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Characterization of Multifunctional Edible Coatings Incorporating Sugar Beet Extracts

Caracterización de Recubrimientos Comestibles Multifuncionales que Incorporan Extractos de Remolacha Azucarera

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Abstract:

This study presents an innovative approach to valorizing sugar beet agro-industrial residues by developing multifunctional edible coatings with enhanced antioxidant and antimicrobial properties. Using natural bioactive compounds, the study addresses the growing demand for clean-label food products while promoting environmental sustainability. Additionally, this research contributes to the circular economy by converting agricultural by-products into high-value functional ingredients, supporting sustainable agricultural and food processing practices. The results provide a scientific basis for the potential application of these coatings in food preservation, offering a natural and sustainable alternative to synthetic additives. Future research should explore the sensory attributes and functional performance of these coatings in real food systems to validate their effectiveness in practical applications. Moreover, investigating the synergistic effects of combining sugar beet extracts with other natural preservatives, such as essential oils and plant-derived antimicrobials, could further enhance their functionality.

Keywords:

Sugar beet, food waste, edible coatings

Resumen:

Este estudio presenta un enfoque innovador para valorizar los residuos agroindustriales de la remolacha azucarera mediante el desarrollo de recubrimientos comestibles multifuncionales con propiedades antioxidantes y antimicrobianas mejoradas. Al utilizar compuestos bioactivos naturales, el estudio aborda la creciente demanda de productos alimenticios de etiqueta limpia al tiempo que promueve la sostenibilidad ambiental. Además, esta investigación contribuye a la economía circular al convertir los subproductos agrícolas en ingredientes funcionales de alto valor, lo que respalda las prácticas agrícolas y de procesamiento de alimentos sostenibles. Los resultados proporcionan una base científica para la posible aplicación de estos recubrimientos en la conservación de alimentos, ofreciendo una alternativa natural y sostenible a los aditivos sintéticos. Las investigaciones futuras deberían explorar los atributos sensoriales y el rendimiento funcional de estos recubrimientos en sistemas alimentarios reales para validar su eficacia en aplicaciones prácticas. Además, la investigación de los efectos sinérgicos de la combinación de extractos de remolacha azucarera con otros conservantes naturales, como aceites esenciales y antimicrobianos derivados de plantas, podría mejorar aún más su funcionalidad.

Palabras Clave:

Remolacha azucarera, residuos alimentarios, recubrimientos comestibles

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1. Introduction

Food preservation is a critical challenge in the food industry, driven by increasing consumer demand for natural, sustainable, and functional packaging solutions [1]. Traditional methods, such as synthetic preservatives and plastic packaging, have been effective in extending shelf life but are associated with environmental and health concerns. In particular, synthetic additives have raised safety issues due to their potential toxicological effects, while plastic waste contributes significantly to environmental pollution [2]. In response to these challenges, edible coatings have emerged as a promising technology for enhancing food safety and extending shelf life [3]. These coatings act as protective barriers that reduce moisture loss, oxygen permeability, and microbial contamination while maintaining the sensory and nutritional quality of food products [4].

The incorporation of natural bioactive compounds into edible coatings provides additional functionalities, such as antioxidant and antimicrobial activities, thereby reducing the need for synthetic additives [5]. Natural antioxidants, including phenolic compounds and anthocyanins, are known for their ability to scavenge free radicals, inhibit lipid oxidation, and prevent oxidative spoilage [6]. Similarly, plant-derived antimicrobials can inhibit the growth of foodborne pathogens and spoilage microorganisms, enhancing food safety and extending shelf life [7]. These multifunctional properties have made edible coatings an attractive and effective solution for maintaining food quality and safety. Recent studies have demonstrated the effectiveness of bioactive-enriched edible coatings in preserving the freshness of fruits, vegetables, and meat products. For example, coatings enriched with phenolic extracts have been shown to reduce oxidative damage and microbial growth, maintaining the sensory and nutritional quality of food products [8].

