Reaktor

p-ISSN 0852 – 0798
e-ISSN 2407 – 5973

Website: http://ejournal.undip.ac.id/index.php/reaktor/

Reaktor, Vol. 25 No. 2, August Year 2025, pp. 90-99

Synthesis of Sorghum Starch–PVA/Gelatin Bioplastics Reinforced with Sorghum Stem Cellulose Nanofibers via Blend Ratio Tailoring

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(Received: 1 October 2025; Accepted: 27 November 2025; Published: 30 November 2025)

Abstract

This study aims to synthesize an LDPE comparable - bioplastic from sorghum starch and PVA/gelatin reinforced with sorghum stem cellulose nanofibers through blend ratio tailoring. The mass ratios of sorghum starch to PVA/gelatin were varied at 9:1 and 8:2 (g/g), with a composition of 70% sorghum starch and 30% PVA. Meanwhile, sorghum stem cellulose nanofiber filler additions were varied at 0 g, 0.1 g, and 0.2 g. Bioplastic fabrication was performed using glycerol concentration of 10% (w/w), while the gelatinization temperature, stirring speed, and stirring time were kept constant at 95°C, 375 rpm, and 35 minutes, respectively. The best bioplastic was achieved at a sorghum starch-PVA:gelatin mass ratio of 8:2 (g/g) with 0.2 g of nanofiber filler, which exhibits a tensile strength of 13.91 MPa, elongation of 3.00%, Young's modulus of 4.63 MPa, water absorption of 1.8%, and density of 0.52 g/mL.

Keywords: Bioplastics; Cellulose Nanofibers; Mechanical Properties Sorghum Starch; Sorghum Stem.

How to Cite This Article: Darni, Y., Asri, N.P., Lismeri, L., Ginting, S.B., Arfiana, A., Setiawan, A. (2025), Synthesis of Sorghum Starch–PVA/Gelatin Bioplastics Reinforced with Sorghum Stem Cellulose Nanofibers via Blend Ratio Tailoring, Reaktor, 25 (2), 90–99, https://doi.org/10.14710/reaktor.25.2.90-99

INTRODUCTION

Technological advances and industrial development have significantly increased the global consumption of plastic-based packaging. Plastic has become indispensable in daily life because of its affordability, strength, lightweight, and high chemical stability. However, most plastic industries manufacture conventional plastics for various applications from petroleum-based synthetic polymers, which are non-biodegradable and rely on limited fossil resources (Kumari et al., 2023). The persistence of plastic waste in the environment, combined with the greenhouse gas emissions generated during incineration, exacerbates pollution and contributes to global climate change. Petroleum as a non-renewable resource is finite,

creating long-term concerns about the sustainability of conventional plastic production (Rajendran et al., 2025).

In response to these environmental and resource challenges, the development of biodegradable plastics has emerged as a promising alternative. The industries produce bioplastics from renewable biomass such as starch, vegetable oils, corn amylum, and microbiota, and they can degrade through microbial activity under appropriate environmental conditions (Emadian et al., 2017). Among these renewable materials, starch has attracted significant interest with regards to its biodegradability, abundance, and low cost (Zhao et al., 2023). As a polysaccharide composed of amylose and amylopectin (Dilshad et al., 2021), starch also plays a central role in food processing systems (Singh et al., 2007). Indonesia's diverse starch-producing crops, including cassava, rice, corn, sweet potatoes, taro, and bananas, provide a strong strategic advantage in ensuring raw material availability for bioplastic production (Aprianita et al., 2014; Sutawijaya et al., 2025).

Sorghum, a starch-rich cereal containing approximately 55.6–70.0% starch content (Khan et al., 2013), exhibits promising potential as the raw material for bioplastic preparation. In addition, polyvinyl alcohol (PVA), with its excellent film-forming ability, biodegradability, biocompatibility, non-toxicity, high tensile strength, and flexibility, has been widely applied as a complementary polymer in bioplastic manufacturing (Tavassoli et al., 2025). Nevertheless, starch-based bioplastics often exhibit inferior mechanical and physical properties compared to petroleum-derived plastics, highlighting the need for reinforcement and modification.

One promising reinforcement strategy is the incorporation of natural fibers from lignocellulosic plants. Sorghum stems, which contain 17–18% cellulose, 18–21% hemicellulose, and 22–23% lignin, are abundant and readily available as filler materials (Billmeyer, 1984). To improve their performance, Addition of cellulose nanofibers as a filler can improve the performance of bioplastics. For instance, (Wicaksono et al., 2013) successfully isolated cellulose nanofibers from tapioca pulp using alkaline treatment, bleaching, acid hydrolysis, and mechanical processing, producing nanofibers of 5–8 nm with high crystallinity. Similarly, (Darni et al., 2020) demonstrated the production of cellulose fibers from sorghum stems using this method, although the resulting fibers were on the micron scale. The nanoscale transformation of fibers enables better dispersion in the polymer matrix, improving structural integrity and mechanical strength.

An appropriate incorporation of additives, such as gelatin and plasticizers can also enhance flexibility and water resistance of bioplastics. Gelatin reduces water absorption and improves film strength (Kavoosi et al., 2014) while glycerol, a widely used plasticizer, forms the least amount of hydrogen bonds, having the shortest hydrogen bond lifetimes and low molecular rigidity (Özeren et al., 2020), thus improving ductility and processability (Halloran et al., 2022).

