from 5.01 to 5.37 g·100 g^{-1} FM. No significant effect of the applied coatings on this parameter was observed (Table 1).

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4.1.3. L-Ascorbic Acid Content

The L-ascorbic acid content varied depending on the applied coating in both cultivars, although similar trends were observed. The mean content in control samples was 184.3 mg·100 g^{-1} FM for Yecla F_1 and 190.8 mg·100 g^{-1} FM for Sunny F_1. The greatest losses relative to the control were recorded after the application of the BAW+CMC coating in both cultivars, amounting to approximately 22% in Yecla F_1 and 9% in Sunny F_1. In Yecla F_1, all applied coatings significantly reduced L-ascorbic acid content, with the smallest decrease observed in the CMC+AE treatment. In contrast, in Sunny F_1, significant reductions were found only after the application of the BAW+CMC coating, whereas the remaining treatments did not differ significantly from the control. This indicates a greater stability of L-ascorbic acid in Sunny F_1.

4.1.4. Polyphenol Content

The total polyphenol content in control samples was 1006 mg·kg^{-1} FM for Yecla F_1 and 773.7 mg·kg^{-1} FM for Sunny F_1.The highest losses were observed after treatment with the BAW+CMC coating, reaching 19.1% and 7.3% for Yecla F_1 and Sunny F_1, respectively. In both cultivars, all coatings resulted in a significant decrease in polyphenol content; however, the BAW coating and coatings enriched with chokeberry extract (AAE, CMC+AE) limited these reductions to a greater extent (Table 1).

4.1.5. Carotenoid Content

The total carotenoid content in control samples was 52.1 mg·kg^{-1} FM for Yecla F_1 and 10.6 mg·kg^{-1} FM for Sunny F_1.The applied coatings did not significantly affect this parameter in either cultivar. All treatments maintained carotenoid levels comparable to the control (Table 1).

4.2. Microbiological Analysis

The microbiological quality of fresh-cut peppers and stored was assessed by determining the counts of mesophilic bacteria, yeasts, and moulds (Tables 2 and 3). Both cultivars exhibited relatively high initial microbial contamination, which is characteristic of fresh-cut produce due to tissue disruption and the release of nutrient rich cellular fluids during cutting operations.

Table 2. Effect of edible coating treatments on the microbiological contamination of fresh-cut pepper cv. Yecla F_1 stored at 5 °C for 7 days.

Treatment	The number of microorganisms presented as $\log_{10}$ cfu g^{-1} of plant material		
	mesophilic bacteria	yeast	moulds
CTRL	7.01±0.046c	6.04±0.088b	3.94±0.34a
BAW	6.20±0.038a	5.67±0.007a	3.85±0.21a
BAW+CMC	6.55±0.038b	5.50±0.063a	3.94±0.34a
CMC+AE	6.35±0.007a	5.60±0.042a	4.00±0.00a

Means in the same columns indicated by the same letter do not differ significantly according to Tukey test at p = 0.05.

In the case of the Yecla F_1 cultivar (Table 2), washing with BioActiW 2000 Food resulted in a significant reduction in mesophilic bacteria (6.20 $\log_{10}$ cfu g^{-1}) and yeast counts (5.67 $\log_{10}$ cfu g^{-1}) compared to the control (7.01 and 6.04 $\log_{10}$ cfu g^{-1}, respectively). The combined treatments, i.e., BAW + CMC (6.55 $\log_{10}$ cfu g^{-1}) and CMC + AE (6.35 $\log_{10}$ cfu g^{-1}), also significantly reduced bacterial counts. However, slightly higher bacterial levels were observed in the BAW + CMC treatment compared to sanitization alone. All treatments significantly reduced yeast counts relative to the control, with no statistically significant differences among the treated variants. Mould counts remained at a

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comparable level across all treatments (3.85 - 4.00 $\log_{10}$ cfu g^{-1}), with no significant differences observed.

Table 3. Effect of edible coating treatments on the microbiological contamination of fresh-cut pepper cv. Yecla F_1 stored at 5 ◦C for 7 days.

Treatment	The number of microorganisms presented as $\log_{10}$ cfu g^{-1} of plant material		
	mesophilic bacteria	yeast	moulds
CTRL	7.36±0.157b	6.30±0.000ab	
BAW	7.13±0.027ab	6.30±0.000ab	
BAW+CMC	6.95±0.009a	6.14±0.088a	<2.00
CMC+AE	7.19±0.016ab	6.07±0.103a	
AAE	7.85±0.000c	6.48±0.000b	

Means in the same columns indicated by the same letter do not differ significantly according to Tukey test at $p < 0.05$.