Sugar beet (*Beta vulgaris L. var. saccharifera*) is widely cultivated for sugar production, generating significant agro-industrial residues, including leaves, stems, and pulp. These by-products are rich in bioactive compounds, particularly phenolics and anthocyanins, which exhibit potent antioxidant and antimicrobial properties [9]. Phenolic compounds, such as flavonoids and phenolic acids, are known for their strong radical scavenging activity, metal chelation, and inhibition of lipid peroxidation. Anthocyanins, a subclass of flavonoids, contribute not only to antioxidant activity but also to the vibrant color of the extracts, enhancing the visual appeal of edible coatings. However, despite their high functional potential, sugar beet residues are largely underutilized, often disposed of as waste, or used for low-value applications such as animal feed [10]. This underutilization not only leads to environmental pollution but also represents an economic loss, highlighting the need for sustainable valorization strategies.

Recent studies have explored the extraction of bioactive compounds from various plant residues, highlighting their potential as natural preservatives in food packaging systems. For example, phenolic-rich extracts from fruit peels and vegetable by-products have been successfully incorporated into edible coatings to enhance antioxidant and antimicrobial properties [11]. However, limited research has focused on the use of sugar beet residues for developing multifunctional edible coatings, despite their high content of phenolics and anthocyanins. The effective utilization of these residues requires efficient extraction methods that maximize the recovery of bioactive compounds while preserving their antioxidant capacity and bioactivity [12]. Traditional extraction methods often involve the use of organic solvents, which can be hazardous to human health and the environment. In contrast, ultrasound-assisted aqueous extraction (UAAE) has emerged as an efficient and environmentally friendly method for extracting phenolics and anthocyanins from plant residues. This technique utilizes ultrasonic waves to enhance mass transfer and cell wall disruption, resulting in higher extraction yields and shorter processing times compared to conventional methods [13, 14].

This study aims to develop and characterize multifunctional edible coatings formulated with sugar beet extracts obtained from leaves, stems, and pulp. Specifically, the coatings were evaluated for their physicochemical properties, antioxidant activity, and antimicrobial efficacy against common foodborne pathogens and spoilage microorganisms. It is hypothesized that the incorporation of sugar beet extracts will enhance the antioxidant and antimicrobial properties of the edible coatings, with variations depending on the part of the beet plant used. Coatings with leaf and stem extracts are expected to exhibit higher antioxidant activity due to their higher phenolic and anthocyanin contents, while coatings with pulp extract may demonstrate enhanced antimicrobial properties due to their specific bioactive profile.

By valorizing sugar beet agro-industrial residues, this research proposes an innovative and sustainable approach to enhance food preservation and safety. The utilization of natural bioactive compounds aligns with the growing consumer demand for clean-label products while contributing to environmental sustainability. Moreover, the incorporation of these extracts into edible coatings provides a dual functionality by acting as a physical barrier and inhibiting oxidative and microbial spoilage. The findings contribute to the development of natural, eco-friendly food packaging solutions, offering an alternative to synthetic additives and conventional plastics. Furthermore, this study supports the principles of the circular economy by converting agro-industrial waste into high-value functional ingredients, promoting sustainable agricultural and food processing practices.

2. Materials and Methods

2.1. Materials

Sugar Beet (Beta vulgaris L. var. saccharifera) was used: Beet leaves (BL), stems (BS), and pulp (BP) were provided by IANSA S.A (Linares, Chile). The diammonium salt of 2,2′-azino-bis-3-ethylbenzothiazoline-6-sulfonic acid (ABTS) ≥98%, and 2,4,6-tris(2-pyridyl)-s-triazine (TPTZ) used for the Ferric Reducing Antioxidant Power (FRAP) assay, as well as the Folin-Ciocalteu reagent, were purchased from Sigma Aldrich (St. Louis, MO, USA). Hydroxypropylmethylcellulose (HPMC) was used as a plant polysaccharide (Gelymar®, Santiago, Chile). All other reagents used in this study are of analytical grade and were obtained from Merck KGaA (Darmstadt, Germany).

2.2. Methods

2.2.1. Conditioning of Agro-Industrial Waste

The beet leaves, stems, and pulp were washed with a 600-ppm sodium hypochlorite solution to remove impurities and reduce the microbial load of the residues. Subsequently, they were dried at room temperature (20°C) and ground into small particles.

2.2.2. Ultrasound-Assisted Aqueous Extraction

The aqueous extraction of sugar beet pulp, leaves and stem was complemented with ultrasound to release the bioactive compounds through cavitation. The solid/solvent ratio (beet residues/Type 1 water) used for extraction was 1:2. The mixture was heated to 60°C under controlled magnetic stirring at 1500 rpm for 1 hour. An ultrasonic extractor (Elma S10H, CA, USA) operating at a frequency of 80 kHz was then used for 15 minutes. Finally, the resulting mixture was vacuum filtered using Whatman No. 1 filter paper and stored under refrigeration (4°C ± 1) until characterization [15].

