

Combination of cassava starch and peel, using corn stalks and husks, and bentonite clay as fillers to enhance the mechanical properties of bioplastics

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Abstract

This study investigates the effect of combining cassava starch gelatin and cassava peel gelatin and evaluates the influence of two different fillers, cellulose and bentonite clay, on the mechanical properties of bioplastics. It aims to obtain bioplastics with tensile strength and elongation properties comparable to low-density polyethylene (LDPE). The study employs different mass ratios of starch to gelatin (9:1, 8:2, and 7:3 g/g) and incorporates bentonite clay and cellulose fillers (corn stalks and husks), each at 0.4 g. The materials were processed with a 200-mesh sieve. Bioplastic synthesis involved a glycerol concentration of 25% (w/w), stirring at 375 rpm for 35 minutes at 90°C. Mechanical properties (tensile strength, elongation, and Young's modulus) were analyzed, along with SEM and FTIR characterization. The results indicate that the bioplastic formulation with a starch-to-gelatin ratio of 8:2 and bentonite clay as a filler exhibits the most promising mechanical properties, with a tensile strength of 1.837 MPa, elongation of 33.584%, and a Young's modulus of 5.47 MPa. Comparatively, bentonite clay enhanced tensile strength and rigidity, while cellulose fillers provided higher elongation and flexibility but lower reinforcement due to particle agglomeration. FTIR analysis identified key functional groups, including O-H, CH₂, C=O, N-H, and C-O. The combination of cassava starch, cassava peels, corn stalk-derived cellulose, fillers, and plasticizers significantly impacts the quality and mechanical properties of bioplastics.

Keywords: Bioplastics, Cassava starch, Cassava peel, Corn stalk, Bentonite clay, Corn husk

1. Introduction

Plastic waste remains a significant environmental issue due to its slow degradation and excessive accumulation. To address this problem, researchers have explored biodegradable alternatives that possess characteristics similar to conventional plastics but are derived from renewable and environmentally friendly materials. Bioplastics, which decompose rapidly through microbial activity, have emerged as a promising solution [1, 2].

Bioplastics are derived from renewable biomass sources such as starch, vegetable oils, and microbial polysaccharides. Their high biodegradability makes them a viable alternative for sustainable packaging applications [3]. This study explores the development of bioplastics using cassava starch and cassava peel as primary raw materials.

Cassava starch and cassava peels were selected as raw materials due to their abundance, low cost, and high starch content. Indonesia ranks among the top cassava-producing countries, ensuring a sustainable and readily available feedstock [4]. Cassava tubers contain approximately 60.15 weight% starch, while the peel contains 44-59 weight% starch, making them suitable for bioplastic production [5]. Cassava starch provides excellent film-forming properties, making it suitable for bioplastic production, while cassava peels, often considered agricultural waste, offer opportunities for value-added utilization and waste minimization. The use of cassava peels reduces environmental burdens associated with agricultural residues and production costs, aligning with the goals of sustainable bioplastic development.

Corn stalks and husks serve as additional fillers in this research. Corn stalks contain 40-50% cellulose, 20-30% hemicellulose, and 10-15% lignin, while corn husks contain significant amounts of cellulose and hemicellulose [6]. The incorporation of cellulose fillers from these materials enhances the mechanical properties of composites [7, 8].

Additionally, bentonite clay has been identified as a promising filler to improve polymer characteristics, particularly by enhancing mechanical strength and elasticity [9, 10]. Plasticizers such as glycerol improve the elasticity and flexibility of bioplastics [11]. Gelatin, often combined with synthetic polymers, enhances the mechanical performance of biodegradable films [12, 13].

Unlike most previous studies that utilized cassava starch alone, this work combines cassava starch with cassava peels to maximize resource utilization and reduce agricultural waste. Furthermore, the study provides a direct comparison between natural cellulose fillers derived from corn stalks and husks and inorganic bentonite clay, highlighting their distinct reinforcing roles in bioplastic synthesis. The identification of an optimal starch-to-gelatin ratio (8:2) with bentonite clay that achieves mechanical properties approaching those of LDPE underscores this research's novelty and practical significance.

In addition to their environmental advantages, composite bioplastics with the characteristics proposed here hold potential for diverse applications. Rigid formulations reinforced with bentonite clay could be suitable for disposable cutlery, trays, or semi-structural

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packaging, where mechanical strength and durability are required. Meanwhile, cellulose-reinforced formulations with higher flexibility are promising for biodegradable films, shopping bags, agricultural mulch films, and food packaging, where elasticity and biodegradability are important. These possible applications highlight the relevance of developing cassava-based composites as sustainable alternatives to petroleum-derived plastics.

2. Materials and methods

2.1 Materials

The primary materials used in this study include cassava peels, cassava husks, corn stalks, corn husks, and bentonite clay sourced from the Tanggamus region. Additional chemicals include sulfuric acid (H₂SO₄) 6.5 M (p.a, Merck), potassium hydroxide (KOH) 4% (p.a, Merck), peroxide (H₂O₂) 6% (p.a, Sigma-Aldrich), aquades (H₂O), gelatin, and glycerol 25%. Equipment used includes a grain grinder, 200-mesh sieve, digital balance, hot plate, magnetic stirrer, SEM, FTIR spectrometer, and mechanical testing apparatus.

2.2 Bioplastics preparations and characterization

2.2.1 Bioplastics preparations

Bioplastic films were synthesized by mixing starch and gelatin at varying mass ratios (9:1, 8:2, and 7:3 g/g). Bentonite clay and cellulose fillers were incorporated at 0.4 g each. The mixture was stirred at 375 rpm for 35 minutes at 90°C, followed by molding and drying.

2.2.2 Mechanical properties

Mechanical properties were tested using a universal testing machine according to ASTM D638 standards. Key parameters measured included tensile strength, elongation, and Young's modulus.

2.2.3 Morphological properties

SEM analysis (The Hitachi TM-3000) was conducted to observe the microstructure and dispersion of fillers within the bioplastic matrix. FTIR analysis was used to identify functional groups and confirm material interactions.

2.2.4 Particle size properties

The Particle Size Analyzer (PSA) was employed to determine the particle size distribution using the Dynamic Light Scattering (DLS) method. This method utilizes the Non-Invasive Back Scatter (NIBS) technique, ensuring precise measurement of particle sizes by detecting fluctuations in scattered light intensity.

By employing PSA analysis, this study ensures that the synthesized bioplastics achieve the desired particle size distribution, leading to improved material performance and commercial viability.

3. Results and discussion

3.1 Particle size of cellulose

The research began by processing corn stalks and husks to a 200-mesh size for use as fillers. Several treatments were applied to enhance the purity and structural integrity of the cellulose: delignification using a 4% KOH solution, which breaks down lignin and increases cellulose content [14]; bleaching with a 6% H₂O₂ solution, which further purifies the cellulose by removing residual lignin and hemicellulose [15]; acid hydrolysis using a 6.5 M H₂SO₄ solution, which degrades amorphous cellulose and refines the material [16]; and mechanical treatment using an ultrasonic bath for 180 minutes, which further reduces cellulose particle size and improves dispersion in the polymer matrix [17]. This study highlights the challenges in cellulose size reduction and provides valuable insights into optimizing bioplastic fillers for improved performance.

The effectiveness of these treatments was analyzed by measuring the particle size and composition of the cellulose before and after processing. The results are presented in Tables 1 and 2.

Table 1 Corn stalks and husks cellulose size

Cellulose	Size (µm)
Before treatment	74
After treatment	1,087

The increase in cellulose particle size from 74 µm to 1087 µm after treatment can be attributed to particle agglomeration during the drying process [18]. Although chemical treatments such as delignification, bleaching, and acid hydrolysis were expected to reduce cellulose size, the subsequent drying step promoted the clustering of fine particles into larger aggregates [14, 16]. This agglomeration effect resulted in an apparent increase in measured particle size despite the removal of lignin and hemicellulose.

