

Development of Cassava Starch-Based Bioplastic Films Reinforced with Jerbung Shrimp Waste Powder (*Fenneropenaeus merguensis de Man*)

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Abstract

Plastic waste is a major environmental concern because of its long-term persistence and slow degradation under environmental conditions. Bioplastics derived from renewable resources offer a potential alternative to conventional petroleum-based plastics. This study evaluated cassava starch-based bioplastic films prepared using five paired formulations in which increasing Jerbung shrimp waste powder (JSWP) content was accompanied by a proportional reduction in glycerol content. A completely randomized design was used to evaluate formulations containing 0, 0.33, 0.67, 1.00, and 1.33% JSWP, paired with 2.00, 1.67, 1.33, 1.00, and 0.67% glycerol, respectively, based on the total mass of the film-forming formulation. Film morphology, functional groups, and crystalline structure were characterized using scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), and X-ray diffraction (XRD), respectively. SEM revealed relatively rough and heterogeneous film surfaces, while FTIR spectra showed bands associated with starch and amide-containing components derived from JSWP. XRD analysis indicated the disappearance of native cassava starch crystallinity after film formation and the appearance of diffraction peaks associated with JSWP components, confirming successful incorporation of the filler into the bioplastic matrix. Thermogravimetric analysis showed that formulations containing more JSWP and less glycerol exhibited lower maximum mass-loss rates and greater residual mass at 600°C, with JSWP_{1.33} producing the highest residual mass among the composite films. Across the paired formulations, tensile strength and water resistance increased, whereas elongation at break and transparency decreased numerically. WVTR also showed a decreasing numerical trend, although differences in WVTR and elongation were not statistically significant. Among the evaluated formulations, JSWP_{1.33} exhibited the highest mean tensile strength, water resistance, thickness, and residual mass, together with the lowest mean elongation, transparency, and WVTR. These findings demonstrate the potential of paired JSWP–glycerol formulation as a strategy for increasing the strength and water resistance of cassava starch-based films (CSBF) although the independent contributions of JSWP and glycerol require further investigation.

Keywords

Cassava Starch, Shrimp Waste, Bio-Based Filler, Glycerol, Water Vapor Transmission Rate, Biodegradable Film

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1. INTRODUCTION

Plastic materials can persist in the environment for decades to centuries, depending on polymer type and environmental conditions (Chamas et al., 2020). As plastics degrade, they fragment into micro- and nanoscale particles that contaminate soil and groundwater system. In addition, improperly managed plastic waste contributes significantly to environmental pollution. Open burning of plastic waste releases greenhouse gases, particulate matter, and hazardous organic compounds, including dioxins, polycyclic aromatic hydrocarbons, phthalates, and other persistent pollutants. Exposure to these emis-

sions has been associated with respiratory and cardiovascular disorders, neurological effects, and increased long-term health risks (Pathak et al., 2024; Velis and Cook, 2021). In response to these concerns, bioplastics have emerged as a promising alternative due to their biodegradability and reduced environmental impact (Atiwesh et al., 2021).

Starch is widely investigated as a film-forming biopolymer because it is renewable, biodegradable, widely available, and relatively inexpensive. Cassava starch is particularly attractive as a film-forming raw material because cassava roots contain a high starch fraction on a dry-matter basis and are cultivated

extensively in tropical regions (Chamorro et al., 2025). Its widespread availability in Indonesia also makes cassava a locally relevant raw material for developing starch-based packaging films (Nazarudin et al., 2023; Windra et al., 2022). However, the abundant hydroxyl groups in starch make starch-based films highly hydrophilic and susceptible to water absorption. Consequently, unmodified starch films often exhibit poor water resistance, relatively high water-vapor transport, and humidity-dependent mechanical properties, which limit their practical use in packaging applications (Bangar et al., 2021).

To address these limitations, starch-based films have been reinforced or modified using bio-derived fillers such as cellulose, chitin, chitosan, and shrimp-shell-derived particles. Many previous studies have focused on purified chitin or chitosan, whereas less attention has been given to minimally purified shrimp-waste powders that retain mineral, protein, and lipid fractions. Jerbung shrimp waste powder is one such complex bio-derived filler that has received limited attention in starch-based film formulations (Saputra and Mursyid, 2023). Unlike purified chitin or chitosan, JSWP retains multiple constituents, including approximately 39.27% ash, 18.37% protein, and 2.43% lipid, as reported previously (Satria et al., 2024). This heterogeneous composition may affect filler dispersion, interfacial interactions, water affinity, and film structure. Its reported low water solubility may also reduce the contribution of readily soluble components to water uptake, although low solubility should not be interpreted directly as hydrophobicity.

Although previous work has demonstrated that JSWP can enhance tensile strength and reduce water vapor transmission rates at certain concentrations (Widiyawati et al., 2024), the material has not been extensively studied as a functionally tunable filler, nor has its behavior been examined in relation to other key formulation variables. In particular, multiple distinct components of JSWP may lead to different interactions with plasticizers compared to more uniform bio-fillers, yet this aspect remains largely unexplored.

However, previous studies have reported that the beneficial effects of shrimp-derived fillers tend to diminish or even reverse at excessive filler loadings because of particle agglomeration, poor interfacial adhesion, and increased structural heterogeneity within the polymer matrix. These findings suggest that the reinforcing efficiency of Jerbung shrimp waste powder (JSWP) depends not only on filler concentration but also on the overall formulation, including the type and amount of plasticizer. Despite the widespread use of glycerol as the primary plasticizer in starch-based bioplastics because of its ability to improve flexibility and processability (Liu et al., 2022; Zhu, 2025). However, the properties of films in which glycerol content changes simultaneously with shrimp-waste filler loading remain poorly documented. Therefore, further investigation is required to determine how paired changes in JSWP and glycerol content affect film morphology, structure, thermal behavior, and functional properties.

In the present study, a paired formulation strategy was applied in which increasing JSWP content was accompanied

by a corresponding reduction in glycerol content while the total formulation mass remained constant. This design enables evaluation of the overall response of the films to coordinated changes in filler and plasticizer levels, but it does not separate their independent effects or statistical interaction. Accordingly, this study aimed to compare the morphological, structural, thermal, mechanical, optical, and barrier properties of cassava starch-based films prepared using five paired JSWP–glycerol formulations and to identify the best-performing formulation within the investigated range.