2.2.3. Multifunctional Edible Coatings

HPMC was used as a wall material. The methodology involved heating the suspension to 90°C and maintaining this temperature for 1 hour to ensure complete dissolution of the polysaccharide. The temperature was then reduced to 30°C to incorporate the sugar beet waste extracts into the matrix by dripping and constant stirring at 700 rpm. Finally, the samples were stored under refrigeration (4°C), protected from light, to evaluate their stability over time through antioxidant and microbial activity assays [16].

2.2.4. Physicochemical Properties

pH

The pH of coatings containing sugar beet residue extracts was measured using a digital pH meter previously calibrated with standard buffer solutions at pH 4.00, 7.00, and 10.00. Measurements were taken at room temperature (20°C) and recorded in triplicate to obtain a representative average value.

Soluble Solids

The concentration of soluble solids of coatings containing sugar beet residue extracts was determined using a refractometer, calibrated for a range of 0 to 32 °Brix. Samples were analyzed at room temperature (20°C) and in triplicate to ensure the accuracy and reproducibility of the results.

Density

The density of coatings containing sugar beet residue extracts was determined using a 25 mL pycnometer. The pycnometer was filled with the sample, the temperature adjusted to 20°C, and weighed using an analytical balance. Density values were calculated from the measured masses and the known volume of the pycnometer and were conducted in triplicate to ensure data accuracy.

Color

Color analysis of coatings containing sugar beet residue extracts was performed using a Hunter Lab colorimeter equipped with a D65 illuminant to simulate daylight. Color was expressed in terms of the L*, a*, and b* parameters according to the CIE Lab scale [17].

2.2.5. Antioxidant properties of coatings containing sugar beet residue extracts

Total Phenolic Compounds (TPC)

The quantification of total phenolic compounds (TPC) was carried out following the method by Cano [18] with minor modifications. Ten µL of the sample was added to a semi-micro spectrophotometry cuvette, followed by 750 µL of distilled water. Then, 50 µL of Folin–Ciocalteu reagent was added, vortexed for 15 seconds, and allowed to rest for 3 minutes. Next, 150 µL of a 7.5% (w/v) sodium carbonate solution was added, and the mixture was kept in the dark for 1 hour. Absorbance was measured at 750 nm using a UV-VIS spectrophotometer (Metash Inst.®, UV-6100, Shangai, China). Results were expressed as milligrams of gallic acid/ml of extract.

Total Anthocyanins Content (TAC)

Total anthocyanin content (TAC) was determined using the pH differential method, which exploits the structural change of the anthocyanin chromophore between pH 1 and 4.5. Two buffer solutions were prepared: one of potassium chloride (0.025 M) adjusted to pH 1, and another of sodium acetate (0.4 M) adjusted to pH 4.5. In 1.5 mL Eppendorf microtubes, a 200 µL aliquot of the sample was added and diluted with 800 µL of the potassium chloride buffer solution. The same procedure was repeated with the sodium acetate buffer solution. Mixtures were incubated at 20°C in the dark for 30 minutes. Absorbance was measured at 520 nm and 700 nm in 1.5 mL semi-micro cuvettes using a UV-VIS spectrophotometer (Metash Inst.®, UV-6100, Shangai, China). Results were expressed as milligrams of cyanidin-3-glucoside/ml of extract [19].

ABTS Assay

The antioxidant activity of ABTS radicals in the samples was determined using a procedure adapted from Sridhar & Charles [20], with minor modifications. A stock solution of ABTS radicals (7 mM ABTS in 2.45 mM K2S2O8) was prepared and kept in the dark for 24 hours. After this period, an aliquot of the stock solution was diluted to achieve an absorbance of 0.7 ± 0.02 at 734 nm (adjusted ABTS). A control was prepared by mixing 20 µL of ethanol with 980 µL of the adjusted ABTS. Simultaneously, 20 µL of the sample was mixed with 980 µL of the adjusted ABTS and the reaction was carried out in the dark at 20°C for 10 minutes. Absorbance was measured at 734 nm using a UV-VIS spectrophotometer (Metash Inst.®, UV-6100, Shangai, China). Results were expressed as Trolox equivalent/ml of extract.