The apparent increase in cellulose content does not indicate the creation of new cellulose, but rather the relative enrichment of cellulose due to the removal of other constituents. During the pretreatment steps, lignin and hemicellulose were selectively degraded and solubilized, leaving cellulose as the dominant fraction in the solid residue. Consequently, although the absolute mass of cellulose may remain similar, its percentage relative to the total biomass increases, explaining the rise from 34.12% to 51.23%. This enrichment enhances the reinforcing potential of the treated cellulose when incorporated into bioplastics.

Table 2 Corn stalks and husks composition

Sample	Lignin (%)	Hemicellulose (%)	Cellulose (%)
Before treatment	8.35	25.58	34.12
After treatment	3.92	17.05	51.23

The treated cellulose exhibited an average particle size of 1,087 μm , indicating that the cellulose remained at the micro-scale rather than achieving nano-sized dimensions. This finding differs from previous studies [19, 20], where cellulose extracted using the alkali-bleaching-hydrolysis method from tapioca pulp successfully reached the nanometer scale.

The inability to achieve nano-sized cellulose in this study is likely due to agglomeration during the drying process [18]. Agglomeration occurs when fine particles cluster together, forming larger aggregates [21]. This phenomenon is influenced by increased contact between particles due to prolonged grinding, leading to stronger intermolecular forces [22], and insufficient mechanical energy to break apart aggregates during drying [23].

Additionally, discrepancies with Wicaksono's (2013) study may stem from differences in mechanical processing equipment. The present study utilized a powder grinder, whereas Wicaksono employed a 22,000 rpm high-speed mixer, which likely facilitated finer particle breakdown and reduced agglomeration [20].

The increased cellulose content post-treatment (from 34.12% to 51.23%) suggests a higher potential for reinforcing bioplastic composites. Although nano-cellulose was not achieved, micro-cellulose still enhances mechanical strength and barrier properties when incorporated into bioplastics.

3.2 Morphological characteristics

Observations of bioplastic samples were conducted using Scanning Electron Microscopy (SEM) at magnifications of 500x and 5000x. The selected samples exhibited mechanical properties closer to low-density polyethylene (LDPE) standards, specifically starch:gelatin (8:2) with cellulose fillers and starch:gelatin (8:2) with bentonite clay fillers.

The results of the morphological analysis using SEM are presented in Figure 1 and 2.

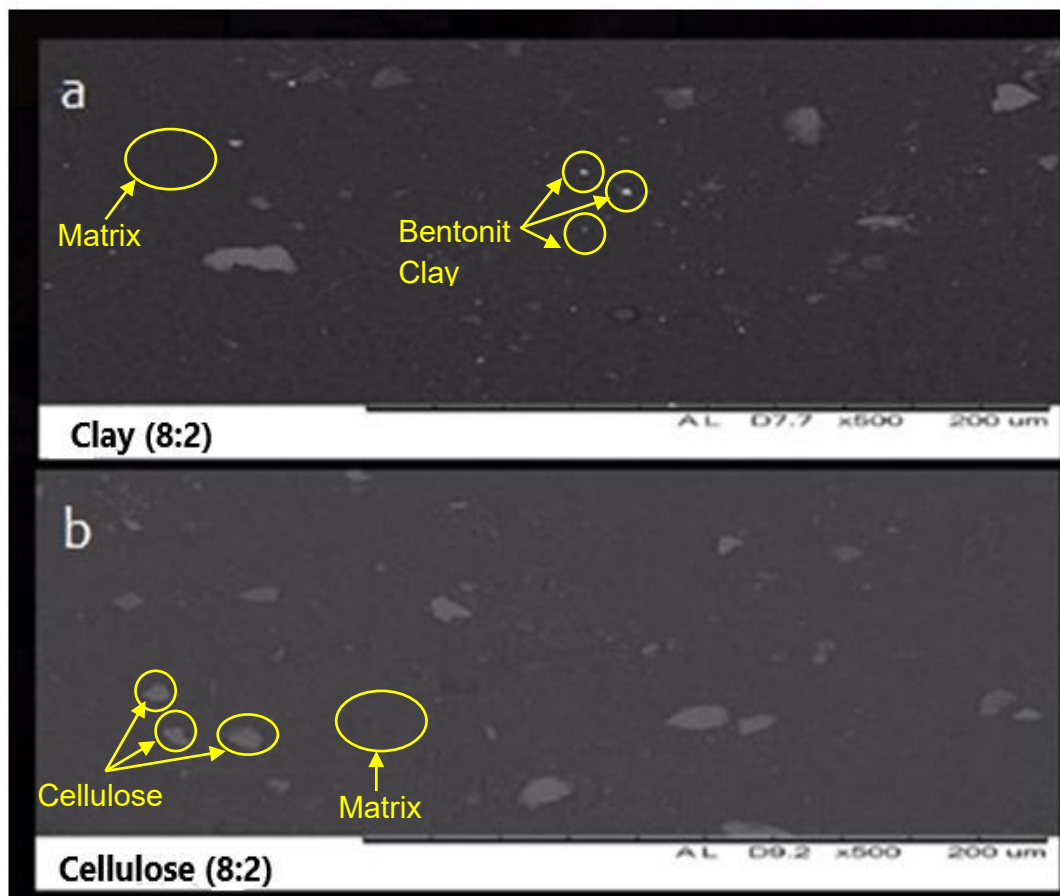


Figure 1 SEM analysis of bioplastic samples (500x Magnification): (a) Starch:Gelatin 8:2 with bentonite clay filler; (b) Starch:Gelatin 8:2 with cellulose filler

In Figure 1 (a), the bioplastic matrix appears as a continuous dark/grey background, while the bright white clusters correspond to bentonite clay particles embedded in the matrix. In Figure 1 (b), the cellulose fillers appear as irregular, elongated white structures dispersed within the darker matrix, though some agglomeration can be observed. The surrounding smoother regions represent the starch-gelatin biopolymer matrix.

From Figure 1, it is evident that both filler types exhibit different dispersion behaviors within the bioplastic matrix. In the sample with bentonite clay (Figure 1a), the continuous darker regions correspond to the starch-gelatin matrix, while the lighter, white particles

indicate bentonite fillers distributed within it. In contrast, in the cellulose-filled sample (Figure 1b), the cellulose appears as brighter, irregular structures embedded in the darker matrix, but with clear signs of agglomeration. These identifications clarify filler-matrix interactions and highlight the role of filler type in the morphological characteristics of the composites.

From Figure 1, it is evident that both filler types exhibit different dispersion behaviors within the bioplastic matrix. The presence of large white clusters suggests that cellulose and bentonite clay particles are not evenly distributed [24]. Inadequate heating and stirring energy during the bioplastic preparation process may have contributed to the non-uniform dispersion of filler particles [25]. Proper stirring at gelatinization temperature is crucial to ensure even filler distribution and to prevent particle agglomeration [26].

The uneven dispersion of cellulose is particularly noteworthy, as cellulose is not easily soluble in organic solvents, leading to surface irregularities in the bioplastic film [27]. Additionally, the SEM images reveal remnants of swollen starch granules, indicating incomplete gelatinization. These granules appear as black voids in the fracture surface, contributing to reduced tensile strength and impact resistance [28].

To gain further insights into particle dispersion and agglomeration, higher magnification imaging (5000x) was performed, as shown in Figure 2.