Research on the utilization of sorghum starch has been developed, including the production of biodegradable plastic films from *Sorghum bicolor* (L.) starch and glycerol plasticizer without the addition of fillers (Juliet et al., 2023), and bioplastics derived from sorghum husks based on cellulose–chitosan (CC) with incorporating zinc oxide (ZnO) nanoparticles and charcoal as fillers (Kour et al., 2025).

However, no studies have reported the development of sorghum starch–PVA/gelatin bioplastics reinforced with cellulose nanofibers extracted specifically from sorghum stalks. The present work introduces a unique full-plant sorghum utilization approach, in which starch from sorghum grains functions as the polymer matrix, while cellulose nanofibers from sorghum stalks serve as the reinforcing agent. This study applies a blend-ratio-tailoring strategy to optimize the sorghum starch–PVA:gelatin ratio and systematically evaluates the effects of nanoscale cellulose incorporation on mechanical, physical, and structural properties. As far as literature has been carried out, no research has reported such an integrated design, showing the first demonstration of comprehensive sorghum biomass valorization into reinforced bioplastics with tunable performance.

Building on this foundation, the present study employs a mixture of sorghum starch and PVA reinforced with cellulose nanofibers derived from sorghum stems, with glycerol as a plasticizer. Cellulose nanofibers are usually isolated using the method developed by (Wicaksono et al., 2013), which integrates alkaline, bleaching, acid hydrolysis, and mechanical treatments. The objectives of this study are: (1) to isolate cellulose fibers from sorghum stems with nanometer-scale dimensions, (2) to evaluate the effect of sorghum starch–PVA ratios and cellulose nanofiber fillers on bioplastic characteristics, and (3) to develop biodegradable plastics with mechanical properties comparable to conventional LDPE.

MATERIALS AND METHODS

Research Design and Location

An experimental design with a quantitative approach was applied to evaluate the effect of the mass ratio of sorghum starch and PVA to gelatin, combined with the addition of sorghum stem cellulose nanofiber filler, on the characteristics of bioplastics. The synthesis of cellulose and the preparation of bioplastics were conducted at the Fiber and Resin Polymer Engineering Laboratory, Department of Chemical Engineering, Universitas Lampung, from February to November 2024.

Characterization of the resulting bioplastics was performed through multi-instrumental analyses in

several laboratories. Fourier Transform Infrared (FTIR) analysis for functional group identification was carried out at the Integrated Laboratory of the Center for Technological Innovation (LTSIT), Universitas Lampung. Bioplastic morphology was characterized using Scanning Electron Microscopy (SEM) and mechanical testing (tensile strength, elasticity, and elongation) were conducted at the Integrated Laboratory of Universitas Diponegoro. Meanwhile, the X-Ray Diffraction (XRD) analysis was carried out at BRIN Tanjung Bintang. Accordingly, Transmission Electron Microscopy (TEM), PBM (Planetary Ball Mill) processing, and particle size distribution tests were conducted at the Center for Nanoscience and Nanotechnology Research Laboratory, Institut Teknologi Bandung.

Materials

The primary raw materials consisted of white sorghum seeds and stalks sourced from Sulusuban, Lampung Tengah Regency, the Province of Lampung, and polyvinyl alcohol (PVA) (p.a. Merck) was procured from Merck and used as bioplastic matrix. Sulfuric acid (p.a. Merck, 95-97%), potassium hydroxide (p.a. Merck), and hydrogen peroxide (Merck, 30%) and distilled water were supplied by local chemical store in Bandar Lampung. Other chemical and reagents were also the product of Merck and purchased from local chemical distributor in Bandar Lampung.

Equipment

The preparation of sorghum flour involved a grain grinder, blender, 200-mesh sieve, and analytical balance. Synthesis of cellulose nanofibers utilized hot plates, beakers, spatulas, thermometers, pH meters, stopwatches, digital balances, centrifuges, Petri dishes, filter paper, pipettes, funnels, Erlenmeyer flasks, mortar and pestle, planetary ball mill, magnetic stirrers, and 200-mesh sieves. Meanwhile, bioplastic manufacturing was carried out using beakers, hot plates with magnetic stirrers, drying ovens, thermometers, digital balances, special molds, zip bags for storage, stopwatches, spatulas, and Petri dishes. Bioplastic characterization employed an autograph for tensile testing, digital calipers for thickness measurements, ZEISS EVO MA 10 for SEM, Variant 2000 FTIR for functional group analysis, Philips Analytical X-Ray diffractometer type PW1710 with Cu anode tube for XRD, HR TEM H9500 for TEM, and Horiba SZ-100 for particle size distribution.

Experimental Design
Fixed Variables

Several optimum parameters curated from relevant previous research were employed as fixed variables. Starch particle size was conditioned to pass through a 200-mesh sieve. The gelatinization temperature was set at 95°C with a stirring time of 35 minutes. Glycerol concentration was kept at 10% of the total dry weight of the starch while starch–PVA mixture composition was fixed at 70% sorghum starch and 30% PVA. Stirring speed was maintained at 375 rpm to ensure homogeneity, whereas the oven drying of bioplastic was conducted at 60°C for 10 hours.