For the Sunny F_1 cultivar (Table 3), the BAW + CMC treatment was the most effective in reducing mesophilic bacteria (6.95 $\log_{10}$ cfu g^{-1}), showing a statistically significant decrease compared to the CTRL (7.36 $\log_{10}$ cfu g^{-1}). Yeast counts were lowest in the BAW + CMC (6.14 $\log_{10}$ cfu g^{-1}) and CMC + AE (6.07 $\log_{10}$ cfu g^{-1}) treatments, although differences among treatments were less pronounced. Notably, the application of AAE (without prior sanitization) resulted in the highest counts of mesophilic bacteria (7.85 $\log_{10}$ cfu g^{-1}) and yeasts (6.48 $\log_{10}$ cfu g^{-1}) among all treatments. Mould counts in all treatments remained below the detection limit (<2.00 $\log_{10}$ cfu g^{-1}).

4.3. Postharvest Treatment

Postharvest treatments affected both softening and marketable value, and the response depended on cultivar. In Yecla F_1, softening did not differ significantly between the control and BAW or BAW+CMC, but it was higher after CMC+AE and AAE. Marketable value was significantly higher in BAW and BAW+CMC than in the control, whereas CMC+AE and AAE did not differ significantly from the control. In Sunny F_1, softening was significantly reduced by BAW and BAW+CMC, while CMC+AE and AAE did not differ significantly from the control. All treatments increased marketable value relative to the control, with the highest scores recorded for BAW and BAW+CMC. Overall, BAW-based treatments, especially when combined with CMC, were the most effective in limiting softening and maintaining marketable quality (Figure 2, 3).

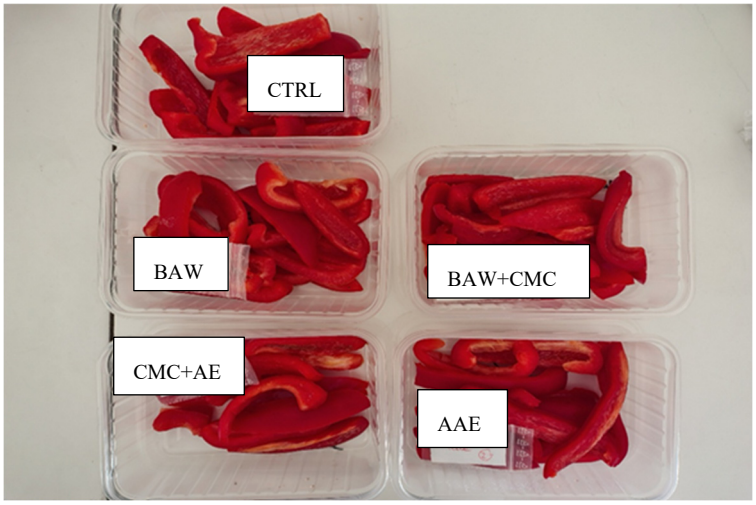

Figure 2. Fresh-cut Yecla F_1 peppers stored at 5 ◦C for 7 days.

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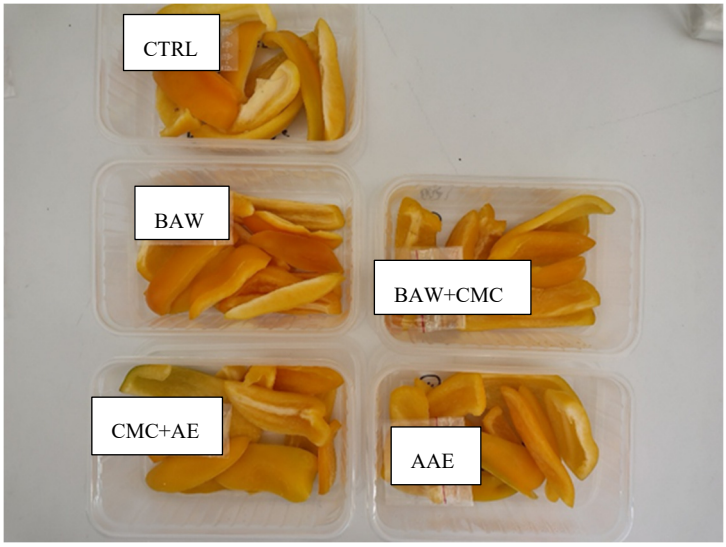

Figure 3. Fresh-cut Sunny F1 peppers stored at 5 ◦C for 7 days.