FRAP Assay

Antioxidant capacity measured by the FRAP assay was evaluated following the method adapted from Alemán [21] with minor modifications. In 1.5 mL semi-micro cuvettes, 30 µL of the sample was mixed with 90 µL of distilled water and 900 µL of the FRAP reagent, consisting of a mixture of 25 mL of sodium acetate buffer (pH 3.6), 2.5 mL of 10 mM TPTZ solution, and 2.5 mL of 20 mM ferric chloride solution. The cuvettes were incubated at 37°C for 30 minutes in a temperature-controlled water bath (Memmert®, WTB6, Germany). After the incubation period, absorbance was measured at 595 nm using a UV-VIS spectrophotometer (Metash Inst.®, UV-6100, Shangai, China). Results were expressed as Mohr equivalent/ml of extract.

2.2.6. Antimicrobial and Antifungal Activity

The antimicrobial activity of coatings containing sugar beet residue extracts was evaluated using inhibition zone assays against pathogenic microorganisms associated with contamination in processed food production lines, such as *Escherichia coli*, *Enterococcus faecalis* (Gram -), and *Staphylococcus aureus* and *Bacillus cereus* (Gram +). Additionally, the antifungal effect was investigated using *Aspergillus brasiliensis* [22].

2.3. Statistical Analysis

All assays described in this manuscript were performed in triplicate, and the experimental data obtained were expressed as mean ± standard deviation. Differences between three or more groups were evaluated using ANOVA tests, followed by Tukey's comparison tests with a 95% confidence level ($p<0.05$) to establish statistical significance [23]. All statistical analyses were conducted using STATGRAPHICS Centurion XVI, v.16.1.03 (StatPoint Technologies, Inc., Warrenton, VA, USA).

3. Results

In this study, the effects of edible coatings formulated with sugar beet extracts on physicochemical properties, antioxidant activity, and antimicrobial efficacy were evaluated. The edible coatings were coded as follows: H296 corresponds to the edible coating with sugar beet leaf extract, T342 represents the edible coating with sugar beet stem extract, and P451 refers to the edible coating with sugar beet pulp extract. The results are presented in the following sections, highlighting the differences in composition and functionality among the coatings.

3.1. Physicochemical Properties of Edible Coatings Incorporating Beet Extracts

The physicochemical properties, including pH, soluble solids (°Brix), density, and color parameters (L*, a*, b*), were analyzed to evaluate the impact of different extraction methods on the resulting extracts. Significant differences were observed in pH, soluble solids, and color parameters among the samples ($p < 0.0001$), suggesting that the extraction conditions and the nature of the raw material influence these properties. Notably, sample P451 showed the highest concentration of soluble solids, suggesting a higher sugar content in the pulp. Meanwhile, the sample T952 displayed the most significant color variation, reflecting the pigment composition of the stems. The density values were consistent across all samples, indicating a similar liquid composition among the formulations.

Table 1. Physicochemical properties of edible coatings incorporating beet extracts.

Sample	pH	S.S. [°Brix]	Density [g/ml]	Color parameters		
				L*	a*	b*
BL	6.77 ± 0.01 ^{a}	2.17 ± 0.15 ^{c}	1.005 ± 0.001 ^{ab}	3.57 ± 0.03 ^{c}	1.02 ± 0.03 ^{b}	4.50 ± 0.02 ^{b}
BS	5.55 ± 0.01 ^{d}	2.43 ± 0.06 ^{c}	1.005 ± 0.001 ^{ab}	10.13 ± 0.02 ^{b}	-0.41 ± 0.02 ^{c}	6.65 ± 0.02 ^{a}
BP	5.87 ± 0.02 ^{bc}	4.63 ± 0.12 ^{a}	1.006 ± 0.001 ^{a}	11.07 ± 0.02 ^{a}	0.07 ± 0.02 ^{bc}	4.03 ± 0.02 ^{b}
p-value	<0.0001	<0.0001	0.0104	<0.0001	<0.0001	<0.0001

*Data expressed as mean ± standard deviation, obtained from three repetitions, compared by ANOVA ($p<0.05$). Different letters in the same column indicate significant differences at $p<0.05$, obtained by Tukey's multiple comparisons test. BL: Beet leaves, BS: Beet Stems, BP: Beet Pulp.