2. EXPERIMENTAL SECTION

2.1 Materials and Reagent

Jerbung shrimp waste was obtained from a local traditional market in Jambi Province, Indonesia and consists of shrimp heads, shells and the tails. Cassava tubers were supplied by local traders. The reagent NaOH, CH_3COOH , anhydrous CaCl_2 , NaCl, and glycerol were analytical grades from Merck (Germany).

2.2 Cassava Starch Extraction

Cassava starch was extracted using a previously reported method (Ulyarti et al., 2022a). The peeled tubers were drained, grated, and blended with water at a 1:2 (w/w) ratio. This mixture was then filtered using a 200-mesh sieve and left to settle for 4 hours to obtain starch sediment (wet starch). The sediment was washed with distilled water and re-precipitated for an additional 2 hours. The cassava starch sediment was then dried in an oven at 50°C for 18 hours, ground into a fine powder, and sieved using a 60-mesh sieve.

2.3 Preparation of JSWP

JSWP was prepared using a previously reported method (Satria et al., 2024). Fresh Jerbung shrimp were selected based on firm texture and the absence of off-odors. The shrimp shells were thoroughly washed under running water and dried in an oven at 100°C for 5 hours. The dried shells were then ground into a fine powder and sieved through a 60-mesh screen. Subsequently, 90 g of JSWP was weighed and soaked in a 10% (v/v) CH_3COOH solution at a ratio of 1:5 (w/v) for 1 hour. The treated powder was rinsed with distilled water until a neutral pH was obtained, followed by soaking in 0.5 M NaOH and stirring on a hot plate at 65°C for 2 hours. After cooling, the mixture was filtered and repeatedly rinsed with distilled water until neutral pH was achieved. The resulting powder was then dried at 100°C for 4 hours and sieved again using a 60-mesh sieve.

2.4 Bioplastic Films Preparation

Bioplastic films were prepared using method described previously (Ulyarti et al., 2025). First, JSWP was dispersed in 5 mL of a 5% (v/v) CH_3COOH solution according to the designated formulation and allowed to soak for 1 hour. Distilled water and cassava starch were subsequently added, and the mixture was heated and homogenized using a low-speed magnetic stirrer

at 80°C for 30 minutes until a semi-solid mass was formed. Glycerol was incorporated after 10 minutes of heating. The resulting bioplastic solution was cast into 20×20 cm molds and dried in an oven at 50°C for 24 hours. After cooling to room temperature, the dried films were carefully removed from the molds. Two bioplastic film sheets were laminated by passing them through a laminating machine at approximately 85°C and subsequently stored in airtight containers before characterization.

The experiment was conducted using a Completely Randomized Design (CRD) with five paired JSWP–glycerol formulations: 0%, 0.33%, 0.67%, 1.00%, and 1.33% (designated as JSWP₀, JSWP_{0.33}, JSWP_{0.67}, JSWP₁, and JSWP_{1.33}, respectively). The JSWP proportion was calculated as a percentage of the total weight of the film-forming solution (150 g). To maintain a constant total formulation weight, the glycerol content was adjusted proportionally as the JSWP proportion increased. The detailed formulation is presented in Table 1.

2.5 Morphological, Spectroscopic, and Structural Analyses

The surface morphology of the bioplastic films was investigated using a FE SEM Thermo Scientific quattro S SEM (The Netherlands). Prior to analysis, the film samples were cut into small pieces and mounted on aluminum stubs using conductive carbon tape. To improve electrical conductivity and reduce charging effects during observation, the samples were sputter-coated with a thin layer of gold. SEM observations were performed under an accelerating voltage of 10–15 kV, and images were recorded at various magnifications to evaluate the surface structure and homogeneity of the films.

The chemical functional groups present in the bioplastic films were identified using Fourier Transform Infrared (FTIR) Spectroscopy (Alpha II, Bruker, Germany) equipped with an Attenuated Total Reflectance (ATR) accessory. The spectra were collected in the wavenumber range of 4000–400 cm⁻¹ with a spectral resolution of 4 cm⁻¹, and each spectrum was obtained from 32 scans to ensure a good signal-to-noise ratio. X-ray diffraction (XRD) measurements were performed using a Bruker D8 X-ray diffractometer (Bruker AXS, Germany) equipped with a Cu K α radiation source ($\lambda = 1.5406 \text{ \AA}$). Diffraction patterns were recorded over a 2θ range of 5°–80° at a scanning rate of 2° min⁻¹ with a step size of 0.02°, operating at 40 kV and 40 mA. The elemental composition of JSWP and cassava starch was determined using X-Ray Fluorescence (XRF) spectrometer (S2 PUMA, Bruker, Germany). The measurements were performed under vacuum conditions using a rhodium (Rh) X-ray source, allowing qualitative and semi-quantitative elemental analysis.

2.6 Thermal Analysis

The thermal degradation behavior of cassava starch and JSWP-containing bioplastic composites, was analyzed using a Perkin Elmer Pyris Diamond TG/DTA (USA) instrument over the temperature range from approximately 30 to 600 °C under the applied heating conditions 5°C min⁻¹.

2.7 Tensile Strength

Tensile properties of the bioplastic films were determined in accordance with JIS K 7127:2019 (Japanese Standards Association, 2019). Tensile strength testing was performed by cutting the bioplastic films into specimens measuring 2 cm × 10 cm. Each sample was clamped horizontally at both ends using clamps with a width of 1.5 cm. The test was conducted by applying a uniaxial tensile load until the bioplastic film fractured. The maximum force recorded at the point of rupture was used to calculate the tensile strength. The tensile strength was determined using Equation 1.

$$T_s = \frac{FT}{WT} \times 20 \quad (1)$$

Where T_s = Tensile strength (N/mm²), FT = Force (N) and WT = Film width (mm)

2.8 Elongation at Break

Percentage elongation was determined in accordance with JIS K 7127:2019 Japanese Standards Association (2019) by measuring the increase in length of the bioplastic film at the point of rupture. The elongation at break was calculated as the ratio of the change in length to the initial gauge length and expressed as a percentage, using Equation 2.

$$\varepsilon = \frac{(L - L_0)}{L_0} \times 100 \quad (2)$$

Where ε = Elongation (%), L = gauge length at break (mm), and L_0 = Initial length (mm).

