

Research article

Development and Characterization of Active, Biodegradable Film from Corn Starch and Pomegranate Peel Powder

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Abstract

Pomegranate (*Punica granatum*) is among the most commonly grown fruits worldwide. Its impressive nutritional benefits make pomegranate a highly utilized fruit in the food industry, generating significant byproducts, primarily the peel. The peel is a rich source of bioactive compounds, making it suitable to be used in active packaging. In this research, we utilized corn starch as the base material for film production owing to its great film-forming capability. Films were produced by incorporating pomegranate peel powder into the corn starch using a casting technique. Findings indicated that a higher concentration of pomegranate peel powder contributed to higher film thickness, withstand repeated folding and reduced water solubility and moisture content. Scanning electron microscope analysis demonstrated good compatibility between the peel powder and starch matrix. The film became more opaque with increasing extract concentration, reducing light transmission and potentially providing better protection for light sensitive foods. Additionally, the films were soil-biodegradable, decomposing within 12 days. Antimicrobial tests showed that the pomegranate peel powder inhibited both Gram-positive and Gram-negative bacteria, with the highest inhibition observed against *Staphylococcus aureus*. The outcome showed that incorporating 10% PPP into corn starch can produce a biodegradable, antimicrobial, and functionally robust active packaging material, suitable for diverse food applications.

Keywords: antimicrobial; starch film; soil degradable; casting technique; fruit waste

1. Introduction

Traditional plastic packaging has long been celebrated as a hallmark of modernization. Since its discovery in 1907 by Belgian chemist Leo Hendrik Baekeland, plastic has been seamlessly integrated into daily life, gradually replacing traditional materials like metal, glass, and ceramic. This shift has largely been attributed to its petroleum-based composition, which offers exceptional durability and lightweight properties, making plastic an adaptable option for diverse functional purposes. However, due to their common usage,

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single-use plastics pose considerable threats to the environment. Their non-degradable nature and poor recyclability contribute to approximately 1.8 gigatons of carbon dioxide equivalent (Gt CO₂e) annually, exacerbating climate change (Bauer et al., 2022; Thakwani et al., 2023). Additionally, the economic burden of plastic pollution is staggering, with estimated costs reaching US\$3.7 trillion (World Wide Fund for Nature, 2021). Beyond these concerns, the pervasive presence of microplastics in water, soil, and air poses serious health risks to humans (Rani et al., 2024). Research by Cox et al. (2019) estimates that a person ingests about 50,000 microplastic particles per year through dietary sources, raising concerns about toxicity, inflammation, and hormonal interference. These findings underscore the essential call for action towards sustainable alternatives to conventional plastics. In this study, sustainability is referred to as the development of materials which encompasses minimizing environmental impact, reducing waste, and promoting the efficient use of resources, while also considering social and economic dimensions.

A key area that demands such sustainable solutions is the food and beverage sector, as it stands out as the major user of single-use plastic packaging (Phelan et al., 2021). This sector relies heavily on food-grade plastic packaging to store, protect, preserve, and provide convenience, as well as to facilitate communication (Ashfaq et al., 2022). Despite these benefits, food spoilage remains a persistent issue due to various processing stages throughout the supply chain that significantly contribute to overall food waste. The use of synthetic chemical preservatives attempts to mitigate spoilage but poses potential health risks (Lucera et al., 2012). Therefore, there has been a growing demand driven by the need for safer food preservation methods that also contribute to extending shelf life and reducing food waste (Zanetti et al., 2018). This transition has driven the development of functional food packaging technologies, moving beyond conventional methods. One such innovation is active packaging, which involves interaction between the packaging, the food itself, and external conditions to extend shelf life while maintaining product quality and sensory attributes, thereby minimizing food waste (Tanwar et al., 2021; Dutta & Sit, 2024). This distinctive property enables any active material, such as an antimicrobial compound, to be embedded within the packaging. The growing interest is reflected in market trends, with the antimicrobial plastics market anticipated to reach USD 85.43 billion by 2032 (Fortune Business Insight, 2024).

