Sustainable and Eco-Friendly Textile Packaging Biomaterials: The Role of Bio-Based Biodegradable Films, Development and Characterizations

BY

Asmare Tezera Admase[1*], Ejigayehu Desalegn Asrade[1]
Faculty of Chemical and Food Engineering, Bahir Dar Institute of Technology-Bahir Dar University,
Bahir Dar, P.O.Box 26, Ethiopia
* Corresponding author: asmaretezera@gmail.com

ABSTRACT

This study provides an in-depth analysis and development of sustainable, eco-friendly textile packaging materials, particularly focusing on bio-based biodegradable films. The study examines the physicochemical properties of bioplastics created with different concentrations of fillers and plasticizers. The optimal moisture uptake was found to be 30.95% ± 0.11 for films containing 9% filler and 15% plasticizer, highlighting the significant impact of glycerol's hygroscopic characteristics. The maximum solubility reached 72.53% ± 0.04 at the same concentrations, while lower solubility values indicated possible degradation at higher plasticizer levels. Tensile strength tests showed notable differences between wet and dry states, with a maximum dry tensile strength of 63.41 ± 0.15 MPa, underscoring the critical role of moisture in mechanical properties. Biodegradability peaked at 22.5% filler and 15% plasticizer, achieving a value of 50.34% ± 0.05, which emphasizes the importance of molecular interactions in improving material performance. Fourier-transform infrared (FTIR) analysis confirmed the presence of functional groups that contribute to structural integrity, while thermogravimetric analysis (TGA) indicated enhanced thermal stability in reinforced samples. Differential scanning calorimetry (DSC) revealed significant thermal transitions. These findings underscore the potential of bio-based biodegradable films as sustainable alternatives for textile packaging, effectively addressing environmental challenges while meeting the functional demands of modern packaging solutions.

KEYWORDS: Packaging, Biofilm, Eco-friendly, Biodegradability, Sustainable

INTRODUCTION

Plastics present serious environmental issues due to their inability to decompose, the substantial energy required for their production, and their role in pollution, which negatively impacts ecosystems and human health through contaminated food and water sources. Additionally, the manufacturing process of plastics generates a considerable carbon footprint (Shafqat *et al.*, 2021) (Emekwisia, 2023). Plastics are not easily degraded by natural processes, leading to environmental issues. This has sparked significant interest in developing biodegradable plastics to address plastic waste concerns (Ezeoha and Ezenwanne, 2013). Plastics are prevalent due to their low cost and durability, with approximately 8.3 billion metric tons produced, resulting in 6.3 billion metric tons of waste only 9% of which is recycled. By 2050, it's estimated that 12 billion metric tons of plastic waste will accumulate in landfills or the environment, potentially surpassing fish in the oceans (Wita and Vliegenthartb, 1996; Zoungranan *et al.*, 2020; Yang *et al.*, 2021). Bioplastics are gaining traction as sustainable alternatives to fossil-based plastics within the Circular Economy and Bioeconomy, being partially or fully made from renewable resources and often biodegradable. Currently representing less than one percent of global plastic production, bioplastics are projected to grow from about 2.4 million tonnes in 2021 to 7.5 million tonnes by 2026. Countries like Brazil, India, China, and Japan are leading in demand, particularly after China's plastic bag ban, which is expected to boost production of PLA, PBAT, and PBS. While the EU has initiated a ban on single-use plastics, including bioplastics, discussions are ongoing. With market growth, effective management of bioplastic waste will become increasingly important (Grossule *et al.*, 2023).

Packaging materials have become increasingly significant, with over 67 million tons of packaging waste raising environmental concerns. These challenges have prompted researchers to explore bio-based bioplastics as alternatives to petroleum-based polymers for packaging (Science, no date d; Gadhave *et al.*, 2018) (Soubam, 2022). Starch-based bioplastics are crucial in addressing the challenges of plastic pollution and reliance on fossil fuels, as they are made from renewable resources, thereby promoting sustainability. Starch based bioplastics are biodegradable, offering a viable solution to reduce waste accumulation (Science, no date b; Hanif *et al.*, 2019; Abe and Branciforti, 2021). Their production can utilize agricultural by-products, aligning with the principles of a Circular Economy and Bioeconomy. As the market for bioplastics expands, particularly in regions with high demand, the adoption of starch-based alternatives can significantly contribute to reducing greenhouse gas emissions and enhancing environmental health (Ashok *et al.*, 2018; Bioplastic and Ngoh, 2022; Marta *et al.*, 2022).

Even though Starch-based biodegradable plastics are ecofriendly, they face several challenges, including rigidity, brittleness, and high hygroscopicity, which lead to poor physical and mechanical properties (Isotton *et al.*, 2015) (Xie *et al.*, 2023). Starch-based bioplastics have low moisture barrier capabilities. Incorporating fillers into the matrix can enhance mechanical properties, reduce permeability, reducing cost of the formulation (Anaç, 2023) (Abotbina *et al.*, 2021). Studies show that fillers significantly improve mechanical strength, resistance to water vapor and gases, and dimensional stability compared to those without fillers (Montero *et al.*, 2017) (Vineeth, Gadhave and Gadekar, 2019). Filler also lead to lowering the absorption of moisture, and other factors based on the specifications for particular applications. (Wong *et al.*, 2020; Yang *et al.*, 2020; Manzoor *et al.*, 2023).

In this study, clay was used as a filler, and plasticizer served as a plasticizer. Incorporating fillers into starch enhances the physical, thermal, and mechanical properties of the bioplastic. Clay fillers are not only cost-effective but also improve mechanical strength, providing essential reinforcement to the starch matrix (Harunsyah, Sariadi and Raudah, 2018). While the incorporation of plasticizer used to make the material more flexible. Plasticizers are another type of common additives used to modify films or polymers, enhancing their flexibility and processability by lowering the glass transition temperature (Alhanish and Abu Ghalia, 2021)(Kasmuri, Safwan and Zait, 2018). The barrier and mechanical properties of biopolymer films depend greatly on their materials and compositions. While starch films are highly elastic, they can be too brittle for effective packaging. Plasticizers are crucial for reducing this brittleness, enhancing flexibility, and improving the workability of the polymers. (Jha, 2020)(Science, no date c). A common method to improve the mechanical properties of these films is to add plasticizers, which reduce chain-to-chain interactions, enhancing flexibility and stretchability. However, the addition of plasticizers beyond optimal limit may also increase film permeability (Mohammadi Nafchi, Cheng and Karim, 2011)(Shanmathy, Mohanta and Thirugnanam, 2021; Yang *et al.*, 2023). Plasticizers enhance the mechanical properties and processability of polymers, with selection based on compatibility, retention, and required amounts. However, common hydrophilic plasticizers like sorbitol, plasticizer, and polyethylene glycol can increase water permeability, making the matrix more susceptible to moisture (Paixão *et al.*, 2019). The aim of this research work is to develop long sustainable bio-based bioplastic with improved properties.

