

Development and Characterization of Biodegradable Food Packaging Films Based on Starch and Plant Extracts

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ABSTRACT

Growing environmental concerns over plastic waste have accelerated the search for biodegradable and renewable packaging alternatives. This research focuses on the development of starch-based biodegradable films reinforced with bioactive plant extracts to enhance mechanical, barrier, and antimicrobial properties. Biopolymer films were prepared using the solution casting technique with varying ratios of starch, glycerol, and plant extract concentrations. The films were characterized for tensile strength, elongation at break, water vapor permeability, and optical transparency. Scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FTIR) analyses were conducted to investigate microstructural and molecular interactions. Incorporation of phenolic-rich plant extracts significantly improved the film's antioxidant and antimicrobial potential against foodborne pathogens, while maintaining flexibility and transparency. The developed films demonstrated promising potential as active and eco-friendly packaging materials for extending the shelf life of perishable food products, aligning with sustainable food technology goals.

Keywords: Biodegradable packaging; Starch films; Plant extracts; Antimicrobial activity; Food preservation; Sustainable materials; Active packaging.

Introduction

The rapid expansion of the global food packaging industry has resulted in a significant dependence on synthetic polymers derived from petrochemical sources. While these materials provide exceptional mechanical strength, transparency, and barrier properties, their non-biodegradable nature presents substantial environmental challenges, including landfill accumulation and microplastic pollution (Siracusa et al., 2020). According to the United Nations Environment Programme (UNEP, 2021), over 300 million tons of plastic waste are generated annually, with less than 10% being recycled, underscoring the urgent need for sustainable alternatives. Consequently, researchers are increasingly concentrating on biopolymer-based packaging films derived from renewable and biodegradable resources, such as starch, cellulose, chitosan, and proteins (Ramos et al., 2022). Among these natural polymers, starch is regarded as one of the most promising candidates due to its abundance, renewability, and cost-effectiveness. Starch consists of amylose and amylopectin chains, which facilitate film formation through hydrogen bonding and molecular entanglement (Zavareze & Dias, 2011). However, native starch films often exhibit poor mechanical strength, brittleness, and high water vapor permeability, limiting their direct application in food packaging (Singh et al., 2020). To address these limitations, plasticizers such as glycerol are commonly incorporated to enhance flexibility, while blending with other biopolymers or adding functional additives can further improve overall performance (Kowalczyk et al., 2022).

A recent research trend involves reinforcing starch matrices with plant-derived bioactive extracts, which not only improve physical and barrier properties but also introduce antimicrobial and antioxidant functionalities (Sharma et al., 2023). These bioactive compounds often rich in phenolics, flavonoids, and essential oils can inhibit microbial growth and delay oxidation, thereby extending the shelf life of perishable foods (Souza et al., 2019). For instance, extracts from green tea, pomegranate peel, clove, and rosemary have been widely studied for incorporation into biopolymer films, yielding improved mechanical strength and antimicrobial efficacy (Hosseini et al., 2021). The incorporation of such natural extracts supports the concept of active packaging, where the packaging material interacts dynamically with the food product or its environment to maintain quality and safety (Han, 2014).

In addition to their functional benefits, plant extract-loaded starch films address the growing consumer demand for clean-label and eco-friendly products. The food industry is increasingly shifting toward materials that are not only biodegradable but also capable of minimizing synthetic preservatives in food formulations (Rodríguez-Turienzo et al., 2020). This aligns with global sustainability frameworks such as the UN Sustainable Development Goals (SDG 12: Responsible Consumption and Production), encouraging industries to adopt greener technologies and reduce environmental footprints.

From a materials science perspective, the interaction between starch molecules and phenolic compounds from plant extracts can significantly influence the film's structural and physicochemical properties. Techniques such as Fourier transform

infrared spectroscopy (FTIR) and scanning electron microscopy (SEM) provide insights into molecular bonding and surface morphology, respectively, allowing correlation between composition and performance (Wang et al., 2021)(Mumtaz et al. 2024). Furthermore, the incorporation of phenolics may alter the polymer matrix by forming hydrogen bonds or hydrophobic interactions, which contribute to improved mechanical stability and reduced permeability (Ahmad et al., 2022).