Values are presented as mean ± standard deviation (SD). Different letters within each cultivar and column indicate significant differences at $p < 0.05$ according to Tukey's HSD test. Quality evaluating scales: **softening**: 1 – lack, 3 – light, 5 – medium (clearly perceptible), 7 – strong (soft stripes), 9 – very strong (completely soft stripes); **marketable value**: 9 – excellent (as after cutting), 7 – good (slight defects, slightly lowering the quality), 5 – sufficient (light and medium defects – lower limit of marketability), 3 – fair (limit of usability) , 1 – poor (inedible)

All treatments significantly reduced weight loss in fresh-cut pepper compared to the control, although their effectiveness varied depending on the cultivar (Table 4).

Table 4. Effect of postharvest edible coating treatments and weight loss (%) of fresh-cut pepper (Yecla F1 and Sunny F1) stored at 5 ◦C for 7 days.

cultivar	post-harvest treatment	Quality of cut pepper		
		softening	marketable value	weight loss (%)
Yecla F1	CTRL	3.0±0.44a	4.3±1.45a	0.34±0.04a
	BAW	2.8±0.32a	5.7±1.15b	0.23±0.03c
	BAW+CMC	2.4±0.27a	5.6±1.44b	0.22±0.02c
	CMC+AE	3.8±0.26b	4.8±1.56a	0.25±0.03bc
	AAE	3.5±0.34b	4.4±1.43a	0.3±0.04ab
Sunny F1	CTRL	2.8±0.43a	5.6±1.21a	0.28±0.03a
	BAW	2.0±0.53b	7.0±1.32c	0.21±0.02b
	BAW+CMC	1.9±0.36b	7.2±1.41c	0.22±0.03b
	CMC+AE	2.9±0.44a	6.5±1.19b	0.23±0.03b
	AAE	2.6±0.38a	6.0±1.23b	0.27±0.02a

All treatments reduced weight loss relative to the control, although the magnitude of the effect varied between cultivars. In Yecla F1, the highest weight loss was observed in the control, while the lowest values were recorded for BAW and BAW+CMC. CMC+AE showed intermediate performance, and AAE was less effective. In Sunny F1, BAW, BAW+CMC, and CMC+AE all reduced weight loss to a similar extent, whereas AAE again showed only limited effectiveness. Overall, the BAW based treatments, particularly in combination with CMC, were the most effective in limiting water loss during storage.

4.4. Results of Sensory Analysis

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The screen plot shows the distribution of eigenvalues obtained from PCA of sensory attributes of fresh-cut peppers and stored (Yecla F_1 and Sunny F_1) (Figure 4). The first principal component (PC1) explained 36.2% of the total variance, while PC2 accounted for 18.9%, giving a cumulative contribution of 55.1%. Eigenvalues decreased progressively for subsequent components, with a clear inflection point ("elbow") observed after the third fourth component. This indicates that the main structure of the data is adequately described by the first few principal components, whereas the remaining components contribute only marginally to the explained variance.

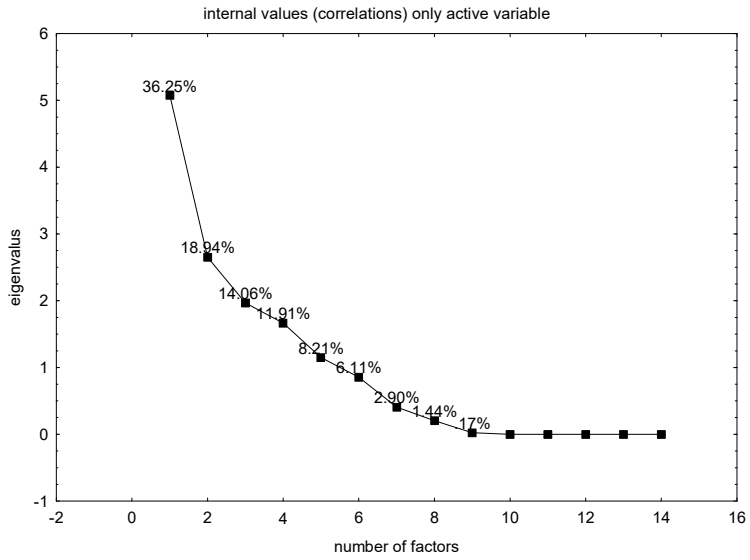

Figure 4. Screen diagram formed based on results of sensory evaluation of fresh-cut pepper.

