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Physical, Mechanical, and Antioxidant Properties of Edible Film from Jackfruit Seed Starch and Microcellulose with Addition of Green Tea Extract

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Abstract

Edible films are gaining popularity as biodegradable alternatives to plastic packaging. Starch-microcellulose-based edible films are known to exhibit favorable physical and mechanical properties. However, enhancing their resistance to deterioration as food packaging is essential for extending shelf life of the product. This study aimed to develop edible films from jackfruit seed starch and microcellulose with the incorporation of green tea extract and to evaluate its effects on the films' antioxidant activity, physical, and mechanical properties. Edible films were prepared with green tea extract at concentrations of 2.5%, 5%, 7.5%, and 10% (w/w of total starch). The produced films exhibited a smooth and elastic texture. The addition of green tea extract enhanced antioxidant properties, as indicated by an increase in 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity, with the highest activity observed at 10% extract concentration. Furthermore, the extract improved the films' thickness, density, tensile strength, and elongation while reducing water absorption and water vapor transmission rate. However, the mechanical properties did not yet meet the Indonesian National Standard for packaging materials.

Keywords: *2,2-diphenyl-1-picryhydrazyl, elongation, food packaging, tensile strength*

Introduction

Edible films are commonly used as coatings for food products and can be consumed along with the packaged food [1], [2]. These films are primarily composed of hydrocolloids (proteins, polysaccharides), lipids (waxes, acyl glycerols, fatty acids), or their composites [3]. Starch, a widely used raw material for edible films, offers advantages such as biodegradability, ease of modification, and affordability due to its abundant availability from various sources [4]. Common starch sources for edible film production include cassava, corn [5], taro [6], sago [3], and ganyong [7]. However, since these materials are also staple food commodities, their use in edible film production may lead to competition with food supply chains.

Jackfruit seeds are an alternative starch source that remains underutilized. In Indonesia, they are often discarded after the fruit's flesh is consumed or processed. According to the Central Bureau of Statistics [8], Indonesia produced 906,514 tons of jackfruit in 2021. Jackfruit seeds contribute significantly to waste percentage, comprising 30–50% of the total fruit mass [9]. They are rich in carbohydrates, containing 36.7 g per 100 g, with starch making up 94.5% of the total carbohydrates [10].

Starch-based edible films typically have poor physical properties and flexibility. These limitations can be addressed by incorporating fillers such as cellulose [11]. However, previous studies have shown that starch-based bioplastics from jackfruit seed starch with added coconut fiber cellulose still exhibit a rough surface and a relatively rigid structure [12]. Reducing cellulose particle size enhances its interaction with starch, improving film elasticity, tensile strength, density, and thickness. Studies have also

reported increased tensile strength with higher concentrations of microcrystalline cellulose (MC) [13]. Therefore, this study incorporates MC as a filler in jackfruit seed starch-based edible films.

To date, no studies have incorporated antioxidant materials into jackfruit seed starch-MC edible films. Antioxidants prevent oxidation by donating electrons to highly reactive free radicals [14]. thereby inhibiting spoilage and extending the shelf life of packaged food products. Green tea is a well-known antioxidant source due to its high catechin content, which reaches 6.9%, the highest among all tea varieties [15]. It also exhibits strong antioxidant activity, with a reported value of 58.6 μg/mL [16]. Edible films enriched with green tea extract have demonstrated significant free radical inhibition (52.9%) while enhancing physical and mechanical properties [17]. Therefore, this study aims to develop a jackfruit seed starch-MC edible film incorporating green tea extract as an antioxidant and to evaluate its antioxidant activity, physical and mechanical properties, and overall performance.

Experimental

Equipment

The equipment used in this study included standard laboratory glassware, an analytical balance, an oven, a hot plate, a centrifuge (Hettich Universal), an ultrasonic cleaner (Elmasonic S), a Microtrac II Particle Size Analyzer (PSA), 40- and 100-mesh sieves, a rotary evaporator, a Fourier-transform infrared (FTIR) spectrophotometer (Thermo Scientific), a liquid chromatography-mass spectrometry (LC-MS) system (Acquity UPLC® H-Class System, Waters, USA), glass plates (molds), a digital micrometer screw gauge (Teclock), a tensile strength and elongation tester (Instron), micropipettes (10, 100, 200, and 1000 μL), a 96-well microplate, and a microplate reader (Spectrostar Nano).

Material

Jackfruit seeds were obtained from a private garden in Bekasi, commercial cellulose (Sigma Aldrich, Singapore; catalog number 9004-34-6) was purchased from Toko Nitra Kimia, Bantul Regency, and young green tea leaves were sourced from the Pangandaran Tea Plantation. Analytical-grade (p.a) chemicals produced by Merck (Darmstadt, Germany) included sulfuric acid (H_2SO_4), ethanol, concentrated HCl, magnesium powder, glacial acetic acid (AcOH), Folin-Ciocalteu reagent, and sodium carbonate (Na_2CO_3). The 2,2-diphenyl-1-picrylhydrazyl (DPPH) reagent and Trolox were obtained from Sigma Aldrich (Singapore). Additionally, gallic acid (Fisher) and glycerol (Ecogreen) were used.