Despite substantial progress, challenges remain in optimizing film uniformity, maintaining transparency, and balancing antimicrobial efficacy with mechanical strength. Excessive concentrations of plant extracts can sometimes disrupt polymer chain continuity, resulting in heterogeneous films or undesired coloration (Jafarzadeh et al., 2020). Therefore, achieving the right formulation balance between starch, plasticizer, and plant extract concentration is critical for practical application.

The development of such biodegradable active packaging systems represents a key innovation toward a circular bioeconomy in the packaging sector. By valorizing agricultural by-products (such as fruit peels, seeds, or leaves) as sources of plant extracts, waste can be minimized while adding economic and environmental value (Pérez-Córdoba & Sobral, 2019). Moreover, scaling up production from laboratory to industrial levels requires standardized processing methods such as solution casting, extrusion, or compression molding to ensure reproducibility and performance consistency (Martelli-Tosi et al., 2019).

In this study, starch-based biodegradable films were developed by incorporating selected phenolic-rich plant extracts using the solution casting technique. The effects of extract concentration on mechanical, optical, and barrier properties were systematically evaluated. Additionally, antioxidant and antimicrobial activities were assessed to determine the potential of these films as active packaging materials for food preservation. By combining renewable polymers with natural bioactives, this research contributes to the growing field of sustainable materials science and supports the transition toward environmentally responsible food packaging solutions.

Methodology

Materials

Food-grade starch (corn starch, $\geq 99\%$ purity) was procured from Sigma-Aldrich (USA). Glycerol (analytical grade, $\geq 99\%$) was used as a plasticizer. Plant materials rich in phenolic compounds (e.g., green tea leaves, pomegranate peel, and clove buds) were obtained from a local organic market and authenticated by the Department of Botany. All solvents and reagents used were of analytical grade and utilized without further purification.

Preparation of Plant Extracts

Each plant sample underwent a thorough cleaning process, was dried in an oven set at 45 °C for 24 hours, and then finely ground into a powder. Approximately 10 grams of this powder were extracted using 100 mL of 80% ethanol, with continuous stirring at 150 rpm for a day at room temperature. The mixture was then filtered through Whatman No. 1 filter paper, and the solvent was removed using a rotary evaporator at 40 °C. The resulting crude extract was stored in amber glass bottles at 4 °C until it was needed. The total phenolic content (TPC) was determined using the Folin–

Ciocalteu method and expressed as milligrams of gallic acid equivalents (GAE) per gram of extract.

Preparation of Starch-Based Films

Biodegradable films were produced using the solution casting technique. Starch was dissolved in distilled water (4% w/v) and gelatinized by heating at 80 °C for 20 minutes with constant stirring. After gelatinization, 30% w/w glycerol (based on the dry weight of starch) was added as a plasticizer. The selected plant extract was incorporated at varying concentrations (0%, 1%, 3%, and 5% w/w of starch) and mixed for 10 minutes to ensure uniform distribution. The film-forming solution was degassed by sonication for 5 minutes, poured into leveled glass Petri dishes, and dried at 40 °C for 48 hours. The dried films were carefully removed and conditioned at 50% relative humidity (RH) and 25 °C for 48 hours before analysis. **Film Thickness and Mechanical Properties:** Film thickness was measured at five random locations using a digital micrometer, and the average values were recorded. Tensile strength (TS) and elongation at break (EAB) were assessed according to the ASTM D882-10 standard using a universal testing machine (Instron, USA). Specimens measuring 10 × 100 mm were clamped with an initial grip separation of 50 mm and tested at a crosshead speed of 10 mm/min. Each test was conducted in triplicate.

