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PRODUCTION AND CHARACTERIZATION OF BIO-PLASTIC FROM BY-PRODUCT OF AVOCADO SEED STARCH FOR FOOD PACKAGING MATERIALS

Gemechu DUGUMA ARGESSA [1*], Meriko EWNETU[2], Hirbo GEREMAW[3]
[1*] Department of Industrial Chemistry, College of Natural and Computational Science, Bule Hora University, Hagere Mariyam, Ethiopia;
[2] Department of Industrial Chemistry, College of Natural and Computational Science, Bule Hora University, Hagere Mariyam, Ethiopia
[3] Department of Industrial Chemistry, College of Natural and Computational Science, Bule Hora University, Hagere Mariyam, Ethiopia;
***Corresponding author: gemechudug@gmail.com, gemachu.duguma@bhu.edu.et**
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Abstract: *Avocado seed starch, a plentiful byproduct of agro-industrial processes, presents considerable promise as a sustainable and biodegradable resource for the creation of bioplastics. With its substantial starch content and ability to form films, it serves as a viable substitute for traditional petroleum-derived plastics, especially in the realm of food packaging. In this study, starch extracted from avocado seeds was utilized to produce bioplastic films, reinforced with microcrystalline cellulose (MCC) derived from Ensete ventricosum fibers. Environmentally friendly processing methods, including aqueous extraction, alkaline treatment, and mechanical dispersion, were employed. Glycerol was incorporated as a plasticizer to enhance film flexibility. Bioplastic films were prepared by solution casting, using glycerol as a plasticizer and varying MCC content (0%, 1%, and 5% by weight). Characterization techniques included tensile strength testing, FTIR spectroscopy, thermal gravimetric analysis (TGA), water retention value (WRV) tests, and UV–Vis spectroscopy. Experimental results showed that MCC significantly enhanced the film's mechanical properties. At 5% MCC loading, tensile strength increased from 714 Pa (pure starch film) to 12.8 MPa, satisfying the minimum requirement for plastic packaging applications (≥10 MPa). Elongation at break improved from 3.25% to 6.52%, and film thickness slightly decreased from 0.847 mm to 0.830 mm, indicating better compactness and structural integrity. FTIR analysis confirmed strong hydrogen bonding between starch and MCC, while thermal and WRV analysis demonstrated improved thermal stability and reduced water absorption. UV–Vis results revealed reduced transparency due to cellulose incorporation, enhancing UV-blocking performance. Future work should investigate optimizing cellulose loading levels, especially beyond 5 wt%, to further improve performance metrics such as tensile strength, moisture barrier properties, and shelf-life protection.*

Key words: Bioplastics, biodegradable, Enset fibers, food packaging, renewable biomass, starch

1. Introduction

An increasing number of nations are adopting national bio-economy strategies to minimize their dependence on fossil fuels. The European Commission's 2022 report, titled Innovating for Sustainable Growth: A Bio-economy for Europe, underscores various initiatives in sectors such as industrial biotechnology, food processing, bio-refineries, and sustainable manufacturing, all aimed at promoting markets for bio-based products and facilitating a shift away from traditional plastic industries [1].

In Ethiopia, the growing demand for plastic in industries such as food packaging is notable. However, conventional plastics, primarily derived from petroleum, are non-

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biodegradable and significantly contribute to environmental degradation. In 2010, global plastic production reached 265 million tons, with Europe accounting for 57 million tons [1]. Out of the 8.3 billion metric tons of plastic produced historically, 6.3 billion have ended up as waste, with a mere 9% being recycled [2]. These synthetic polymers can take centuries to decompose and frequently release toxic byproducts into the environment [3, 4].

The excessive use of petroleum-based plastics has highlighted the urgent necessity for sustainable and biodegradable alternatives. In this regard, bioplastics materials sourced from renewable origins are increasingly being recognized. These bio-plastics are typically formulated from natural polymers such as starch, cellulose, and polylactic acid (PLA), and they present the benefit of more rapid biodegradation in comparison to their synthetic equivalents [5, 6]. Nevertheless, starch-based bio-plastics face challenges, including inadequate mechanical strength and heightened sensitivity to moisture, which necessitate enhancements for wider applicability [7, 8]. Among the various sources of starch, avocado seeds, often regarded as waste in fruit markets, remain underexploited, despite their starch content exceeding 30% [9]. In Ethiopia, particularly in the Oromia region, such as Bule Hora and Dila city in the Sidama region, there is a substantial generation of avocado waste, providing a cost-effective and readily available starch source for the production of biodegradable films. Furthermore, the performance of starch-based bio-plastics can be augmented through the incorporation of reinforcements such as microcrystalline cellulose (MCC). Enset (false banana) fiber, which is abundantly found in Ethiopia, serves as a promising source of microcrystalline cellulose (MCC). The process of acid hydrolysis applied to this fiber produces cellulose microcrystals that significantly improve the mechanical and barrier characteristics of starch-based bio-plastics [10]. The production of bio-plastics typically entails the hydrolysis of plant residues to dismantle the cellular structure, subsequently forming viscous films via casting or extrusion techniques [11]. The incorporation of natural fibers, such as those derived from sugar palm or enset, offers significant advantages, including affordability, renewability, and diminished wear on processing equipment [12, 13].

However, despite the inherent benefits of bio-plastics, issues related to their thermoplastic properties and durability persist. To mitigate these challenges, the addition of plasticizers like glycerol is employed to enhance flexibility and ease of processing [14]. Furthermore, the combination of starch with microcrystalline cellulose (MCC) has been shown to improve both dimensional stability and mechanical strength, rendering it suitable for food packaging applications [15].