Methods

Preparation of Jackfruit Seed Starch and Microcrystalline Cellulose [18]

Jackfruit seeds were sun-dried for three days, after which the outer skin was peeled off and the seeds were washed with tap water. A total of 100 g of cleaned jackfruit seeds were cut into small pieces and blended with 1 L of distilled water. The resulting suspension was filtered through a filter cloth, and the starch was allowed to settle from the filtrate for 12–24 hours. The wet starch precipitate was separated from the filtrate and then dried in an oven at 70 °C for approximately six hours until a fine, light brownish-white powder was obtained. The starch yield was calculated using Equation (1).

$$\text{Yield (\%)} = \frac{\text{Weight of starch (g)}}{\text{Weight of juckfruit seeds (g)}} \times 100\% \qquad (1)$$

A 1:20 (w/v) mixture of commercial cellulose and 40% (v/v) H_2SO_4 solution was heated at 45 °C for 60 minutes with continuous stirring. After cooling, distilled water was added at twice the volume of the H_2SO_4 solution, and followed by centrifugation at 5000 rpm for 20 minutes. The cellulose precipitate was separated from the supernatant and neutralized with distilled water until reaching a pH of 6-7. The neutralized cellulose precipitate was then ultrasonicated for 30 minutes, forming a fine white microcrystalline cellulose (MC) powder, which was subsequently dried in an oven at 60 °C. The MC yield was calculated using Equation (2):

$$\text{Yield (\%)} = \frac{\text{Weight of MC (g)}}{\text{Weight of cellulosa (g)}} \times 100\% \qquad (2)$$

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The particle size of MC was analyzed using a Particle Size Analyzer (PSA). The MC suspension in distilled water was placed into a cuvette and positioned in the sample compartment. The measurement results were presented as a particle size distribution curve relative to particle diameter.

Preparation and Analysis of Green Tea Extract Content [19], [20]

Green tea leaves were dried, ground using a blender, and sieved using 40- and 100-mesh sieves. A total of 50 g of tea powder was then soaked in 500 mL of 70% ethanol and heated at 40 °C for 40 minutes with continuous stirring. The suspension was filtered using filter paper, and the filtrate was concentrated using a rotary evaporator. The concentrated extract was then dried in an oven at 55 °C and stored in a refrigerator until use in edible film preparation.

Flavonoid Test [22]. A total of 0.1 g of green tea extract was placed in a test tube, followed by the addition of 0.05 g of magnesium powder and 1 mL of concentrated HCl. The mixture was shaken, and a positive result was indicated by a color change to yellow or reddish-orange.

FTIR Analysis. The green tea extract was prepared as a pellet with KBr and subjected to FTIR spectrum measurement within the wavenumber range of 400–4000 cm^{-1}. The resulting FTIR spectrum was presented as a graph of wavenumber versus transmittance percentage**.**

Analisis LC-MS. The green tea extract was analyzed using ultra-performance liquid chromatography-mass spectrometry (UPLC-MS) to identify its compound content based on retention time and mass (m/z) data. The UPLC column used was Acquity UPLC HSS C18 (1.8 µm, 2.1 mm × 150 mm) with a capillary temperature of 100 °C. The elution process utilized 5 mM ammonium formate (solvent A) and 0.05% formic acid in acetonitrile (solvent B) with a total flow rate of 0.2 mL/min. Mass spectrometry (MS) ionization was conducted using an electrospray ionization (ESI) source in positive ionization mode. Detection was performed using quadrupole time-of-flight (QTOF) mass spectrometry with a Xevo G2-S QTOF detector, covering a mass analysis range of (m/z) 50–1200.

Moisture Content Determination [21]

A total of 3 g of starch, 1 g of MC, and 2 g of green tea powder were accurately weighed and placed into porcelain crucibles with known empty weights. The crucibles containing the samples were then dried in an oven at (105 ± 2) °C for 3 hours. After cooling in a desiccator, the samples were weighed. The drying and weighing process was repeated until a constant weight was achieved. The moisture content was calculated using Equation (2).

$$\text{Moisture content} = \frac{b-c}{a} \times 100 \quad (2)$$

Description:
a = initial sample weight (g)
b = weight of sample + crucible before drying (g)
c = weight of sample + crucible after drying (g)

Edible Film Preparation (modified from (Ningrum, 2022))

Microcrystalline cellulose (MC) (5% [w/w] of the total composition) was dissolved in 10 mL of 10% [v/v] acetic acid (AcOH) for 30 minutes and then mixed with a starch solution (95%, 92.5%, 90%, 87.5%, and 85% [w/w]) in 100 mL of distilled water. Green tea extract (0%, 2.5%, 5%, 7.5%, and 10% [w/w]) was subsequently added, followed by 1.5 mL of glycerol. The mixture was heated at 70-80 °C for 1 hour until homogeneous, then cooled to 50 °C, poured onto a mold, and spread evenly. After air-drying for three days, the edible film was carefully peeled from the mold.