Methodology

Materials

The root is locally sourced, while the filler and clay were obtained from Bahir Dar and Addis Zemen, Ethiopia, respectively. The primary chemicals used during the experiment included plasticizer as a plasticizer, sodium meta-bisulfite ($Na_2S_2O_5$) as an antioxidant, as well as sodium hydroxide, methanol, ethanol, iodine solution, potassium iodide (KI), acetic acid, hydrochloric acid, sulfuric acid, and sodium chloride. All chemicals were of analytical reagent grade, and distilled water was utilized for all analyses.

2.2 . Raw Starch Extraction

The cassava root was thoroughly washed, peeled, and shredded into small pieces before being sun-dried for a week. The dried sample was then crushed to a mesh size of 0.125 µm. Meanwhile, the fine powdered was soaked in distilled water for four days. After this period, each starch slurry was filtered and allowed to settle for 30 minutes. The sediment was separated from the slurry using nylon cloth and washed with distilled water to obtain pure starch. Finally, the starch was dried in an oven (oven/incubator-PH-030A) at 100 °C for 24 hours (Admase, Mersha and Kebede, 2024).

Preparation of filler

The preparation of chemicals and fillers followed a modified procedure. After drying, the fillers were ground in a blender and sieved through a 63 mm mesh for uniformity. Six grams of raw clay were mixed with 50 mL of distilled water and stirred for 12 hours at room temperature. This mixture was then added to 500 mL of sodium hydroxide solution and shaken for 30 hours at 90 °C. The resulting precipitate was washed with 100 mL of 30% ethanol. Finally, the clay was dried at 100 °C for 12 hours and sieved through a 0.125 µm mesh (Admase, Sendekie and Alene, 2022).

Experimental Design

The research was constructed using design expert software with a randomized blocks design with a factorial experiment. The first factor was filler to starch ratio of 4.5:5%, 9:5% and 13.5:5% w/w. The second factor was plasticizer to starch ratio with concentration varied from 7.5:5%, 15:5 % and 22.5:5 % v/w.

Bioplastic Preparation

As depicted in **Figure 1:** Five grams of starch was mixed with 50 mL of distilled water and heated in a water bath at temperatures of 55, 65, 75, and 85ºC, with a heating rate of 10ºC/min. After gelatinization, the solution was cooled to 50ºC at 15ºC/min, held for one minute, and viscosity was measured using a viscometer at 95 rpm. (Nilani *et al.*, 2010). This process results in a gelatinized starch solution and the solution is mixed with filler (4.5%, 9%, and 13.5% w/w) and plasticizer (7.5, 15% and 22.5 % w/v) based on the experimental design. After casting the solution and oven drying for 6hrs at 33ºC, the plates (petri-dishes) were taken out from the oven and bioplastic s were peeled off (Harunsyah, Sariadi and Raudah, 2018) (Behera, Mohanta and Thirugnanam, 2022).

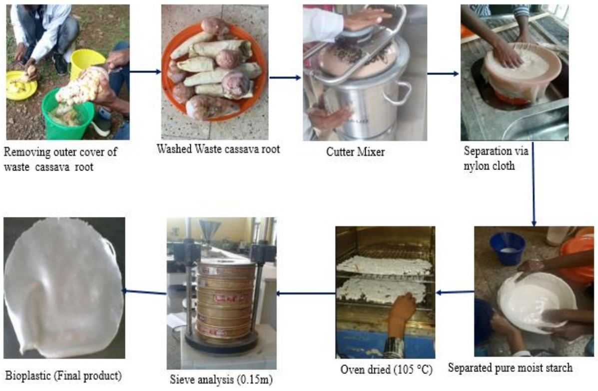

Figure 1: Preparation of Bio-based bioplastic

Characterizations of Bioplastic

Tensile Strength (wet and dry state)

The tensile strength of the bioplastic was measured in accordance with ASTM D-882-9 using a universal testing machine (UTM-1422).

Biodegradablity

The biodegradability of the developed bioplastic was evaluated using the ASTM D5988-03a method through a soil burial technique over a period of fourteen days, maintained at a temperature of 28°C and a relative humidity of 30%. Mass loss was quantified by weighing the bioplastic samples prior to and following burial, with the weight variation (degree of degradability, %W) calculated from these measurements (Mooney, 2009) (Vasile *et al.*, 2018).

FTIR Analysis

The surface functional groups, chemical bonds, and chemical characteristics of the biodegradable bioplastics derived from cassava root were analyzed using an FTIR spectrophotometer (Jasco-FT/IR-6600A). Shredded and finely ground bioplastic samples were mixed with spectral grade KBr in a 1:100 ratio and pressed into pellets using a mechanical press. The spectra were recorded in terms of percent transmittance over the range of 4000–400 cm^{-1} with a resolution of 0.4 cm^{-1}.

Thermal Analysis

The thermal stability of the bioplastic was assessed using thermogravimetric analysis (TGA) (Exstar 6000-TG/DTA6100) under a nitrogen atmosphere with a flow rate of 50 mL/min. The temperature was gradually increased from 20°C to

200°C at a heating rate of 10°C/min. The thermal properties of both reinforced and non-reinforced bioplastics were examined.

DSc analysis

Differential Scanning Calorimetry (DSC) analysis was performed using a DSC Q200 apparatus from TA Instruments (New Castle, DE, USA). The biofilms were subjected to heating from 30°C to 220°C at a rate of 20°C/min, all conducted under an inert nitrogen atmosphere with a flow rate of 25 mL/min.

Results and Discussion

Tensile Strength

The tensile strength of bioplastic as shown in **Figure 2,** in both wet and dry states demonstrates significant variations based on the composition. In the wet state, the tensile strength values are consistently low, with measurements of 3.68 ± 0.05, 35.74 ± 0.12, and 23.37 ± 0.08 across different formulations (as depicted in **Figure 2 (a)**). These low values indicate that the bioplastics are less resilient when exposed to moisture. This significant disparity between wet and dry states highlights the importance of moisture content in influencing the mechanical properties of bioplastic films, suggesting that formulations should be optimized for desired performance in specific environmental conditions (Alamsyah and Pribadi, no date; Souza *et al.*, 2012; Lee Jie Shin *et al.*, 2020). As shown in **Figure 2 (b)**, the maximum tensile strength of the bioplastic in dry state was found to be 63.41 ±0.15Mpa at plasticizer concentration of 15% and filler content of 9% while in wet state 35.74±0.12Mpa. In contrast, the dry state exhibits much higher tensile strengths, with values of 27.70 ± 0.10, 63.41 ± 0.15, and 36.98 ± 0.20, reflecting improved structural integrity and resistance when moisture is absent. Plasticizer's poly-hydroxyl groups form hydrogen bonds with starch, replacing starch-starch interactions in bioplastics; however, exceeding 15% plasticizer reduces tensile strength (63.41 ±0.1536.98 ±0.20) by disrupting internal hydrogen bonds and weakening filler-matrix interactions (Lutfi *et al.*, 2017; Triawan *et al.*, 2020; Abotbina *et al.*, 2021). On the other hand, increasing filler content beyond 9% causes a decrease in tensile strength because of the agglomeration of the particles reducing the binding capacity.