Independent Variables

Two independent variables were systematically varied. First, the mass ratio of sorghum starch-PVA mixture to gelatin was set at 9:1 and 8:2. Second, filler mass variations included sorghum stem cellulose nanofibers at 0, 0.1, and 0.2 g, respectively.

Table 1. Research Design

Mass of fillers (g)	Ratio of sorghum starch-PVA mixtures to gelatin (g/g)
0	9:1 ; 8:2
0.1	9:1 ; 8:2
0.2	9:1 ; 8:2

Methods
Preparation of Sorghum Flour

Sorghum seeds were cleaned from impurities and sun-dried to constant weight. The dried seeds were milled with a grain grinder to produce fine flour, which was sieved through a 200-mesh sieve to ensure uniform particle size. The flour was stored in sealed containers to avoid any possible contaminations.

Synthesis of Cellulose Nanofibers

The semi-mechanical method was employed to synthesize cellulose nanofibers from sorghum stem. Sorghum stems were cleaned, cut to ± 2 cm, and sun-dried to the achievement of constant weight. The dried stems were then milled and sieved through 200 mesh. Ten grams of sorghum stems powder were placed into a 500 mL beaker and mixed with 4% KOH solution at a 1:10 (w/v) ratio. Extraction was carried out at 80°C for 1 hour under continuous stirring. The resulting mixture was filtered and washed until the filtrate reached pH 11. Bleaching was performed twice using 6% H_2O_2 solution at 70°C for 1 hour. After second alkaline treatment employing 4% KOH solution under the same conditions, the bleached sorghum fiber was subjected to acid hydrolysis.

Sorghum stems fibers were dispersed in 200 mL of 6.5 M sulfuric acid solution and stirred at 60°C for 1 hour. The suspension was centrifuged at 375 rpm for 10 minutes and filtered using 200-mesh cloth to yield pulp. Then, the resulting pulp was washed with distilled water until the achievement of neutral pH and further oven-dried at 60°C to constant weight. Finally, the dried pulp was ground using a planetary ball mill to obtain cellulose nanofibers. The cellulose nanofiber was stored in sealed containers to avoid any possible contaminations.

Bioplastic Synthesis

The casting method was implemented for bioplastic preparation. Sorghum starch, PVA, and gelatin were weighed according to the experimental design. Glycerol, acetic acid, and distilled water volumes were calculated stoichiometrically. For example, in a 9:1 ratio with a total of 10 g, the mixture consisted of 6.3 g starch, 2.7 g PVA, and 1 g gelatin. Gelatin solution (5 mL at 20% concentration) and glycerol solution (0.79 mL, density 1.26 g/mL) were prepared.

Starch and PVA were dissolved in distilled water in a 500 mL beaker glass. Then, a solution of gelatin in acetic acid, glycerol and cellulose nanofiber were introduced to the starch solution. The mixture was heated to 95°C and continuously stirred at 375 rpm for 35 minutes. The solution was poured and uniformly spread into 100 mL molds and oven-dried at 80°C for 7 hours. The dried bioplastics were released from the molds and stored in zip bags for further analysis.

Analytical Method
Mechanical Properties Test

Ultimate tensile strength (σ_u) was calculated using $\sigma_u = F_m/A_o$ (MPa), where F_m is the maximum load and A_o is the initial cross-sectional area. Elongation at break (ε) was determined by $\varepsilon = (\Delta L/L_o) \times 100\%$, where ΔL is the change in length and L_o is the original specimen length. Both tests were performed following the ASTM D638 and ASTM D882-12 standards

Instrumental Characterization

Fourier Transform Infrared (FTIR) Spectrophotometry analysis was conducted at room temperature to identify functional groups. Scanning Electron Microscopy (SEM) was employed to observe surface morphology and microstructure. X-Ray Diffraction (XRD) analysis was applied to determine sample's crystallinity, which influences its mechanical and physical properties. Transmission Electron Microscopy (TEM) (HR TEM H9500) observed the internal structures at high magnification. Finally, particle size distribution was observed using a Horiba SZ-100 with laser beam diffraction, counter principle, and beam scattering methods, covering sizes from nanometers to millimeters.

RESULTS AND DISCUSSION

Table 2 presents the cellulose particle size before and after treatment. As seen in Table 2, sorghum stalk cellulose increased in particle size after the treatment. The chemical composition of the lignocellulosic compounds of sorghum stems showed notable changes in hemicellulose, cellulose, and lignin content after treatment (Table 3). Cellulose content of the lignocellulosic compounds of sorghum stalks increased substantially from 20.02% to 65.07%, whereas hemicellulose decreased from 26.04% to 20.04%, and lignin declined from 14.14% to 10.26%. Based on these data, the increase in cellulose content could be due to the reduction of hemicellulose and lignin contents. This increase in cellulose content demonstrates the effective isolation of cellulose from other lignocellulosic components (Litowczenko *et al*., 2021).