This study develops a novel biodegradable biopolymer film by integrating starch derived from avocado seed waste with microcrystalline cellulose (MCC) fibers extracted from Enset (Ensete ventricosum), a traditionally underutilized agricultural by-product. The innovative aspect of this work lies not only in the valorization of agro-industrial waste but also in the development of a mechanically reinforced, thermally stable, and optically improved biofilm suitable for food packaging applications.

Specifically, the study proposed an active starch/MCC biopolymer film for food preservation, emphasizing its superior functional properties compared to conventional bioplastics.

Furthermore, the developed film demonstrated a rapid mechanical stress response and cost-effectiveness, primarily due to the availability and low cost of the

agricultural raw materials used. This makes it a viable, eco-friendly alternative to petroleum-based plastics, with added advantages in performance and sustainability. To the best of the authors' knowledge, this is among the first studies to utilize both avocado seed starch and Enset-derived MCC in combination, thereby offering a novel pathway for creating biodegradable and functional packaging materials aligned with circular economy principles.

In addition to its mechanical and optical properties, the formulation also supports environmental safety and scalability, suggesting its potential for large-scale applications in the food packaging industry, especially for dry and semi-moist food items. This positions the research as a significant contribution to the field of green materials science and sustainable packaging innovation.

The development of bioplastics from avocado seed starch reinforced with microcrystalline cellulose (MCC) extracted from *Ensete ventricosum* contributes meaningfully to climate change mitigation and supports the objectives of the United Nations Sustainable Development Goals (SDGs). The use of agro-industrial waste materials significantly reduces the carbon footprint associated with conventional plastic production by avoiding petroleum feedstocks, minimizing greenhouse gas emissions, and generating minimal hazardous wastewater. This environmentally friendly approach directly supports SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 6 (Clean Water and Sanitation), while indirectly promoting SDG 9 (Industry, Innovation, and Infrastructure) by fostering the development of bio-based circular economies [16, 17]. Additionally, the biodegradable nature of the bioplastic films contributes to SDG 14 (Life Below Water) and SDG 15 (Life on Land) by reducing the risk of plastic pollution in ecosystems. Although this research is laboratory-scale, it aligns with future pathways of intelligent manufacturing under Industry 4.0 and 5.0 by offering a scalable and sustainable raw material base for eco-friendly materials [18, 19]. With enhanced integration of green chemistry, renewable resource valorization, and smart production systems, such innovations have the potential to support climate-resilient industrial transitions and sustainable material engineering [20, 21].

2. Materials and methods

2.1. Chemicals and apparatus

During the experimental work conducted in the laboratory, apparatus and equipment were used for the extraction, production, and characterization of bioplastics from avocado seed starch and enset fiber: FTIR spectrometer (Shimadzu IRTracer-100, Japan), UV-Visible spectrophotometer (Shimadzu UV-1800, Japan), thermogravimetric analyzer (PerkinElmer TGA 4000, USA), universal testing machine (Instron 3365, USA; 5 kN), and glass petri dishes. These instruments were utilized for the preparation, processing, and physicochemical characterization of bioplastic samples.

The following analytical-grade chemicals and reagents were used in this study: Hydrochloric acid (HCl) – 37%, analytical grade, obtained from Alpha Chemical Import (Addis Ababa, Ethiopia): It was used for the acid hydrolysis process in the cellulose isolation from Ensete ventricosum fibers. Sodium hydroxide (NaOH) – 98% purity in pellet form, analytical grade, purchased from Chemo Ethiopia PLC (Addis Ababa, Ethiopia), used in the alkaline treatment of enset fibers to remove hemicellulose and lignin. Glycerol – ≥ 99.5%, analytical grade, obtained from the

Ethiopian Pharmaceutical Supply Agency (EPSA), used as a plasticizer in the formulation of the bio-plastic film.

Sodium metabisulfite ($Na_2S_2O_5$) – 98% analytical grade, acquired from Alpha Chemical Import (Addis Ababa, Ethiopia). It was utilized during the extraction of starch from avocado (Persea americana) seeds to prevent enzymatic browning and microbial contamination by inhibiting polyphenol oxidase activity, thereby improving starch purity and yield [22].

Distilled water – laboratory-grade, produced on-site and used in all solution preparations, extraction, and washing steps.

2.2. Sample collection and preparation

The avocado seeds and Enset (*Ensete ventricosum*) were collected from Bule Hora Town, West Guji zone. Then milled by using a milling machine and inserted into a sample holder [23]. After cooling to room temperature, the sample was placed in polyethylene plastic bags, brought to the lab, and kept there until a blending machine ground it.

2.3. Extraction of avocado seed starch (ASS)

In this study, starch was extracted from avocado seeds employing sodium metabisulfite ($Na_2S_2O_5$) to enhance yield and prevent enzymatic browning. Initially, 50 g of avocado seeds were ground using a laboratory mixer-grinder. The ground material was then soaked in 100 mL of distilled water containing 0.075% (w/v) sodium metabisulfite. This compound acts as both an antioxidant and an antimicrobial agent, effectively inhibiting polyphenol oxidase (PPO) activity, which is responsible for enzymatic browning in plant tissues [24]. The mixture was allowed to settle at room temperature (28 ± 2 °C) for four hours, facilitating the sedimentation of starch granules. Subsequently, the starch sediment was repeatedly washed with the sodium metabisulfite solution until a clear suspension was achieved, ensuring the removal of non-starch residues. The clear supernatant was then decanted, and the purified starch sediment was collected for further drying and analysis [25]. The sedimentary starch was repeatedly cleaned with distilled water till the wash water was found to be clear and impure-free. Following its isolation, 26.5 g of the starch was sieved and allowed to air dry at room temperature. The quantities of amylopectin and amylose in the extracted starch were measured using the procedure described by Nogueira [39]. The AOAC method identified the presence of moisture in the starch [13].