2.9 Water Resistance

Water absorption and water resistance were determined according to a modified immersion method adapted from Piñeros-Hernandez et al. (2017). Bioplastic samples measuring 2 cm × 2 cm were weighed to obtain their initial weight. The samples were then immersed in distilled water at room temperature for 20 minutes. After immersion, surface water was gently removed using tissue paper, and the samples were reweighed to obtain the final weight (W). Water absorption and water resistance were calculated using Equations 3 and 4 respectively.

$$\text{Water absorption (\%)} = \frac{W - W_0}{W_0} \times 100\% \quad (3)$$

Where W_0 is the initial weight of the sample and w is the weight of the sample after soaking

$$\text{Water resistance (\%)} = 100 - \text{Water absorption (\%)} \quad (4)$$

Table 1. Bioplastic Films Formulations

Materials	Treatment Code				
	JSWP ₀	JSWP _{0.33}	JSWP _{0.67}	JSWP ₁	JSWP _{1.33}
JSWP (g)	0	0.5	1	1.5	2
Glycerol (g)	3	2.5	2	1.5	1
Cassava Starch (g)	5	5	5	5	5
Acetic acid solution, 5% (g)	5	5	5	5	5
Distilled water (g)	137	137	137	137	137
Total (g)	150	150	150	150	150

2.10 Water Vapor Transmission Rate (WVTR)

Water vapor transmission rate (WVTR) was determined using a modified gravimetric desiccant-cup method adapted from Piñeros-Hernandez et al. (2017). A test tube containing 5 g of anhydrous CaCl₂ was sealed at the mouth with a bioplastic film (6 cm × 6 cm), which was tightly folded and secured. The initial weight of the sealed tube was recorded. The tube was then placed in a desiccator containing a saturated NaCl solution. The tube was weighed at 30 minute intervals, and the change in weight was plotted as a function of time. WVTR was calculated using Equation 5.

WVTR = Slope / A (5)

Where the slope is obtained from the linear function of the weight gain versus time plot (g/hour) and A is the exposed film area, corresponding to the mouth of the test tube (m²).

2.11 Transparency

Film transparency was determined following the principles of ASTM D1746-23 (ASTM, 1997) with minor modifications. Bioplastic samples were cut into rectangular specimens measuring 25 mm × 15 mm and placed in a spectrophotometer cell. Prior to measurement, the UV-Vis spectrophotometer was calibrated, and baseline correction was performed using an empty cuvette (air) as the reference. The percentage transmittance was measured using a UV-Vis spectrophotometer at a wavelength of 600 nm. Film transparency was then calculated using Equation 6.

Transparency = -log(T₆₀₀) / X (6)

Where T is the transmittance at a wavelength of 600 nm and x is the bioplastic thickness (mm).

3. RESULTS AND DISCUSSIONS

3.1 Surface Morphology

The bioplastic specimens consisted of two film layers laminated before characterization, as shown in Figure 1. As the JSWP proportion increased, the films became progressively darker

and less visually transparent. The brownish-yellow coloration was more pronounced in JSWP-rich formulations, presumably because naturally colored proteinaceous and mineral components from the shrimp waste were dispersed within the starch matrix. Because JSWP content increased simultaneously with a reduction in glycerol content, the observed appearance should be interpreted as a response to the paired formulation rather than to JSWP alone.

The SEM micrographs in Figure 2 show relatively rough and heterogeneous surfaces, particularly in the JSWP-containing films, with visible particulate domains suggesting incomplete dispersion of the filler within the starch matrix. Film formation in starch-based systems begins with starch gelatinization during heating, followed by polymer-chain reassociation and matrix formation during cooling and drying (Gonçalves et al., 2020). During heating in the presence of water, starch granules initially absorb water within their amorphous regions, causing granule swelling. Further heating disrupts the ordered crystalline regions and promotes the release of amylose from the swollen granules. During subsequent cooling and water removal, the released starch chains reassociate to form a continuous polymer network. Hydrogen-bond-mediated reassociation during cooling and drying contributes to gel development and consolidation of the final film structure (Yang et al., 2024).

Several factors can influence gelatinization and network formation, including the presence of metal ions and salts (Ulyarti et al., 2022b; Yang et al., 2024). XRF analysis revealed relatively high concentration of Mg and Ca in JSWP (Table 3), which may influence starch gelatinization and film structure. Previous studies have reported that divalent metal ions can interact with hydroxyl groups in starch and affect water mobility, gelatinization behavior, and intermolecular associations within starch systems. During heating, these ions may partially leach from JSWP into the film-forming solution, potentially contributing to enhanced structural organization and reduced polymer chain mobility within the matrix.

3.2 FTIR

FTIR analysis was carried out to evaluate the functional groups and intermolecular interactions in bioplastic films prepared with different JSWP proportions. Figure 3 shows that at least five principal absorption regions were observed in all tested bio-