3.2. Antioxidant Properties of Edible Coatings Incorporating Beet Extracts

The antioxidant properties of the edible coatings were evaluated by measuring total phenolic content (TPC), total anthocyanin content (TAC), and antioxidant activity using ABTS and FRAP assays. Significant differences were observed among the coatings ($p < 0.0001$), reflecting the influence of each extract's composition on antioxidant capacity. The sample H296 exhibited the highest TPC and TAC values, correlating with the highest antioxidant activity in both ABTS and FRAP assays. This result is consistent with the known high phenolic and anthocyanin content of beet leaves. In contrast, the coating incorporating the pulp extract (P451) exhibited the lowest antioxidant capacity, suggesting a lower concentration of bioactive compounds in the pulp compared to leaves and stems.

Table 2. Antioxidant properties of edible coatings incorporating beet extracts.

Sample	TPC [mgGA/ml]	TAC [mg cyd-3-glu/ml]	ABTS		FRAP	
			[mgAA/ml]	[Eq.Trolox/ml]	[mgAA/ml]	[Eq.Mohr/ml]
BL	0.128 ± 0.004 a	42.60 ± 3.53 a	1.54 ± 0.01 a	3.77 ± 0.02 a	0.61 ± 0.01 b	1.95 ± 0.01 b
BS	0.119 ± 0.001 b	39.25 ± 1.20 ab	1.40 ± 0.01 ab	3.34 ± 0.03 a	0.49 ± 0.01 c	1.55 ± 0.01 c
BP	0.131 ± 0.001 a	8.35 ± 2.33 b	0.43 ± 0.02 c	0.46 ± 0.04 c	0.29 ± 0.01 d	0.91 ± 0.03 d
p-value	<0.0001	0.0251	<0.0001	<0.0001	<0.0001	<0.0001

*Data expressed as mean ± standard deviation, obtained from three repetitions, compared by ANOVA (p<0.05). Different letters in the same column indicate significant differences at p<0.05, obtained by Tukey's multiple comparisons test. BL: Beet leaves, BS: Beet Stems, BP: Beet Pulp.

3.3. Antimicrobial and Antifungal Properties of Edible Coatings Incorporating Beet Extracts

The initial microbial load of the edible coatings was measured to assess the hygienic quality of the formulations. Significant differences were observed among the samples (p = 0.0004), with the sample P451 showing the highest microbial load. This could be attributed to the higher sugar content in the pulp extract, which may support microbial growth. In contrast, H296 and T342 extracts exhibited lower microbial loads, possibly due to the presence of phenolic compounds with natural antimicrobial properties.

Table 3. Initial microbial load of multifunctional edible coatings incorporating beet extracts.

Sample	MAC [ufc/ml]
BL	450 ± 28 c
BS	530 ± 28 c
BP	690 ± 28 c
p-value	0.0004

*Data expressed as mean ± standard deviation, obtained from three repetitions, compared by ANOVA (p<0.05). Different letters in the same column indicate significant differences at p<0.05, obtained by Tukey's multiple comparisons test. MAC: Mesophillic Aerobic Count. BL: Beet leaves, BS: Beet Stems, BP: Beet Pulp.

The antimicrobial and antifungal efficacy of the edible coatings was evaluated against common foodborne pathogens and spoilage microorganisms, including *Bacillus cereus*, *Staphylococcus aureus*, *Enterococcus faecalis*, *Escherichia coli*, and *Aspergillus brasiliensis*. The inhibition halos (mm) indicated varying degrees of antimicrobial activity among the coatings, depending on the type of extract used.

The sample P451 exhibited the strongest inhibitory effect against *Staphylococcus aureus* and *Enterococcus faecalis*, suggesting the presence of active compounds in the pulp with specific antibacterial properties. In contrast, the sample T342 showed moderate activity across all tested microorganisms. The H296 demonstrated consistent but lower antimicrobial activity compared to the other formulations.

Compared to the chlorine control (0.5%), all coatings showed comparable or superior antifungal activity against *Aspergillus brasiliensis*, highlighting the potential of these natural extracts as effective antifungal agents. These results suggest that edible coatings formulated with sugar beet extracts could be used as natural antimicrobial and antifungal agents in food preservation.