2.4. Isolation of cellulose from Enset Stem (*Ensete ventricosum*)

The process of extracting cellulose fibers from the stem of *Ensete ventricosum* involved a series of pretreatment steps aimed at eliminating non-cellulosic components such as lignin, hemicellulose, and extractives, thus isolating high-purity cellulose that is suitable for bio-plastic formulation. Initially, the stem was manually stripped of its outer bark and cut into manageable pieces to facilitate subsequent treatments. The material was subjected to hot water washing to remove soluble impurities, followed by an alkaline treatment with sodium hydroxide (NaOH), which disrupted the lignin carbohydrate matrix and solubilized hemicellulose. A bleaching stage using sodium hypochlorite (NaOCl) further purified the fibers by degrading residual lignin and enhancing the whiteness of the cellulose.

These sequential treatments are essential to produce cellulose of adequate purity and quality for downstream processing [26].

2.4.1. Bark removal and size reduction

The outer bark, which is rich in lignin and other impurities, was manually peeled from the Ensete stem to enhance the efficiency of

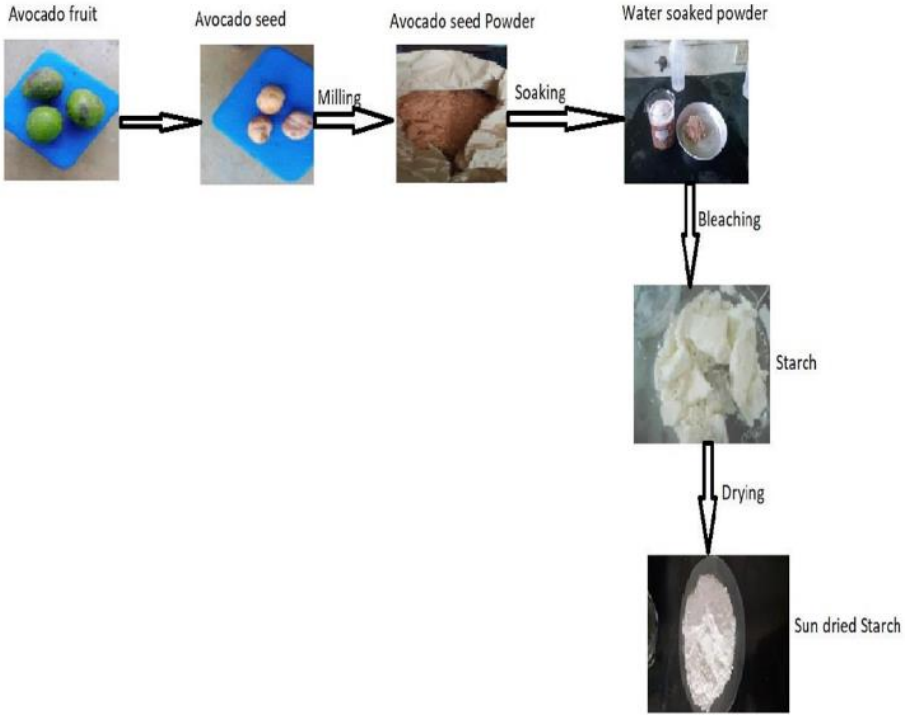

Fig.1 Diagrammatic representation of Avocado Seed Starch (ASS) extraction

chemical treatments. The cleaned stem segments were separated from roots and leaves, then sun-dried for seven days to reduce moisture, followed by oven drying at 60 °C for 24 hours to eliminate bound water. The dried material was milled and sieved through a 1 mm mesh to obtain a uniform powder, which was rinsed with distilled water to remove surface soluble substances and stored under airtight conditions for subsequent processing. These steps ensure a consistent, contaminant-reduced starting material [27].

2.4.2. Removal of extractives

To remove surface-bound waxes, oils, and pectins, the powdered stem underwent a dewaxing process utilizing a toluene: ethanol (2:1 v/v) solvent system under reflux conditions at 85 °C for a duration of five hours. Toluene serves to effectively dissolve non-polar hydrophobic components, whereas ethanol is responsible for extracting semi-polar substances [28]. Following the extraction, the material was subjected to multiple washes with ethanol and distilled water, followed by vacuum filtration to eliminate any residual solvents. This procedure significantly enhances the accessibility of cellulose for subsequent chemical reactions by removing surface barriers.

2.4.3. Alkaline pretreatment

The dewaxed powder was subjected to two treatments with a 4% (w/w) NaOH solution at 80 °C for two hours, maintaining a solid-to-liquid ratio of 1:20 (g/mL). Sodium hydroxide acts to cleave ester and ether linkages within the hemicellulose-lignin complex, thereby facilitating the solubilization of amorphous materials and enhancing the purity of cellulose [29]. After each treatment, the samples were washed with distilled water and neutralized using diluted acetic acid until a neutral pH was achieved. The color of the fiber transitioned from gray to white-brown, indicating the

partial removal of hemicellulose and lignin. The suspension was allowed to settle overnight, and the sediment was collected for the bleaching process.