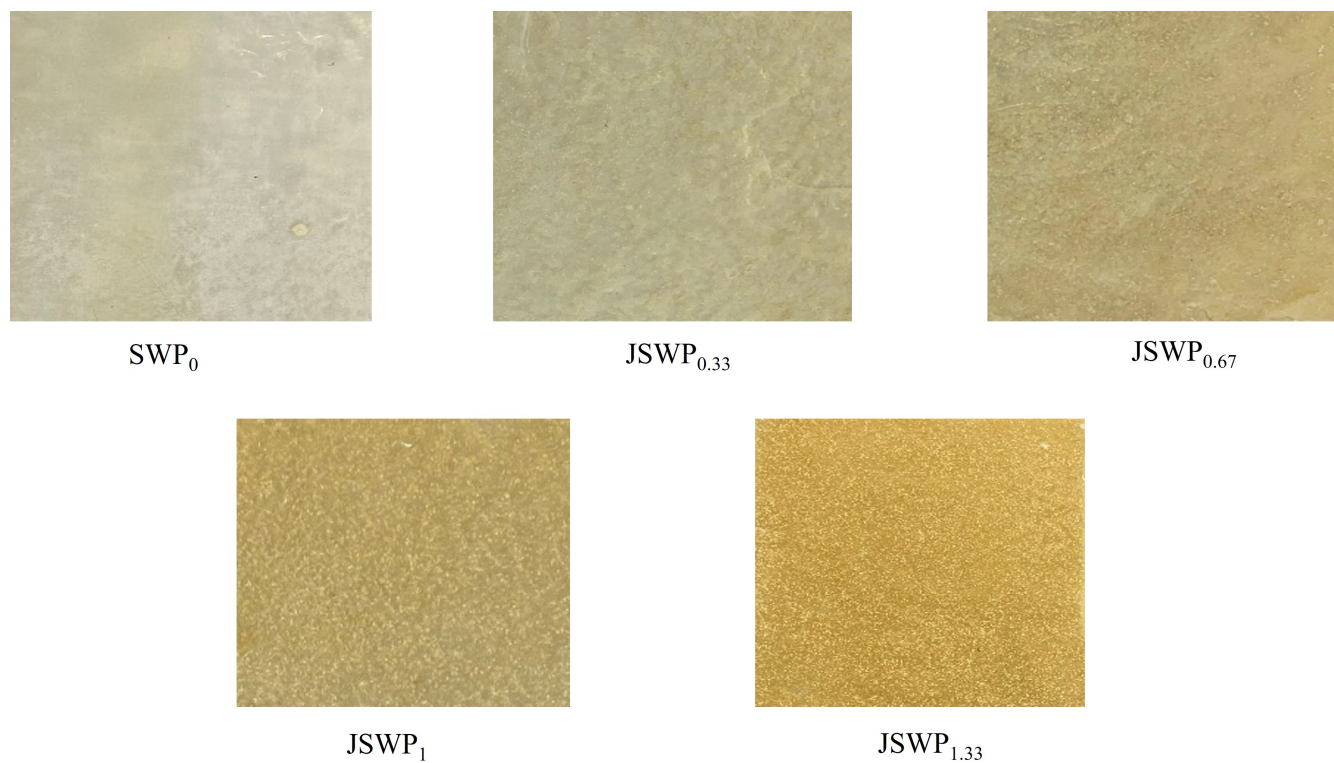


Figure 1. Visual Appearance of Cassava Starch-Based Bioplastic Films Prepared Using Different Paired Jswp–glycerol Formulations

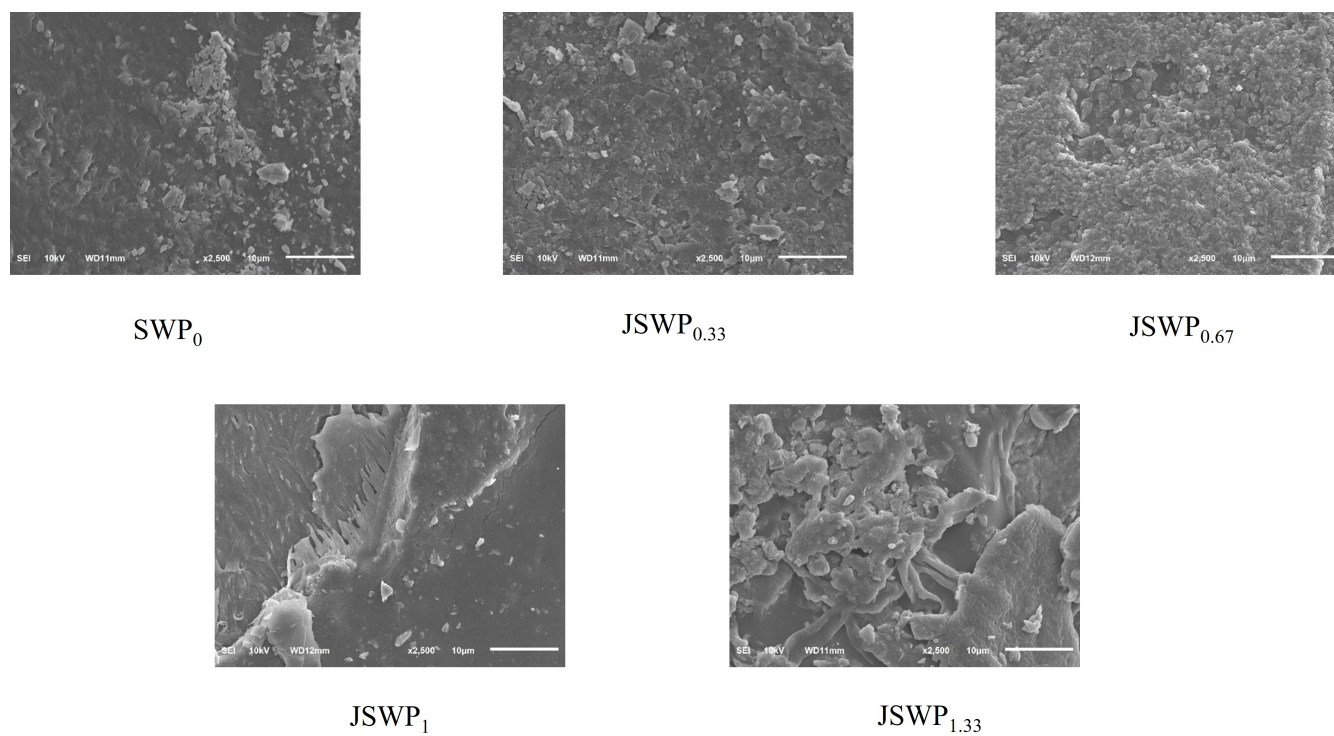


Figure 2. Sem Images of Bioplastic Films Prepared With Different Jswp Concentrations

plastic films. The differences among the samples were mainly reflected in variations in peak intensities and slight shifts in wavenumber suggesting changes in intermolecular interactions within the system. Similar observations have been reported in previous studies involving varying additive concentrations in starch-based films (Shanmathy et al., 2021).