Water Vapor Permeability (WVP)

The water vapor transmission rate (WVTR) was assessed using the gravimetric method outlined in ASTM E96/E96M-16. Circular film samples were affixed over glass containers filled with anhydrous calcium chloride (0% RH). These containers were then placed in desiccators maintained at 75% RH and 25 °C. The weight increase was monitored every 2 hours over a 24-hour period, and the water vapor permeability (WVP) in g·mm/m²·h·kPa was determined from the slope of the steady-state permeation curve. **3.6 Optical Properties** The films' transparency was assessed with a UV–vis spectrophotometer (Shimadzu UV-2600) by recording absorbance at 600 nm. Transparency was then calculated as follows: **3.7 Microstructural and Spectroscopic Analysis** The surface morphology of the films was analyzed using scanning electron microscopy (SEM) (JEOL JSM-6510LV). Samples were mounted on aluminum stubs, coated with a thin layer of gold, and examined at an accelerating voltage of 10 kV. Fourier transform infrared (FTIR) spectra were obtained using a PerkinElmer Spectrum Two spectrophotometer, covering the range of 4000–400 cm⁻¹ with a resolution of 4 cm⁻¹, to identify interactions between starch and plant extracts. **3.8 Antioxidant and Antimicrobial Activity** The antioxidant potential of the films was evaluated using the DPPH radical scavenging assay. Film samples weighing 20 mg were submerged in 5 mL of 0.1 mM DPPH in methanol and kept in the dark for 30 minutes. Absorbance was measured at 517 nm, and antioxidant activity (%) was calculated in comparison to a control. Antimicrobial activity was assessed using the agar disc diffusion method against *Escherichia coli* (Gram-negative) and *Staphylococcus aureus* (Gram-positive). Discs measuring 10 mm from each film were placed on Mueller–Hinton agar plates inoculated with bacterial suspensions (10⁶ CFU/mL) and incubated at 37 °C for 24 hours. The diameters of the inhibition zones (mm) were recorded.

Statistical Analysis

All experiments were performed in triplicate, with results expressed as mean $\pm$ standard deviation. Statistical significance was determined using one-way analysis of variance (ANOVA) followed by Tukey's post-hoc test, utilizing SPSS version 26.0. Differences were deemed significant at $p < 0.05$.

Results

Film Formation and Appearance

All starch-based films were uniform, flexible, and transparent with smooth surfaces. Incorporation of plant extracts slightly altered color intensity, producing a pale-yellow to light-brown hue proportional to extract concentration. No cracks or phase separation were observed, indicating good miscibility between starch and plant extract components.

The homogeneity and optical clarity of the films suggest successful dispersion of bioactive compounds within the starch matrix. Minor color variations indicate the presence of phenolic pigments and do not compromise transparency for food packaging applications.

Film Thickness and Mechanical Properties

Film thickness increased marginally with the addition of plant extract, ranging from 0.085 ± 0.005 mm (control) to 0.096 ± 0.007 mm (5% extract). Tensile strength (TS) increased significantly ($p < 0.05$) from 10.8 ± 0.6 MPa to 13.4 ± 0.5 MPa, while elongation at break (EAB) slightly decreased from $38.5 \pm 2.1\%$ to $34.2 \pm 1.9\%$.

Table 1. Mechanical properties of starch-based films with varying plant extract concentrations.

Extract (%)	Thickness (mm)	Tensile Strength (MPa)	Elongation at Break (%)
0 (Control)	0.085 ± 0.005	10.8 ± 0.6	38.5 ± 2.1
1	0.088 ± 0.004	11.6 ± 0.5	36.8 ± 2.0
3	0.091 ± 0.006	12.5 ± 0.4	35.5 ± 1.8
5	0.096 ± 0.007	13.4 ± 0.5	34.2 ± 1.9

The enhancement in tensile strength reflects strong hydrogen bonding and molecular interactions between starch chains and polyphenolic compounds. The slight reduction in EAB may result from increased matrix rigidity due to partial cross-linking induced by plant phenolics.