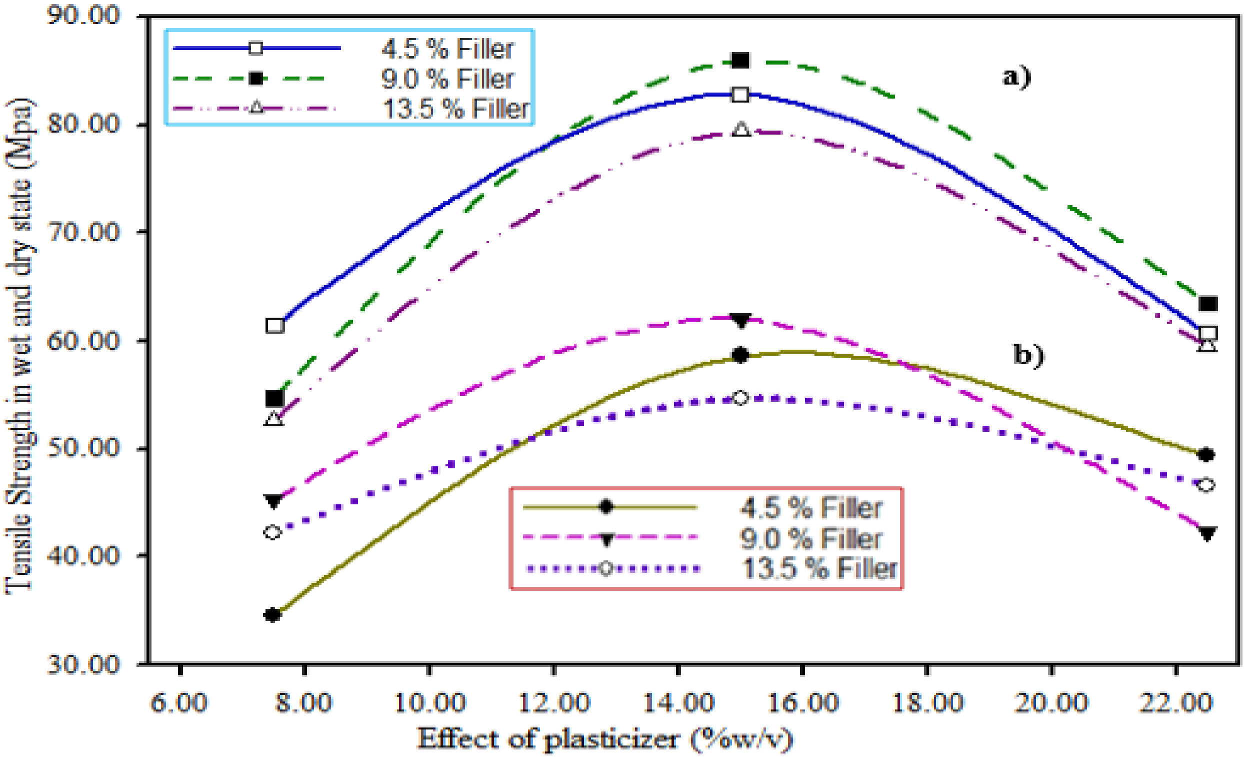

Figure 2: Effect of plasticizer and Filler on the bioplastic Tensile strength ((dry state (a) and wet state, (b))

Biodegradability Test

As shown in **Figure 3,** the optimum biodegradability was achieved at a filler content of 22.5% and a plasticizer concentration of 15%, yielding a value of 50.34 ± 0.05. At this level, the material exhibits a significant improvement in biodegradability compared to lower filler concentrations, such as 16.84 ± 0.01 at 9% filler with 7.5% plasticizer and 22.11 ± 0.01 at 4.5% filler with 7.5% plasticizer. The optimal combination allows for enhanced molecular interactions, improving hydrogen bonding between starch and plasticizer, which is crucial for structural integrity (Jadhav *et al.*, 2009; Jiang *et al.*, 2019; Mora-Sánchez *et al.*, 2023). Values like 59.22 ± 0.08 at 22.5% filler and 15% plasticizer indicate strong performance, but as filler content increases beyond this point, such as in the 22.5% filler and 22.5% plasticizer combination, biodegradability can decline to 47.08 ± 0.10. Furthermore, excessive plasticizer content, as seen with 34.55 ± 0.01 at 7.5% filler and 15% plasticizer, can disrupt intermolecular forces, weakening the matrix and adversely affecting mechanical properties (Manshor *et al.*, 2018; Manzoor *et al.*, 2023; Homavand, Cree and Wilson, 2024). The optimum value of degradability for the reinforced bioplastic at 9% clay and 15% plasticizer was found to be 36.83 ± 0.07.

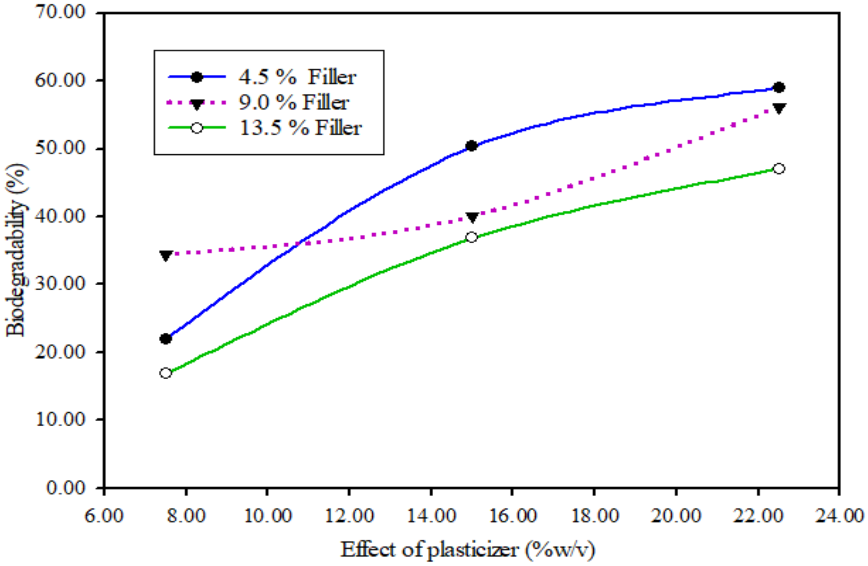

Figure 3: Effect of plasticizer and Filler on the biodegradability

FTIR Analysis

As shown in **Figure 4a (**Sample with filler - shown in blue line**)**, The FTIR spectrum for the sample with filler reveals distinct peaks that indicate the presence of various functional groups interacting with the starch matrix. Notably, a broad peak around 3400 cm^{-1} indicates O-H and N-H stretching vibrations, suggesting significant moisture absorption capabilities with a transmittance of approximately 60%. Additionally, a peak near 1730 cm^{-1} represents C=O stretching from carbonyl groups, which could enhance the films mechanical properties and biodegradability, with a transmittance of 45% (Shayan *et al.*, 2019; Hirphaye, 2022; Romainor, Chin and Lihan, 2022; Sanghvi, Tambare and More, 2022). Peaks in the 1000-1200 cm^{-1} range associated with C-O stretching show transmittance values around 70%, indicating a stable polymer backbone. These interactions suggest that the incorporation of fillers improves the structural integrity and thermal stability of the bioplastic, making it more suitable for various applications (Admase, Sendekie and Alene, 2022; Admase, Fanta and Mersha, 2024; Admase, Mersha and Kebede, 2024).