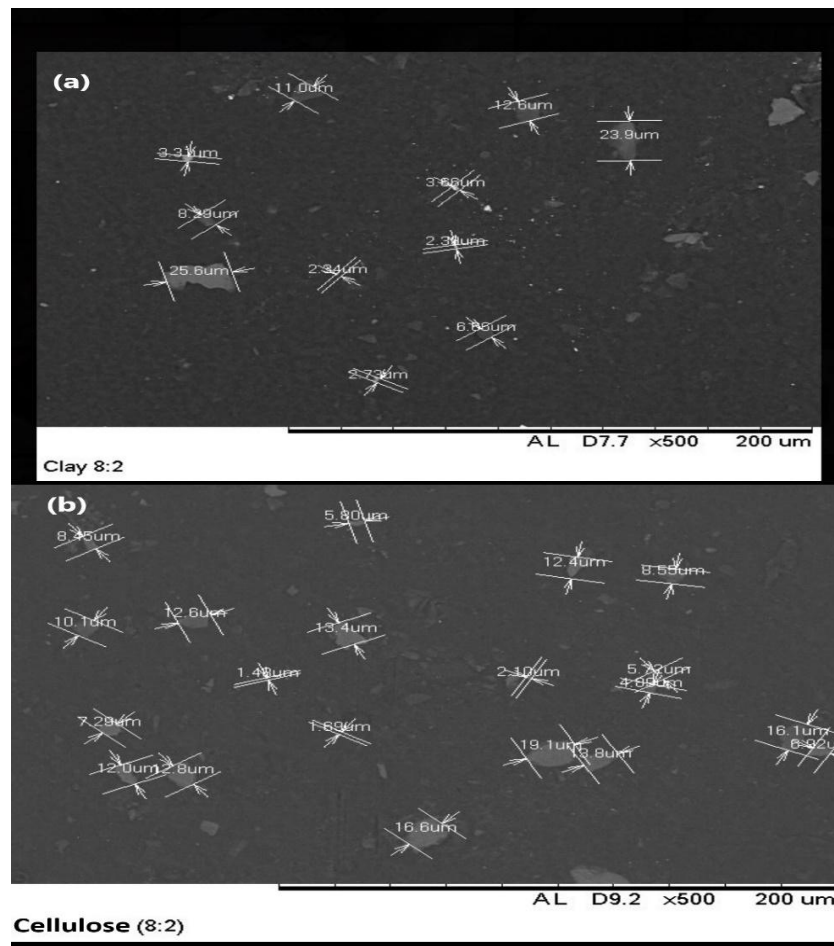


Figure 2 SEM analysis of bioplastic samples (5000x Magnification) (a) starch:gelatin 8:2 with bentonite clay filler; (b) starch:gelatin 8:2 with cellulose filler

From Figure 2, several key observations can be made. The aggregated particle sizes range from 46.9 nm to 505 nm, indicating partial size reduction of the cellulose and bentonite clay fillers within the matrix. The bioplastic surface exhibits white agglomerated clusters, likely composed of starch particles that failed to fully integrate into the polymer matrix [29]. The presence of residual starch suggests that not all starch molecules reacted with gelatin during gelatinization, leading to inconsistencies in film formation [26]. Poor filler dispersion in certain regions may contribute to variations in mechanical properties, particularly tensile strength and elongation [30].

Bentonite clay appears to disperse more uniformly compared to cellulose fillers, contributing to a denser and more compact matrix [24]. The agglomeration of cellulose fillers results in a more porous structure, which may negatively affect mechanical strength and flexibility [31]. Optimizing stirring speed, temperature control, and filler pretreatment could further enhance filler distribution and overall bioplastic performance.

3.3 Mechanical properties

3.3.1 Elongation properties

To assess the impact of starch-to-gelatin mass ratio and the incorporation of fillers (cellulose fillers and bentonite clay), six bioplastic samples were analyzed for tensile strength, elongation percentage, and Young's modulus. The experimental results are summarized in Table 3.

Table 3 Bioplastic mechanical properties

Run	Starch:Gelatin (gr/gr)	Ratio Cellulose Filler (gr)	Ratio Bentonite Clay Filler (gr)	Elongation (%)
1	9:1	0.4	-	71.5
2	8:2	0.4	-	24.7
3	7:3	0.4	-	22.4
4	9:1	-	0.4	7.8
5	8:2	-	0.4	33.6
6	7:3	-	0.4	21.9
				150-600

It should be noted that the filler amount of 0.4 g was applied selectively depending on the formulation. Runs 1-3 correspond to bioplastics with cellulose fillers at starch-gelatin ratios of 9:1, 8:2, and 7:3, respectively. Runs 4-6 correspond to the same starch-gelatin ratios but with bentonite clay fillers.

The large variation in elongation values between runs with the same starch-gelatin ratio (e.g., run 1 vs. run 4 at 9:1) is due to the difference in filler type. Cellulose fillers enhance flexibility, leading to higher elongation, whereas bentonite clay increases rigidity and tensile strength but reduces elongation. This distinction arises from the contrasting reinforcing mechanisms of organic versus inorganic fillers in the starch-gelatin matrix.

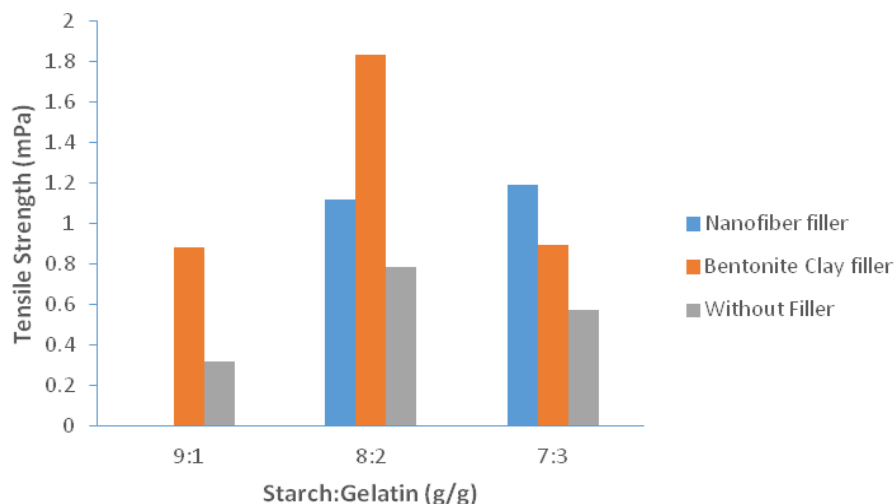
Cellulose-based bioplastics exhibited higher elongation values, with the 9:1 starch-to-gelatin ratio reaching 71.5%, indicating greater flexibility. The 8:2 ratio with bentonite clay achieved an elongation of 33.6%, balancing flexibility and mechanical integrity. Bentonite clay fillers improved rigidity but resulted in lower elongation values compared to cellulose fillers [24].

The mechanical properties of bioplastics, including tensile strength, elongation, and Young's modulus, were plotted in Figures 3–5 to illustrate their trends and variations.

3.3.2 Tensile strength analysis

Bentonite clay fillers resulted in higher tensile strength values compared to cellulose fillers. Uneven dispersion of cellulose fillers could lead to reduced tensile strength due to weak interfacial bonding [32]. The incorporation of fillers is essential to fill pore spaces within the bioplastic matrix, thereby improving strength and rigidity [33]. The effect of different starch-to-gelatin ratios and filler types on tensile strength are illustrated in Figure 3. As shown, bentonite clay consistently provided higher tensile strength values than cellulose fillers across all ratios, with the maximum strength achieved at an 8:2 starch-to-gelatin ratio. Without fillers, it showed the lowest tensile strength across all ratios, confirming that neat starch-gelatin blends have weaker intermolecular interactions.

Previous research suggests that higher filler compositions contribute to stronger bioplastics by reinforcing the polymer network [34]. The starch-to-gelatin ratio also influenced tensile strength, with gelatin enhancing elasticity. However, excessive gelatin content may reduce stiffness [35]. The highest tensile strength (1.837 MPa) was observed at an 8:2 starch-to-gelatin ratio with bentonite clay filler.

**Figure 3** The effect of bioplastic formulations on tensile strength

The results of Figure 3 are shown for cellulose-filled, bentonite-filled, and control specimens without filler across different starch:gelatin ratios (9:1, 8:2, and 7:3). The inclusion of the control specimens (without filler) provides a clear baseline to evaluate the reinforcing effect of cellulose and bentonite fillers.