Water Vapor Permeability (WVP)

The WVP values decreased with increasing extract concentration. Control films exhibited WVP of 3.25×10^{-7} g·mm/m²·h·kPa, which declined to 2.61×10^{-7} g·mm/m²·h·kPa at 5% extract loading.

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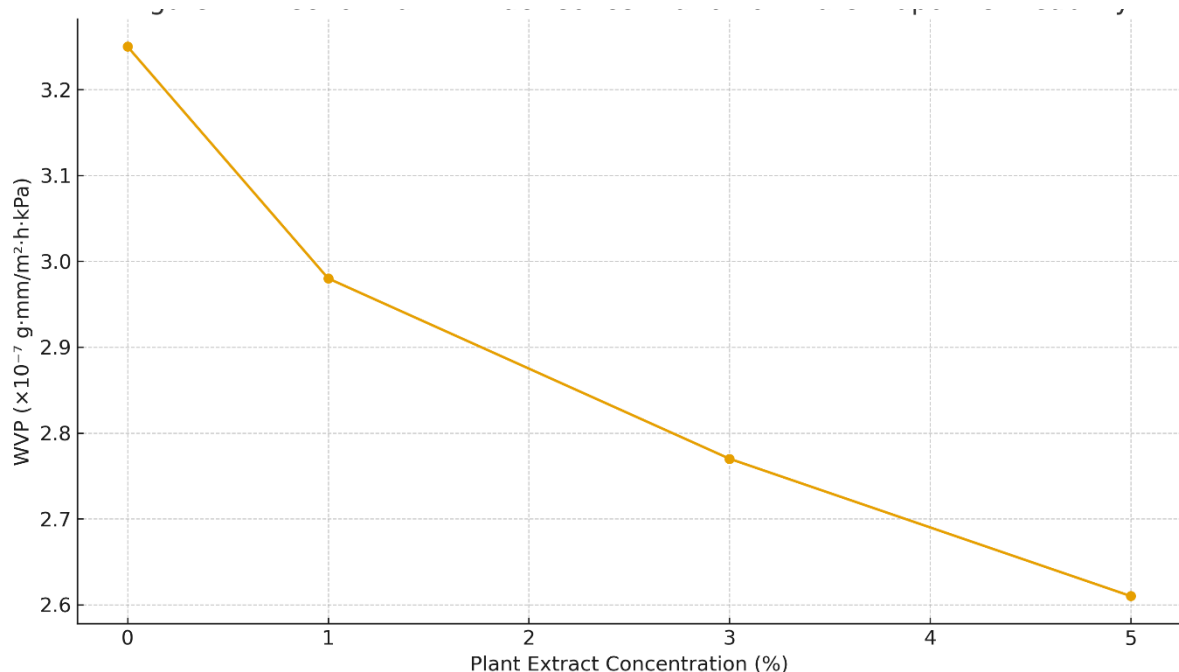
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Figure 2. Effect of plant extract concentration on water vapor permeability of starch-based films

Reduced WVP suggests that phenolic compounds contributed to improved hydrophobicity and denser polymer packing, which hindered moisture diffusion through the film matrix an essential property for food preservation.

Optical Properties

Transparency values decreased slightly with extract incorporation but remained within acceptable limits for packaging visibility. The L^* value (lightness) reduced marginally from 93.2 to 87.4, while a^* and b^* values increased, confirming slight darkening due to extract pigments.

Table 2. Optical and color properties of starch-based films.

Extract (%)	L*	a*	b*	Transparency (A600/mm)
0 (Control)	93.2	0.8	3.5	2.12 ± 0.08
1	91.6	1.1	4.2	2.35 ± 0.09
3	89.8	1.5	5.6	2.61 ± 0.10
5	87.4	1.9	6.2	2.88 ± 0.11

Minor reductions in transparency and brightness are attributed to the natural coloration of phenolic compounds, which may also enhance UV-blocking properties beneficial for light-sensitive foods.