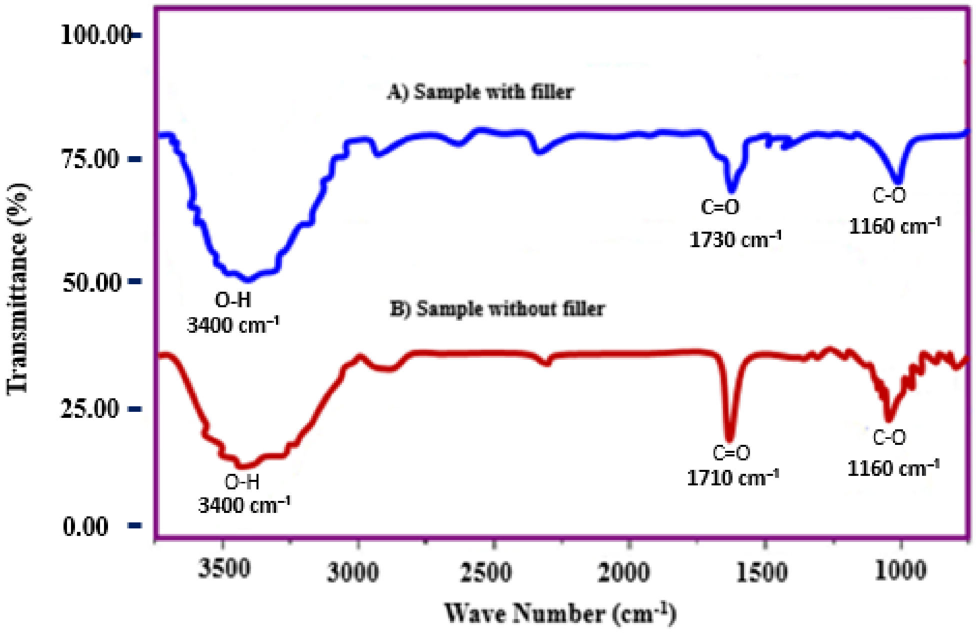

Figure 4: FTIR analysis of Bioplastic for control (B, sample without filler), and Reinforced (Sample with Filler)

Thermogravimetric Analysis (TGA)

As the picture depicted in **Figure 5,** TGA analysis primarily determines the thermal stability of the bioplastics. As shown in Figure 10, the thermal decomposition of the control bioplastic (0% filler) occurred in four main steps. The initial stage of thermal degradation began at temperatures below 50°C, with a mass loss of approximately 8%, attributed to the evaporation or dehydration of loosely bound water and low molecular weight compounds (Ma *et al.*, 2010)(Kasmuri, Safwan and Zait, 2018; Marichelvam *et al.*, 2022; Yang *et al.*, 2023). The control bioplastic exhibited higher mass loss compared to the reinforced bioplastic at temperatures below 100°C, indicating greater moisture content (Khazaei *et al.*, 2014). . In the second stage, an apparent weight loss of about 37% was observed within the temperature range of 40-81°C. This decrease in transition and melting temperatures can be linked to the presence of plasticizer. The third stage, characterized by a rubbery state, showed minimal mass loss (around 5%) between 81-102°C, suggesting enhanced chain entanglement and flexibility (Yang *et al.*, 2023; Vinay, Modi and Prakasha, 2024). The glass transition temperature (Tg) for the control bioplastic (indicated in blue) ranged from 40-81°C, while the Tg for the reinforced bioplastic (shown in red) ranged from 45-140°C. This indicates that the reinforced bioplastic has higher temperature resistance, with melting occurring around 158°C (Khazaei *et al.*, 2014; Sanyang, 2015; Shayan *et al.*, 2019)

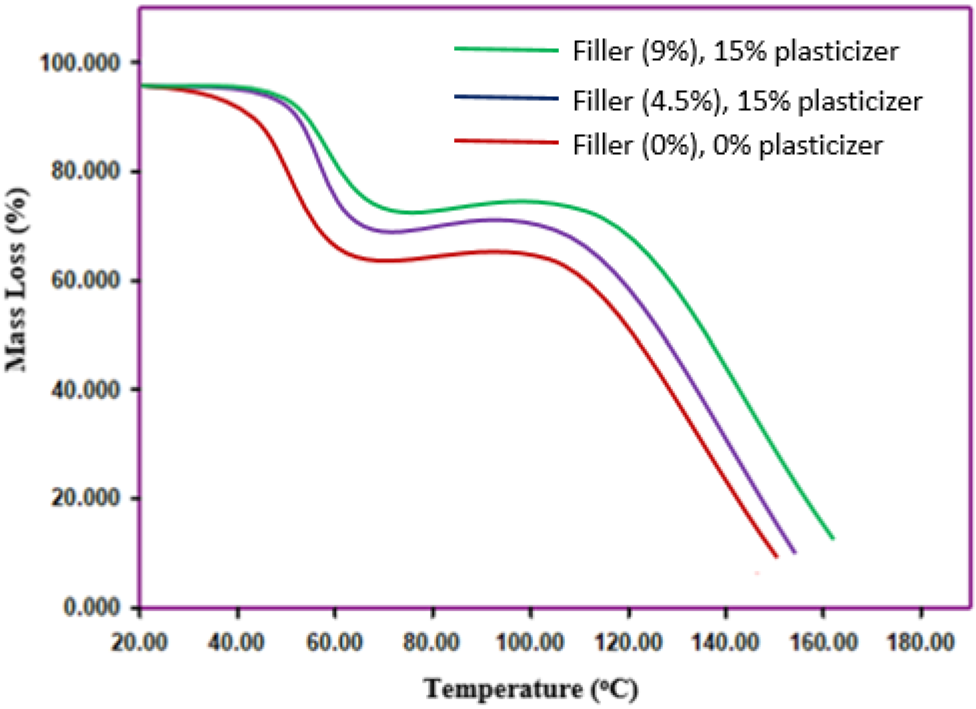

Figure 5: TGA analysis of Bioplastic for control

Differential Scanning Calorimetry (DSC) analysis

As the graph shows in **Figure 6,** the graph illustrates heat loss percentage as a function of temperature, ranging from 60°C to 200°C. At 60°C, the heat loss was approximately 96.5%, indicating stability. As the temperature rose to around 98°C, the red curve peaked at 100.5%, suggesting an endothermic process (Agustin *et al.*, 2014; Hamin *et al.*, 2022; Sharif, Mohanta and Thirugnanam, 2023). Following this peak, the heat loss decreased back to about 96.5% at 100°C.

A second peak occurred at 140°C, reaching around 101%, indicating another phase change. In contrast, the blue curve showed a dip at 120°C, with heat loss dropping to approximately 92%, suggesting an exothermic reaction (Ferreira *et al.*, 2018; Fiandini *et al.*, 2020; Yang *et al.*, 2021). Further dips were observed near 180°C, where heat loss decreased to around 91%. By 200°C, the heat loss stabilized around 98%, demonstrating significant thermal variations and phase transitions in the material throughout the temperature range (Ginting and Hasibuan, no date).