For comparison, specimens without filler were also tested as controls. These control samples consistently exhibited the lowest tensile strength across all starch-gelatin ratios, confirming that neat starch-gelatin blends alone provide weaker intermolecular interactions. The addition of fillers, particularly bentonite clay, significantly increased tensile strength relative to the control, while cellulose fillers provided more moderate reinforcement. Including control specimens in Figure 3 highlights the clear reinforcing role of both fillers compared to the baseline.

Based on the analysis of tensile strength trends, bentonite clay exhibited superior dispersion within the polymer matrix, leading to enhanced mechanical properties [36]. In contrast, cellulose fillers formed agglomerates, reducing their effectiveness as reinforcement agents [37]. Higher gelatin content improved flexibility [38] but resulted in decreased tensile strength beyond an optimal ratio. Filler selection significantly influenced bioplastic performance [39], with bentonite clay outperforming cellulose in tensile reinforcement.

Based on the experimental findings, the best mechanical properties were achieved with a starch-to-gelatin ratio of 8:2 and 0.4 g of bentonite clay filler. This formulation balanced tensile strength, elongation, and Young's modulus, making it a viable alternative to LDPE-based plastics.

Bentonite clay fillers enhanced tensile strength and rigidity due to their fine particle size and superior dispersion. Cellulose fillers contributed to greater flexibility but exhibited lower tensile reinforcement due to poor dispersion and agglomeration.

Although the optimized bioplastic formulation (8:2 starch-to-gelatin with bentonite clay) showed the best performance in this study, its tensile strength and elongation remain considerably lower than those of commercial LDPE. As summarized in Table 4, LDPE typically exhibits tensile strengths of 8-12 MPa and elongation between 200-600%, compared to 1.837 MPa and 33.584% for the optimized bioplastic. These results confirm that, while the developed bioplastics demonstrate improved properties relative to filler-free formulations, further optimization is required before they can fully match the mechanical performance of LDPE.

Table 4 Comparison of mechanical properties of optimized bioplastic (8:2 starch-gelatin with bentonite clay) and LDPE

Material	Tensile Strength (MPa)	Elongation (%)	Young's Modulus (MPa)
Bioplastic (8:2 + Bentonite)	1.837	33.584	5.47
LDPE (literature range)	8-12	200-600	100-250

LDPE data from [40, 41, 42].

3.3.3 Percent elongation analysis.

Elongation percentage is a key parameter in determining the flexibility and ductility of bioplastics [40]. Figure 4 illustrates the effect of different bioplastic formulations on elongation properties.

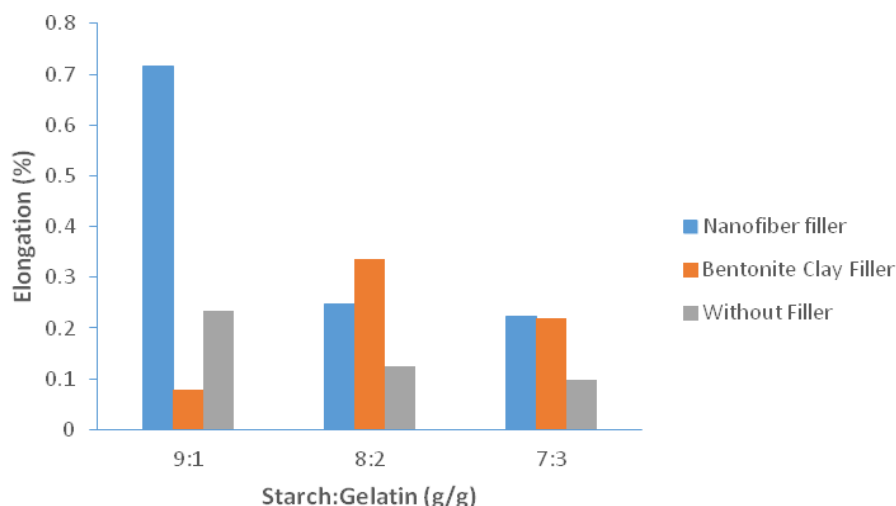


Figure 4 The effect of bioplastic formulation on percent elongation

Results from Figure 4 are shown for cellulose-filled, bentonite-filled, and control specimens without filler across different starch:gelatin ratios (9:1, 8:2, and 7:3). The inclusion of the control specimens (without filler) provides a baseline for comparing the effect of fillers on flexibility.

For comparison, control specimens without filler were included in the elongation analysis. These control samples consistently demonstrated the lowest elongation values across all starch-gelatin ratios, indicating limited flexibility in neat starch-gelatin blends. By contrast, cellulose fillers markedly improved elongation due to their fibrous and flexible nature, while bentonite fillers reduced elongation as a result of their rigid, reinforcing characteristics. Including control specimens in Figure 4 thus highlights the contrasting effects of organic and inorganic fillers relative to the baseline.

Figure 4 shows that cellulose-filled bioplastics demonstrated higher elongation percentages at lower gelatin concentrations. Gelatin increases tensile strength but reduces elongation, as reported by Fauziah et al. [24]. The optimal elongation (33.584%) was observed at a starch-to-gelatin ratio of 8:2 with bentonite clay filler, balancing flexibility and structural integrity.

Figure 4 indicates that filler impacts elongation. Without filler, the baseline elongation is consistently the lowest across all ratios. Bentonite clay fillers reduced elongation due to their rigid, reinforcing nature [43]. Cellulose fillers improved flexibility [44], but excessive aggregation led to inconsistent elongation performance. The relationship between tensile strength and elongation followed an inverse correlation, where higher tensile strength resulted in lower elongation.

The optimal bioplastic formulation for elongation was the starch-to-gelatin ratio of 8:2 with bentonite clay filler, which exhibited the best mechanical balance. Cellulose-based bioplastics provided higher flexibility but lower mechanical strength [45].

This study demonstrates that fillers influence mechanical performance. Bentonite clay fillers enhanced rigidity and tensile strength, making them suitable for rigid bioplastic applications. In contrast, cellulose fillers improved elongation properties, making them ideal for flexible bioplastic films.

3.3.4 Young's modulus analysis

Young's modulus measures the stiffness of bioplastics, indicating their resistance to deformation under applied stress [29]. Figure 5 presents the effect of bioplastic formulations on Young's modulus.

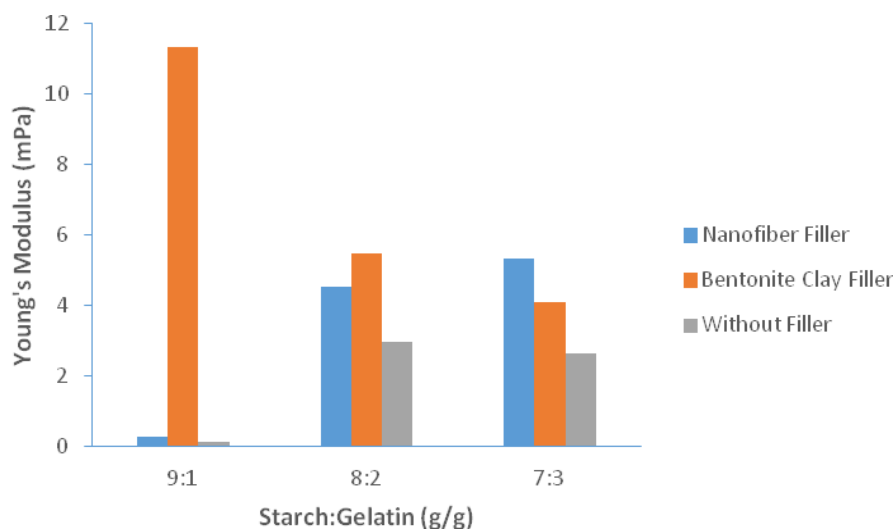


Figure 5. The effect of bioplastic formulation on Young's modulus

Results from Figure 5 are shown for cellulose-filled, bentonite-filled, and control specimens without filler across different starch:gelatin ratios (9:1, 8:2, and 7:3). Including control specimens (without filler) provides a baseline for evaluating how fillers alter stiffness in the composites.