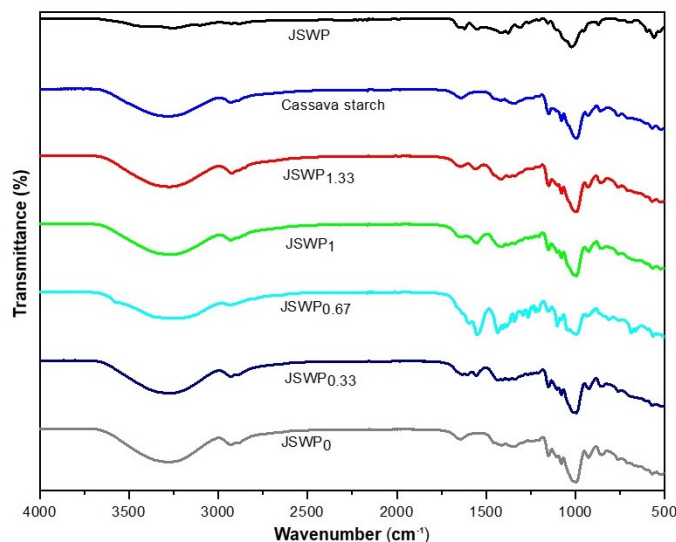


Figure 3. Ftir Spectra of Cassava Starch, JSWP and Bioplastic Films Prepared With Different JSWP Concentrations

In the current study, the main absorption bands appeared at approximately 3400 cm^{-1} , 2900 cm^{-1} , 1500 cm^{-1} , 1300 cm^{-1} , and 1000 cm^{-1} . The broad absorption band around 3400 cm^{-1} is primarily attributed to O–H stretching vibrations of hydroxyl groups present in starch and glycerol (Ulyarti et al., 2022a), although contributions from N–H stretching vibrations of amide groups may also be present (El Feky et al., 2024). The observed broadening and slight shift of this band with increasing JSWP content suggest changes in hydrogen bonding interactions among starch, glycerol, and JSWP components, indicating intermolecular compatibility within the matrix.

Glycerol plays a crucial role in determining the intermolecular interactions within starch-based bioplastic films because its three hydroxyl groups readily form hydrogen bonds with starch molecules. At higher glycerol concentrations, glycerol competes with starch–starch hydrogen bonding, resulting in increased free volume and greater molecular mobility within the polymer network. Consequently, the broad O–H absorption band reflects not only interactions between starch and JSWP but also the extent of plasticization induced by glycerol. As the glycerol concentration decreases from 3.0 to 1.0 g across the formulations, starch–starch and starch–JSWP interactions become relatively more dominant, producing a more compact hydrogen-bonded network. This stronger intermolecular association is consistent with the gradual increase in tensile strength and thermal stability observed in the present study.

The absorption band around 2900 cm^{-1} corresponds to

C–H stretching vibrations associated with the aliphatic backbone of starch and glycerol, with possible contributions from carboxylic acid groups introduced by acetic acid during bioplastic films preparation (El Feky et al., 2024). Variations in intensity in this region may reflect structural rearrangements related to plasticization and JSWP incorporation.

The absorption band at approximately 1500 cm^{-1} is assigned to the amide II vibration of proteins and chitin present in JSWP, confirming the successful incorporation of shrimp-derived components into the bioplastic matrix. Likewise, the absorption band near 1300 cm^{-1} is attributed to C–N stretching and C–O–H deformation vibrations associated with proteinaceous compounds. The presence and slight variation in the intensity of these bands suggest modifications in the chemical environment following JSWP incorporation and are consistent with possible intermolecular interactions between the proteinaceous components of JSWP and the starch matrix. However, FTIR peak assignments alone cannot unequivocally confirm the nature or strength of these interactions, and complementary characterization techniques would be required to verify specific intermolecular bonding. Furthermore, the slight shift and broadening of the O–H (approximately $3200\text{--}3400\text{ cm}^{-1}$) stretching band indicate alterations in the hydrogen-bonding network within the starch matrix, which is consistent with the incorporation of JSWP. Although these spectral changes suggest modified intermolecular interactions, FTIR alone cannot conclusively establish the formation of specific hydrogen bonds.

The sharp absorption peak at approximately 1000 cm^{-1} corresponds to C–O stretching vibrations associated with the polysaccharide backbone of starch. Variations in this region suggest modifications in the local starch structure, possibly related to changes in intermolecular hydrogen bonding and interactions with glycerol and JSWP. Overall, the FTIR results suggest that incorporation of JSWP influences intermolecular interactions within the starch–glycerol matrix, which may contribute to the observed changes in mechanical and barrier properties of the bioplastic films.

3.3 XRD

Figure 4 reveals the characteristic native-starch diffraction features were substantially diminished after processing into bioplastic films, indicating a loss of native starch crystallinity. The JSWP diffractogram exhibited characteristic diffraction peaks of chitin nanocrystals at 2θ values of 9.25° , 19.31° , 23.21° , and 26.5° (Ma et al., 2023). The peak observed at approximately 19.35° is consistent with the characteristic reflection of chitin. In addition, intense diffraction peaks at approximately 29.34° and 32.13° were attributed to crystalline calcium carbonate, most likely in the calcite form (Béres et al., 2025).

These peaks indicate the presence of mineral components originating from JSWP. The incorporation of JSWP into cassava starch bioplastic films modified the diffraction patterns, leading to the appearance of peaks characteristic of both chitin and calcium carbonate, depending on the JSWP content. Overall, the reduction in starch crystallinity and the appearance

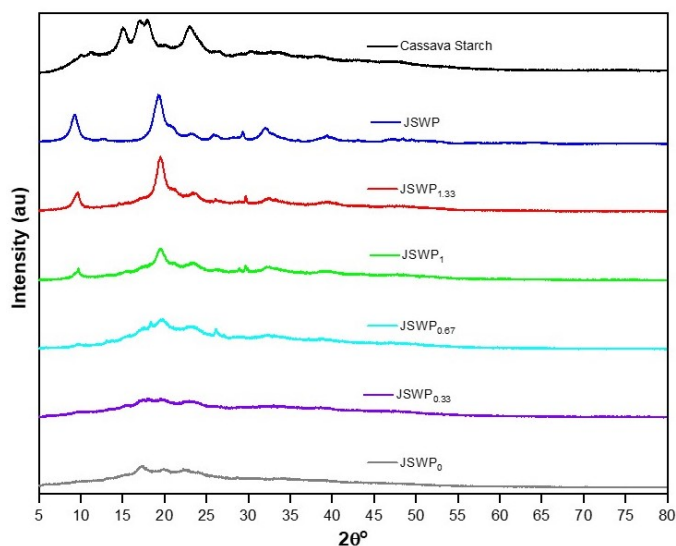


Figure 4. Xrd Spectra of Cassava Starch, Jswp, and Bioplastic Films Prepared With Different Jswp Concentrations

of filler-related reflections support the presence of crystalline JSWP-derived phases within the bioplastic films, indicating successful incorporation of the filler and partial disruption of the native crystalline structure of cassava starch during film formation. These findings are in good agreement with FTIR results, which confirmed the incorporation of JSWP into the starch–glycerol blends.