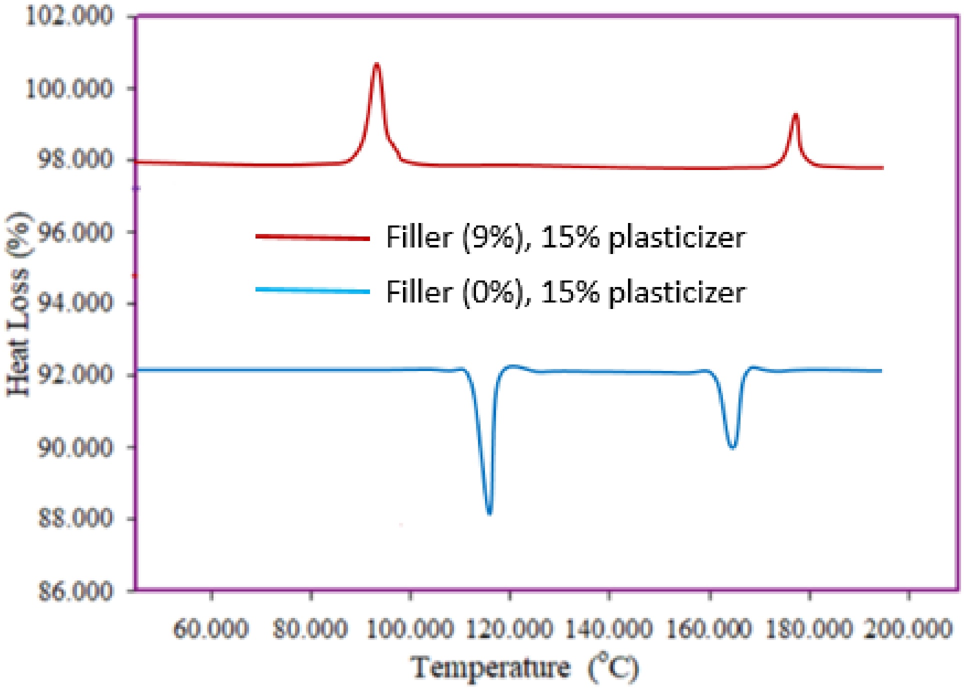

Figure 6: DSc analysis of Bioplastic for control and filler Reinforced

Scanning electron microscope (SEM) analysis

As shown in **Figure 7,** the image highlighted the differences in structural characteristics between the control and reinforced bioplastics and provide insights into the surface morphology of the bioplastics with varying filler and plasticizer content. The control sample (0% filler) exhibits a rough surface with irregular structures and noticeable voids, indicating a less homogeneous distribution of components which may lead to lower mechanical properties and stability. (Chemistry, 2021; Noorjahan, Banu and Subhashree, 2022; Sirbu *et al.*, 2024). In contrast, the reinforced bioplastic with 13.5% filler and 7.5% plasticizer displays a more uniform texture with smaller, well-dispersed particles, suggesting enhanced interfacial bonding. As shown in **Figure 7 (a),** the morphology shows a rough surface with poorly soluble insoluble starch. The differences between the two images highlight that the absence of fillers results in increased fragility and a less cohesive surface. The ultrasonic method used for the filler prevents agglomeration, ensuring a homogeneous dispersion and enhancing starch miscibility. The SEM analysis provided insights into the microstructure of the bioplastics, with images labeled as (a) for the control sample and (b) for the reinforced sample, both taken at a magnification of 3,490x. In contrast, Figure 7 (b**)** depicts bioplastics with fillers and plasticizers, revealing a smoother surface and uniform dispersion of the filler within the starch matrix (Ginting and Hasibuan, no date; Amin and Chowdhury, 2019). The control sample exhibited a relatively smooth surface with minimal texture, indicating a homogeneous structure. In contrast, the reinforced sample displayed a more complex morphology (Bioplastic *et al.*, 2014; Kasmuri, Safwan and Zait, 2018; Wicaksono *et al.*, 2022), which characterized by distinct surface roughness and the presence of particulate matter. These features suggested that the reinforcement led to enhanced interfacial interactions and potentially improved mechanical properties. The bioplastic with 15% plasticizer shows further improvement in smoothness and compatibility, while the sample with 22% plasticizer may exhibit a more flexible surface due to increased plasticization; however, it could also lead to reduced structural integrity (Student *et al.*, 2021; Mohamed Abdoul-Latif *et al.*, 2022; Jakubowska *et al.*, 2023).

Conclusion

This research marks a notable progress in the creation of sustainable bio-based plastics, establishing them as promising alternatives for intelligent packaging solutions. Through a thorough examination of different proportions of plasticizers and fillers, we discovered an ideal formulation consisting of 9% filler and 15% plasticizer, which significantly improved both mechanical and physical properties. The achieved maximum tensile strength of 63.41 MPa in a dry state, along with enhanced transparency and color, demonstrates the capability of these bioplastics to satisfy the stringent requirements of contemporary packaging. Furthermore, our findings indicate that increasing the filler content can boost optical characteristics while serving as a barrier against light-induced oxidation, thereby extending the shelf life of the packaged goods. However, challenges related to cost and scalability need to be addressed to facilitate broader implementation. This study not only underscores the potential of bio-based plastics in promoting sustainability but also stresses the importance of continuous innovation and collaboration among material scientists and industry partners. By refining material compositions and investigating new formulations, we can advance towards a new generation of eco-friendly packaging solutions that align with global sustainability objectives. This research lays the groundwork for future studies, inspiring the pursuit of advanced bioplastic materials that balance functionality with environmental stewardship.

Acknowledgement

The authors thank the Faculty of Chemical and Food Engineering, Bahir Dar Institute of Technology, Bahir Dar University, Ethiopia allowing them to use the laboratory materials, chemicals, and instruments.

References

Abe, M.M. and Branciforti, M.C. (2021) ‘Biodegradation of Hemicellulose-Cellulose-Starch-Based Bioplastics and Microbial Polyesters’.

Abotbina, W. *et al.* (2021) ‘Development and Characterization of Cornstarch-Based Bioplastics Packaging Film Using a Combination of Different Plasticizers’, pp. 1–18.

Admase, A.T., Fanta, S.W. and Mersha, D.A. (2024) ‘Development and characterization of sustainable biodegradable wood adhesive using starch as the main ingredient Development and characterization of sustainable biodegradable wood adhesive using starch as the main ingredient’, *Journal of the Indian Academy of Wood Science* [Preprint], (August). Available at: https://doi.org/10.1007/s13196-024-00352-3.

Admase, A.T., Mersha, D.A. and Kebede, A.Y. (2024) ‘Cassava starch-based hot melt adhesive for textile industries’, *Scientific Reports*, 14(1), pp. 1–11. Available at: https://doi.org/10.1038/s41598-024-70268-y.

Admase, A.T., Sendekie, Z.B. and Alene, A.N. (2022) ‘Biodegradable Film from Mango Seed Kernel Starch Using Pottery Clay as Filler’, *Journal of Polymers and the Environment*, 30(8), pp. 3431–3446. Available at: https://doi.org/10.1007/s10924-022-02449-7.

Agustin, M. *et al.* (2014) ‘Journal of Reinforced’, (December). Available at: https://doi.org/10.1177/0731684414558325.