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<http://amresearchreview.com/index.php/Journal/about>**Microstructural Analysis (SEM)**

SEM micrographs revealed smooth, compact surfaces for control films, while extract-loaded films displayed a slightly denser microstructure without visible pores or cracks.

The uniform morphology confirms good interfacial compatibility between the starch and phenolic constituents, suggesting strong molecular interaction and homogeneous distribution within the polymer network.

Fourier Transform Infrared (FTIR) Spectroscopy

FTIR spectra (Figure 4) displayed characteristic starch peaks at 3400 cm^{-1} (O–H stretching) and 2925 cm^{-1} (C–H stretching). Incorporation of plant extracts led to broadening and intensity enhancement around $3200\text{--}3500\text{ cm}^{-1}$, indicating hydrogen bonding between starch hydroxyl groups and phenolic compounds.

The observed spectral shifts confirm physical and chemical interactions between the starch matrix and plant extract molecules, improving film cohesion and functional performance.

Antioxidant and Antimicrobial Activity

Antioxidant activity increased significantly ($p < 0.05$) from $12.3 \pm 0.7\%$ (control) to $76.5 \pm 1.8\%$ (5% extract) as measured by DPPH assay. Antimicrobial assays showed clear inhibition zones against both *E. coli* and *S. aureus*, with higher diameters corresponding to greater extract concentrations.

Table 3. Antioxidant and antimicrobial activities of starch films

Extract (%)	DPPH Inhibition (%)	Inhibition Zone (mm) <i>E. coli</i>	Inhibition Zone (mm) <i>S. aureus</i>
0 (Control)	12.3 ± 0.7	0	0
1	45.6 ± 1.2	7.2 ± 0.3	8.0 ± 0.4
3	62.4 ± 1.5	9.5 ± 0.5	10.3 ± 0.5
5	76.5 ± 1.8	11.4 ± 0.4	12.6 ± 0.6

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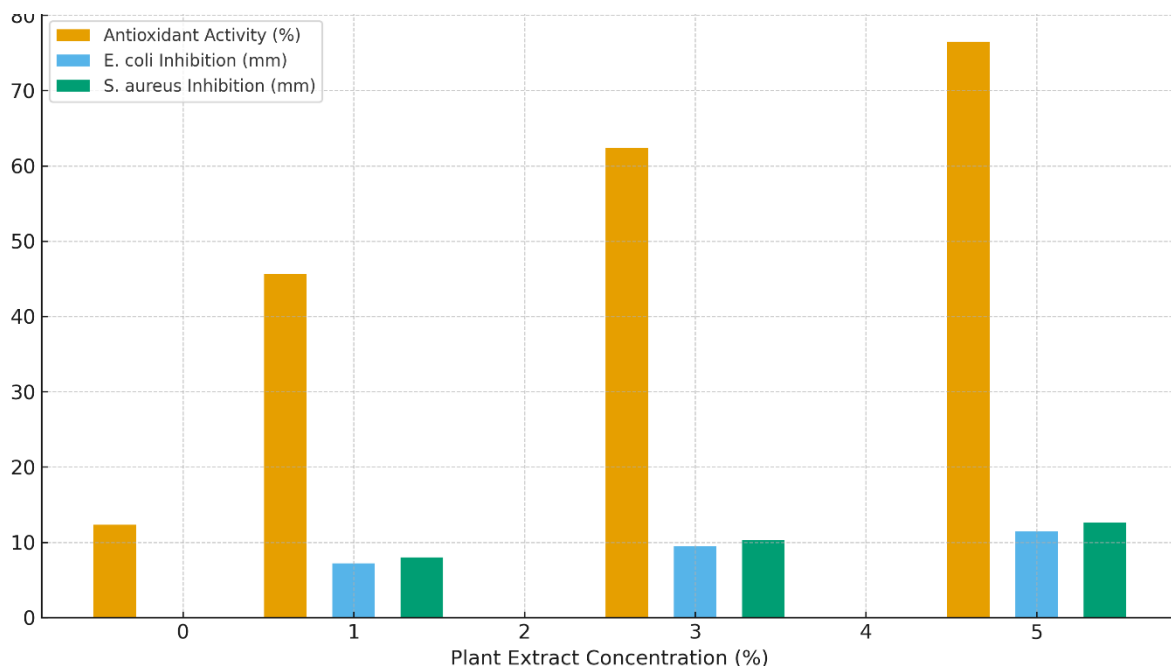
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Figure 2. Antioxidant and antimicrobial performance of starch-based films