2.4.3. Bleaching

The fibers, which had been partially purified, were subjected to a bleaching procedure aimed at further removing residual lignin and enhancing the whiteness of the cellulose. The bleaching process in an acidic environment (pH 4) utilizes a 5% (w/w) sodium hypochlorite solution mixed with glacial acetic acid in a 4:1 (v/v) ratio. These fibers were immersed in the solution at a temperature of 80 °C for a duration of two hours while being continuously agitated, maintaining a sample-to-solvent ratio of 1:20 (g/mL). Sodium hypochlorite serves as a potent oxidizing agent, facilitating the breakdown of residual lignin and chromophores, which leads to a transformation in color from grayish-white to pristine white [30]. After the bleaching process, the fibers were rinsed with diluted sodium hydroxide and distilled water until a neutral pH was achieved, resulting in purified cellulose in a slurry form (1 wt%) that was prepared for subsequent processing.

2.4.4. Production of microcrystalline cellulose (MCC)

The purified cellulose underwent /taken in to hydrolysis using 2.5 N hydrochloric acid (HCl) at a temperature of 90 °C for 15 minutes while being stirred continuously. This process selectively hydrolyzes the amorphous regions of cellulose, thereby preserving the crystalline domains that are characteristic of MCC. The reaction was halted by placing the mixture in an ice bath, followed by centrifugation and multiple washings until a neutral pH was attained. The resulting MCC was then dried in an oven at 60 °C and stored in a desiccator to avoid moisture absorption. This method produces MCC with elevated crystallinity and thermal stability, making it suitable as a reinforcing component in bio-plastic composites [20].

2.4.5. Mechanical processing of the extracted cellulose

In addition to acid hydrolysis, microcrystalline cellulose (MCC) was also produced through mechanical fibrillation to improve fiber quality. An 11% (w/w) cellulose dispersion was created in water and subjected to high-shear treatment using a commercial blender for a duration of 30 minutes. This mechanical processing broke down the cellulose into finer microfibrils, leading to a homogeneous and stable MCC suspension. Mechanical fibrillation enhances the surface area of the fibers, improves uniformity, and boosts functional properties such as binding and reinforcement potential in bio-plastic matrices. Furthermore, it diminishes the dependence on harsh chemicals, which aligns with environmentally friendly production objectives.

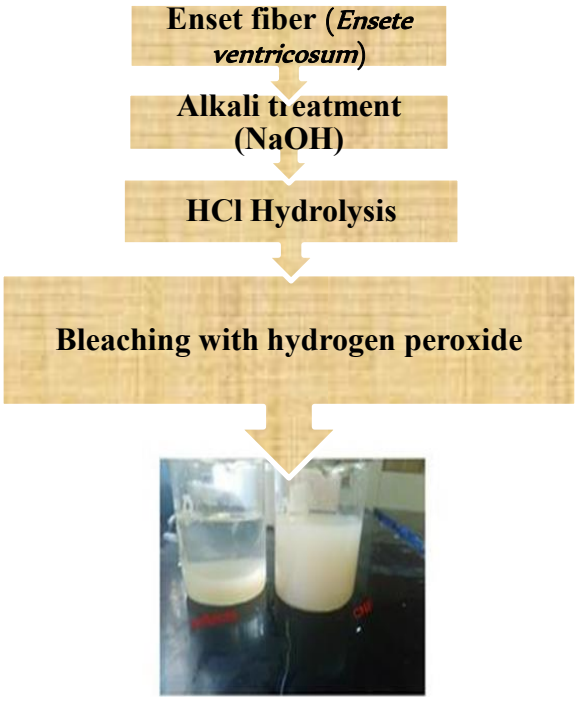

Fig. 2 Schematic diagram showing the isolation of cellulose fiber suspension from Enset

2.5. Bio-plastic film preparation

Bioplastic films were synthesized using solvent casting and evaporation methods to create thermoplastic starch-based composites reinforced with microcrystalline cellulose (MCC). Two distinct types of films were developed: one consisting entirely of starch and the other integrating MCC as a reinforcement. The starch–MCC composite was formulated at a weight ratio of 8:2 (starch: MCC), chosen to enhance the mechanical and thermal characteristics of the resultant bioplastic. Initially, starch was dispersed in distilled water at a ratio of 1:10 (w/v) and heated with constant stirring for 10 minutes to facilitate gelatinization. In a separate process, MCC was dispersed in a 5% (w/v) NaOH solution to improve its solubility and dispersion. Glycerol, a widely utilized plasticizer, was incorporated into the starch solution at a rate of 0.1 mL per gram of starch to enhance film flexibility and minimize brittleness. Once the starch solution reached 70 °C, the MCC dispersion was gradually added while maintaining the mixture at 85 °C under continuous stirring to ensure the fibers were uniformly integrated. The resulting biocomposite slurry was then allowed to cool to room temperature. It was subsequently poured into leveled, flat molds and dried in a hot air oven at 60 °C for 24 hours to promote solvent evaporation and film formation. After drying, the bioplastic films were carefully extracted from the molds and stored in a desiccator to avoid moisture absorption before further analysis [31].

2.6. Bio-plastic film water retention value

The water retention value (WRV) test measures a material's ability to absorb water and swell, which is closely related to its fiber bonding ability. To conduct the test, dried samples are first weighed, then rinsed in distilled water for a specified time. This test provides valuable insights into the hydration and bonding potential of cellulose materials, which directly influence their mechanical and barrier properties in bioplastic applications [32].

Fig. 3 Bio-plastic prepared by film casting

The samples are weighed at 1-minute intervals using an analytical balance, and the WRV is calculated using the formula [32]:

$$WRV = (Wwet - Wdry) * 100 / Wdry \quad (1)$$

Where:

- **Wwet** is the weight of the wet sample,
- **Wdry** is the weight of the dry sample.