Ahmed, T. *et al.* (2018) ‘Biodegradation of plastics : current scenario and future prospects for environmental safety’, pp. 7287–7298.

Alamsyah, D.N. and Pribadi, A.S. (no date) ‘Tensile Strength and Elongation Testing for Starch-Based Bioplastics using Melt Intercalation Method : A Review Tensile Strength and Elongation Testing for Starch-Based Bioplastics using Melt Intercalation Method : A Review’. Available at: https://doi.org/10.1088/1742-6596/1858/1/012028.

Alhanish, A. and Abu Ghalia, M. (2021) ‘Developments of biobased plasticizers for compostable polymers in the green packaging applications: A review’, *Biotechnology Progress*, 37(6), pp. 1–17. Available at: https://doi.org/10.1002/btpr.3210.

Amin, R. and Chowdhury, M.A. (2019) ‘Heliyon Characterization and performance analysis of composite bioplastics synthesized using titanium dioxide nanoparticles with corn starch’, 5(June). Available at: https://doi.org/10.1016/j.heliyon.2019.e02009.

Anaç, N. (2023) 'The Effect of Organic Fillers on the Mechanical Strength of the Joint in the Adhesive Bonding', *MDPI Switzerland* [Preprint].

Ashok, A. *et al.* (2018) 'US CR'. Available at: https://doi.org/10.1142/S0219581X18500370.

Behera, L., Mohanta, M. and Thirugnanam, A. (2022) 'Environmental Technology & Innovation Intensification of yam-starch based biodegradable bioplastic film with bentonite for food packaging application', *Environmental Technology & Innovation*, 25(206), p. 102180. Available at: https://doi.org/10.1016/j.eti.2021.102180.

Bioplastic, E.C.S. *et al.* (2014) 'Effect of Plasticizer on Mechanical and Moisture Absorption Properties of', 13(2).

Bioplastic, S.S. and Ngoh, G.C. (2022) 'A Comprehensive Review on the Emerging Roles of Nanofillers Fabrication'.

Bootklad, M. and Kaewtatip, K. (2013) 'Biodegradation of thermoplastic starch/eggshell powder composites', *Carbohydrate Polymers*, 97(2), pp. 315–320. Available at: https://doi.org/10.1016/j.carbpol.2013.05.030.

Chemistry, C. (2021) 'STARCH BASED BIODEGRADABLE BIOPLASTIC USING VARIOUS', 55, pp. 867–881.

Emekwisia, C.C. (2023) 'Treatment Time Influence of Alkali Upon i t ' s Characteristics for the Palm Oil Plant Fiber Composites', (November). Available at: https://doi.org/10.1007/978-981-99-5567-1.

Ezeoha, S.L. and Ezenwanne, J.N. (2013) 'Production of Biodegradable Plastic Packaging Film from Cassava Starch', 3(10), pp. 14–20.

Ferreira, R. *et al.* (2018) 'Characterization of starch-based bioplastics from jackfruit seed plasticized with glycerol', 55(January), pp. 278–286. Available at: https://doi.org/10.1007/s13197-017-2936-6.

Fiandini, M. *et al.* (2020) 'MECHANICAL AND BIODEGRADATION PROPERTIES OF CORNSTARCH-BASED BIOPLASTIC MATERIAL', 44, pp. 380–391.

Frangopoulos, T. *et al.* (2023) 'Biodegradable Films'.

Gadhave, R. V *et al.* (2018) 'Starch Based Bio-Plastics : The Future of Sustainable Packaging', pp. 21–33. Available at: https://doi.org/10.4236/ojpchem.2018.82003.

Ginting, M.H.S. and Hasibuan, R. (no date) 'Mechanical , SEM and FTIR characteristics of bioplastics from mango seed starch with nanoparticle zinc oxide as filler and ethylene glycol as plasticizers Mechanical , SEM and FTIR characteristics of bioplastics from mango seed starch with nanoparticle zinc oxide as filler and ethylene glycol as plasticizers'. Available at: https://doi.org/10.1088/1757-899X/1003/1/012122.

Grossule, V. *et al.* (2023) 'Treatment of food waste contaminated by bioplastics using BSF larvae : Impact and fate of starch-based bioplastic films', *Journal of Environmental Management*, 330(October 2022), p. 117229. Available at: https://doi.org/10.1016/j.jenvman.2023.117229.

Hamin, S.H. *et al.* (2022) 'Effect of chemical treatment on the structural , thermal , and mechanical properties of sugarcane bagasse as fi ller for starch-based bioplastic', 2022(September). Available at: https://doi.org/10.1002/jctb.7218.

Hanif, A. *et al.* (2019) 'Effects of starch-glycerol concentration ratio on mechanical and thermal properties of cassava starch-based bioplastics', 20(4), pp. 3–8.

Harunsyah, Sariadi and Raudah (2018) 'The effect of clay nanoparticles as reinforcement on mechanical properties of bioplastic base on cassava starch', *Journal of Physics: Conference Series*, 953(1). Available at: https://doi.org/10.1088/1742-6596/953/1/012021.

Hirphaye, B.Y. (2022) 'Bio-ethanol production potential of Water Hyacinth (Eichhornia crassipes) as alternative energy feedstocks', pp. 1–17.

Homavand, A., Cree, D.E. and Wilson, L.D. (2024) 'Polylactic Acid Composites Reinforced with Eggshell/CaCO3 Filler Particles: A Review', *Waste*, 2(2), pp. 169–185. Available at: https://doi.org/10.3390/waste2020010.

Indrianingsih, A.W. and Rosyida, V.T. (2018)

‘Characteristics of water solubility and color on edible film from bioselulosa nata nira siwalan with the additional of glycerol films color measurement using colory metry Characteristics of water solubility and color on edible film from bioselulosa nata n’.

Isotton, F.S. *et al.* (2015) ‘The plasticizer effect on preparation and properties of etherified corn starchs films’, *Industrial Crops and Products*, 76, pp. 717–724. Available at: https://doi.org/10.1016/j.indcrop.2015.04.005.

Jadhav, N.R. *et al.* (2009) ‘Glass transition temperature: Basics and application in pharmaceutical sector’, *Asian Journal of Pharmaceutics*, 3(2), pp. 82–89. Available at: https://doi.org/10.4103/0973-8398.55043.

Jafarzadeh, S. *et al.* (2016) ‘Preparation and characterization of bionanocomposite films reinforced with nano kaolin’, *Journal of Food Science and Technology*, 53(2), pp. 1111–1119. Available at: https://doi.org/10.1007/s13197-015-2017-7.

Jakubowska, E. *et al.* (2023) ‘Development and characterization of active packaging films based on chitosan, plasticizer, and quercetin for repassed oil storage’, *Food Chemistry*, 399(August). Available at: https://doi.org/10.1016/j.foodchem.2022.133934.

Jha, P. (2020) ‘Effect of plasticizer and antimicrobial agents on functional properties of bionanocomposite films based on corn starch-chitosan for food packaging applications’, *International Journal of Biological Macromolecules*, 160, pp. 571–582. Available at: https://doi.org/10.1016/j.ijbiomac.2020.05.242.