The resulting edible films were analyzed for their physical properties, including thickness [23] and density [22]; mechanical properties, including tensile strength and elongation percentage (ASTM D882); and performance characteristics, including water absorption (ASTM D570-98) and water vapor transmission rate (WVTR) [26].

Film Thickness Test. The thickness of a 2 cm × 10 cm film sample was measured using a micrometer with an accuracy of 0.01 mm at five

different points: four at the edges and one at the center. The film thickness was calculated as the average of these five measurements.

Tensile Strength and Elongation Test. A 2 cm × 10 cm film sample was clamped at both ends using a universal testing machine (UTM) and subjected to tensile testing at a crosshead speed of 10 mm min^{-1}. The tensile strength was calculated using Equation (3), while the elongation percentage was determined using Equation (4).

$$\sigma = \frac{F_{maks}}{A} \quad (3)$$

Descripsion:
σ = tensile strength (MPa)
F_{maks} = maximum tensile force (N)
A = Cross-sectional area (mm^2)

$$\varepsilon = \frac{\Delta L}{L} \times 100\% \quad (4)$$

Descripsion:
ε = elongation/extension (%)
$\Delta L = (L - L_0)$ = increase in length (mm)
L_0 = initial length (mm)

Density Test. An empty pycnometer was weighed (*W0*), then a piece of the film was placed inside, and the pycnometer was weighed again (W1). The pycnometer was then filled completely with distilled water, ensuring no air bubbles, and weighed once more (*W2*). Additionally, the pycnometer filled only with distilled water, without the film sample, was weighed (*W3*). The density (*D*) in g mL^{-1} was calculated using Equation (5).

$$D = \frac{(W_1 - W_0)}{(W_3 - W_0) - (W_2 - W_1)} \times [D_1 - D_a] + D_a \quad (5)$$

Keterangan:
D_1 = density of water (g/mL)
D_a = density of air at the experimental temperature (g/mL)

Water Absorpsion Capacity (WAC) Test. A film sample measuring 2 cm × 2 cm with a known dry weight (W_0) was immersed in distilled water for 24 hours. The film was then removed and weighed again to obtain its wet weight (W_1). The water absorption capacity was calculated using Equation (6).

$$WAC = \frac{(W_1 - W_0)}{W_0} \times 100\% \quad (6)$$

Water Vapor Transmission Rate (WVTR) Test. A petri dish was filled with 15 mL of distilled water and covered with aluminum foil, which had a 3 cm × 3 cm hole in the center sealed with the film sample. The dish was then heated in an oven at 40 °C for 60 minutes, with its weight recorded every 20 minutes. The water vapor transmission rate was calculated using Equation (7).

$$WVTR = \frac{\text{Mass of Water Lost}}{\text{Time (det)} \times \text{Area } (m^2)} \quad (7)$$

Determination of Total Phenolic Content [27]

Edible film and green tea extract (10 g each) were dissolved in 10 mL of 70% [v/v] ethanol. A 20 µL aliquot of the solution was transferred into a microplate using a micropipette, followed by the addition of 120 µL of 10% [v/v] Folin-Ciocalteu reagent. The mixture was left in the dark for 5 minutes before adding 80 µL of 10% [w/v] Na_2CO_3 solution. The sample was then incubated in the dark for 30 minutes until a blue color developed. Absorbance was measured at 754 nm using a microplate reader. The total phenolic content was calculated based on a gallic acid standard curve prepared at concentrations of 0, 30, 45, 60, 75, 90, 105, and 120 ppm and expressed as mg gallic acid equivalents (GAE) per gram of dry weight.

Determination of Antioxidant Activity Using the DPPH Method (modified from [28])

Edible film and green tea extract (10 g each) were dissolved in 10 mL of 70% [v/v] ethanol. A 40 µL aliquot of the solution was transferred into a microplate using a micropipette, followed by the addition of 250 µL of 125 µM DPPH stock solution. The mixture was incubated in the dark for 30 minutes until it turned yellow. The absorbance (A) was measured at 517 nm using a microplate reader. A standard curve was prepared using Trolox solutions at concentrations of 0, 25, 50, 75, 100, and 150

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μg/mL. The DPPH radical scavenging activity was calculated using Equation (8).