3.4 Thermal Properties

Figure 5 presents the simultaneous thermogravimetric (TG), derivative thermogravimetric (DTG), and differential thermal analysis (DTA) profiles of cassava starch, JSWP, and the composite films at temperature from approximately 30 to 600 °C. The thermograms show a typical multistage degradation profile of polysaccharide-based bioplastic films, involving moisture evaporation, plasticizer-rich phase volatilization, main-chain decomposition of starch/chitin-based structures, and final carbonaceous/mineral residue formation. Similar multistep degradation has been reported for starch-, chitosan-, and glycerol-plasticized biopolymer films, where mass loss below 150 °C is mainly attributed to water evaporation, while the major degradation between 250 and 380 °C is related to polysaccharide depolymerization and decomposition (Pigłowska et al., 2020). The neat cassava starch sample exhibited the largest overall mass loss, reaching approximately 89.2% at 600 °C, leaving only about 10.8% residue. This indicates that cassava starch is predominantly organic and thermally degradable under the applied heating condition. The main Derivative Thermogravimetry (DTG) peak appeared at approximately 295 °C, corresponding to the maximum decomposition rate of the starch backbone. This region is commonly associated with dehydration, cleavage of glycosidic bonds, depolymerization, and formation of volatile degradation products from amylose and amylopectin.

The amount of glycerol also influences the thermal degradation behavior of starch-based bioplastic films. Glycerol possesses a relatively low thermal stability compared with starch and chitin and therefore contributes to mass loss during the early stages of heating. Plasticized starch films containing higher glycerol concentrations generally exhibit lower thermal stability because glycerol increases polymer-chain mobility and reduces intermolecular hydrogen bonding. In the present formulation, the gradual reduction of glycerol content together with increasing JSWP proportion likely contributed to the observed decrease in degradation rate and higher residual char yield. Therefore, the improved thermal stability of JSWP-rich formulations should be attributed to the synergistic effects of mineral-rich JSWP reinforcement and reduced plasticizer content rather than to the filler alone.

Incorporation of JSWP significantly modified the degradation behavior. The final residue increased progressively from approximately 17.7% for JSWP0 to 26.9% for JSWP1.33, while pure JSWP gave the highest residue of approximately 42.5% at 600 °C. This increase in residual mass suggests that JSWP contributes thermally stable inorganic and carbonaceous fractions to the composite matrix. Shrimp waste is known to contain chitin/chitosan, proteinaceous matter, and calcium carbonate-based minerals; the mineral-rich fraction, at 600 °C, mineral residue may include CaCO₃ and/or its decomposition products depending on atmosphere and heating conditions. Calcium-carbonate-enriched chitosan derived from shrimp shell waste has been reported to improve thermal stability and processability because the inorganic phase acts as a reinforcing and heat-resistant component (Zhang et al., 2022).

The DTG curves further confirm that JSWP addition reduces the intensity of the main degradation peak. The maximum DTG rate decreased from approximately 1.42 mg/min for cassava starch to 0.24–0.38 mg/min for JSWP-containing composites, depending on composition. This reduction indicates that JSWP suppresses rapid thermal decomposition of the starch-rich phase, probably through restricted polymer-chain mobility, enhanced intermolecular interactions, and dilution of the combustible organic fraction by inorganic minerals. The shift of the main DTG peak from about 295 °C in cassava starch to approximately 288–294 °C in most JSWP composites suggests that the degradation mechanism is not simply delayed, but altered by the presence of shrimp-waste-derived components (Yin et al., 2020).

The DTA profiles support the TG–DTG interpretation. The low-temperature endothermic region below 150 °C is attributed mainly to evaporation of absorbed and bound water. This effect is expected in starch-based bioplastic films because hydroxyl-rich polysaccharide chains readily interact with water through hydrogen bonding. At higher temperatures, the broad thermal events between approximately 250 and 400 °C correspond to decomposition of the starch/chitin/glycerol network, while the continued DTA response above 400 °C is associated with char rearrangement, oxidation/decomposition of residual organics, and thermal transformation of mineral components.

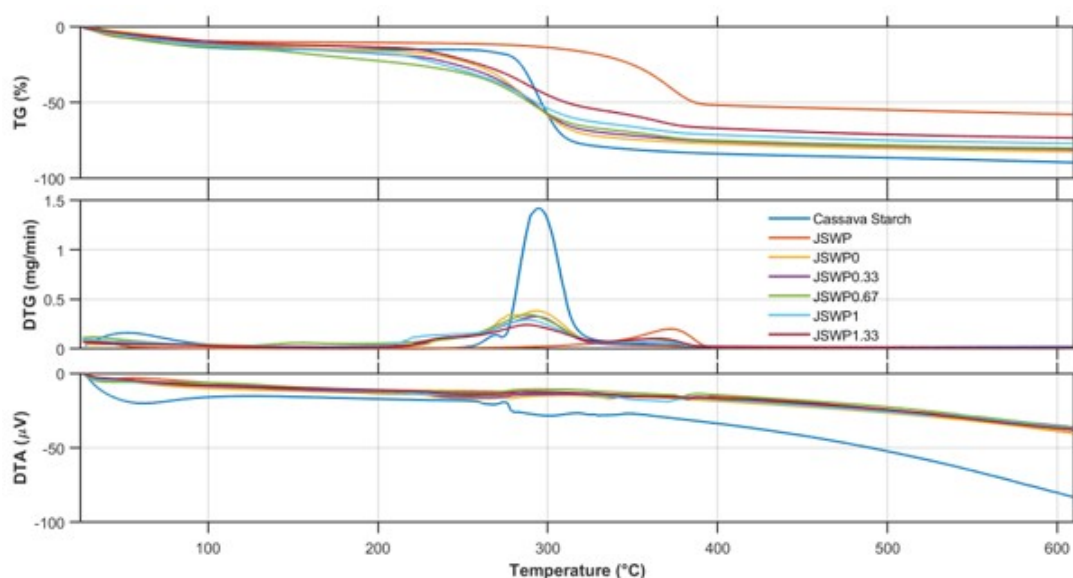


Figure 5. TG, DTG, and DTA Profiles of Cassava Starch, Jswp, and Bioplastic Films Prepared With Different Jswp Concentrations

Overall, the combined TG–DTG–DTA results demonstrate that JSWP improves the thermal stability of CSBF by increasing the non-volatile residue and reducing the maximum degradation rate. The best thermal stability among the composite series was observed for JSWP_{1.33}, which showed the lowest total mass loss and highest residue among the starch–JSWP formulations. Therefore, incorporation of JSWP contributed to improved thermal resistance to mass loss and increased residual char formation, making it promising for developing biodegradable composite materials with improved thermal stability (Yin et al., 2020).