As demand for sustainable solutions grows, biodegradable forms of active packaging are now considered a promising substitute. The exploration of starch as a biodegradable polymer for active packaging has become a focal point in sustainable material research. Starch is recognized as a natural, low-cost polymer that is highly abundant and possesses superior film-forming capabilities, making it a promising source of biobased and biodegradable materials for food packaging applications (Fonseca-García et al., 2020). Among various types of starch, corn starch is particularly favored due to its low cost (Tabasum et al. 2018; Ghizdareanu et al. 2023), wide availability (Ghizdareanu et al., 2023) and excellent biodegradability (Luchese et al. 2017; Wang et al. 2021), which make it an ideal candidate for creating film matrices. According to the ASTM standard D5988-03, biodegradability denotes the potential of plastic materials to disintegrate into methane, water, inorganic compounds, carbon dioxide or biomass, primarily through the enzymatic activity of microorganisms (Mohee et al., 2007). Corn starch's versatility enables it to be blended with diverse materials, including synthetic biopolymers (e.g., PVA) (Kong et al., 2020), plant extracts (e.g., *Hibiscus sabdariffa* L.) (Gómez-Aldapa et al., 2021), and essential oils (e.g., *Zanthoxylum bungeanum*) (Wang et al., 2020), and agro-wastes (e.g., date palm pits), (Alqahtani et al., 2021) to develop a tailored film solution. Nevertheless, films derived from corn starch typically show poor mechanical strength and barrier performance, restricting their practical application (Silva et al., 2020). To overcome these

limitations, plasticizers are frequently incorporated into starch formulations to improve extensibility, flexibility, and overall versatility (Sadeghizadeh-Yazdi et al., 2019).

One promising approach to enhance the functionality of starch-based films is the incorporation of natural by-products such as *Punica granatum*, also known as pomegranate. Pomegranate is a widely cultivated fruit renowned for its numerous health benefits. It is commercially processed into products like jam, juice, and fresh-cut fruits to meet market demand (Salim et al., 2023). However, the processing of pomegranates generates significant agro-industrial waste, with peels alone making up approximately 50% of the total waste (Bertolo et al., 2021). Globally, approximately 1.62 million tons of pomegranate fruit waste are produced annually, leading to environmental pollution and high waste management costs (Phiri et al., 2024). Therefore, the fruit peels can be reutilized as they contain a good source of polyphenols, flavonoids, and soluble tannins and are rich in natural antimicrobial properties, making them suitable as the active ingredient to be incorporated into the film (Ghimire et al., 2022; Soleimanzadeh et al., 2024). Studies have reported that pomegranate peel contains hydrolysable tannins (139.63 ± 4.25 mg TAE/g DW), polyphenols (85.60 ± 4.87 mg GAE/g DW), and flavonoids (51.52 ± 8.14 mg RE/g DW) (Elfalleh et al., 2012).

Many studies have shown that pomegranate peel extracts inhibit the growth of various gram-positive bacteria, such as *Listeria monocytogenes*, *Bacillus cereus*, and *Staphylococcus aureus*, and gram-negative bacteria *Escherichia coli*, *Pseudomonas aeruginosa*, and *Salmonella typhi*, all of which contribute to food spoilage, safety concerns, and food waste (Hanafy et al., 2021). Additionally, the peel could also act as a natural filler which added to the starch matrix to improve the film matrix, such as thickness, water vapor permeability, mechanical properties, optical properties, thermal properties (Soleimanzadeh et al., 2024) and biodegradability (Ali et al., 2019). Through the conversion of pomegranate peels, this strategy both decreases farming waste and enhances the pursuit of environmentally responsible packaging materials.

Recent studies have demonstrated pomegranate peel incorporation in various matrices. Hanani et al. (2022) developed gelatin films using oven-dried peel via casting. Ali et al. (2019) utilized freeze-dried peel in hydroxypropyl high-amylose starch while Esfahani et al. (2022) created intelligent films from cassava starch with shade-dried peel. Zeng et al. (2021) incorporated oven-dried peel into chitosan films, and Zhang et al. (2024) employed oven-dried peel in corn starch films using variable-speed homogenization. However, in this study, three key advances are presented: (1) we systematically evaluated a range of pomegranate peel powder (PPP) concentrations (0-10%) to identify the optimal loading for antimicrobial efficacy, (2) employed a simple oven-drying process rather than chemically modified starches or advanced processing methods, and (3) demonstrated broad-spectrum antimicrobial activity against five foodborne pathogens to evaluate PPP's potential as a natural active agent. The findings of this study contribute to sustainable packaging innovation by valorizing agro-industrial waste, improving food safety by reducing food spoilage, and promoting scalable eco-friendly materials, aligning with Sustainable Development Goal 12 (SDG 12) through waste-to-resource solutions and sustainable industrial practices.