Table 2. Cellulose Size of Sorghum Stalk

Cellulose	Size
Before Treatment	200 (mesh)
After Treatment	200-500 (nm)

Table 3. Composition of Lignocellulose Sorghum Stems

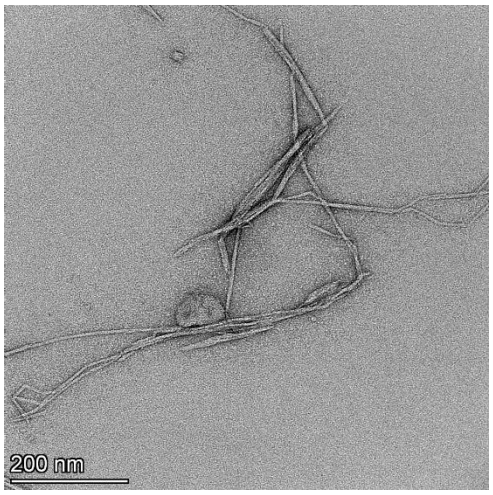
Sample	Hemicellulose (%)	Cellulose (%)	Lignin (%)
Before Treatment	26.0423	20.0216	14.1452
After Treatment	20.0467	65.0725	10.2608

Mechanical Characteristics of Bioplastics

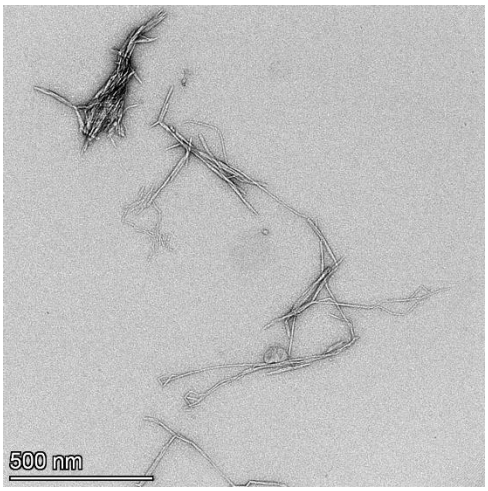
The mechanical properties of the bioplastics were evaluated and compared with those of the mechanical properties standard for LDPE. The results show that the 8:2 starch/PVA–gelatin ratio without filler (Run 2) resulted in a bioplastic with the highest tensile strength of 19.290 MPa, which exceeded the LDPE standard. Although the addition of cellulose nanofiber as a filler decreased tensile strength of the bioplastic, it improved Young's modulus, indicating an enhanced rigidity. The density of bioplastics ranges between 0.5029 and 0.5212 g/mL, which is lower than the LDPE standard. Incorporation of filler also reduced water absorption, suggesting an improved resistance to moisture.

Characterization of Sorghum Stem Cellulose Nanofibers

Cellulose nanofibers were successfully prepared using a combination of chemical and mechanical treatments. TEM analysis revealed that the size of the cellulose nanofibers ranges between 200 – 500 nm (Figure 1). The TEM analysis results displayed in Figure 1 show that cellulose extracted from sorghum stems successfully formed nanofibers with an elongated morphology resembling fine fibers. The fibrous structure appears to be interconnected and forms a network-like structure that indicates the potential of cellulose to strengthen the polymer matrix through hydrogen bonding. At 200 nm magnification, a relatively even distribution of fibrils can be clearly observed, while at 500 nm magnification, there are still a few amorphous particles that possibly originate from the residual hemicellulose or lignin had not completely been eliminated. The presence of nanofibers with a high aspect ratio is important because it can improve the mechanical properties of sorghum starch-PVA/gelatin-based bioplastics,



(a)



(b)

Figure 1. TEM Results of Cellulose Sorghum Stems (a) 200 nm scale; (b) 500 nm scale

especially in terms of tensile strength and elasticity. In addition, the arrangement of nanofibers in the matrix is expected to improve compatibility between polymers and reduce the rate of water diffusion, resulting in bioplastics with better thermal stability and moisture resistance. Thus, these TEM results confirm that sorghum stem cellulose plays a significant role as a reinforcement filler in bioplastic synthesis through a blend ratio tailoring approach.

Mechanical Properties of Bioplastics

Tensile Strength

The tensile strength test results in Figure 2 show that the sorghum starch – PVA:gelatin:filler bioplastic formulation with a ratio of 8:2:0 (without filler) provided the highest value, namely 19.061 MPa, which is within the standard range of LDPE (8 – 31.4 MPa).

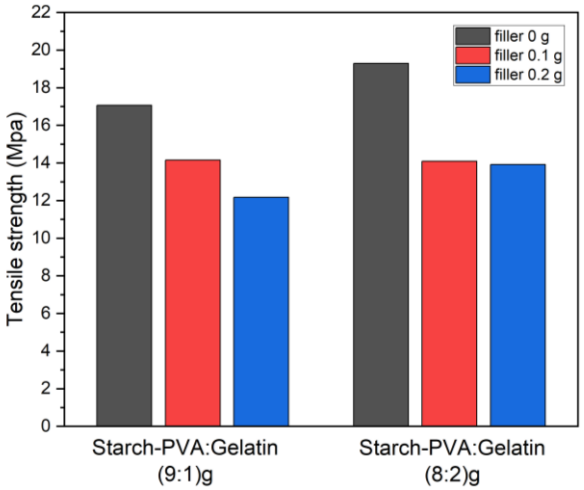


Figure 2. Effect of Bioplastic Formulations on Tensile Strength

This increase in tensile strength indicates the role of gelatin in strengthening intermolecular interactions through the formation of hydrogen bonds with starch and PVA. However, the addition of cellulose nanofibers as filler at a concentration of 0.1 – 0.2 g resulted in a decrease in tensile strength value. This decline was likely caused by lower filler dispersion homogeneity in the starch matrix, resulting in filler agglomeration leading to weakening the polymer matrix. This finding is in line with reports that excess filler can reduce mechanical performance due to inhomogeneity (Lanzalaco & Armelin, 2017). For that reason, blend ratio optimization (blend ratio tailoring) is necessary to achieve a balance between tensile strength and flexibility of bioplastics.