Inhibition Activity DPPH (%)

$$= \frac{A_{blank} - A_{sample}}{A_{blank}} \times 100\% \quad (8)$$

Results and Disscusion

Edible Film from Jackfruit Seed Starch, Microcellulose, and Green Tea Extract

The edible film was formulated using a mixture of starch, microcellulose (MC), and green tea extract. Starch was isolated from jackfruit seeds, yielding 42% with a moisture content of 10.1%, which is higher than previously reported values of 30% [12] and 31% [18]. This difference may be due to variations in the jackfruit seed source. MC was produced from commercial cellulose through acid hydrolysis, centrifugation, and ultrasonication. Strong acids hydrolyze the amorphous regions of the cellulose chain [29]. The optimal conditions for achieving the desired cellulose crystallinity without further hydrolysis into reducing sugars were a 40% (v/v) acid concentration and heating for 60 minutes [22]. Centrifugation separated the cellulose precipitate from the residual acid, while ultrasonication further broke down the crystalline aggregates into smaller particles [30]. The average MC yield was 72% with a mean moisture content of 7%. Particle size analysis (PSA) (Figure 1) revealed that MC particle size ranged from 0.22 to 5.72 μm, with the highest volume distribution (72.9%) at 1.03 μm. The particle size distribution was uniform, with a polydispersity index of 0.12.

Green tea was extracted using ethanol at 40 °C to minimize the degradation and oxidation of phenolic compounds, including flavonoids and non-flavonoids, which are abundant in tea leaves [31]. The average extract yield was 16% with a mean moisture content of 8%. A flavonoid test showed a positive result, indicated by a color change from greenish-brown to reddish-brown [32]. This change occurs due to the formation of Mg (II) ion complexes with ketone or phenolic hydroxyl groups in flavonoids [33].

The FTIR spectrum of the green tea extract (Figure 2) exhibited a strong and broad absorption at 3236 cm^{-1}, corresponding to the O–H stretching vibration in polyphenols, particularly catechins [34]. Other absorption peaks were observed at 1691 cm^{-1}, 1605 and 1518 cm^{-1}, 1451 cm^{-1}, as well as 1234, 1142, and 1031 cm^{-1}, which were attributed to C=O stretching, aromatic C=C stretching, $–CH_2–$ bending, and C–O stretching vibrations, respectively. Similar results have been previously reported by [35], [36], and [37], supporting the presence of polyphenolic compounds in the extract.