2. Materials and Methods

2.1 Materials

Pomegranate fruits (Bhagwa variety, India) were purchased from Cold Storage (Kuala Lumpur, Malaysia). Glycerol with (99%) purity was purchased from Classic Chemicals Sdn Bhd (Selangor, Malaysia) and corn starch (~28% amylose) was purchased from a local shop. All other chemicals used for this research were from Management and Science University, Shah Alam, Selangor research laboratory.

2.2 Preparation of pomegranate peel powder

Pomegranate peels were first washed, cut into smaller segments, and dried in a hot air oven (Venticell, MMM, Munich, Germany) at 30°C for 24 h. After drying, the peels were finely ground using a household grinder (MX-GM 1011, Panasonic, Kuala Lumpur, Malaysia). The resulting powder was then sieved through a 100-mesh screen to achieve a uniform particle size. The processed pomegranate peel powder (PPP) was stored at 4°C until further use (Hanani et al., 2019).

2.3 Preparation of film

Film preparation followed the procedure outlined by Leites et al. (2021), with slight modifications. A starch suspension was created by dissolving 8% (w/v) corn starch and incorporating glycerol at 30% (w/w) relative to the starch content. This mixture was heated in a water bath (Memmert, Germany) at 80°C under continuous mechanical stirring at 350 rpm for 30 min to induce starch gelatinization. Pomegranate peel powder (PPP) was incorporated into the suspension at concentrations of 2, 4, 6, 8, and 10% (w/w based on corn starch) prior to gelatinization. Subsequently, 10 mL of the film-forming solution was cast into 9 cm diameter Petri dishes as shown in Figure 1 and dried in an oven (Venticell, MMM, Munich, Germany) at 35°C for 24 h. The resulting films were then conditioned in a desiccator set at approximately 25±3°C and 50% relative humidity for 24 h before undergoing further analysis.

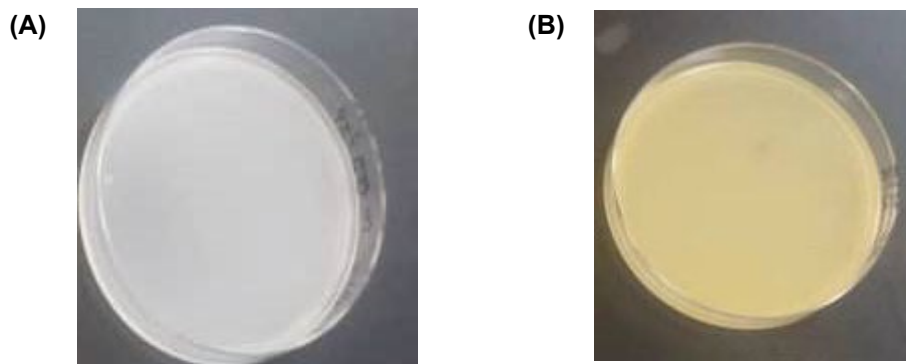


Figure 1. Samples of casted films: (A) control, (B) film with PPP

2.4 Characterization of films

2.4.1 Film Thickness

The thickness of the films was determined using a manual micrometre (China) with a precision of 0.01 mm. Measurements were taken at ten randomly selected points across each film. Each measurement was performed in triplicate, and the average thickness was calculated and recorded.

2.4.2 Water solubility

The film samples (4 cm x 4 cm) were dried in an oven (Venticell, MMM, Munchen, Germany) at 100°C for 24 h to measure the initial dry mass (W_0). Then, the films were submerged in distilled water and were left at room temperature for 24 h. Later, the samples were filtered and dried again in the oven at 100°C for 24 h to obtain the dry mass (W_f). The analysis was triplicated (Najwa et al., 2020). The film water solubility (WS) was calculated using the equation (1):