Jiang, T. *et al.* (2019) ‘Starch-based Biodegradable Materials : Challenges and Opportunities Advanced Industrial and Engineering Polymer Research Starch-based biodegradable materials : Challenges and opportunities’, *Advanced Industrial and Engineering Polymer Research* [Preprint], (November). Available at: https://doi.org/10.1016/j.aiepr.2019.11.003.

Kasmuri, N., Safwan, M. and Zait, A. (2018) ‘Enhancement of Bio-plastic using Eggshells and Chitosan on Potato Starch Enhancement of Bio-plastic using Eggshells and Chitosan on Potato Starch Based’, (August). Available at: https://doi.org/10.14419/ijet.v7i3.32.18408.

Khazaei, N. *et al.* (2014) ‘Characterization of new biodegradable edible film made from basil seed (Ocimum basilicum L .) gum’, *Carbohydrate Polymers*, 102, pp. 199–206. Available at: https://doi.org/10.1016/j.carbpol.2013.10.062.

Kusumayanti, H., Handayani, N.A. and Santosa, H. (2015) ‘Swelling power and water solubility of cassava and sweet potatoes flour’, *Procedia Environmental Sciences*, 23(Ictcred 2014), pp. 164–167. Available at: https://doi.org/10.1016/j.proenv.2015.01.025.

Lee Jie Shin *et al.* (2020) ‘Tensile and Compressive Properties of Glass Fiber-Reinforced Polymer Hybrid Composite with Eggshell Powder’, *Arabian Journal for Science and Engineering*, 45(7), pp. 5783–5791. Available at: https://doi.org/10.1007/s13369-020-04561-z.

Lutfi, M. *et al.* (2017) ‘The Glycerol Effect on Mechanical Behaviour of Biodegradable Plastic from the Walur (Amorphophallus paenifolius Var . sylvestris)’.

Ma, X. *et al.* (2010) ‘Preparation and characterization of silica/polyamide-imide nanocomposite thin films’, *Nanoscale Research Letters*, 5(11), pp. 1846–1851. Available at: https://doi.org/10.1007/s11671-010-9726-7.

Manshor, N.M. *et al.* (2018) ‘Synthesis of biodegradable plastic from tapioca with N-Isopropylacrylamid and chitosan using glycerol as plasticizer Synthesis of biodegradable plastic from tapioca with N-Isopropylacrylamid and chitosan using glycerol as plasticizer’. Available at: https://doi.org/10.1088/1757-899X/345/1/012049.

Manzoor, A. *et al.* (2023) ‘Recent insights into green antimicrobial packaging towards food safety reinforcement: A review’, *Journal of Food Safety*, 43(4), pp. 1–15. Available at: https://doi.org/10.1111/jfs.13046.

Marichelvam, M.K. *et al.* (2022) ‘Current Research in Green and Sustainable Chemistry Extraction and development of starch-based bioplastics from Prosopis Juliflora Plant : Eco-friendly and sustainability aspects’, *Current Research in Green and Sustainable*

Chemistry, 5(March), p. 100296. Available at: https://doi.org/10.1016/j.crgsc.2022.100296.

Marta, H. *et al.* (2022) 'The Properties , Modification , and Application of Banana Starch', pp. 1–20.

Mohamed Abdoul-Latif, F. *et al.* (2022) 'Use of Thymus Plants as an Ecological Filler in Urea-Formaldehyde Adhesives Intended for Bonding Plywood', *Processes*, 10(11), pp. 1–11. Available at: https://doi.org/10.3390/pr10112209.

Mohammadi Nafchi, A., Cheng, L.H. and Karim, A.A. (2011) 'Effects of plasticizers on thermal properties and heat sealability of sago starch films', *Food Hydrocolloids*, 25(1), pp. 56–60. Available at: https://doi.org/10.1016/j.foodhyd.2010.05.005.

Montero, B. *et al.* (2017) 'Effect of nanocellulose as a filler on biodegradable thermoplastic starch films from tuber, cereal and legume', *Carbohydrate Polymers*, 157, pp. 1094–1104. Available at: https://doi.org/10.1016/j.carbpol.2016.10.073.

Mooney (2009) 'CHAPTER 2 2 PRODUCTION OF BIODEGRADABLE PLASTIC FILM', pp. 14–38.

Mora-Sánchez, M. *et al.* (2023) 'Developing active chitosan-based edible film for extending the shelf life of guacamole', *Frontiers in Sustainable Food Systems*, 7(September), pp. 1–10. Available at: https://doi.org/10.3389/fsufs.2023.1254337.

Nilani, P. *et al.* (2010) 'Formulation and Evaluation of Polysaccharide Based Biopolymer – an Ecofriendly Alternative for Synthetic Polymer .', 2(3), pp. 178–184.

Noorjahan, C.M., Banu, S.N. and Subhashree, V. (2022) 'BIOPLASTIC SYNTHESIS USING BANANA PEELS AND ITS CHARACTERIZATION', 13(7), pp. 2855–2863. Available at: https://doi.org/10.47750/pnr.2022.13.S07.380.

Nor, M.H.M., Nazmi, N.N.M. and Sarbon, N.M. (2017) 'Effects of plasticizer concentrations on functional properties of chicken skin gelatin films', *International Food Research Journal*, 24(5), pp. 1910–1918.

Paixão, L.C. *et al.* (2019) 'Alginate biofilms plasticized with hydrophilic and hydrophobic plasticizers for application in food packaging', *Journal of Applied Polymer Science*, 136(48), pp. 1–11. Available at: https://doi.org/10.1002/app.48263.

Rhim, J.W. and Wang, L.F. (2014) 'Preparation and characterization of carrageenan-based nanocomposite films reinforced with clay mineral and silver nanoparticles', *Applied Clay Science*, 97–98, pp. 174–181. Available at: https://doi.org/10.1016/j.clay.2014.05.025.

Romainor, A.N., Chin, S.F. and Lihan, S. (2022) 'Antimicrobial Starch-Based Film for Food Packaging Application', *Starch/Staerke*, 74(3–4), pp. 1–9. Available at: https://doi.org/10.1002/star.202100207.

Sanghvi, M.R., Tambare, O.H. and More, A.P. (2022) *Performance of various fillers in adhesives applications: a review*, *Polymer Bulletin*. Springer Berlin Heidelberg. Available at: https://doi.org/10.1007/s00289-021-04022-z.

Sanyang, M.L. (2015) 'Effect of Plasticizer Type and Concentration on Tensile, Thermal and Barrier Properties of Biodegradable Films Based on Sugar Palm (Arenga pinnata) Starch', pp. 1106–1124. Available at: https://doi.org/10.3390/polym7061106.

Science, E. (no date a) 'Characteristics of bioplastic made from modified cassava starch with addition of polyvinyl alcohol Characteristics of bioplastic made from modified cassava starch with addition of polyvinyl alcohol'. Available at: https://doi.org/10.1088/1755-1315/591/1/012016.

Science, E. (no date b) 'Effect of chitin addition on water resistance properties of starch-based bioplastic properties Effect of chitin addition on water resistance properties of starch-based bioplastic properties'. Available at: https://doi.org/10.1088/1755-1315/483/1/012002.