For comparison, control samples without filler were also analyzed. These control specimens consistently showed the lowest Young's modulus values, confirming that neat starch-gelatin blends have limited stiffness and resistance to deformation. The addition of cellulose fillers increased modulus due to their fibrous reinforcement effect, while bentonite fillers produced intermediate stiffness, influenced by their dispersion and interfacial bonding with the matrix. Including the control specimens in Figure 5 clearly demonstrates the reinforcing roles of both fillers relative to the baseline.

Figure 5 shows that cellulose-filled bioplastics exhibited higher Young's modulus values, indicating greater stiffness. Without filler, it shows the lowest modulus values across both ratios, indicating that the polymer matrix alone has limited stiffness. Bentonite clay fillers led to a reduction in Young's modulus, likely due to inhomogeneous dispersion that weakened filler-matrix interactions. The highest Young's modulus (11.329 MPa) was observed in the 9:1 starch-to-gelatin ratio with bentonite clay filler, confirming its ability to enhance rigidity. In contrast, the lowest Young's modulus (0.278 MPa) was recorded for 9:1 starch-to-gelatin bioplastics with cellulose fillers, highlighting their greater flexibility.

Analysis of Young's Modulus trends from Figure 5 show that the cellulose fillers contributed to increased stiffness, as their fibrous structure reinforced the polymer matrix [46]. Bentonite clay fillers, despite their fine particle size, showed a decline in modulus, likely due to insufficient distribution or weak interfacial bonding. Higher starch content (9:1 ratio) enhanced Young's modulus, suggesting that starch contributes to structural rigidity.

The 9:1 starch-to-gelatin ratio with bentonite clay filler provided the highest Young's modulus, making it ideal for rigid applications. In contrast, cellulose-filled bioplastics had lower stiffness, making them suitable for applications requiring greater flexibility.

This study demonstrates that fillers influence structural properties. Bentonite clay improved tensile strength but reduced stiffness, making it suitable for applications requiring a balance between strength and flexibility. In contrast, cellulose fillers increased Young's modulus by reinforcing the polymer structure, resulting in a stiffer material.

Bioplastics with high Young's modulus (bentonite clay-based) are ideal for rigid packaging, structural components, and durable biodegradable products [41]. Meanwhile, bioplastics with Young's modulus (cellulose-based) are suitable for flexible films, coatings, and applications requiring elasticity [42].

3.4 Fourier transform infrared (FTIR) analysis

3.4.1 FTIR analysis of bioplastics with cellulose extracted

Figure 6 shows that the FTIR spectra of extracted cellulose. The presence of key functional groups in both spectra confirms the structural integrity of the extracted cellulose. O-H (hydroxyl group, $\sim 3325\text{ cm}^{-1}$) represents hydrogen bonding in cellulose. CH₂ ($\sim 2892\text{ cm}^{-1}$) indicates aliphatic C-H stretching vibrations. C=O (carbonyl group) contributes to the structural stability of cellulose. N-H (amide groups) suggests interactions with protein-based components. C-O ($\sim 1021\text{ cm}^{-1}$) corresponds to ether linkages in the cellulose backbone.

The presence of O-H stretching vibrations suggests strong hydrogen bonding interactions between starch, gelatin, and fillers [47]. Absorption peaks associated with C-H (alkane) and C=O (carbonyl) groups indicate effective cross-linking in the bioplastic matrix [48]. The FTIR spectrum also confirms the incorporation of bentonite clay, as indicated by characteristic Si-O stretching vibrations, demonstrating effective filler integration [49].

The FTIR spectra of bioplastics containing bentonite clay fillers confirm strong intermolecular interactions between starch, gelatin, and fillers. The successful incorporation of bentonite clay into the bioplastic matrix is evidenced by the presence of characteristic Si-O stretching vibration.

Hydroxyl and carbonyl functional groups contribute to bioplastic flexibility and mechanical strength [50]. Bentonite clay enhances structural integrity, thereby improving the durability and thermal resistance of bioplastics [51].

This FTIR analysis confirms the successful extraction of cellulose, effective integration of bentonite clay, and strong molecular interactions within the bioplastic matrix, contributing to enhanced material performance and sustainability.

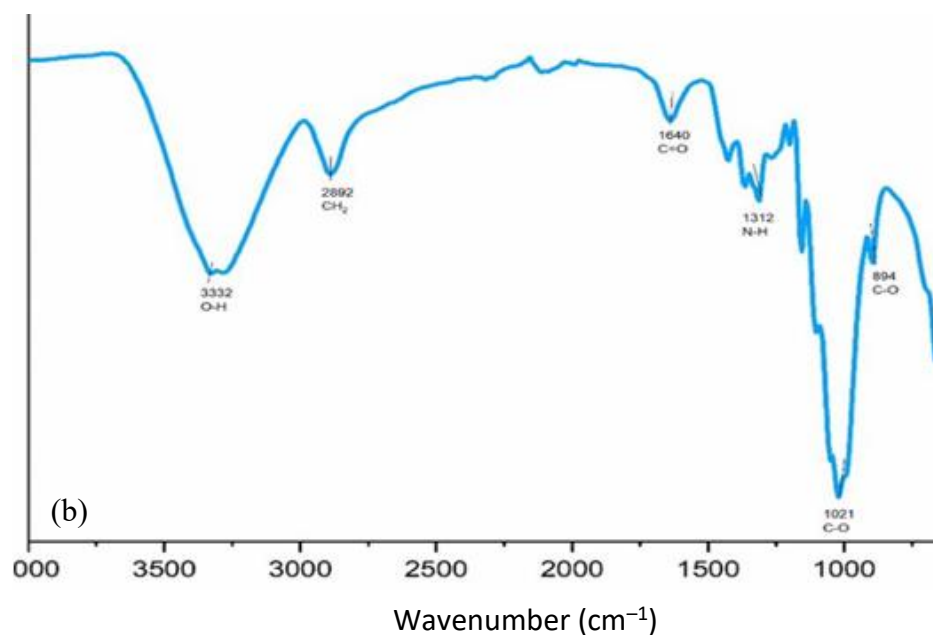


Figure 6 FTIR Analysis cellulose extracted from corn stalks and husks

3.4.2 FTIR Analysis of bioplastics with bentonite clay fillers

FTIR analysis was performed to examine the chemical interactions within bioplastics incorporating bentonite clay fillers. The results are shown in Figure 7.

Based on Figure 7, several key spectral features were observed. The absorption band at 3622 cm^{-1} (O-H Stretching) indicates the presence of hydroxyl (-OH) groups found in Al-OH or Mg-OH-Al, which are characteristic of bentonite clay. The peak at 3391.9 cm^{-1} (hydrated O-H stretching) has suggested hydrogen-bonding interactions resulting from adsorbed water molecules within the bioplastic matrix. The band at 984 cm^{-1} (Si-O-Si and SiO_2 quartz vibration) represents the presence of silicate structures, confirming the incorporation of bentonite clay into the polymer network. Additionally, the band at $1400\text{--}800\text{ cm}^{-1}$ (Si-O vibrations) correspond to asymmetric Si-O stretching vibrations, indicating the presence of montmorillonite, a key component of bentonite clay [52].