2.7. Bio-plastic tensile testing

The mechanical characteristics of the produced bio-plastic films, such as tensile strength, elongation at break, and thickness, were assessed utilizing a computerized universal testing machine (Model: UTM-5, Fine Testing Machines Pvt. Ltd., India) that was fitted with a 500 N load cell. The tensile tests were carried out in accordance with the ASTM D882 standard. The samples were prepared in strips measuring 100 mm × 10 mm, with a gauge length established at 50 mm. Testing was conducted at a crosshead speed of 5 mm/min under standard laboratory conditions (25 ± 2 °C and 50% RH). Tensile strength was determined by dividing the maximum applied load by the cross-sectional area of the sample and

expressed in megapascals (MPa). Elongation at break was calculated as the percentage increase in length before failure, using the formula [33]:

$$\text{Elongation } (\%) = \frac{(\text{Final Length} - \text{Initial Length})}{\text{Initial Length}} \text{ x100} \quad (2)$$

The starch-based bioplastic film produced without the reinforcement of microcrystalline cellulose (MCC) exhibited a tensile strength of 714 Pa, significantly lower than the minimum requirement of 10 MPa for plastic packaging applications, corroborating findings from previous studies on native starch films [24].

However, the addition of 5wt % MCC sourced from Enset (*Ensete ventricosum)* markedly improved the tensile strength to 12.8 MPa, surpassing this essential threshold. This improvement is consistent with earlier research that suggests MCC serves as an effective reinforcing filler by enhancing interfacial bonding and load transfer within the polymer matrix, thus augmenting mechanical strength and stiffness [34].

These findings underscore the potential of Enset/MCC composite as a sustainable reinforcing agent in starch-based bio-plastics. To further enhance the mechanical properties and expand the applicability of these materials for food packaging, subsequent research should investigate higher MCC loadings (>10 wt%), which have been demonstrated to provide additional strength improvements in similar biopolymer composites [35].

2.8. Transparency of bioplastic film

The spectrophotometer (Shimadzu UV-1800, Japan) is used to measure the materials' transparency. At 600 nm, the transmittance of films was measured. The transmittance was measured when the rectangular sample piece was positioned against the side of the spectrophotometer cell.

2.9. FTIR analysis of bio-plastic film

The functional groups present in the bioplastic film samples were characterized using Fourier Transform Infrared (FTIR) spectroscopy. The analysis was performed using an FTIR spectrometer (Shimadzu IRTracer-100, Japan) at Addis Ababa University, Ethiopia. Spectra were recorded over the range of 4000 to 400 cm^{-1} to identify characteristic absorption bands corresponding to various functional groups. The resulting spectra were used to analyze the chemical structure and confirm the presence of expected functional groups in the produced bioplastic films.

2.10. Thermo gravimetric analysis (TGA) of bio-plastic film

Thermal stability of the samples was assessed using a thermo-gravimetric analyzer (PerkinElmer TGA 4000, USA), operating under a continuous nitrogen atmosphere to prevent oxidation. Samples were heated from ambient temperature up to 600 °C at a controlled rate of 20 °C per minute. This method enabled precise evaluation of the thermal decomposition behavior and stability of the bioplastic films.

3. Results and discussion

Innovation description

The study proposed an active biopolymer film based on starch and MCC for food preservation, emphasizing the unique advantages of this formulation. Specifically, the film demonstrated enhanced performance in terms of tensile strength (12.8 MPa), elongation, thermal stability, and optical clarity. Its response speed to mechanical stress and cost-effectiveness stemming from the use of agro-waste make it a competitive and sustainable alternative to petroleum-derived plastics. Growing awareness of plastic pollution has sparked interest in biodegradable substitutes. This work focused on food packaging applications by

creating and characterizing a bio-plastic from avocado seed starch reinforced with cellulose from Ensete fiber (*Ensete ventricosum*). Glycerol was used as a plasticizer to provide the bio-plastic flexibility after it was made using the solution casting method.

Characterization of this study included mechanical, thermal, and physical characteristics. Enset fiber (*Ensete ventricosum*) reinforces increased tensile strength, elongation at break, and flexibility, according to the results. The starch/MCC composite showed improved thermal stability, according to thermo-gravimetric measurements. The composite's reduced WRV from water retention tests suggests improved moisture control, which prolongs the shelf life of food.

Improved mechanical strength ensures longevity during shipping and packaging, and semi-transparency and heat stability offer both practical and decorative benefits. All things considered, the avocado starch-Enset fiber (*Ensete ventricosum*) bioplastic exhibits great promise as an environmentally friendly food packaging solution. For even greater performance, future studies should concentrate on formulation optimization and the addition of additional natural fibers.

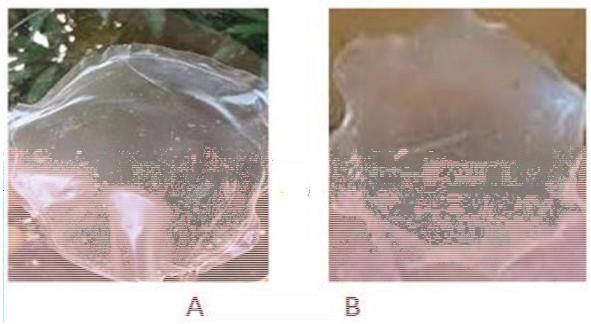

Fig. 4 Images of A). Synthesized starch bioplastic without MCC & B). After the addition of MCC.

3.1. FTIR analysis of Enset fiber and extracted cellulose

The FTIR spectra of the isolated cellulose and Enset fiber (*Ensete ventricosum*) are shown in Figure 5. A wide peak that corresponded to –OH stretching from hydrogen bonding was visible in both samples between 3500 and 3000 cm^{-1}. Aliphatic saturated compounds are confirmed by peaks in the 3000–2800 cm^{-1} range, which show C–H stretching.