$$\text{Water Solubility (\%)} = \frac{W_0 - W_f}{W_0} \times 100 \quad (1)$$

2.4.3 Moisture content

The moisture content of the films was evaluated following the procedure outlined by Syafiq et al. (2021), with minor adjustments. Film samples (2 cm x 2 cm) were initially weighed to obtain their initial weight (W_0), then dried in a hot air oven (Venticell, MMM, Munich, Germany) at 105±2°C for 24 h. After drying, the final weight (W_f) was recorded. All measurements were conducted in triplicate. The moisture content was calculated using equation (2):

$$\text{Moisture content (\%)} = \frac{W_0 - W_f}{W_0} \times 100 \quad (2)$$

2.4.4 Opacity

The transmittance and opacity of the produced films was assessed using the method previously described by Susmitha et al. (2021) with slight modification. The films were cut into rectangle pieces (1 cm x 4 cm) and placed directly in the light path by positioning them vertically inside a clean glass cuvette. The absorbance was recorded using a UV-vis spectrophotometer (DR6000, HACH, Wilayah Persekutuan Kuala Lumpur, Malaysia). The analysis was triplicated. The opacity was determined using the following equation (3):

$$O = \frac{Abs_{600}}{T} \quad (3)$$

Where, O is the opacity, Abs600 is the absorbance value at 600 nm and T is the film thickness (mm).

2.4.5 Folding endurance

Folding endurance was determined using a manual method adopted from Nilani et al. (2010). Films (of diameter 86 mm) were repeatedly folded at the same location along a central line (approximately 180°) until the film broke. The number of folds sustained before breakage was recorded as the folding endurance value. The test was carried out at an ambient temperature of $28\pm 2^{\circ}\text{C}$ with relative humidity of $65\pm 5\%$. Each sample was tested in triplicate.

2.4.6 Scanning electron microscopy

The microstructure of the films was analyzed using scanning electron microscopy (JSM6400, JEOL, Japan). The films were fixed on the bronze stub and sputtered with gold layer for 20 min. The magnification range of $\times 10 - 5000$ was used with a voltage of 12-15 kV (Najwa et al., 2020).

2.4.7 Biodegradability test

A biodegradability test was conducted following Susmitha et al. (2021) with slight modification. The film samples were cut into pieces of 1 cm $\times$ 4 cm and placed on an iron wire gauze. The samples were then buried at 2 cm in a plastic container containing black soil (pH 6.8 ± 0.2 , moisture content 25-30%). The soil was watered every day to maintain the moisture throughout the test. The test was carried out at an average temperature of $28\pm 2^{\circ}\text{C}$ with ambient relative humidity of $65\pm 5\%$. The films were observed and photographed at intervals of three days to observe the degradation.

2.4.8 Antimicrobial activity

Antimicrobial activity of the films was done according to Gulzar et al. (2022) with slight modification. The strains of bacteria that were used to assess the antimicrobial activity were (a) Gram-positive *Staphylococcus aureus* and (b) Gram-negative bacteria, *Salmonella enterica*, *Pseudomonas aeruginosa*, *Klebsiella pneumoniae* and *Escherichia coli*. The agar disc diffusion method was employed to conduct the antimicrobial analysis. Before analysis, all the equipment was sterilized and placed in a laminar flow cabinet for 30 min. Later, the films were cut into a 6 mm puncher-size hole by using paper punchers under sterile conditions. Bacterial suspensions (0.1 mL of 10^6 CFU/mL) were spread on Mueller-Hinton agar plates using a sterile cotton swab. Using sterile forceps, the film disks with and without PPP were placed on the inoculated plates. The plates were inverted and incubated at a temperature of 37°C for 24 h. Tests were in triplicate. The inhibition zones were measured using a Vernier caliper and photographed after 24 h of incubation.

2.4.9 Data analysis

All data for each analysis were statistically analyzed and evaluated using the analysis of variance (ANOVA) by Minitab software (Version 18, PA, USA) and presented as the mean $\pm$ standard deviation. The Tukey test was used, and means was considered significant when $p < 0.05$.

3. Results and Discussion

3.1 Thickness

The thickness of the film is a significant quality indicator that governs the mechanical as well as physical attributes of the film (Nazurah et al., 2022). As presented in Table 1, a notable increase in average thickness ($p<0.05$) was observed as PPP concentration was elevated. The value of thickness from control to 10% ranged from 0.10 mm to 0.14 mm. The increases in thickness are due to the increased film solid content contributed by the peels (Gaikwad et al., 2015). As a result, the increase in film thickness can be attributed to the composition of PPP, which contains both soluble and insoluble fibers that remain partially undissolved in the film-forming solution (Hanani et al., 2019). This was evident in the SEM analysis, which revealed embedded undissolved particles on the film surface, confirming the contribution of insoluble fibers to the increased thickness. Similar results were found when pomegranate peel was added to chitosan (Zeng et al., 2021) and mung bean protein (Moghadam et al., 2020).