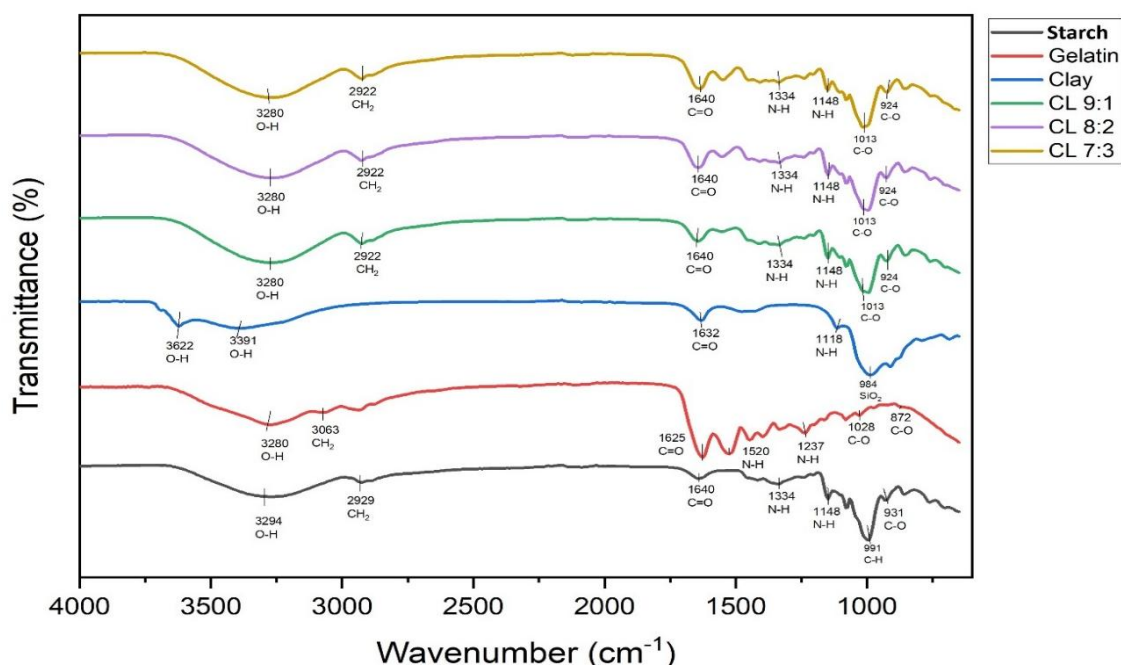


Figure 7 FTIR graph of bioplastic with bentonite clay filler

The presence of O-H groups at 3622 cm^{-1} and 3391.9 cm^{-1} suggests that bentonite clay interacts with starch and gelatin through hydrogen bonding, thereby improving structural integrity [51]. The strong Si-O-Si peak at 984 cm^{-1} confirms the high silicate content of bentonite clay, which reinforces the polymer matrix [53]. The asymmetric Si-O vibrations ($1400\text{--}800\text{ cm}^{-1}$) further indicate effective dispersion of bentonite clay within the bioplastic, contributing to enhanced mechanical properties [54].

The FTIR analysis confirms the successful incorporation of bentonite clay into the bioplastic formulation. The presence of strong silicate vibrations indicates a high montmorillonite content, contributing to the reinforcement of the bioplastic structure. Hydrogen bonding interactions (O-H stretching) between bentonite clay and starch/gelatin suggest improved mechanical stability. The Si-O-Si stretching vibrations confirm enhanced structural rigidity, making bentonite-filled bioplastics suitable for stronger and more durable applications.

This study confirms that bentonite clay effectively enhances bioplastic performance by improving mechanical strength, structural stability, and moisture resistance, thereby demonstrating its potential for use in sustainable, high performance biodegradable materials.

3.4.3 FTIR analysis of bioplastics with cellulose fillers

FTIR analysis was conducted to evaluate the functional groups present in bioplastics containing cellulose fillers derived from corn stalks and husks. The results are presented in Figure 8.

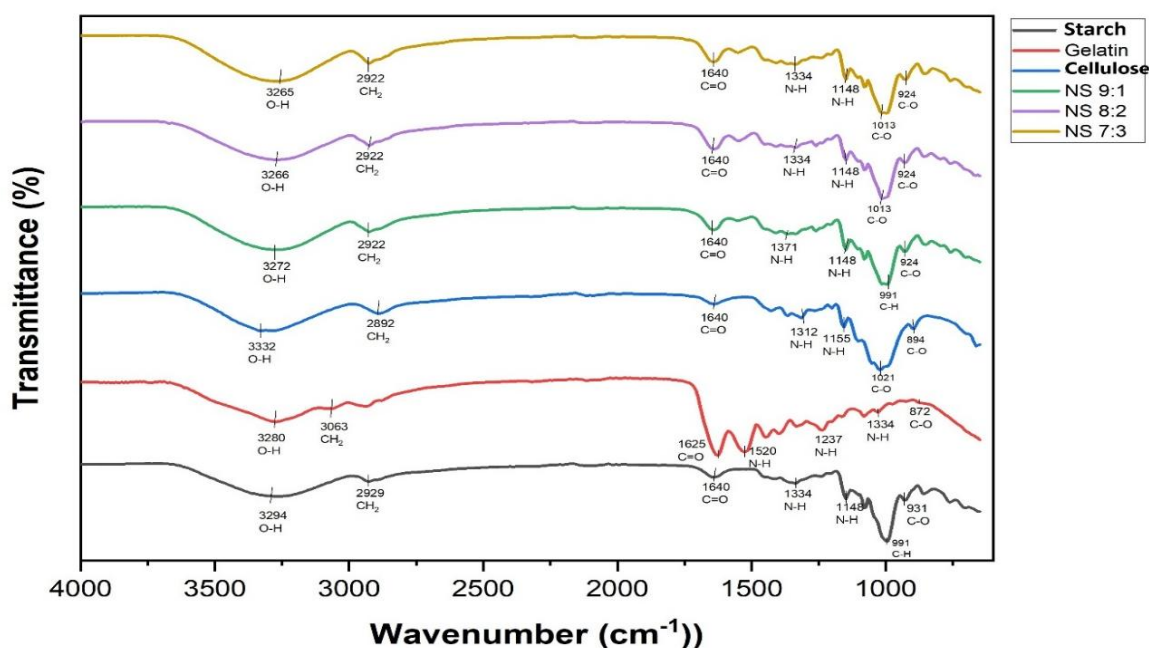


Figure 8 FTIR graph of bioplastic with cellulose fillers from corn stalks and husks

Based on Figure 8, several key spectral features were observed. O-H (Hydroxyl Group, Broad Peak) indicates strong hydrogen bonding, contributing to the hydrophilic nature of bioplastics [47]. CH₂ (Aliphatic C-H Stretching) suggests the presence of cellulose and starch components in the bioplastic matrix [55]. The C=C (Carbon-Carbon Stretching) implies structural interactions between polymeric constituents [55]. N-H (Amide Group) confirms the presence of gelatin as a protein-based biopolymer [55]. Additionally, C-O (Ether Linkages) reflects the polysaccharide backbone of starch and cellulose [55].

Based on the FTIR analysis, the functional groups detected in the bioplastic samples correspond to those of their constituent materials (starch, gelatin, cellulose). The absence of new functional groups suggests that bioplastic formation occurs through physical blending rather than chemical modification [29]. The presence of hydroxyl (-OH) groups contributes to the hydrophilic nature of the bioplastic, allowing significant water absorption [56].

The FTIR spectra further confirm the physical blending mechanism [57]. The results indicate that the bioplastics were formed through physical mixing of starch, gelatin, and cellulose, as no new chemical bonds were detected. This confirms that the bioplastic retains the inherent properties of its raw materials, including hydrophilicity.

Hydrogen bonding interactions (O-H stretching) suggest strong intermolecular forces, contributing to bioplastic integrity. The hydrophilic nature of cellulose-based bioplastics may affect water absorption and biodegradability, making them suitable for applications where moisture interaction is required [58].

This study confirms that bioplastics containing cellulose fillers retain hydrophilic properties due to physical blending, making them ideal for moisture sensitive applications while presenting opportunities for further material enhancements.

4. Conclusions

This study successfully synthesized bioplastics using cassava starch, cassava peel, and fillers derived from corn stalks, husks, and bentonite clay. Among the formulations tested, the best performance was achieved with a starch-to-gelatin ratio of 8:2 incorporating 0.4 g of bentonite clay, yielding a tensile strength of 1.837 MPa, elongation of 33.6%, and a Young's modulus of 5.47 MPa.