3.5 Physical Properties

Film thickness uniformity is important to minimize its influence on other parameters (Alves Lopes et al., 2020; Gujral et al., 2021), which in the present experiment include transparency, tensile strength, and elongation at break. As shown in Table 2, the uniformity is indicated by a small variation in thickness ranging from 0.01 and 0.03 mm.

The thickness of the bioplastic films increased with changes in the JSWP proportion. Although the total formulation mass remained constant, replacing glycerol with particulate JSWP increased the non-volatile solid fraction and altered film packing. (Bangar et al., 2021; Gujral et al., 2021; Widiyawati et al., 2024) In this formulation, increasing JSWP content is accompanied by a corresponding adjustment in glycerol; therefore, the observed increase in thickness reflects the combined effect of these components rather than the contribution of JSWP alone. This behavior may also be influenced by the compositionally diverse nature of JSWP, where mineral and protein fractions contribute to increased solid loading and structural packing within the film matrix. This higher solid fraction can

promote the formation of a denser polymer network, contributing to increased thickness and potentially enhanced mechanical properties.

Water resistance was also influenced by the JSWP–glycerol content. Formulations with higher JSWP proportions exhibited lower water absorption, which may be related to the presence of relatively water-insoluble components in JSWP and the increased solid fraction within the matrix. Glycerol is a highly hydrophilic polyol containing three hydroxyl groups capable of forming hydrogen bonds with water molecules. Consequently, increasing glycerol concentration generally enhances water uptake and decreases water resistance in starch-based bioplastic films. In the present study, glycerol concentration decreased progressively from 2% to 0.67% as JSWP content increased. This reduction in glycerol likely decreased the availability of hydrophilic sites within the polymer matrix, thereby limiting water absorption. Simultaneously, the presence of relatively hydrophobic components in JSWP, less water-soluble components, lower glycerol content, and altered matrix packing including proteins, lipids, and calcium-rich minerals, further reduced water affinity. The combined effect produced a gradual increase in water resistance from 61.0% to 79.75%, indicating that optimization of both filler loading and plasticizer content is essential for improving moisture barrier performance.

The highest transparency value (10.66/mm) was observed in the formulation without JSWP (JSWP0). Transparency decreased progressively with increasing JSWP proportion in the mixture. This reduction may be associated with both increased film thickness and the presence of dispersed particles, which enhance light scattering and reduce light transmission through the film matrix. As with other properties, this trend reflects the overall formulation effect, including both increased solid

Table 2. Average Characteristics of Bioplastic Films Prepared With Different JSWP–glycerol Formulations

JSWP (%)	Tensile strength (MPa)	Elongation (%)	Water resistance (%)	Thickness (mm)	WVTR (g m ⁻² h ⁻¹)	Transparency (mm ⁻¹)
0	4.63 ± 2.91a	5.60 ± 4.38 a	61.00 ± 1.29a	0.23 ± 0.02a	14.33 ± 3.50 a	10.66 ± 0.86d
0.33	4.90 ± 1.38a	4.28 ± 1.41 a	68.78 ± 2.76b	0.33 ± 0.03b	14.33 ± 0.84 a	8.49 ± 1.16c
0.67	5.73 ± 2.98a	4.00 ± 1.40 a	72.32 ± 4.11b	0.40 ± 0.01c	13.75 ± 2.49 a	7.11 ± 0.58a
1	6.40 ± 1.14a	2.95 ± 1.30 a	74.58 ± 7.92bc	0.47 ± 0.03d	12.83 ± 5.29 a	6.47 ± 0.71a
1.33	10.94 ± 3.79b	2.18 ± 0.56 a	79.75 ± 3.32c	0.53 ± 0.03e	8.09± 2.84 a	6.11± 0.70a

content and changes in glycerol concentration, rather than a single independent factor. Furthermore, the heterogeneous composition of JSWP may promote phase separation or particle dispersion within the matrix, increasing light scattering and contributing to reduced transparency.

3.6 Mechanical Properties

Tensile strength and elongation at break are key parameters used to characterize bioplastic films (Bangar et al., 2021). These mechanical properties are closely related to the thickness and microstructure of the film. As discussed earlier, variations in the JSWP proportion influenced film thickness and structural organization, which in turn affected the mechanical behavior of the bioplastic films. Tensile strength increased across the paired formulations, with JSWP_{1.33} significantly higher than the other treatments; this response reflects both higher JSWP and lower glycerol with increasing JSWP proportion in the formulation (Table 2). However, since glycerol content was simultaneously adjusted, this trend reflects the combined effect of increased solid content and changes in plasticizer level. This suggests that the tensile strength behavior is governed by the interaction between JSWP and glycerol, rather than by the independent contribution of each component. The tensile strength obtained in this study is comparable to that reported for CSBF (Lim et al., 2020) as well as other starch-based systems (Gudeta, 2026).

However, the elongation at break of the present bioplastic films is numerically lower than that reported for material with similar tensile strength, although similarly low elongation values have been observed in other high-strength bioplastic films (Bian et al., 2026). This behavior can be attributed to the microstructure of the films. Formulations with higher JSWP proportions and lower relative glycerol content tend to exhibit a more compact but less flexible structure. The non-continuous and heterogeneous morphology observed in Figure 2 likely restricts polymer chain mobility within the matrix. This heterogeneity may arise from the compositionally diverse nature of JSWP, where mineral, protein, and lipid components are unevenly distributed within the starch matrix. As a result, the material becomes more rigid and fractures at lower strain levels, leading to reduced elongation at break.

The mechanical behavior is strongly influenced by glycerol because plasticizers reduce intermolecular attractions between

starch chains and facilitate molecular movement during deformation. At high glycerol concentrations (JSWP0), the polymer network becomes more flexible, resulting in greater elongation but lower tensile strength. As glycerol concentration decreases, polymer chains become more tightly associated through hydrogen bonding, increasing stiffness and tensile strength while reducing ductility. This behavior explains the simultaneous increase in tensile strength from 4.63 to 10.94 MPa and decrease in elongation from 5.60% to 2.18% observed across the formulations. The reinforcing effect of JSWP further restricts polymer-chain movement through physical interactions with starch, producing a more rigid composite structure.