Science, E. (no date c) 'Preliminary study of biodegradability of starch- based bioplastics using ASTM G21-70 , dip- hanging , and Soil Burial Test methods Preliminary study of biodegradability of starch-based bioplastics using ASTM G21-70 , dip-hanging , and Soil Burial Test methods'. Available at: https://doi.org/10.1088/1755-1315/277/1/012007.

Science, E. (no date d) 'The role of various plastisizers and fillers additions in improving tensile strength of starch-based bioplastics : A mini review The role of various plastisizers and fillers additions in improving tensile strength of starch-based bioplastics : A mini review'. Available at: https://doi.org/10.1088/1755-1315/1115/1/012076.

Shafqat, A. *et al.* (2021) 'Saudi Journal of Biological Sciences Synthesis and characterization of starch based bioplatics using varying plant-based ingredients , plasticizers and natural fillers', *Saudi Journal of Biological Sciences*, 28(3), pp. 1739–1749. Available at: https://doi.org/10.1016/j.sjbs.2020.12.015.

Shanmathy, M., Mohanta, M. and Thirugnanam, A. (2021) 'Development of Biodegradable Bioplastic films from Taro Starch Reinforced with Bentonite Development of biodegradable bioplastic films from Taro starch reinforced with bentonite', *Carbohydrate Polymer Technologies and Applications*, 2(November), p. 100173. Available at: https://doi.org/10.1016/j.carpta.2021.100173.

Sharif, N., Mohanta, M. and Thirugnanam, A. (2023) 'Eggshell Reinforced Yam Starch - Based Bioplastic for Packaging Applications', *Journal of Packaging Technology and Research*, 7(2), pp. 75–86. Available at: https://doi.org/10.1007/s41783-023-00152-z.

Shayan, M. *et al.* (2019) 'Influence of modified starch and nanoclay particles on crystallization and thermal degradation properties of cross-linked poly (lactic acid)', *Journal of Polymer Research*, 26(238).

Sifuentes-nieves, I. *et al.* (2015) 'Structural Characterization of Films Based on Gelatin / Glycerol and Carbon Nanotubes', 2015.

Sirbu, E. *et al.* (2024) 'Influence of Plasticizers Concentration on Thermal , Mechanical , and Physicochemical Properties on Starch Films'.

Soubam, T. (2022) 'Eco-Friendly Bio-Based Adhesive for Plyboard from Natural Rubber Latex (NRL) Blended Isocyanate Crosslinked Starch', pp. 1–16.

Souza, A.C. *et al.* (2012) 'LWT - Food Science and Technology Cassava starch biodegradable fi lms : In fl uence of glycerol and clay nanoparticles content on tensile and barrier properties and glass transition temperature', 46, pp. 110–117. Available at: https://doi.org/10.1016/j.lwt.2011.10.018.

Student, M.T. *et al.* (2021) 'No 主観的健康感を中心とした在宅高齢者における 健康関連指標に関する共分散構造分析Title', *Frontiers in Neuroscience*, 14(1), pp. 1–13.

Šupová, M., Martynková, G.S. and Barabaszová, K. (2014) 'Effect of Nanofillers Dispersion in Polymer Matrices : A Review Effect of Nanofillers Dispersion in Polymer Matrices : A Review', (August 2010). Available at: https://doi.org/10.1166/sam.2011.1136.

Triawan, F. *et al.* (2020) 'The influence of turmeric microparticles amount on the mechanical and biodegradation properties of cornstarch-based bioplastic material : from bioplastic literature review to experiments', 46, pp. 99–114.

Vasile, C. *et al.* (2018) 'AC SC', *Composites Part B* [Preprint]. Available at: https://doi.org/10.1016/j.compositesb.2018.01.026.

Vinay, G.M., Modi, R.B. and Prakasha, R. (2024) 'Banana Pseudostem : An Innovative and Sustainable Packaging Material : A Banana Pseudostem : An Innovative and Sustainable Packaging Material : A Review', *Journal of Packaging Technology and Research* [Preprint], (May). Available at: https://doi.org/10.1007/s41783-024-00167-0.

Vineeth, S.K., Gadhave, R. V and Gadekar, P.T. (2019) 'Chemical Modification of Nanocellulose in Wood Adhesive : Review', pp. 86–99. Available at: https://doi.org/10.4236/ojpchem.2019.94008.

Wicaksono, J.A. *et al.* (2022) 'Bacterial dynamics during the burial of starch - based bioplastic and oxo - low - density - polyethylene in compost soil', *BMC Microbiology*, pp. 1–11. Available at: https://doi.org/10.1186/s12866-022-02729-1.

Wita, D. De and Vliegenthartb, J.F.G. (1996) 'INDUSTRIALCROPS Crystallinity in starch bioplastics', 5.

Wong, L.W. *et al.* (2020) 'Preparation of antimicrobial active packaging film by capacitively coupled plasma treatment', *Lwt*, 117(April 2019), p. 108612. Available at: https://doi.org/10.1016/j.lwt.2019.108612.

Xie, D. *et al.* (2023) 'International Journal of Biological Macromolecules A novel , robust mechanical strength , and naturally degradable double crosslinking starch-based bioplastics for practical applications', *International Journal of Biological Macromolecules*, 253(P4), p. 126959. Available at: https://doi.org/10.1016/j.ijbiomac.2023.126959.

Yang, J. *et al.* (2021) 'Preparation and characterization of starch-based bioplastic composites with treated oil palm empty fruit bunch fibers and citric acid', *Cellulose*, 28(7), pp. 4191–4210. Available at: https://doi.org/10.1007/s10570-021-03816-8.

Yang, J. *et al.* (2023) 'Preparation and Characterization of Starch - Based Bioplastic Films Modified by Citric Acid - Epoxidized Soybean Oil Oligomers', *Journal of Polymers and the Environment*, 31(3), pp. 954–964. Available at: https://doi.org/10.1007/s10924-022-02661-5.

Yang, Y. *et al.* (2020) 'Bio-based antimicrobial packaging from sugarcane bagasse nanocellulose/nisin hybrid films', *International Journal of Biological Macromolecules*, 161, pp. 627–635. Available at: https://doi.org/10.1016/j.ijbiomac.2020.06.081.

Yaradoddi, J. *et al.* (2016) 'BIODEGRADABLE PLASTIC PRODUCTION FROM FRUIT WASTE MATERIAL AND ITS SUSTAINABLE USE FOR GREEN APPLICATIONS Biomaterials Laboratory , Centre for Material Science , B . V . Bhoomaraddi College of School of Mechanical Engineering , B . V . Bhoomaraddi College', 5(4), pp. 56–65.

Zhou, Y. *et al.* (2022) 'Preparation of functional fiber hybrid enhanced high strength and multifunctional protein based adhesive', *Materials and Design*, 224, p. 111289. Available at: https://doi.org/10.1016/j.matdes.2022.111289.

Zoungranan, Y. *et al.* (2020) 'Journal of Environmental Chemical Engineering Influence of natural factors on the biodegradation of simple and composite bioplastics based on cassava starch and corn starch', *Journal of Environmental Chemical Engineering*, 8(5), p. 104396. Available at: https://doi.org/10.1016/j.jece.2020.104396.