Comparative analysis revealed distinct differences between filler types. Bentonite clay provided superior reinforcement, significantly enhancing tensile strength and rigidity due to its fine particle size and more uniform dispersion. In contrast, cellulose fillers improved elongation and flexibility, achieving values up to 71.5% at the 9:1 starch-gelatin ratio, but with lower tensile strength (around 0.8-1.2 MPa) due to particle agglomeration and weaker interfacial bonding. These results highlight the trade-off between strength and flexibility depending on filler choice.

Compared to LDPE, the optimized bioplastic demonstrated improved mechanical performance relative to filler-free starch-gelatin films but remained inferior to commercial plastics, particularly in tensile strength (LDPE: 8-12 MPa) and elongation (LDPE: 200-

600%). This confirms that, while cassava-based bioplastics offer a sustainable and low-cost alternative, further optimization of filler dispersion and hybrid formulations is required to achieve the performance levels closer to LDPE.

Overall, this research underscores both the qualitative advantages (renewable feedstock, waste valorization, and filler reinforcement strategies) and quantitative outcomes (1.8 MPa tensile strength, 33.6% elongation, 5.47 MPa modulus) of cassava-based composite bioplastics. By valorizing agricultural residues such as cassava peels and corn stalks, this approach promotes sustainable materials development and circular economy initiatives. Future work would focus on nano-scale filler dispersion, plasticizer optimization, and biodegradation testing under real environmental conditions to advance the application of these bioplastics in packaging, agricultural films, and disposable products.

5. References

- [1] Pilapitiya PGCNT, Ratnayake AS. The world of plastic waste: a review. *Cleaner Mater.* 2024;11:100220.
- [2] Moshood TD, Nawanir G, Mahmud F, Mohamad F, Ahmad MH, AbdulGhani A. Sustainability of biodegradable plastics: new problem or solution to solve the global plastic pollution?. *Curr Res Green Sustainable Chem.* 2022;5:100273.
- [3] Pooja N, Chakraborty I, Rahman MH, Mazumder N. An insight on sources and biodegradation of bioplastics: a review. *3 Biotech.* 2023;13:220.
- [4] Parmar A, Sturm B, Hensel O. Crops that feed the world: production and improvement of cassava for food, feed, and industrial uses. *Food Sec* 9. 2017;9:907-27.
- [5] Azkiya NI, Udjiana SS, Irangga AR, Febiyanti AT. The potential of cassava peel waste as a material of biodegradable plastic using calcium silicate filler. *J Tek Kim Ling.* 2023;7(2):85-91.
- [6] Liang J, Li Z, Dai S, Tian G, Wang Z. Production of hemicelluloses sugars, cellulose pulp, and lignosulfonate surfactant using corn stalk by prehydrolysis and alkaline sulfite cooking. *Ind Crops Prod.* 2023;192:115880.
- [7] Pramudia M, Umami MK, Prihantoko A. Effect of fiber volume fraction on tensile strength and fracture analysis of corn husk reinforced epoxy resin composite. *International Conference on Science and Technology 2022 "Advancing Science and Technology Innovation on Post Pandemic Through Society 5.0" (ICST-2022); 2022 Nov 18; West Java, Indonesia. France: EDP Sciences; 2022. p. 1-4.*
- [8] Sari NH, Suteja S. Corn husk fibers reinforced polyester composites: tensile strength properties, water absorption behavior, and morphology. *3rd International Conference on Engineering Technology for Sustainable Development (ICET4SD); 2019 Oct 23-24; Yogyakarta, Indonesia. UK: IPO Science; 2019. p. 1-11.*
- [9] Mapossa AB, da Silva Júnior AH, de Oliveira CRS, Mhike W. Thermal, morphological and mechanical properties of multifunctional composites based on biodegradable polymers/bentonite clay: a review. *Polymers.* 2023;15(16):3443.
- [10] Fernández MV, González MJA, Oyanadel RB, Rivera JLV, Soto AR, Ortega AG, et al. Effect of nanometric particles of bentonite on the mechanical properties of a thermoset polymeric matrix reinforced with hemp fibers. *Polymers* 2023;15(6):1571.
- [11] Żołek-Tryznowska Z, Cichy L. Glycero derivatives as a modern plastisizers for starch films. *9th International Symposium on Graphic Engineering and Design 2018; 2018 Nov 1; Cluj-Napoca, Romania. Serbia: Graphic Engineering and Design; 2018. p. 217-22.*
- [12] El-Seedi HR, Said NS, Yosri N, Hawash HB, El-Sherif DM, Abouzid M, et al. Gelatin nanofibers: recent insights in synthesis, bio-medical applications, and limitations. *Heliyon.* 2023;9(5):e16228.
- [13] Lu Y, Luo Q, Chu Y, Tao N, Deng S, Wang L, et al. Application of gelatin in food packaging: a review. *Polymers.* 2022;14(3):436.
- [14] Wu Y, Liu C, Song X, Liang J, Zhi M, Lu J, et al. A novel lignocellulose pretreatment technology by combining KOH, urea peroxide and organosilane to improve glucose yield. *Chem Eng J.* 2023;457:141296.
- [15] Zhang J, Ying Y, Yi X, Han W, Yin L, Zheng Y, et al. H₂O₂ solution steaming combined method to cellulose skeleton for transparent wood infiltrated with cellulose acetate. *Polymers.* 2023;15(7):1733.
- [16] Zhang Y, Zhang Y, Xu W, Wu H, Shao Y, Han X, et al. Preparation methods of cellulose nanocrystal and its application in treatment of environmental pollution: a mini-review. *Colloid Interface Sci Commun.* 2023;53:100707.
- [17] Hoo DY, Low ZL, Low DYS, Tang SY, Manickam S, Tan KW, et al. Ultrasonic cavitation: an effective cleaner and greener intensification technology in the extraction and surface modification of nanocellulose review. *Ultrason Sonochem.* 2022;90:106176.
- [18] Widiarto S, Pramono E, Suharso, Rochliadi A, Arcana IM. Cellulose nanofibers preparation from cassava peels via mechanical disruption. *Fibers.* 2019;7(5):44.
- [19] Wicaksono R, Syamsu K, Yuliasih I, Nasir M. Characteristics of cellulose nanofibers from cassava pulp and its use as tapioca-film reinforcement. *J Teknol Ind Pertan.* 2013;23(1):38-45.
- [20] Maghsoodi M, Yari Z. Effect of drying phase on the agglomerates prepared by spherical crystallization. *Iran J Pharm Res.* 2015;14(1):51-7.
- [21] Chen J, Javaheri H, Sulaiman BAC, Dahman Y. Chapter 1 - synthesis, characterization and applications of nanoparticles. In: Grumezescu AM, editor. *Fabrication and self-assembly of nanobiomaterials applications of nanobiomaterials.* UK: William Andrew; 2016. p. 1-27.
- [22] Endres SC, Ciacchi LC, Mädler L. A review of contact force models between nanoparticles in agglomerates, aggregates, and films. *J Aerosol Sci.* 2021;153:105719.
- [23] Sellman FA, Benselfelt T, Larsson PT, Wågberg L. Hornification of cellulose-rich materials – a kinetically trapped state. *Carbohydr Polym.* 2023;318:121132.
- [24] Ludvik CN, Glenn CM, Klamczynski AP, Wood DF. Cellulose filler/bentonite clay/biodegradable thermoplastic composites. *J Polym Environ.* 2007;15:251-7.
- [25] Li T, Li R, Luo H, Peng L, Wang J, Li S, et al. Eggshell powder as a bio-filler for starch and gelatin: ternary biodegradable composite films manufactured by extrusion compression molding. *Food Hydrocolloids.* 2024;150:109632.
- [26] Yang Y, Fu J, Duan Q, Xie H, Dong X, Yu L. Strategies and methodologies for improving toughness of starch films. *Foods* 2024;13(24):4036.