The variable importance analysis showed that aroma and taste related attributes were the main contributors to perceived quality (Figure 5). Pepper smell, off-smell, pepper taste, fleshiness, color, and sweet taste had the highest importance values, while overall quality and off-taste made a moderate contribution. In contrast, cultivar related variables had lower importance, suggesting that the sensory profile was driven mainly by attribute composition rather than cultivar identity alone.

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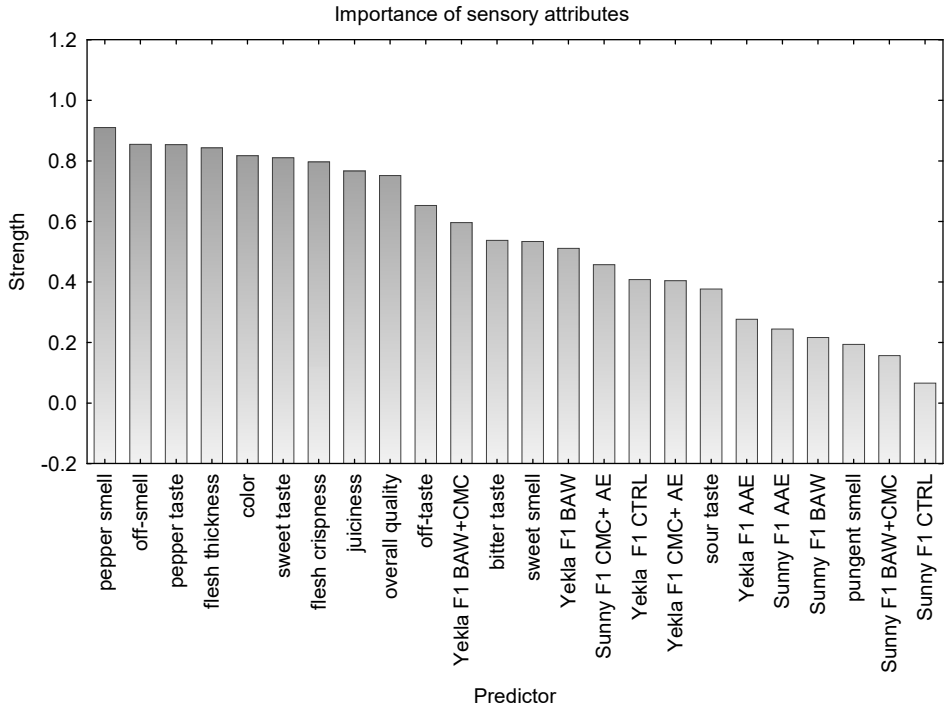

Figure 5. Variable importance ranking showing the relative contribution of individual variables to the model. Variables are ordered from highest to lowest importance.

Principal component analysis (PCA) was applied to explore the relationships between sensory attributes and fresh-cut bell pepper samples cv. Yecla F_1 and Sunny F_1 subjected to different edible coating treatments after short-term storage (Figure 6). The first two principal components accounted for 55.70% of the total variance (PC1: 36.25%; PC2: 19.45%). PC1 differentiated the samples according to overall sensory quality. On the positive side of PC1, vectors corresponding to juiciness, overall quality, sweet taste, pepper smell, and flesh thickness and flesh crispness were grouped, and Sunny F_1 samples in particular the CTRL, BAW+CMC, and CMC+AE treatments - clustered in this area, indicating their superior sensory profile. Conversely, the negative side of PC1 was characterized by vectors for off-taste, off-smell, bitter taste, and, to a lesser extent, sour taste and sour smell. This area was occupied predominantly by Yecla F_1 samples, especially the uncoated control (CTRL) and the aqueous chokeberry extract treatment (AAE). PC2 resolved differences in the aromatic profile of the samples. Pepper taste and off-smell loaded toward the positive end of PC2, whereas sweet smell and pungent smell loaded toward the negative end, reflecting variation in the volatile perception among treatments and cultivars. Among the coating treatments, CMC+AE produced the most pronounced shift toward favorable sensory coordinates, particularly for the Sunny F_1 cultivar. A similar, though less marked, trend was observed for BAW+CMC. Overall quality was positively correlated with flesh texture and firmness, as indicated by the codirectional orientation of the corresponding vectors along PC1, confirming that textural preservation is a key determinant of perceived quality in coated fresh-cut peppers.