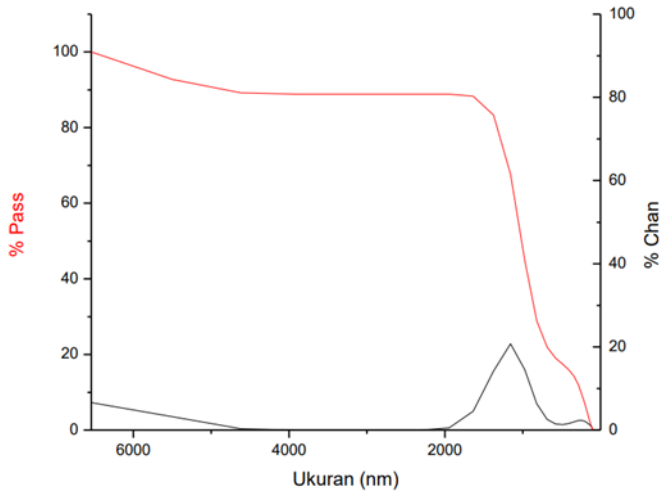

Figure 1. Particle size distribution of microcrystalline cellulose

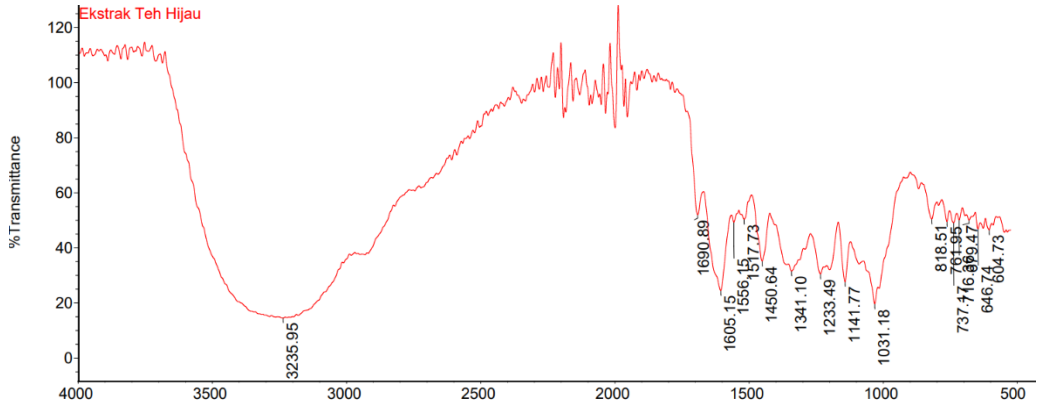

Figure 2. FTIR spectrum of green tea extract

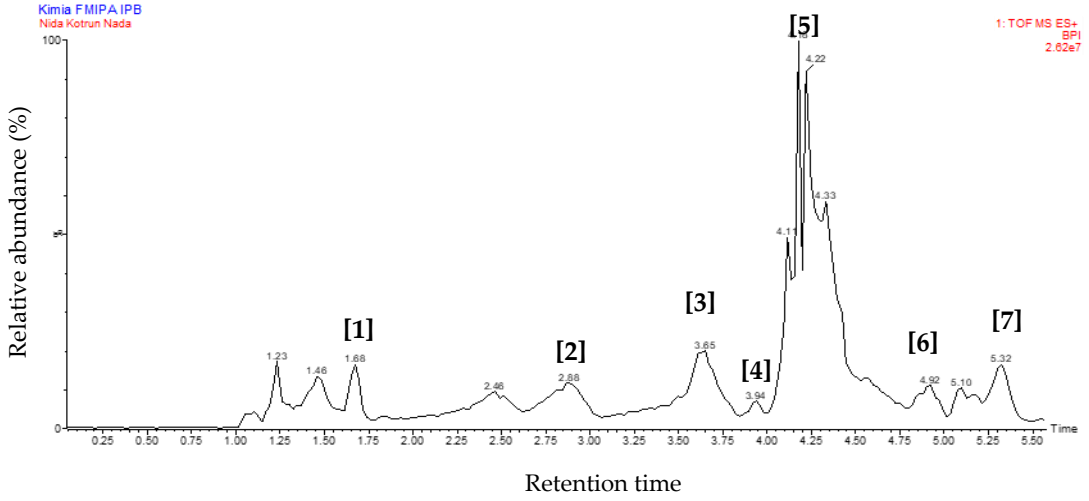

Figure 1. LC-MS chromatogram of green tea extract. Compound identities are provided in Figure 4.

The LC chromatogram of the green tea extract (Figure 3) shows peaks at retention times of 3.650 and 3.939 minutes, corresponding to m/z 291.0863 and 307.0779, respectively, which match the molecular weights of catechin and epigallocatechin. However, caffeine was the most abundant compound in the extract. Previous studies have also reported that catechin and epigallocatechin are not the major constituents of green tea [38]. Other abundant compounds include L-theanine and theophylline (non-phenolic), as well as quercetin and kaempferol (phenolic) with their molecular structures illustrated in Figure 4.

The edible film was prepared by mixing jackfruit seed starch, MC, green tea extract, and glycerol, followed by heating at 70-80 °C. The mixture thickened due to the gelatinization of the starch solution. After cooling and air-drying for three days, a greenish film with a smooth and elastic surface was formed (Figure 5). The film's transparency decreased as the green tea extract concentration increased.

Total Phenolic Content and Antioxidant Activity

The total phenolic content of green tea extract and edible films was determined using the Folin-Ciocalteu method. This method relies on the oxidation of phenolic compounds in an alkaline medium by molybdenum and tungsten phosphates, forming a blue tungsten-molybdenum complex, whose absorbance is measured at 750 nm [39]. The total phenolic

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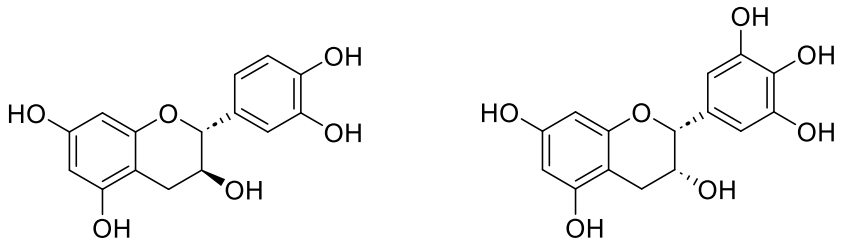
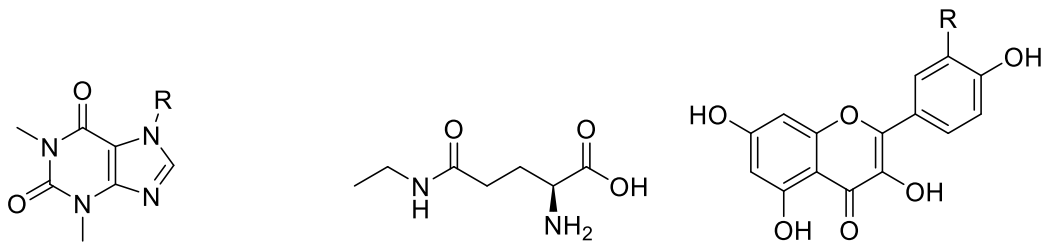
content was calculated from the standard calibration curve equation for gallic acid: $y = 0.005x - 0.0204$ with $R^2 = 0.9914$. The average total phenolic content of green tea extract was 346.78 mg GAE g^{-1} dry weight, lower than the previously reported of 422.04 mg GAE g^{-1} dry weight [20]. This variation may result from differences in geographical origin, harvest time, and storage conditions of the green tea leaves [40].