- [27] Nurintan S, Ahmad A, Natsir H, Fauziah S, Soekamto NH, Hala Y, Anita A. Isolation of cellulose from *Gracilaria sp.* for the development of biodegradable edible film: A sustainable approach for eco-friendly food packaging, *Ecol Eng Environ Technol.* 2026;27(3):188-208.
- [28] Safitri A, Sinaga PSD, Nasution H, Harahap H, Masyithah Z, Iriany, et al. The role of various plasticizers and fillers additions in improving tensile strength of starch-based bioplastics: a mini review. *IOP Conf Ser: Earth Environ Sci.* 2022;1115:012076.
- [29] Boey JY, Lee CK, Tay GS. Factors affecting mechanical properties of reinforced bioplastics: a review. *Polymers.* 2022;14(18):3737.
- [30] Serrano-Martínez VM, Pérez-Aguilar H, Carbonell-Blasco MP, Llobell-Andrés C, Aran-Ais F, García-García A, et al. Exploring the mechanical and thermal impact of natural fillers on thermoplastic polyurethane and styrene-butadiene rubber footwear sole materials. *Polymers.* 2024;16(22):3201.
- [31] Shojaeiarani J, Bajwa DS, Chanda S. Cellulose nanocrystal based composites: a review. *Composites Part C Open Access.* 2021;5:100164.
- [32] Zhou Y, Fan M, Chen L. Interface and bonding mechanisms of plant fibre composites: an overview. *Composites Part B.* 2016;101:31-4.
- [33] Tan SX, Andriyana A, Ong HC, Lim S, Pang YL, Ngoh GC. A Comprehensive review on the emerging roles of nanofillers and plasticizers towards sustainable starch-based bioplastic fabrication. *Polymers.* 2022;14(4):664.
- [34] Melani A, Herawati N, Kurniawan AF. Bioplastik Pati Daging Talas Melalui Proses melt intercalation (Kajian Pengaruh Jenis Bahan Pengisi, Konsentrasi Bahan Pengisi Dan Jenis plasticizer). *J Distil.* 2017;2(2):53-67. (In Indonesian)
- [35] Jang Y, Jang J, Kim BY, Song YS, Lee DY. Effect of gelatin content on degradation behavior of PLLA/gelatin hybrid membranes. *Tissue Eng Regen Med.* 2024;21(4):557-69.
- [36] Romisuhani A, Salmah H, Akmal H. Tensile properties of low density polypropylene (LDPE)/palm kernel shell (PKS) biocomposites. 9th National Symposium on Polymeric Materials (NSPM 2009); 2009 Dec 14-16; Putrajaya, Malaysia. UK: IPO Science; 2009. p. 1-7.
- [37] de Carvalho Benini KCC, Arantes V. Evaluating the reinforcing potential of enzymatic cellulose nanocrystals in polypropylene nanocomposite. *Carbohydr Res.* 2024;542:109171.
- [38] Rather JA, Akhter N, Ashraf QS, Mir SA, Makroo HA, Majid D, et al. A comprehensive review on gelatin: understanding impact of the sources, extraction methods, and modifications on potential packaging applications. *Food Packag Shelf Life.* 2022;34:100945.
- [39] Abang S, Wong F, Sarbatly R, Sariau J, Baini R, Besar NA. Review bioplastic classifications and innovations in antibacterial, antifungal, and antioxidant applications. *J Bioresour Bioprod.* 2023;8(4):361-87.
- [40] Zhao X, Wang Y, Chen X, Yu X, Li W, Zhang S, et al. Sustainable bioplastics derived from renewable natural resources for food packaging. *Matter.* 2023;6(1):97-127.
- [41] Sarifuddin N, Ismail H. Comparative study on the effect of bentonite or feldspar filled low density polyethylene/thermoplastic sago starch/kenaf core fiber composites. *Biores.* 2013;8(3):4238-57.
- [42] Negrete-Bolagay D, Guerrero VH. Opportunities and challenges in the application of bioplastics: perspectives from formulation, processing, and performance. *Polymers.* 2024;16(18):2561.
- [43] Ruamcharoen J, Ratana T, Ruamcharoen P. Bentonite as a reinforcing and compatibilizing filler for natural rubber and polystyrene blends in latex stage. *Polym Eng Sci.* 2014;54(6):1436-43.
- [44] Huang X, Sun Z, Zhong Y, Ding X, Chen L, Chen H, et al. Constructing a “micro-nano collaboration” network via disk-milling: value-enhanced utilization of flexible temperature-resistant cellulose insulation films. *Int J Biol Macromol.* 2024;26(2):130345.
- [45] Zaborowska M, Bernat K, Pszczółkowski B, Kulikowska D, Wojnowska-Baryła I. Assessment of biodegradability of cellulose and poly(butylene succinate)-based bioplastics under mesophilic and thermophilic anaerobic digestion with a view towards biorecycling. *Waste Manage.* 2023;168:413-22.
- [46] Venkatarajan S, Athijayamani A. An overview on natural cellulose filler reinforced polymer composites. *Mater Today Proc.* 2021;37(2):3620-4.
- [47] Lee CM, Kubicki JD, Fan B, Zhong L, Jarvis MC, Kim SH. Hydrogen-bonding network and OH stretch vibration of cellulose: comparison of computational modeling with polarized IR and SFG spectra. *J Phys Chem B.* 2015;119(49): 15138-49.
- [48] Vonnice JM, Rovina K, Nur 'Aqilah NM, Felicia XWL. Development and characterization of biosorbent film from eggshell/orange waste enriched with banana starch. *Polymers.* 2023;15(11):2414.
- [49] Zhirong L, Uddin MA, Sun Z. FT-IR and XRD analysis of natural Na-bentonite and Cu(II)-loaded Na-bentonite. *Spectrochim Acta Part A.* 2011;79(5):1013-6.
- [50] Amin MR, Chowdhury MA, Kowser MA. Characterization and performance analysis of composite bioplastics synthesized using titanium dioxide nanoparticles with corn starch. *Heliyon.* 2019;5(8):e02009.
- [51] Trigueiro P, de L Pereira JP, Ferreira MG, Silva LB, Neves L, Peña-García RR. Clay minerals and biopolymers in film design: overview of properties and applications. *Minerals.* 2024;14(6):613.
- [52] Lisovsky IP, Litovchenko VG, Mazunov DO, Kaschieva S, Koprinarova J, Dmitriev SN. Infrared spectroscopy study of Si-SiO₂ structures irradiated with high-energy electrons. *J Optoelectron Adv Mater.* 2005;7(1):325-8.
- [53] Alekseeva OV, Rodionova AN, Bagrovskaya NA, Agafonov AV, Noskov AV. Effect of the bentonite filler on structure and properties of composites based on hydroxyethyl cellulose. *Arab J Chem.* 2019;12(3):398-404.
- [54] Moldovan A, Cuc S, Prodan D, Rusu M, Popa D, Taut AC, et al. Development and characterization of polylactic acid (PLA)-based nanocomposites used for food packaging. *Polymers.* 2023;15(13):2855.
- [55] Rao LS, Naidu CD, Tiwari S. Investigation on synthesis, structure and degradability of starch-based bioplastics. *Mater Today Proc.* 2021;49(2):257-61.
- [56] Tabassum N, Rafique U, Qayyum M, Mohammed AAA, Asif S, Bokhari A. Kaolin-polyvinyl alcohol-potato starch composite films for environmentally friendly packaging: optimization and characterization. *J Compos Sci.* 2024;8(1):29.
- [57] Zidan HM, Abdelrazek EM, Abdelghany AM, Tarabiah AE. Characterization and some physical studies of PVA/PVP filled with MWCNTs. *J Mater Res Technol.* 2019;8(1):904-13.
- [58] Jayalath UT, Samaraweera H, Samarasinghe A. Development and characterization of gelatin-starch bioplastics: a comparative study of cassava, corn, and rice-based alternatives. *J Mater Res Technol.* 2025;9:100190.