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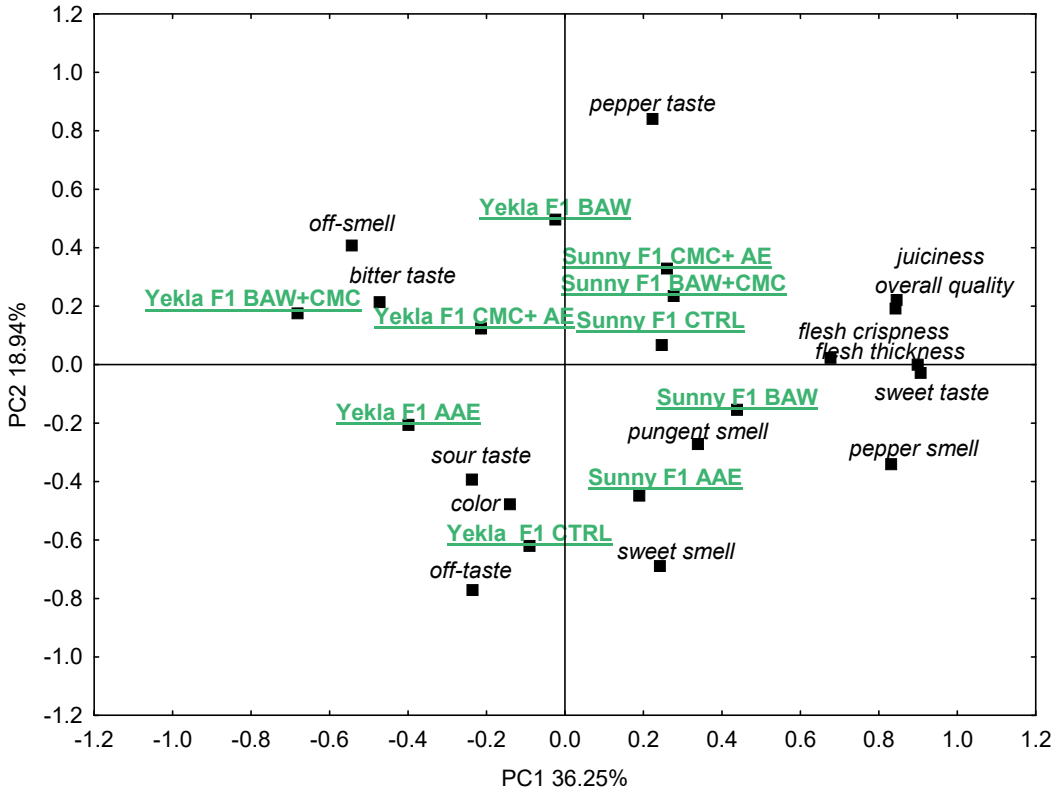

Figure 6. Principal component analysis (PCA) biplot of sensory attributes and samples of fresh-cut pepper (*Capsicum annuum* L.) cultivars Yecla F_1 and Sunny F_1 treated using the following combinations: control (**CTRL**) – washing with water, washing with Bio-ActiW 2000 Food (**BAW**), washing in Bio-ActiW 2000 Food followed by treatment with a carboxymethylcellulose (CMC) coating (**BAW+CMC**), application of a CMC coating with the addition of a 3.5% alcoholic extract from chokeberry pomace (**CMC+AE**), and soaking in a 3.5% aqueous extract from chokeberry pomace (**AAE**). Sensory attributes (e.g., overall quality, juiciness, sweet taste, sweet smell, pepper smell, pepper taste, off-taste, off-smell, color) are represented as vectors, indicating their contribution to sample differentiation.