The XRF analysis (Table 3) revealed relatively high concentrations of Ca and Mg, which can be attributed to the mineral composition of JSWP. Shrimp shells are known to contain significant amounts of calcium carbonate (CaCO₃), along with other components such as Mg. These metal ions can significantly influence the properties of the bioplastic films. For example, the mineral fraction may contribute to stiffness and heterogeneity, but ion-mediated crosslinking should be presented as a hypothesis unless ionic state and matrix interactions were measured.

Table 3. Semi-Quantitative XRF Elemental Composition of JSWP and Cassava Starch

Elements	Concentration (%)	
	JSWP	Cassava starch
Magnesium (Mg)	10.82	63.07
Aluminum (Al)	2.49	-
Phosphorus (P)	9.47	1.74
Chloride (Cl)	-	0.39
Bromide (Br)	0.08	-
Strontium (Sr)	1.4	-
Potassium (K)	-	25.23
Calcium (Ca)	75.17	9.22
Rhodium (Rh)	-	0.36
Zirconium (Zr)	0.02	-

However, within the context of this study, these effects should be interpreted as part of the overall formulation rather than as isolated variables. In particular, the presence of these

Table 4. Comparison of the Present Bioplastic Film With Selected Starch-Based Films Reported in the Literature

Matrix	Tensile strength (MPa)	Elongation (%)	Water absorption (%)	Reference
Cassava /JSWP/Glycerol	10.94	2.18	20.25	Present study
Cassava/Chitosan/Glycerol	2.01	54.22	-	(Kusumawati et al., 2025)
Cassava/Rice Husk Cellulose/ PVA/ZnO/Glycerol	<25	<20	-	(Hendrawati et al., 2023)
Cassava/Cellulose Fiber/Glycerol	6.11	<10	16.83	(Anh Duy et al., 2026)
Cassava/Coconut Meal Waste/ Glycerol	7.85	<8	71	(Tankaew et al., 2026)
Cassava/Brown Algae/Glycerol	2 - 2.5	<40	-	(Jantasrirad et al., 2021)

mineral components, together with organic fractions such as proteins and lipids, contributes to the multiphase nature of JSWP, which can influence its interaction with both starch and glycerol. In addition, the presence of these inorganic components may affect the dispersion of JSWP within the polymer matrix, contributing to the non-homogeneous morphology observed in SEM analysis. This structural heterogeneity, together with reduced polymer chain mobility associated with both mineral content and lower plasticizer proportion, provides a plausible explanation for the observed increase in tensile strength and decrease in elongation at break.

Therefore, the elevated Ca and Mg content is not only characteristic of the shrimp-derived filler but may also contribute to the mechanical and structural behavior of the resulting bioplastic films. Overall, the mechanical properties of the bioplastic films are governed by interactions between JSWP and the starch matrix, which are influenced by the heterogeneous composition of JSWP. This highlights the importance of considering both filler composition and plasticizer interactions in the design of starch-based bioplastic films.

3.7 Barrier Property

The barrier properties of the bioplastic films were evaluated by measuring the WVTR, and the results are presented in Table 2. Although the differences were not statistically significant, a decreasing trend in WVTR was observed with increasing JSWP proportion. This trend suggests that the overall formulation influences the water vapor barrier properties of the films.

Glycerol also plays an important role in water vapor transport because its hydrophilic nature increases the free volume within the starch matrix and facilitates diffusion of water molecules. Films containing higher glycerol concentrations generally exhibit higher WVTR owing to increased polymer-chain mobility and moisture sorption. In contrast, the lower glycerol concentrations used in JSWP-rich formulations promote a denser polymer network with fewer diffusion pathways. Combined with the mineral and protein components of JSWP, this structural densification contributes to the lower WVTR values observed in the present study.

A decreasing numerical trend was observed, but the treat-

ment effect was not statistically significant; therefore, the data do not establish improved WVTR. Unlike nanoparticles, which typically reduce WVTR by filling pores within the film matrix and creating a more tortuous diffusion pathway for water vapor (Gujral et al., 2021; Laksanawati et al., 2026), the mechanism in the present system may differ. In this formulation, increasing JSWP content is accompanied by a relative reduction in glycerol concentration; therefore, the observed trend likely reflects the interaction between these two components rather than the independent effect of JSWP alone. Components within JSWP, particularly proteins and lipids, may reduce the water affinity of the starch matrix, thereby limiting water vapor diffusion through the film (Jafarzadeh et al., 2026). In addition, the compositionally diverse nature of JSWP may influence the microstructure and phase distribution of the matrix, as observed in Figure 2, which could further affect vapor transport behavior.

Similar behavior has been reported in starch-based films containing bentonite, where dispersed components contributed to improved barrier performance by modifying matrix structure and reducing moisture transport pathways (Shanmathy et al., 2021). In the present study, the combined effects of JSWP composition, glycerol concentration, and resulting film morphology likely contributed to the observed reduction in WVTR.

However, given the lack of statistical significance, these interpretations should be considered indicative trends rather than definitive conclusions. Overall, the WVTR behavior is best understood as the result of the interaction between the JSWP and the starch matrix and the resulting film microstructure. As summarized in Table 4, the mechanical and barrier properties obtained in the present study are comparable to those reported for other starch-based bioplastic films. Although the elongation at break was relatively low, the developed films exhibited favorable tensile strength and reduced WVTR, suggesting that the formulation provides a balanced combination of strength and barrier performance.

4. CONCLUSIONS

This study demonstrated that JSWP is promising bio-based reinforcing filler for cassava starch bioplastic films. Increasing JSWP proportion, together with a proportional reduction in glycerol content, increased tensile strength and water resistance, while WVTR showed a non-significant decreasing trend. However, elongation at break and transparency decreased with increasing JSWP content. Structural characterization by SEM, FTIR, and XRD confirmed successful incorporation of JSWP into the starch matrix and indicated changes in intermolecular interactions and crystalline structure. TG-DTG-DTA analysis showed that JSWP increased thermal stability by lowering the maximum degradation rate and increasing residual char yield, with the JSWP_{1.33} formulation exhibiting the best thermal performance. Overall, the optimized JSWP_{1.33} formulation produced bioplastic films with the most balanced mechanical, thermal, and barrier properties, demonstrating the potential of shrimp-processing waste as a sustainable reinforcing material for biodegradable starch-based packaging.

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