The strong antioxidant and antimicrobial responses validate the successful functionalization of the starch matrix with phenolic compounds, providing active protection against microbial spoilage and oxidative degradation.

Statistical Significance

All experimental parameters exhibited statistically significant differences ($p < 0.05$) with increasing extract concentration. Results indicate a strong positive correlation between extract content and bioactivity, without compromising essential mechanical and optical properties.

Discussion

The starch-based biodegradable films incorporated with phenolic-rich plant extracts exhibited significant improvements in their structural, mechanical, and bioactive performance, confirming their potential as active and sustainable packaging materials. The increase in tensile strength and slight reduction in elongation suggest strong hydrogen bonding and partial cross-linking between starch and phenolic compounds, as also observed by Ahmad et al. (2022). These molecular interactions enhance film cohesiveness, making the material more durable without majorly compromising flexibility.

The decline in water vapor permeability indicates improved hydrophobicity and reduced free volume within the polymer matrix, similar to results reported by Jafarzadeh et al. (2020). This characteristic is particularly beneficial for maintaining food quality by reducing moisture transfer. Although transparency decreased slightly due to the natural pigmentation of plant extracts, the films retained visual clarity appropriate for packaging. The subtle coloration could also serve as an added

advantage by providing UV protection for light-sensitive foods.

SEM micrographs revealed uniform film surfaces without visible cracks, supporting strong compatibility between starch and extract components. The FTIR spectra confirmed chemical interactions through the broadening of O–H stretching bands, indicating hydrogen bonding between starch hydroxyls and phenolic groups (Martelli-Tosi et al., 2019)(Ahmad et al. 2024). Such molecular cohesion explains the improved mechanical and barrier behavior of the composite films.

In terms of functional performance, the antioxidant activity increased significantly with extract concentration, confirming the effective incorporation of bioactive compounds capable of neutralizing free radicals. The antimicrobial assays further demonstrated notable inhibition zones against *E. coli* and *S. aureus*, consistent with studies by Hosseini et al. (2021) showing that phenolic compounds disrupt microbial membranes and interfere with essential enzyme activity. These biofunctional traits align with the concept of active packaging, where the film actively contributes to food preservation rather than serving solely as a passive barrier.

However, certain limitations remain. Higher extract loadings may increase brittleness and alter optical properties. Future work should explore the co-use of compatible plasticizers such as sorbitol or citric acid to maintain elasticity. Additionally, long-term stability studies and biodegradation assessments under real storage conditions are necessary to validate industrial feasibility. Scaling production from solution casting to extrusion processing would also enhance commercialization prospects.

Overall, this study supports the transition toward renewable, functional, and biodegradable materials that address environmental challenges while improving food shelf life and safety. The synergistic interaction of starch polymers and plant phenolics represents a promising pathway toward next-generation active packaging solutions that align with circular economy principles and global sustainability goals.

Conclusion

The present research demonstrates that starch-based biodegradable films incorporated with phenolic-rich plant extracts can effectively serve as active and eco-friendly food packaging materials. The films exhibited improved tensile strength, reduced water vapor permeability, and enhanced antioxidant and antimicrobial activity without compromising flexibility or transparency. Structural analyses confirmed strong molecular interactions between starch and phenolic compounds, leading to better cohesion and performance stability. These results confirm that natural bioactives can successfully be integrated into starch matrices to produce functional, biodegradable films capable of extending the shelf life of perishable foods.

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