5. Discussion

Studies by Hassan et al. [49,50] demonstrated that coatings based on carboxymethyl cellulose (CMC) indirectly affect dry matter content in vegetables, mainly by reducing transpiration and respiration rates. Such coatings form a semi-permeable barrier that likely limits water loss and gas exchange, thereby reducing moisture loss and slowing metabolic processes. Furthermore, reduced water loss in CMC-coated products results in relatively stable dry matter content, in contrast to control samples, where its apparent increase may result from more intensive tissue dehydration [51]. Similarly, Sapper and Chiralt [52] reported that polysaccharide-based coatings, including CMC, stabilize the chemical composition of plant materials by limiting gas exchange and slowing metabolic processes. Therefore, the results obtained in this study are consistent with literature data and indicate that CMC coatings can contribute to the stabilization of dry matter content by reducing tissue dehydration. In turn, studies by Rojas-Graü et al. [53], Khaliq et al. [54], Hassan et al. [49], and Ali et al. [55] have shown that the application of sodium hypochlorite does not significantly affect the dry matter content of vegetables, as it does not form a barrier limiting transpiration and gas exchange. Its effect is short-term; therefore, changes in this parameter are minor and mainly result from natural physiological processes. Unlike polysaccharide-based coatings (e.g., CMC), sodium hypochlorite does not stabilize dry matter content and, in some cases, may even promote water loss, which was also observed in the present study.

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The lack of significant differences in total sugar content further suggests that the applied treatments had only a minor direct effect on carbohydrate metabolism and acted mainly through physical modification of the fruit surface environment [53,55]. This interpretation is consistent with literature reports indicating that edible coatings, particularly those based on polysaccharides such as CMC, reduce transpiration and respiration rates but do not necessarily lead to substantial changes in soluble sugar content [53,55]. Overall, the stability of this parameter supports the conclusion that the coatings functioned primarily as a physical barrier without significantly interfering with carbohydrate metabolism

In the present study, coating treatments, particularly CMC+Activ, led to a significant reduction in L-ascorbic acid content. At the same time, coatings enriched with chokeberry extract limited these losses, although they did not prevent them to a level comparable with the control. This indicates that the composition of the coating plays a crucial role in the stability of this vitamin, which may be related to its high susceptibility to oxidation and changes in physiological conditions within plant tissues.

The obtained results are partially consistent with literature reports. Perez-Vazquez et al. [56] and Ali et al. [57]indicated that L-ascorbic acid is highly susceptible to oxidation, and its degradation depends on oxygen availability and respiration intensity. On the one hand, coatings limit oxygen access, which should favor its preservation; on the other hand, they may induce physiological changes in tissues that accelerate its degradation. Other studies have shown that properly designed coatings, especially those enriched with antioxidant compounds, can effectively reduce vitamin C losses and improve its stability during storage [58]. This is also confirmed by recent studies, where the application of active coatings (e.g., containing antioxidants) resulted in better quality retention and higher L-ascorbic acid content compared to control samples [59]. This may explain the higher retention of L-ascorbic acid observed in the present study for coatings containing chokeberry extract in both cultivars.

In the present study, in both cultivars, the application of edible coatings resulted in a significant decrease in polyphenol content; however, the Active coating and coatings enriched with chokeberry extract limited this reduction to a lesser extent. This phenomenon is supported by literature data. Vallverdú-Queralt et al. [60] emphasized that phenolic compounds are synthesized in response to oxidative stress, and their levels may decrease under conditions of reduced exposure to stress factors. Edible coatings, by limiting oxygen availability and slowing metabolic processes, may reduce oxidative stress, leading to lower accumulation of polyphenols. In contrast to vitamin C, whose decrease is mainly associated with oxidative degradation, the reduction in polyphenol content may result both from decreased biosynthesis and changes in enzyme activity. Similar relationships were described by Rojas-Graü et al. [53], who indicated that edible coatings can modify plant secondary metabolism. According to Mannozzi et al. [61] and Khaliq et al. [54] polysaccharide-based coatings may limit oxygen access and slow metabolic processes; however, their effect depends on the coating type and storage conditions.

Here, total carotenoid content showed considerably lower variability compared to L-ascorbic acid and polyphenols, confirming their greater stability under different coating treatments. Only minor changes were observed, often within the range of experimental error. In some cases, a slight increase in carotenoid content was noted, which may be attributed to reduced degradation processes.

These results are consistent with literature reports. Meléndez-Martínez et al. [62] indicated that carotenoids are more resistant to storage conditions than vitamin C, and their degradation occurs mainly under the influence of light, high temperature, and oxygen. Under limited gas exchange conditions, such as those provided by edible coatings, the rate of these processes may be further reduced [63]. Moreover, edible coatings can act as a physical barrier that reduces oxygen availability and limits pigment oxidation. It has been shown that polysaccharide-based coatings (e.g., CMC) can slow the degradation of β-carotene and lycopene in carrots and tomatoes during refrigerated storage [64,65].