Elongation and Modulus Young

Figure 3 displays the effect of sorghum starch–PVA/gelatin bioplastic formulations with the addition of cellulose nanofibers on elongation properties. Bioplastics without filler exhibit the highest elongation value (3.83%), particularly at the 8:2 ratio.

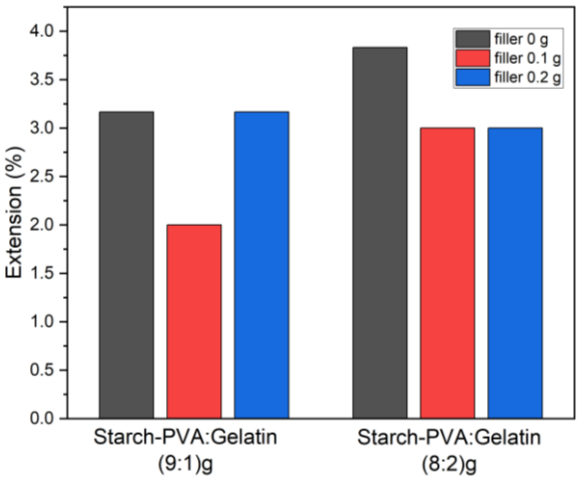


Figure 3. Effect of Bioplastic Formulation on Elongation

This result indicates that a higher gelatin portion contributes to a greater material flexibility. This is because gelatin is plastic in nature and enhances polymer chain mobility. However, the addition of 0.1 g cellulose nanofiber significantly decreases elongation in both the sorghum starch – PVA:gelatin ratios. Indeed, cellulose nanofibers have the tendency to increase stiffness and restrict plastic deformation. Interestingly, the addition of 0.2 g of filler into the starch – PVA:gelatin matrix resulted in a slight increase in elongation compared to the addition of 0.1 g of filler, suggesting that the filler reinforces matrix interactions, enabling the material to withstand strain, although flexibility remains lower than that of the filler-free sample.

Figure 4 presents the effect of formulation on the Young's modulus of bioplastics. At sorghum starch – PVA:gelatin ratio of 9:1, the addition of 0.1 g filler produced bioplastic with the highest Young's modulus, reaching 7.07 MPa compared with samples without the addition of filler (5.38 MPa). This finding confirms that a moderate addition of cellulose nanofibers effectively functions as a reinforcing agent, enhancing stiffness and elastic strength. However, at a filler addition of 0.2 g, the Young's modulus decreases sharply to 3.84 MPa, which may be attributed to filler agglomeration and uneven distribution within the matrix, thereby reducing reinforcement efficiency. A different trend is observed at sorghum starch – PVA:gelatin ratio of 8:2, where the addition of either 0.1 g or 0.2 g filler produced bioplastic with relatively similar Young's Modulus values, slightly lower than those of the filler-free sample. This behavior can be explained by the higher gelatin content, which confers greater plasticity, thus diminishing the reinforcing effect of cellulose nanofibers.

Overall, these results highlight a trade-off between elongation and Young's modulus. Formulations with higher gelatin content (8:2) tend to increase elongation but reduce modulus, whereas the addition of cellulose nanofibers at the optimum concentration (0.1 g) improves modulus at the expense of elongation.

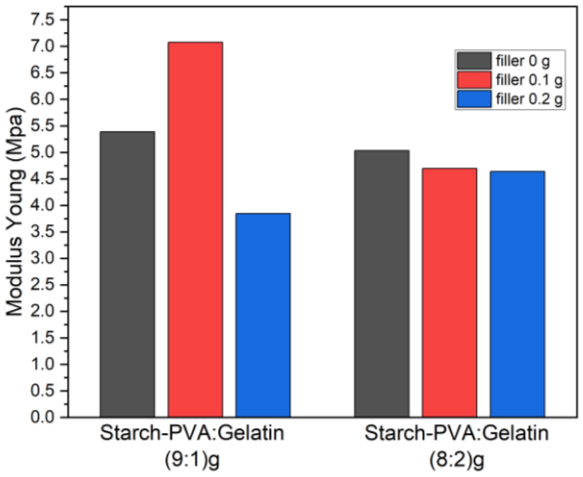


Figure 4. Effect of Bioplastic Formulation on Modulus Young

Therefore, selecting the appropriate sorghum starch–PVA/gelatin ratio and filler amount is crucial for achieving bioplastics with a balanced set of mechanical properties suitable for specific applications.