Table 1. Film thickness, water solubility, moisture content and opacity of corn starch film incorporated with different concentrations of pomegranate peel powder (PPP)

Films	Thickness (mm)	Water solubility (%)	Moisture content (%)	Opacity
Control	0.10±0.02 ^c	26.38±2.84 ^a	16.65±5.60 ^a	2.403±0.086 ^c
Corn starch+2 % PPP	0.11±0.02 ^{bc}	29.44±2.23 ^a	14.32±2.88 ^a	2.784±0.061 ^b
Corn starch+4 % PPP	0.11±0.02 ^{bc}	28.63±0.51 ^a	14.38±0.51 ^a	2.839±0.041 ^b
Corn starch+6 % PPP	0.12±0.03 ^b	28.94±2.45 ^a	13.12±3.78 ^a	2.895±0.057 ^b
Corn starch+8 % PPP	0.12±0.03 ^b	27.74±1.79 ^a	13.95±3.63 ^a	3.165±0.116 ^a
Corn starch+10 % PPP	0.14±0.03 ^a	27.48±1.39 ^a	13.35±1.48 ^a	3.195±0.103 ^a

Note: Values above are given as mean±standard deviation. Means with different alphabetical letters are significantly different ($p<0.05$).

3.2 Water solubility

Water solubility reflects the film's commercial potential, with low water solubility films suitable for low-water-resistance food (Tajik et al., 2013), whereas high water solubility allows for other forms of use, such as edible coatings (Pérez-Vergara et al., 2020). As shown in Table 1, the addition of PPP did not cause significant changes in the water solubility of the corn starch films ($P>0.05$). The control film showed the lowest solubility, likely due to the crystalline regions formed by amylose molecules, which created a compact structure resistant to water penetration (Choi et al., 2022). The observed reduction in film solubility at higher PPP concentrations, corroborated by SEM images showing undissolved powder, is a desirable trait for moisture resistance in food packaging. This could be due to interactions between anthocyanins in PPP (Gullón et al., 2020) and the hydroxyl and carboxylic groups in the polymer materials, such as glycerol, which reduce their ability to interact with water and make the films less soluble (Sanches et al., 2020). Comparable findings were observed by Hanani et al. (2019), who incorporated pomegranate peel powder into gelatin films, and by Zhang et al. (2019), who used mangosteen peel powder in chitosan-based films.

3.3 Moisture content

Table 1 shows the results of the moisture content analysis of all the films. The results showed no significant difference ($p>0.05$) in the moisture content of the films regardless of the concentration of the PPP. The moisture content of the films ranged from 16.65% in the control sample to 13.35% in films with 10% PPP. This could be attributed to the interaction between polyphenolic compounds in PPP and the hydrogen bonding sites in starch, which may hinder the film matrix's ability to bind with water, consequently lowering its moisture-absorbing capacity (Zeng et al., 2021). A comparable pattern was reported by Yun et al. (2023), who incorporated passion fruit peel powder into sodium alginate films; Wu et al. (2018), who used pomelo peel flour along with tea polyphenols; and Qin et al. (2019), who blended red pitaya peel extract with starch and polyvinyl alcohol.

3.4 Opacity

The ability of bio-based films to block UV light is important for food packaging applications, as it prevents lipid oxidation, preserves both nutritional and organoleptic qualities, and extends the food's freshness (Haghighi et al., 2019). As evidenced in Table 1, the opacity of films increased ($P<0.05$). This phenomenon is attributed to the presence of ellagic acid in pomegranate peel (Ismail et al., 2012), which possesses the ability to absorb UV light (Vilela et al., 2017). This aligns with findings by Zeng et al. (2021), who noted that the availability of phenolic compounds in films can reduce the transmission of UV and visible light. Furthermore, pomegranate peel contains anthocyanins, natural pigments responsible for red, purple, and orange coloration (Abdelrahman et al., 2024), which also contribute to the darker color of the films and consequently to their higher opacity. An equivalent outcome was reported by Rambabu et al. (2019) with mango leaf extract in chitosan film, and by Hanani et al. (2018), who reported that fruit peel powders such as pomegranate, papaya, and jackfruit increased the opacity of bilayer films. Hence, PPP can enhance the ultraviolet-visible light barrier properties of corn starch films, thereby mitigating food deterioration. Since the films are partially transparent, they may enhance marketability by providing consumers with visibility of the food product inside (Simmonds & Spence, 2016).