The relatively high initial microbial loads are typical of minimally processed produce, where cutting releases nutrients and creates favorable conditions for microbial growth [66,67]. In this

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context, the effect of BioActiW 2000 Food confirms that an effective sanitization step is an important prerequisite for reducing initial contamination before coating application [68,69]. The additional reduction seen with BAW+CMC suggests that the CMC layer contributed mainly by limiting surface exchange and modifying the product microenvironment [70–72]. By contrast, the addition of chokeberry extract did not consistently increase antimicrobial efficacy beyond that of CMC alone. Although chokeberry phenolics have documented antimicrobial activity, their performance in a coating matrix depends on extract composition, concentration, release kinetics, and the structure of the resident microflora [73–75]. The poorer microbiological outcome of AAE in Sunny F_1 indicates that the extract alone was not sufficient to suppress native contamination and may even have provided a more favorable medium for microbial growth under some conditions [76].

The postharvest quality results show that sanitization was the main driver of quality retention, while the CMC coating added a further protective effect, especially with respect to weight loss. In both cultivars, BAW and BAW+CMC were the most effective treatments for limiting softening and maintaining higher marketable value. This pattern is consistent with earlier reports showing that microbiological control is closely linked to slower quality deterioration in fresh-cut vegetables [77,78], and that CMC coatings can reduce water loss by limiting transpiration in bell pepper [79,80]. The weaker performance of AAE suggests that the extract alone was not sufficient to preserve tissue integrity during the 7 day storage period. The greater softening observed in Yecla F_1 after CMC+AE and AAE may reflect cultivar specific sensitivity to the formulation rather than a universal effect of chokeberry extract. One possible explanation is the acidic nature of the extract, which could influence tissue firmness, but this remains speculative because tissue pH, respiration rate, and cell wall modifying enzyme activity were not measured.

The sensory results reinforce the cultivar dependence of the response to treatment. PCA showed that aroma, taste, and texture were the main drivers of perceived quality, whereas cultivar identity contributed less than the sensory attributes themselves [81–83]. Sunny F_1 generally occupied the more favorable region of the sensory map, especially after BAW+CMC and CMC+AE treatment, suggesting better compatibility with the tested coatings. Yecla F_1, by contrast, was more strongly associated with off-taste and off-smell descriptors, particularly in the control and AAE samples. This pattern is consistent with the idea that chokeberry extract may introduce sensory trade off that are acceptable in some cultivars but not in others [84]. The favorable position of CMC+AE in Sunny F_1 indicates that the extract can be incorporated without compromising acceptability in selected materials, but the negative response in Yecla F_1 shows that formulation must be optimized for the raw material.

Taken together, the data show that the strongest and most reproducible benefits were obtained when sanitization was combined with a CMC coating. In this study, adding chokeberry extract to the coating produced mixed effects: it may have helped retain selected bioactive compounds, but it did not consistently improve microbiological or textural performance, and its sensory impact depended on cultivar. The practical value of chokeberry pomace extract therefore appears conditional rather than universal, and its use requires careful adjustment of concentration and pH as well as attention to the characteristics of the pepper cultivar [85].

6. Conclusions

This study shows that CMC based edible coatings can help maintain the quality and microbiological safety of fresh-cut sweet peppers during refrigerated storage, but their effectiveness depends strongly on prior sanitization. Among the tested treatments, BioActiW 2000 Food combined with CMC coating (BAW+CMC) gave the most consistent overall performance, reducing microbial contamination, limiting weight loss, and preserving marketable quality and tissue firmness in both cultivars. These results indicate that sanitization is the key step for microbiological stability, while the CMC coating provides an additional barrier effect.

The incorporation of chokeberry pomace extract into the CMC coating had mixed effects. It helped retain some bioactive compounds, particularly polyphenols and L-ascorbic acid, but did not consistently improve antimicrobial performance or texture, and its sensory impact depended on

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cultivar. Sunny F_1 responded more favorably to treatments containing chokeberry extract, whereas Yecla F_1 was more sensitive to off-flavors, showing that the same formulation may behave differently depending on the raw material.

Overall, the findings support CMC based coatings as a promising approach for fresh-cut pepper preservation, but the addition of plant extracts should be treated as a cultivar-sensitive modification rather than a universal improvement.

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