Physical Properties of Bioplastics

Water Absorption

Water absorption tests demonstrate that cellulose nanofiber fillers effectively reduce the water uptake of bioplastics (Figure 5). The lowest water absorption of 1.878% was observed on a bioplastic sample prepared from the 8:2 starch-PVA:gelatin formulation with the addition of 0.2 g sorghum stem cellulose nanofiber filler.

Bioplastics samples without filler addition (ratio 9:1:0 and 8:2:0) have the highest water absorption value, which is above 2%. This can be explained by the hydrophilic nature of starch, PVA, and gelatin which are rich in hydroxyl groups (-OH), so they easily interact with water molecules through hydrogen bonds. However, along with the addition of cellulose nanofibers in the formulation, water absorption tends to decrease. At a filler concentration of 0.2 g, both at a ratio of 9:1 and 8:2, water absorption was recorded as the lowest, approaching 1.7%. This reduction is likely caused by the role of cellulose nanofibers as a reinforcing agent that improves the density of the polymer network and reduces the free space (free volume) in the matrix, so that water diffusion into the material is more limited. Moreover, the interfacial interaction between the filler and the polymer matrix strengthens the structure and reduces the availability of free hydroxyl groups that can bind water. Thus, these results confirm that the addition of cellulose nanofibers can increase the resistance of bioplastics to water absorption, which is an important aspect in improving the stability and durability of starch-based bioplastics.

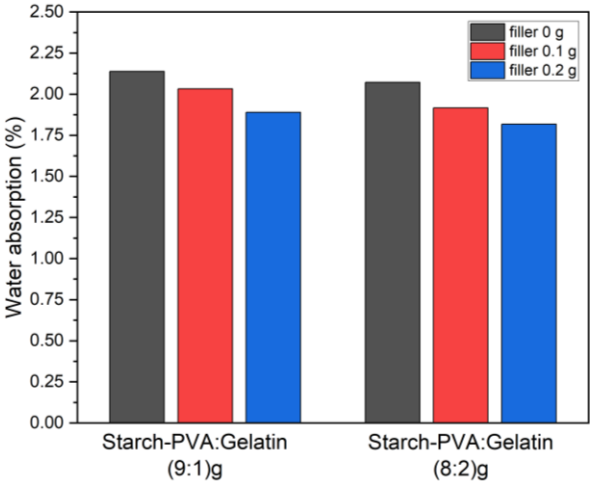


Figure 5. Effect of Bioplastic Formulations on Water Absorption

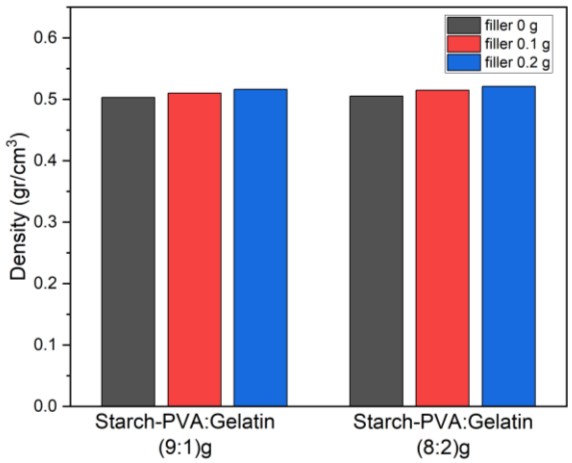


Figure 6. Effect of Bioplastic Formulations on Density

Density

The density of bioplastics increases with the addition of cellulose nanofiber fillers (Figure 6). The highest density of 0.512 g/mL is observed in the 8:2 starch-PVA:gelatin formulation with 0.2 g filler. Increased density reflects fewer pores in the bioplastic structure due to filler incorporation, correlating with improved mechanical properties. Nonetheless, this value remains below the LDPE standard of 0.91 – 0.93 g/mL (Lalita et al., 2017). Overall, formulations with an 8:2 starch – PVA:gelatin ratio exhibit the best performance, with optimal filler concentrations between 0.1 and 0.2 g depending on the target property.

Physicochemical Characteristics of Bioplastic Derived from Sorghum Starch/PVA and Cellulose Nanofibers

Fourier Transform Infrared Spectroscopy Analysis

FTIR analysis confirms the successful synthesis of sorghum starch/PVA – based bioplastics reinforced

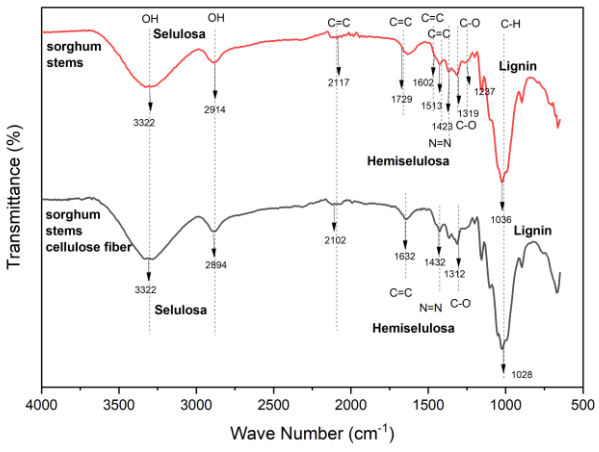


Figure 7. Results of FTIR Analysis of Sorghum Stem and Sorghum Stem Cellulose Fiber