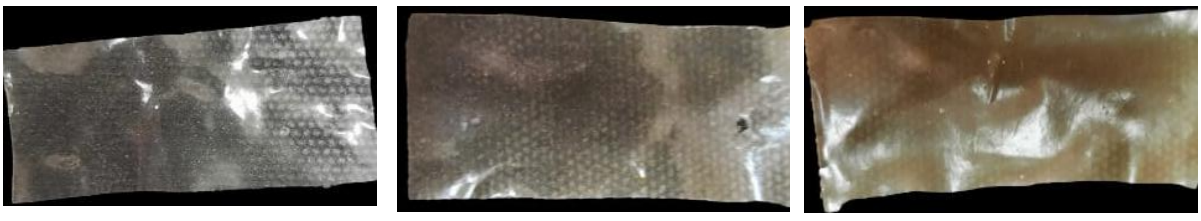
Catechin **[3]** Epigallocatechin **[4]**



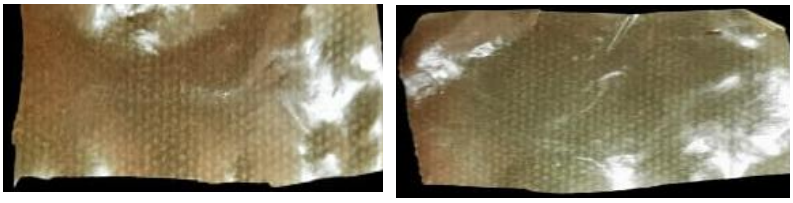
Caffeine (R = CH_3) **[5]** L-theanine **[1]** Quercetin (R = OH) **[6]**

Theophylline (R = H) **[2]** Kaempferol (R = H) **[7]**

Figure 4. Structures of major compounds in green tea extract based on LC-MS analysis.



(95%:0%:5%) (92,5%:2,5%:5%) (90%:5%:5%)



(87,5%:7,5%:5%) (85%:10%:5%)

Figure 5. Appearance of edible films with various compositions of starch:green tea extract:MC

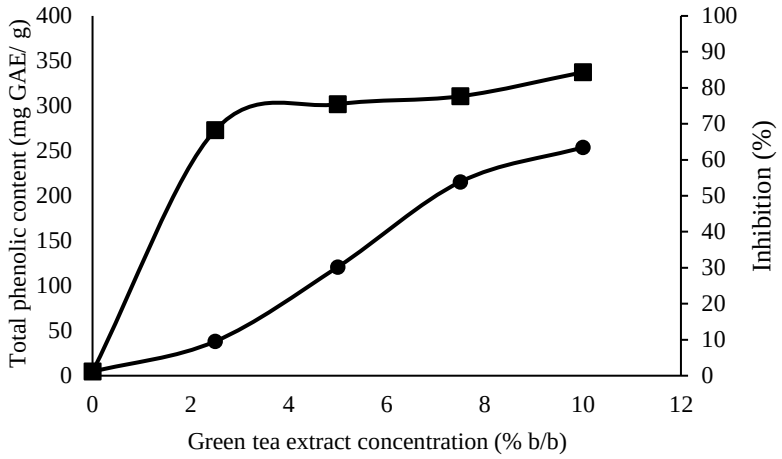


Figure 6. Total phenolic content (■) and DPPH radical scavenging activity (•) of jackfruit seed starch-MC edible films with varying concentrations of green tea extract.

The edible film without green tea extract exhibited a low total phenolic content of 4.56 mg GAE g^{-1} dry weight. The addition of 2.5% extract increased the total phenolic content to 272.89 mg GAE g^{-1} dry weight. A further increase in green tea extract concentration led to a corresponding rise in total phenolic content, reaching a maximum of 337.33 mg GAE g^{-1} dry weight at 10% extract (Figure 6). This trend is consistent with previous studies [41]. The high total phenolic content suggests that the extract is strongly retained within the film and does not easily evaporate during heating. This also highlights the potential of edible films enriched with green tea extract to prevent oxidation in packaged food products.

The antioxidant activity of green tea extract and edible films was further evaluated using the DPPH free radical scavenging method. The purple-colored DPPH radical can accept a hydrogen atom from an antioxidant compound, forming the yellow-colored 2,2-diphenyl-1-picrylhydrazine. This reaction reduces the absorbance measured at a wavelength of 515–517 nm [42]. The percentage of DPPH radical inhibition was calculated based on the Trolox standard curve equation $y = 0{,}4446x - 1{,}8478$ with $R^2 = 0.9978$.

The DPPH radical inhibition percentage of green tea extract was found to be 63.52%, which falls within the moderate category (50–70%). In contrast, a higher antioxidant activity of 80.65%, classified as strong (>70%) [43], was previously reported for tea leaves obtained from the National Research Institute in Shinkiari, Pakistan [19]. Differences in regional growth conditions may contribute to variations in antioxidant activity. In this study, the tea leaves used was sourced from Pangandaran, West Java.