3.5 Folding endurance

The folding endurance test serves as an important indicator of a film's mechanical strength, particularly its resistance to damage from repeated folding. This test indicates how well the film maintains its physical integrity during use (Ahmad et al., 2022). In this study, the films were folded more than 350 times at the same spot without any physical changes, demonstrating high durability. This could be attributed to the effect of the plasticizer, glycerol's hydroxyl groups, which form hydrogen bonds within and between polymer chains, increasing the flexibility of the films (Souza et al., 2012). These findings align with Mendua starch films (Malik et al., 2022) and pea starch films (Patil & Mahajan, 2021), who reported that their film could withstand over 300 folds at the same spot without breaking.

3.6 Scanning electron microscope analysis

Scanning electron microscopy (SEM) analysis enables the examination of film structure and elucidates the effects of treatments on the configuration of the film-forming matrix (Boeira et al., 2022). Figure 2 depicts the microstructure of the corn starch film surface area,

incorporating varying concentrations of PPP. Both the starch films, with and without PPP addition, display a heterogeneous structure characterized by visible agglomerated starch granules. Notably, unlike the films described in previous research by De Araújo et al. (2015), Ali et al. (2019), and Lai et al. (2023), the films in this study exhibited no apparent cracks or pores, suggesting enhanced structural integrity. However, the incorporation of PPP introduces clusters within the film matrix, potentially arising from insoluble particles (Terzioğlu et al., 2021), which results in poor dispersion of powder in high-viscosity solutions (Nogueira et al., 2019). This phenomenon aligns with reports by Dai et al. (2018), where pineapple peel-derived nanocellulose also demonstrated agglomeration tendencies even at low concentrations. Furthermore, Nogueira et al. (2019) also reported particle clustering when blackberry powders were directly incorporated into starch films. Similarly, De Moraes Crizel et al. (2017) observed clustering as the concentration of papaya peel powder increased in gelatin films, whereas a smooth surface was achieved when the powder was added as microparticles, suggesting that microparticle incorporation is a more effective method.