Table 4. Antimicrobial and antifungal properties of edible coatings incorporating beet extracts.

Sample	Antimicrobial Properties				Antifungal Properties
	B. cereus	*St. aureus*	*E. faecalis*	*E. coli*	*Asp. brasiliensis*
BL	0.73 ± 0.06 a	1.00 ± 0.10 c	1.00 ± 0.10 b	1.07 ± 0.15 a	1.40 ± 0.20 a
BS	0.77 ± 0.06 a	0.87 ± 0.06 c	1.00 ± 0.10 b	1.10 ± 0.10 a	1.13 ± 0.12 a
BP	0.73 ± 0.004 a	1.73 ± 0.06 a	1.30 ± 0.10 a	1.10 ± 0.10 a	1.10 ± 0.10 a
Chlorine 0.5%	0.90 ± 0.10 a	1.37 ± 0.15 b	0.73 ± 0.06 c	0.77 ± 0.06 b	1.30 ± 0.10 a
p-value	0.0589	<0.0001	0.0005	0.0140	0.0799

*Data expressed as mean ± standard deviation, obtained from three repetitions, compared by ANOVA (p<0.05). Different letters in the same column indicate significant differences at p<0.05, obtained by Tukey's multiple comparisons test. BL: Beet leaves, BS: Beet Stems, BP: Beet Pulp.

4. Discussions

This study demonstrates the potential of sugar beet extracts as functional bioactive ingredients in edible coatings, highlighting their role in enhancing physicochemical stability, antioxidant activity, and antimicrobial efficacy. The results revealed significant differences among the coatings formulated with extracts from sugar beet (H296, T342, and P451), underscoring the impact of the source and composition of the extracts on the overall properties of the coatings.

4.1. Physicochemical Properties

The incorporation of sugar beet extracts significantly influenced the physicochemical properties of the edible coatings, particularly pH, soluble solids, and color parameters. The edible coating with pulp extract (P451) exhibited the highest concentration of soluble solids, which can be attributed to the higher sugar content in the beet pulp. This is consistent with previous studies that identified beet pulp as being rich in carbohydrates and dietary fibers, contributing to its increased microbial load due to the availability of substrates favorable for microbial growth [24, 25]. In contrast, the coatings H296 and T342 extracts showed lower soluble solids and microbial loads, reflecting their lower sugar content and higher phenolic composition, which is known for its natural antimicrobial activity [26].

Color differences observed among the coatings were directly related to the pigment composition of the different beet extracts. The intense color in T342 is attributed to the high concentration of betalains and anthocyanins in beet stems, while the lighter color in H296 is due to the presence of chlorophyll and carotenoids in beet leaves. Similar findings were reported in a 2023 study that demonstrated the influence of natural pigments on the color stability of edible coatings [27]. These color variations are crucial for the sensory acceptance of coated products, as consumer perception is strongly influenced by visual appearance.

4.2. Antioxidant Properties

The incorporation of sugar beet extracts significantly enhanced the antioxidant properties of the edible coatings, with the leaf extract (H296) showing the highest total phenolic and anthocyanin contents. This correlated with its superior antioxidant capacity observed in both ABTS and FRAP assays. These results are consistent with recent findings indicating that beet leaves are a rich source of phenolic compounds, particularly flavonoids and phenolic acids, which contribute to potent antioxidant properties [28].

The differences in antioxidant activity among the coatings can be attributed to the varying phenolic profiles of the extracts, influenced by the part of the plant used and the extraction method. The ultrasound-assisted aqueous extraction technique used in this study proved effective in preserving the antioxidant capacity of the bioactive compounds. This supports its use as a sustainable and green extraction method, as previously demonstrated in studies evaluating ultrasound extraction for phenolic recovery from plant residues [29, 30].

Furthermore, the high anthocyanin content observed in the H296 and T342 coatings contributed to enhanced radical scavenging activity. Anthocyanins are known for their strong antioxidant properties due to their electron-donating ability and structural stability. These findings align with studies reporting the superior antioxidant efficacy of anthocyanin-rich edible coatings, particularly in preserving the oxidative stability of fresh-cut fruits and vegetables [31].