A peak at 1735 cm^{-1} was found in Enset fiber, which was ascribed to carboxylic groups from hemicellulose and lignin. The fact that this peak disappeared from the isolated cellulose suggests that these components were successfully removed. The treated sample showed a decrease in the raw fiber's peak at 1639 cm^{-1}, which was linked to adsorbed water.

Further evidence of lignin removal was provided by the absence of a lignin-related peak at 1248 cm^{-1} in the untreated fiber following treatment. On the other hand, OH bending of adsorbed water caused a new peak to form in the cellulose between 1570 and 1606 cm^{-1}. All samples had the typical cellulose C–O–C stretching peak in the 1030–1070 cm^{-1} region, and both samples had a peak at 1426 cm^{-1} associated with CH_2 bending.

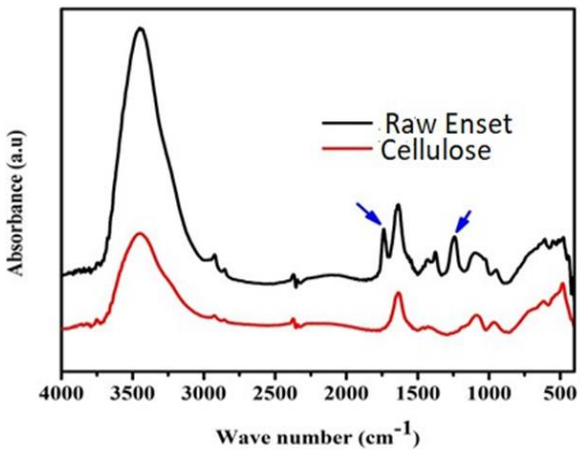

Fig. 5 FTIR analysis of Enset fiber and extracted cellulose

3.2. FTIR characterization of starch plastic sheet and starch /MCC composite

The FTIR spectra of the starch/MCC composite and the starch plastic sheet are displayed in Figure 6. Because both spectra

share a polysaccharide foundation, they exhibit structural similarities. However, the peaks at 3410 cm^{-1}, which correspond to –OH groups, considerably decrease in the starch/MCC composite. This reduction implies that there is a strong hydrogen connection between the starch matrix and the cellulose fibers, which restricts the mobility of hydroxyl groups. Effective interaction between the filler (MCC) and the starch matrix is shown by the composite's sharper peaks and generally lower intensity. The hydroxyl-rich starch and the reactive -OH groups in cellulose create hydrogen bonds, improving compatibility and strengthening the composite structure. Enhancing the bioplastic's mechanical and functional qualities requires these interactions [36].

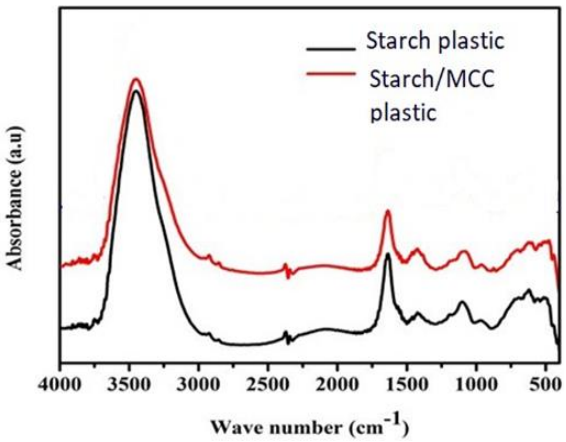

Fig. 6 FTIR characterization of starch plastic sheet and starch /MCC composite

The FTIR spectrum exhibited distinct peaks at 3280 cm^{-1} (O–H stretching), 2925 cm^{-1} (C–H stretching), and 1640 cm^{-1} (H–O–H bending of absorbed water), indicating the presence of functional groups typical of starch and MCC. Upon incorporation of MCC, shifts in the O–H region indicated hydrogen bonding interactions, confirming enhanced molecular compatibility between starch and cellulose. These interactions contribute to the improved mechanical and barrier properties.

3.3. Optical Properties of starch plastic sheet and starch/MCC composite

The light transmittance of starch plastic sheet and starch/MCC composite was examined using UV-Vis spectroscopy. As illustrated in Figure 7, the starch/MCC composite was dispersion displayed somewhat lower transmittance, but the starch plastic sheet dispersion displayed low absorbance, indicating great transparency. The cellulose fibers' introduction of structural imperfections and light-scattering surfaces is the cause of this discrepancy. Since light can travel through pure starch films with little scattering because of their homogeneity and consistent molecular structure, they are more transparent.

Conversely, this homogeneity is broken by the addition of cellulose, which results in less clarity. Furthermore, sulfate groups in the cellulose may have an impact on dispersibility through electrostatic interactions, but they also contribute to the composite's opacity.

When it comes to applications where optical clarity is crucial, starch-based plastics are more appropriate because they are generally more transparent than starch/MCC composites.

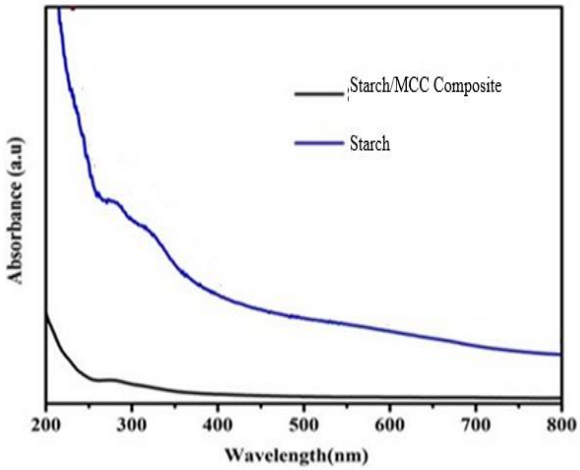

Fig. 7 Optical Properties of Raw starch without MCC, and starch & MCC composite

UV-Blocking properties

The bioplastic films demonstrated moderate UV-blocking ability, with reduced transmittance in the 200–400 nm region. This property is especially valuable in food packaging applications, where protection against UV degradation is essential.