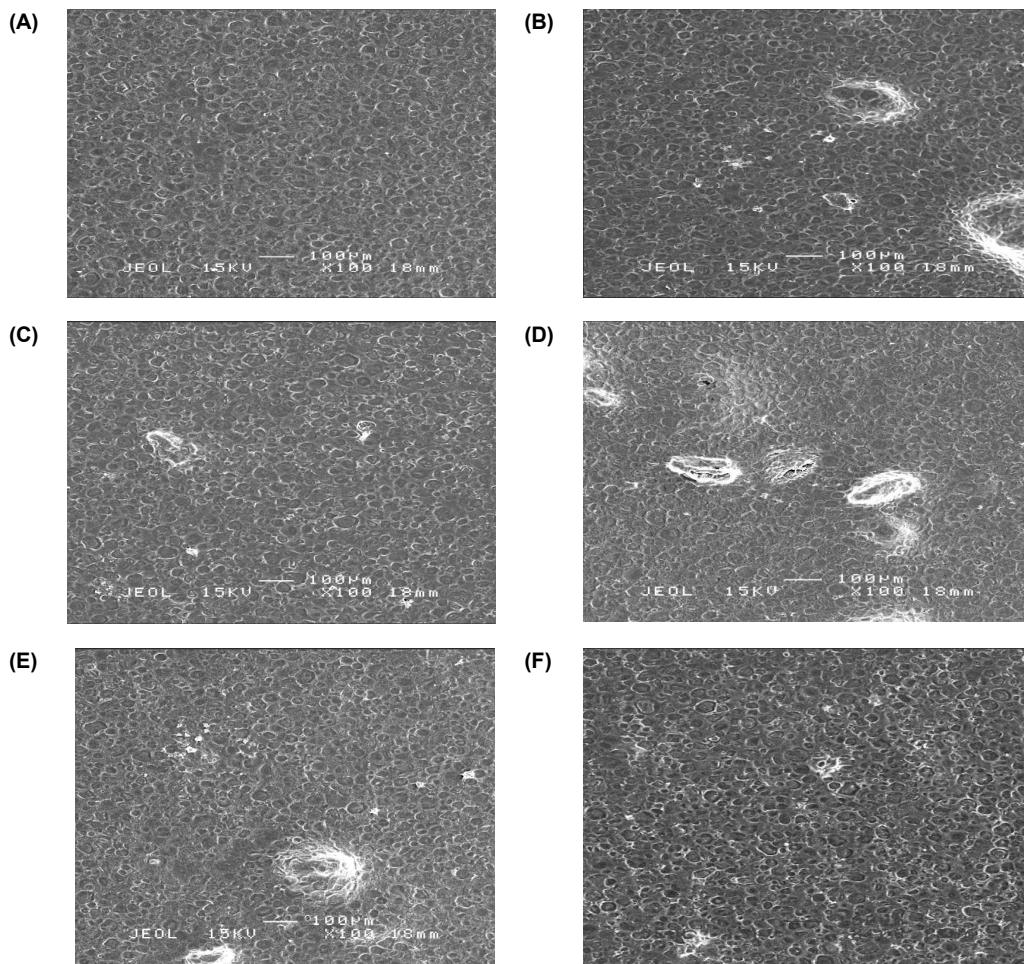


Figure 2. Scanning electron microscopy view of the surface of corn starch films with pomegranate peel powder (PPP): (A) control, (B) film with 2% PPP, (C) film with 4% PPP, (D) film with 6% PPP, (E) film with 8% PPP, and (F) film with 10% PPP.

3.7 Antimicrobial activity

Table 2 illustrates the antimicrobial performance of corn starch films enriched with varying levels of pomegranate peel powder (PPP) against selected bacterial strains. These include the Gram-positive *Staphylococcus aureus* and Gram-negative species such as *Salmonella typhi*, *Escherichia coli*, *Klebsiella pneumoniae*, and *Pseudomonas aeruginosa*.

As anticipated, the control film exhibited no inhibition zone for any of the bacterial strains. The films containing PPP demonstrated antimicrobial activity against all the bacteria and exhibited a significant ($p < 0.05$) increase in antimicrobial activities as the PPP concentration increased. This effect was attributed to punicalagin, which constitutes the major proportion of pomegranate peel and contributes most significantly to antibacterial action (Chen et al., 2021). Among all the bacterial strains tested with PPP, the highest antimicrobial activity was observed against *S. aureus*, a Gram-positive strain, with 10% of PPP resulting in a 1.36 cm inhibition zone, as shown in Figure 3. The increased susceptibility of Gram-positive bacteria to phytochemicals is attributed to the absence of an outer membrane, facilitating easier access through their cell wall. In contrast, Gram-negative bacteria possess a lipopolysaccharide layer and a periplasmic space that hinder the penetration of antimicrobial agents (Salim et al., 2023). This finding was corroborated by Rahnemoon et al. (2021), Yuan et al. (2015), and Hanani et al. (2019), who observed that *S. aureus* exhibited the highest inhibition.

3.8 Biodegradability test

The biodegradability of the natural polymer-based packaging films serves as a crucial parameter in assessing their environmental compatibility and sustainability. From Table 3, it is evident that as the concentration of PPP in the film increased, the time required for complete degradation in the soil also increased. This was likely due to the presence of polyphenols in PPP, which can inhibit microbial activity and decelerate the degradation process (Piñeros-Hernandez et al., 2016). While the control and films containing 2% and 4% PPP degraded within 3 days, the film with the highest concentration (10% PPP) required 12 days for full degradation. During this process, the film gradually lost its structural integrity and ultimately degraded completely. The rapid degradation of starch film was attributed to the presence of acetal bonds in starch (Hanapiah et al., 2024), which facilitate the degradation process and are readily metabolized by microbes naturally occurring in soil (Thakwani et al., 2023). Furthermore, the organic origin of starch and PPP enhances microbial degradation (Siddiqui et al., 2023). A comparable 12 day degradation period was observed in cassava starch film by Jaramillo et al. (2016) and antioxidant films developed by Grisales-Mejía et al. (2024). In comparison, other films such as poly(lactic acid) with orange peel powder (Sambudi et al., 2022), corncob-derived film (Paudel & Janaswamy, 2024), and jackfruit peel cellulose film (Reshmy et al., 2021) degraded in 28 days, 29 days, and 50 days, respectively. In compliance with the ASTM D6400–12 standard (Prajapati & Jadeja, 2024), all our films achieved degradation in less than 180 days. Therefore, the corn starch films with PPP hold promise as sustainable food packaging material, offering a potential solution for food packaging to reduce environmental pollution.