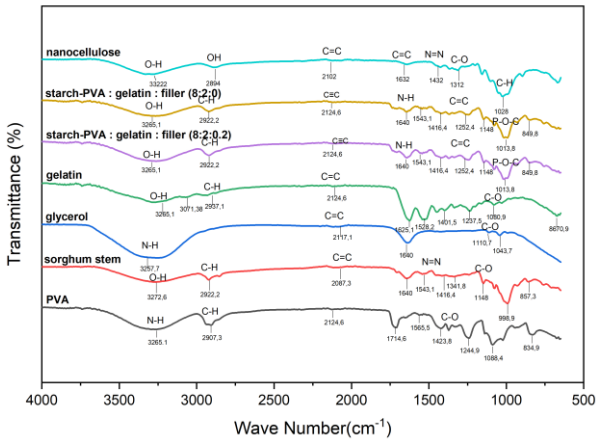


Figure 8. FTIR Analysis Results of Functional Groups of Nanofibers Cellulose, Gelatin, Glycerol, Sorghum Starch, PVA, Bioplastic 8:2 0 Filler, Bioplastics 8:2 0.2 Filler

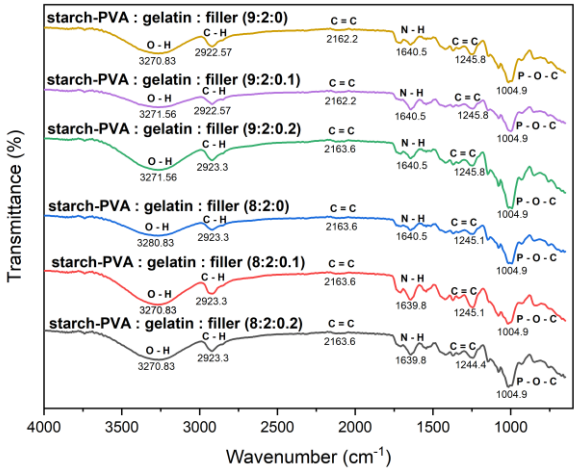


Figure 9. FTIR Analysis Results of Functional Groups of Bioplastics

with sorghum stem cellulose nanofibers. Comparative spectra between sorghum stems and isolated cellulose (Figure 7 and 8) show distinct functional group differences. Cellulose exhibits peaks at 3332 cm^{-1} (O–H stretching) and 2894 cm^{-1} (aliphatic C–H stretching), while sorghum stems reveal additional peaks at 1729 cm^{-1} (C=O from hemicellulose) and 1600, 1517 cm^{-1} (C=C aromatic lignin) (Halperin et al., 2015).

A mixed spectrum of bioplastic components (Figure 9) indicates synergistic interactions among cellulose nanofibers, gelatin, glycerol, sorghum starch, and PVA. Hydroxyl groups appear at 3200–3400 cm^{-1}, can be assigned as the unique characteristic of polysaccharides and PVA. The N–H bands of gelatin are detected at 3300 cm^{-1} and 2100 – 2200 cm^{-1}, while C–H group appears at 2800–3000 cm^{-1}. The carbonyl C=O stretch at 1640–1740 cm^{-1} confirms the contribution of gelatin and PVA. Comparisons of 8:2 bioplastics with and without 0.2 g filler reveal intensity shifts, especially in O–H and N–H regions,

indicating hydrogen bonding between fillers and the matrix without new chemical bond formation.

Scanning Electron Microscopy Analysis

SEM observations at 10,000× magnification reveal the microstructure and homogeneity of bioplastics. The 8:2 starch – PVA:gelatin formulation without filler (Figure 10) shows undissolved starch granules due to incomplete mixing. In contrast, the addition of 0.2 g filler (Figure 11) results in a rougher surface with increased contact area, improving inter-component interactions (Gobeze et al., 2020).

Despite this, unincorporated glycerol and voids are still visible, although some cavities are filled by nanofibers. This emphasizes the need to optimize mixing parameters for higher-quality bioplastics (Futscher et al., 2017).

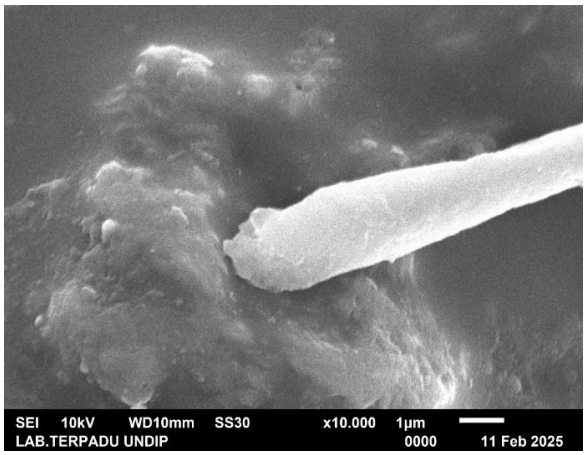


Figure 10. Starch-PVA Bioplastic Surface Morphology: gelatin (8:2) without Filler Addition at 10,000x Magnification