3.4. Thermal analysis (TGA) of starch plastic sheet and starch /MCC composite

The thermal breakdown patterns of cellulose, starch, and their composite are displayed in Figure 8, based on the TGA results. Below 100 °C, all samples stayed stable and lost very little weight as a result of moisture evaporation. The evaporation of volatiles was the primary cause of the weight loss seen in starch and the starch /MCC composite between 100 °C and 250 °C. Dehydration and the breakdown of sugar units were connected to the onset of cellulose degradation above 230 °C, with notable degradation taking place beyond 300 °C. Because cellulose fibers and the starch matrix form hydrogen bonds, the starch /MCC composite showed better heat stability than pure starch. By strengthening the structure, these interactions postpone thermal breakdown.

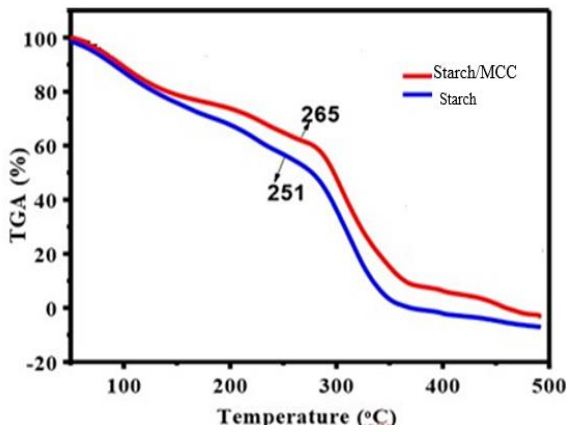

Fig. 8 Starch plastic sheet and starch /MCC composite

3.5. Water retention value of starch plastic sheet and starch /MCC composite

Starch and starch /MCC composite sheets were evaluated for their water absorption capacity. The water retention value (WRV %) decreased as the cellulose fiber content increased, indicating that the neat starch sheet had the highest moisture absorption due to its greater affinity for water (Figure 9). In contrast, the starch /MCC composite sheets exhibited lower water holding capacity, attributed to the strong hydrogen bonding network between starch and cellulose fibers, which hindered water penetration. This test demonstrates that incorporating cellulose fibers significantly enhances the limited application of starch by reducing its high-water sensitivity.

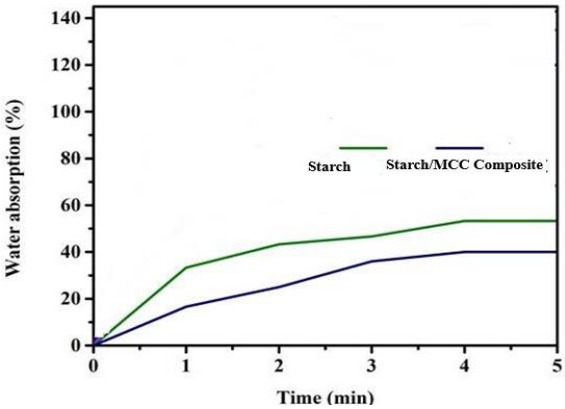

Fig. 9 Water retention value of starch plastic sheet and starch /MCC composite

3.6. Mechanical properties of the synthesized bioplastic

Determining mechanical characteristics is crucial for practical, scientific, and technical reasons. As a result, the mechanical characteristics of the produced bio-plastic are measured, including its tensile strength (TS) and percent of elongation at break (E). Table 1 displays the values of the parameters.

The mechanical performance, particularly tensile strength and elongation at break, was significantly improved by the inclusion of 5 wt% MCC. Similar enhancements have been reported by Rajic [16] and Cruz-Muniz [17], who used lignocellulosic fillers to reinforce starch-based polymers, highlighting the potential of biofillers in bioplastic engineering.

Table 1

Experimental results for the parameters of thickness, tensile strength, and elongation at break of the film

Property	Units	Starch bio-plastics	Starch/MCC Composite	
Samples	%	0% wt of MCC	1% wt of MCC	5% wt of MCC
Thickness	mm	0.847	0.833	0.830
Tensile strength	pa	714	1120	12,800,000
Elongation	%	3.245	4.427	6.528
** Note: Testing speed is 100 mm/minute, and sample size is 50 mm by 10 mm.				

The synthesized starch/MCC composite film, which contains 5 wt% MCC and demonstrates a tensile strength of 12.8 MPa, signifies a notable advancement compared to unreinforced starch films (714 Pa). This improvement aligns with earlier research that emphasizes the reinforcing properties of microcrystalline cellulose (MCC) in starch-based bioplastics.

Kalia [27] and Cherian [26] have documented comparable mechanical enhancements in starch and cellulose-reinforced systems, linking the increase in tensile strength to robust hydrogen bonding and effective interfacial adhesion between starch and MCC. Furthermore, El-Sakhawy and Hassan [20] validated that MCC, owing to its crystalline structure and fiber-like characteristics, enhances both the tensile strength and structural stability of bioplastics.

In comparison to conventional bio-based food packaging materials such as PLA, PHA, and starch blends, the starch/MCC film, with a tensile strength of 12.8 MPa, is situated within an acceptable range for semi-rigid packaging. While it exhibits lower elongation than petroleum-derived plastics, it maintains sufficient mechanical integrity for applications in dry food packaging.