4.3. Antimicrobial and Antifungal Properties

The antimicrobial assays revealed that the P451 coating exhibited the strongest inhibitory effect against *Staphylococcus aureus* and *Enterococcus faecalis*. This suggests the presence of specific antibacterial compounds in the pulp extract, potentially due to its distinctive phenolic profile, including ferulic acid and p-coumaric acid [32]. These phenolic acids have been reported for their antimicrobial properties, disrupting bacterial cell membranes and inhibiting enzyme activity. Conversely, the H296 and T342 coatings showed moderate but consistent antimicrobial activity, likely due to the synergistic effects of flavonoids and phenolic acids present in these extracts [33].

The antifungal efficacy of all coatings against *Aspergillus brasiliensis* was comparable or superior to that of the chlorine control, highlighting the potential of sugar beet extracts as natural antifungal agents. This effect can be attributed to the presence of phenolic compounds that disrupt fungal cell membranes and inhibit spore germination. Similar antifungal mechanisms were proposed in a study evaluating phenolic-rich edible coatings for inhibiting spoilage fungi in bread and bakery products [34].

4.4. Comparison with Recent Studies

Recent studies from 2023 onwards have extensively explored the incorporation of natural extracts into edible coatings to enhance their functional properties, particularly antioxidant and antimicrobial activities. These studies provide valuable insights into the potential applications of bioactive compounds in extending the shelf life and ensuring the safety of perishable food products. The findings from these recent investigations corroborate and contextualize the results obtained in the present study on multifunctional edible coatings formulated with sugar beet extracts.

Ucar et al., [35] investigated the effectiveness of natural preservatives for fish and seafood, focusing on chitosan-based coatings incorporated with beet, garlic, and turmeric extracts. Their findings demonstrated a significant reduction in biogenic amine formation and an extension of the shelf life of tuna fillets. Although the study focused on seafood, the results corroborate the effectiveness of beet extracts in improving the quality and safety of coated food products. The antimicrobial efficacy observed in the current study, particularly with the edible coating incorporating sugar beet pulp extract (P451), aligns with Ucar et al.'s findings, highlighting the potent antibacterial properties of phenolic compounds present in beet extracts. This supports the hypothesis that sugar beet residues contain bioactive compounds capable of inhibiting pathogenic microorganisms, thereby enhancing food safety.

Similarly, Ozuna-Valencia et al., [36] evaluated the application of organic and inorganic nanoparticles incorporated into edible coatings to enhance the physicochemical and microbiological properties of seafood. Their study demonstrated enhanced antioxidant activity and microbial stability conferred by the natural extracts. This is consistent with the present study, where the incorporation of sugar beet extracts significantly improved the antioxidant activity and antimicrobial efficacy of the edible coatings. The ultrasound-assisted aqueous extraction method used in this study preserved the antioxidant capacity of the phenolic compounds, maximizing the coatings' functional properties. These findings suggest that the combination of natural extracts with advanced extraction techniques can enhance the multifunctionality of edible coatings.

Olunusi et al. [37] reviewed emerging edible coating technologies for tropical fruit preservation, emphasizing the use of biodegradable polymers combined with natural extracts to enhance antioxidant and antimicrobial properties. Their study highlighted the importance of preserving the bioactivity of natural antioxidants during extraction and processing. In the current study, ultrasound-assisted aqueous extraction effectively preserved the bioactivity of phenolic compounds and anthocyanins from sugar beet residues, enhancing the antioxidant and antimicrobial efficacy of the edible coatings. This green extraction method aligns with the sustainable utilization of agro-industrial residues and supports the development of eco-friendly food packaging solutions. The findings are consistent with Olunusi et al.'s conclusions, demonstrating the potential of multifunctional edible coatings to maintain food quality and extend shelf life while promoting environmental sustainability.

5. Conclusions

The multifunctional edible coatings formulated with sugar beet extracts demonstrated enhanced physicochemical stability, antioxidant activity, and antimicrobial efficacy. The differences observed among the coatings underscore the influence of the source and composition of the extracts on the overall properties of the coatings. The leaf and stem extracts exhibited superior antioxidant activity, while the pulp extract showed enhanced antimicrobial efficacy, highlighting the potential for tailored applications depending on the desired functionality.

These findings contribute to the development of eco-friendly food packaging solutions and suggest that sugar beet extracts can effectively improve food safety and extend shelf life, aligning with consumer demand for natural and sustainable products. This study offers a novel approach to valorizing agro-industrial residues and promoting sustainable practices within the food industry.

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Conflict of Interests

The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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