Table 2. Inhibition zone of corn starch film incorporated with different concentrations (0%, 2%, 4%, 6%, 8%, 10%) of pomegranate peel powder (PPP)

Films	<i>S. aureus</i> (cm)	<i>S. typhi</i> (cm)	<i>E. coli</i> (cm)	<i>K. pneumoniae</i> (cm)	<i>P. aeruginosa</i> (cm)
Control	0.00±0.00 ^e	0.00±0.00 ^f	0.00±0.00 ^f	0.00±0.00 ^e	0.00±0.00 ^d
Corn starch+2% PPP	0.85±0.01 ^d	0.76±0.03 ^e	0.77±0.03 ^e	0.77±0.05 ^{de}	0.81±0.06 ^c
Corn starch+4 % PPP	0.99±0.00 ^c	0.88±0.03 ^d	0.93±0.03 ^d	0.89±0.03 ^{cd}	0.89±0.05 ^c
Corn starch+6 % PPP	1.21±0.02 ^b	1.06±0.02 ^c	1.03±0.04 ^c	1.02±0.10 ^{bc}	1.09±0.03 ^b
Corn starch+8 % PPP	1.31±0.01 ^a	1.20±0.01 ^b	1.16±0.02 ^b	1.14±0.05 ^{ab}	1.19±0.05 ^{ab}
Corn starch+10 % PPP	1.36±0.00 ^a	1.32±0.01 ^a	1.33±0.01 ^a	1.20±0.03 ^a	1.26±0.03 ^a

Note: Mean±standard deviation in the same column with different superscripts are significantly different ($p<0.05$).

**Figure 3.** Highest inhibition zone for *Staphylococcus aureus* inhibition zone for Control (C), 2%, 4%, 6%, 8% and 10% PPP films

Table 3. Biodegradation of corn starch film incorporated with different concentrations of pomegranate peel powder (PPP)

	Control	2%	4%	6%	8%	10%
Day 1						
Day 3						
Day 5						
Day 7						
Day 12						

4. Conclusions

Biodegradable active packaging films were prepared effectively using a casting technique, with corn starch incorporated with pomegranate peel powder (PPP) to enhance their properties. This addition resulted in thicker films while reducing moisture content and water solubility. The resulting films were more opaque and able to withstand repeated folding, indicating good compatibility between PPP and the corn starch matrix. Notably, these films demonstrated measurable antimicrobial activity, particularly against *Staphylococcus aureus*, with efficacy against diverse bacterial groups. This highlights their potential in extending shelf life and minimizing food spoilage. Additionally, the films exhibited excellent biodegradability, fully degrading within 12 days, reinforcing their role as an environmentally friendly alternative to conventional plastic packaging. Films with 10% PPP emerged as the optimal formulation, delivering moderate antimicrobial efficacy, particularly against *Staphylococcus aureus*, while maintaining good physical properties and complete biodegradability. These findings suggest that biodegradable active packaging films have significant potential in contributing to sustainability within the food and beverage sector. This study has a few limitations, as advanced mechanical properties, water and air permeability were not included and are recommended for future research. Furthermore, future studies could focus on scaling up production and evaluating the films' performance under real-world storage conditions to further assess their commercial viability and long-term benefits.

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6. Authors' Contributions

Shivania Kathiresan: Conceptualization, Supervision, Validation, Writing, Review and Editing. Nur Hidayah Md Isa: Methodology, Investigation, Formal Analysis, Writing Original Draft. Nerosna K.V. Mohan Raja: Methodology, Investigation, Formal Analysis, Writing Original Draft.

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7. Conflicts of Interest

The authors declare no conflict of interest.

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