Table 2

Comparison of Starch/MCC composite vs other bio-based food packaging materials

Material	Tensile Strength (MPa)	Elongation (%)	Thickness (mm)	Suitability for Food Packaging	Reference
Pure starch film	0.000714	3.25	0.847	Too weak mechanically	This study
Starch + 1% MCC	0.00112	4.43	0.833	Still very weak	This study
Starch + 5% MCC	**12.8**	**6.53**	**0.830**	Suitable for semi-rigid/dry food	This study
PLA (Polylactic acid)	30–60	6–10	0.02–0.10	Widely used	[5]
PHA (Polyhydroxyalkanoates)	20–40	3–15	0.02–0.10	Used for packaging, bottles	[14]
TPS/Glycerol composite	2–15	15–40	0.05–0.20	Flexible, low strength	[8]
MCC-reinforced starch film	10–20	5–10	~0.8	Comparable performance	[20]

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3.7. Sustainable development goals (SDG) and climate change impact

The development of bioplastics from agro-industrial waste such as avocado seeds and Enset fibers directly supports SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 9 (Industry, Innovation, and Infrastructure). These bioplastics offer reduced carbon emissions compared to petroleum-based plastics, limit microplastic pollution, and reduce reliance on fossil resources. Moreover, the use of agricultural waste aligns with the circular bioeconomy model highlighted in the 2023 UN SDG report. The process minimizes solid waste and energy use, indirectly contributing to SDG 6 (Clean Water and Sanitation) and SDG 14 (Life Below Water). Linking this with Industry 4.0 and 5.0 frameworks could further improve process efficiency and sustainability [36, 37, and 38].

4. Conclusion and recommendation

4.1. Conclusion

The current research effectively illustrated the preparation and characterization of bioplastic films made from avocado seed starch, which are reinforced with enset cellulose fibers. The addition of cellulose fibers markedly improved the mechanical strength, flexibility, and thermal stability of the bioplastic, establishing it as a sustainable and efficient alternative to traditional petroleum-based plastics. These improvements are ascribed to the robust intermolecular interactions, mainly hydrogen bonding between the starch matrix and the cellulose fibers. The utilization of agricultural by-products, particularly avocado seed starch and enset fibers, highlights the potential for waste valorization in the creation of biodegradable materials. This approach is consistent with the principles of a circular economy, wherein organic waste is converted into high-value, eco-friendly products, thus aiding in the mitigation of plastic pollution.

Chemical purification methods successfully eliminated non-cellulosic components, resulting in purified cellulose fibers. These fibers were extracted through high-shear mechanical treatment, and their incorporation into the starch matrix led to a significant enhancement in tensile strength and elongation at break, as demonstrated by mechanical testing. Fourier-transform infrared (FTIR) spectroscopy, along with transparency and thermal analyses, further corroborated the existence of strong fiber–matrix interactions within the composite. At the optimal fiber loading, the bioplastic displayed decreased transparency, which can be attributed to the bonding of cellulose fibers with the starch matrix through hydrogen bonds. This optical alteration, in conjunction with the mechanical reinforcement, underscores the dual function of fibers in altering both the physical and functional characteristics of the bioplastic.

In summary, the findings affirm that starch-based composites reinforced with enset cellulose fibers represent promising options for biodegradable packaging applications, merging environmental advantages with enhanced material performance.

4.2. Future work and recommendations

While the present study demonstrated the successful development of starch-based bioplastics reinforced with enset cellulose fibers, further research is recommended to optimize the formulation and broaden the application potential of these biodegradable materials.

A key limitation of this study is the lack of scanning electron microscopy (SEM) or other morphological analysis, which would have provided insight into the interfacial bonding and microstructure of the starch–MCC matrix. Future work should include SEM characterization and explore MCC concentrations above 5 wt% to further optimize mechanical properties, and the following directions are proposed for future work:

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1. **Barrier Property Analysis**: Evaluate the water vapor permeability, oxygen transmission rate, and overall barrier performance of the bioplastics to determine their suitability for various food packaging applications, especially those requiring moisture and gas resistance.
2. **Biodegradation Studies**: Conduct controlled biodegradation and compostability assessments under different environmental conditions (e.g., soil, marine, landfill) to validate the environmental sustainability of the material.
3. **Food Safety and Migration Tests**: Perform chemical migration and toxicity studies to ensure the material complies with food contact safety standards and regulatory requirements (e.g., FDA, EFSA).
4. **Shelf-Life Testing**: Investigate how the bioplastic affects the shelf life of packaged food products, particularly for dry and semi-moist foods.
5. **Nanocellulose Reinforcement**: Explore the use of **nanocellulose or cellulose nanofibers (CNFs)** in place of microcrystalline cellulose to further enhance mechanical, thermal, and barrier properties due to their higher aspect ratio and surface area.
6. **Plasticizer Optimization**: Assess the influence of various plasticizers (e.g., sorbitol, glycerol blends) on flexibility, water uptake, and mechanical stability over time.
7. **Scalability and Cost Analysis**: Evaluate the economic feasibility and scalability of bioplastic production using locally sourced agro-wastes like avocado seeds and enset fiber in industrial settings.
8. **Multi-Layer Film Development**: Design and test bioplastic-based multilayer films or composites with coatings to tailor the properties for specific applications, such as ready-to-eat food trays or biodegradable pouches.

By addressing these aspects, future studies can help transition this research from laboratory-scale formulation to real-world commercial applications, ultimately contributing to sustainable packaging solutions and the reduction of synthetic plastic waste.

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