Consistent with the trend in total phenolic content, increasing the concentration of green tea extract led to a higher percentage of DPPH radical inhibition in the edible films (Figure 6). The edible film without green tea extract exhibited the lowest inhibition percentage (1.12%), while the film with 10% green tea extract showed the highest inhibition (63.47%). This trend aligns with previous findings [44]. Similar to total phenolic content, the DPPH radical inhibition percentage in this study falls within the moderate category (<70%) [43]. However, the inhibition percentage observed here is still higher than the 52.9% reported in a previous study [17]. Therefore, the antioxidant potential of jackfruit seed starch-MC edible films containing 10% green tea extract in this study remains promising.

Physical, Mechanical, and Performance Properties of Edible Films

The physical, mechanical, and performance properties of the produced edible films were evaluated. The analyzed physical properties

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included thickness and density. Film thickness can be influenced by several factors, such as the composition of the materials, mold surface area, and solution volume. The edible film without green tea extract had a thickness of 62 μm. The film became thicker with the addition of increasing amounts of green tea extract (Figure 7). The edible film with 10% green tea extract had the highest thickness, measuring 116 μm. This result aligns with previous reports [17], [41] and is attributed to the higher total solids content in the film [23]. Overall, the thickness of the edible films in this study meets the Japanese Industrial Standard, which specifies a maximum thickness of 250 μm.

Density was measured to assess the film's ability to inhibit water vapor migration from packaged food products [45]. Similar to thickness, the lowest density was observed in the film without green tea extract, measuring 0.9969 g mL^{-1}, and it increased with higher concentrations of green tea extract, reaching 2.3007 g mL^{-1} for the film containing 10% extract (Figure 7). Phenolic compounds in green tea extract can form hydrogen bonds or covalent bonds with functional groups in the biopolymer chains [46]. These enhanced intermolecular interactions lead to a more compact molecular structure, thereby increasing film density. Similar findings have been reported previously [17], [47]. The density of the edible films in this study meets the packaging plastic criteria outlined in the Indonesian National Standard (SNI 7188-11-2018), which specifies a minimum density of 0.95 g mL^{-1}.

Higher density is associated with improved mechanical properties, particularly tensile strength. A stronger and more compact interactions among film components can enhance the film strength [49]. However, the measured tensile strength values (Figure 8) show a slightly different trend compared to density. The edible film without green tea extract exhibited a tensile strength of 4.37 MPa. The tensile strength decreased with the addition of 2.5% and 5% green tea extract to 2.87 MPa and 3.77 MPa, respectively. However, it subsequently increased to 5.55 MPa and 6.40 MPa with the addition of 7.5% and 10% green tea extract, surpassing the tensile strength of the film without extract. The tighter arrangement of active components within the film matrix strengthens intermolecular interactions, enhancing tensile strength by improving matrix cohesion and compactness [50]. Previous studies have reported that the incorporation of green tea extract enhances film tensile strength due to hydrogen bonding interactions between phenolic compounds and the polymer matrix, thereby modifying the film structure and its tensile properties [44], [50]. However, the highest tensile strength value obtained in this study has not yet met the tensile strength standard for films according to SNI 7188-11-2018, which ranges from 24.7 to 302 MPa.

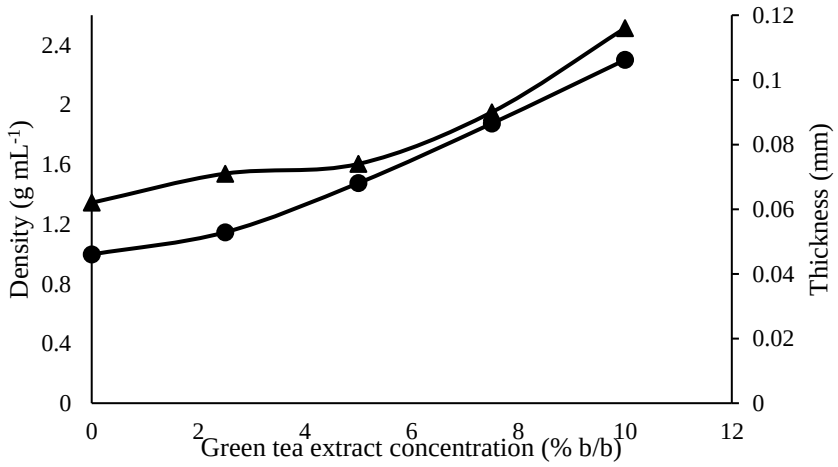

Figure 7. Thickness (▲) and density (●) of jackfruit seed starch-MC edible films with varying concentrations of green tea extract