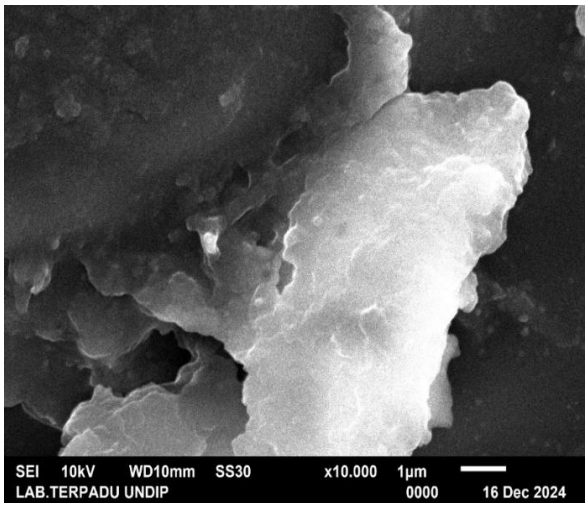


Figure 11. Starch-PVA Bioplastic Surface Morphology: gelatin (8:2) with 0.2 Filler at 10,000× Magnification

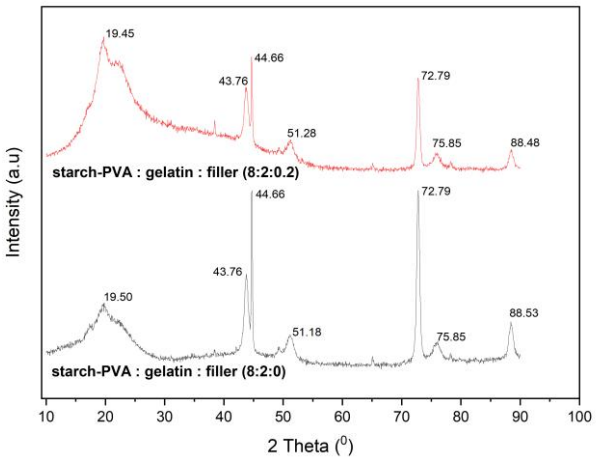


Figure 12. Diffractograms of bioplastic with and without filler addition

Table 5. Crystallinity of Bioplastics and LDPE Plastics

Filler (% weight)	Crystallinity (%)
0	32.6
0.2	28.2
LDPE	45 – 55

X-Ray Diffraction Analysis

XRD analysis evaluates the crystallinity of bioplastics relative to LDPE (Figure 12 and Table 5). Bioplastics without fillers exhibit 32.6% crystallinity, which decreases to 28.2% with the incorporation of 0.2 g filler. Both values are below the LDPE standard range (45–55%), indicating a mixed crystalline – amorphous structure (Erlanger et al., 1961). The low crystallinity is attributed to the dominance of amylopectin (branched chains) in sorghum starch, which hinders crystalline region formation and affects mechanical and physical properties. Nevertheless, the observed crystallinity remains suitable for practical applications of bioplastics with adequate performance (Cummings et al., 2013; Ding et al., 2014).

CONCLUSION

This study demonstrates that sorghum starch – PVA bioplastics reinforced with sorghum stem cellulose nanofibers exhibit improved mechanical, physical, and structural characteristics compared with bioplastics derived from starch-only. Variation in the blend ratio significantly influence bioplastic characteristics. The 8:2 starch – PVA:gelatin formulation without filler yields the highest tensile strength (17.06 MPa), indicating that gelatin enhances intermolecular hydrogen bonding, and thus strengthens the polymer matrix. In contrast, the addition of cellulose nanofibers up to 0.2 g increases Young's modulus and decreases water absorption, reflecting greater stiffness, improved polymer

packing, and a reduction in free hydroxyl groups, as supported by density and water absorption measurements.

FTIR spectra confirm strong intermolecular interactions among starch, PVA, gelatin, glycerol, and cellulose nanofibers, without evidence of new chemical bond formation. SEM micrographs show that the incorporation of nanofibers improves surface morphology, although localized agglomeration persists and corresponds to the reduced tensile strength observed at higher filler concentrations. XRD analysis indicates a semi-crystalline structure with crystallinity values of 28.2 – 32.6%, consistent with the high amylopectin content of sorghum starch and explaining the moderate mechanical properties relative to LDPE standards.

Overall, the incorporation of cellulose nanofibers from sorghum stalks enhances rigidity and moisture resistance, while gelatin contributes to increased tensile strength and flexibility. Although the bioplastics have not fully equalized the characteristics of LDPE, the results position sorghum-based bioplastics as a viable and sustainable alternative. Further improvements in filler dispersion and blend homogeneity are recommended to achieve higher performance in future developments.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Yuli Darni: Writing - review & editing, Writing-original draft, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Nabilla Puspita Asri**: Visualization, Investigation. **Lia Lismeri**: Conceptualization, Investigation, Formal analysis. **Simparmin Br Ginting**: Conceptualization, Formal analysis. **Aris Setiawan**: Writing-review & editing, Visualization, Investigation. **Arfiana**: Methodology, Formal analysis.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. No funding related this study.

ACKNOWLEDGEMENTS

We would like to express our gratitude to the National Research and Innovation Agency (BRIN) for providing analysis facilities and to the Faculty of Engineering, Universitas Lampung for funding through the DIPA FT Unila scheme.

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