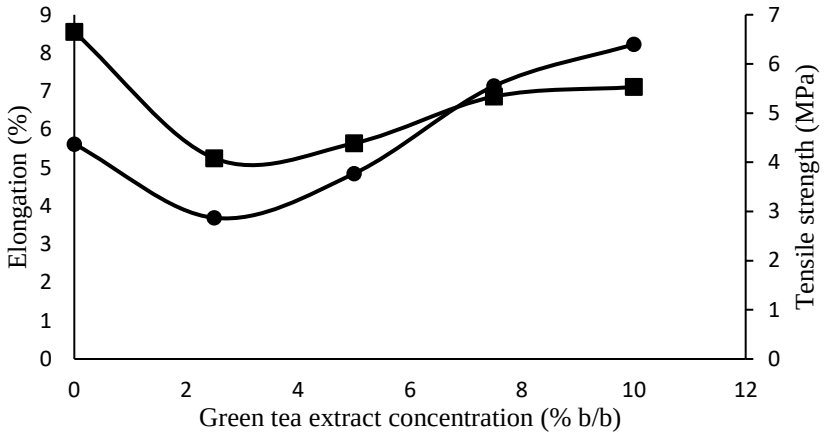

Figure 8. Tensile strength (•) and elongation percentage (▪) of jackfruit seed starch-MC edible films with varying concentrations of green tea extract.

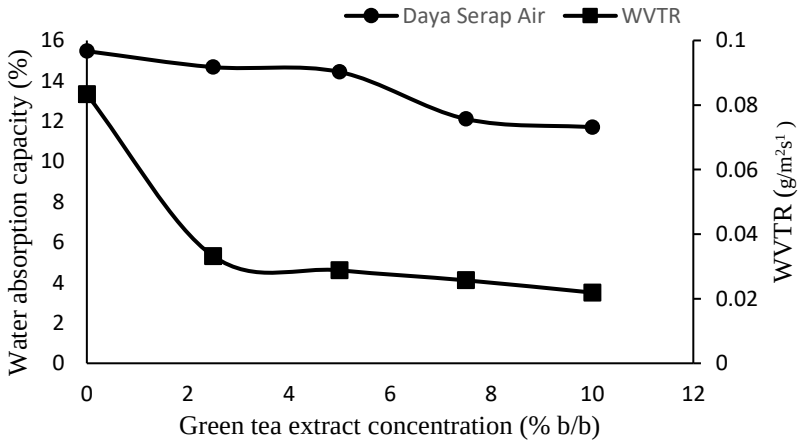

Figure 9. Water absorption capacity (•) and WVTR (▪) of jackfruit seed starch-MC edible films with varying concentrations of green tea extract

In addition to tensile strength, the mechanical property measured for the edible film was the elongation percentage. The addition of green tea extract reduced the elongation percentage to 5.25–7.11%, compared to 8.55% for the film without green tea extract (Figure 8). The incorporation of green tea extract increased intermolecular interactions within the film, thereby reducing its ability to stretch (elongate before breaking under tensile force). Typically, the elongation percentage trend is inversely related to the tensile strength trend. However, in this study, the elongation percentage increased as the concentration of green tea extract increased. The addition of 2.5% and 10% green tea extract resulted in elongation percentages of 5.25% and 7.11%, respectively. Despite this variation, the elongation percentage observed in this study remains below the standard range of 21–220% set by SNI 7188-11-2018 for film materials.

The performance of the edible film was further evaluated based on its water absorption capacity and water vapor transmission rate (WVTR). A lower water absorption capacity indicates better film quality, as it can extend the shelf life of packaged materials [51]. As shown in Figure 9, the water absorption capacity of the film decreased with increasing concentrations of green tea extract. The highest water absorption capacity was observed in the film without green tea extract (15.47%), which then decreased to 14.68–11.70% with the addition of 2.5–10% green tea

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extract. The lower hydrophilicity of films containing green tea extract was attributed to the reduction of free hydroxyl groups, which formed intermolecular interactions with the biopolymer. Previous studies have also reported a decrease in film solubility in water with the increasing concentrations of green tea extract [17], [44]. The water absorption capacity of all edible films in this study met the packaging plastic criteria based on SNI 7188-11-2018, which sets a maximum limit of 21.5%.

Water vapor transmission rate (WVTR) measures the amount of water vapor capable of passing through the film layer. As the film layer thickens, water molecules encounter greater resistance, resulting in a lower WVTR value [23]. A lower WVTR value helps reduce film degradation. As shown in Figure 9, the edible film without green tea extract exhibited the highest WVTR value of 83.3 mg s^{-1} m^{-2}. This value decreased with increasing concentrations of green tea extract in the film, reaching a minimum of 21.9 mg s^{-1} m^{-2}. This reduction aligns with the observed increase in film density with higher concentrations of green tea extract (Figure 7). The denser film structure, attributed to the strengthened interactions between phenolic compounds in the green tea extract and hydroxyl groups from starch-MC, decreases the film's permeability to water [41], [50].

Conclusions

The edible film based on jackfruit seed starch-MC with the addition of green tea extract was successfully developed. The incorporation of green tea extract enhanced the antioxidant activity of the edible film, with the film containing 10% green tea extract exhibiting the highest antioxidant activity, classified as moderate. The addition of green tea extract also influenced the physical, mechanical, and functional properties of the edible film. Film thickness, density, tensile strength, and elongation percentage increased, while water absorption and WVTR decreased. However, the mechanical properties of the resulting edible film have not yet met the packaging material standards set by SNI.

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