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FDRE TECHNICAL & VOCATIONAL TRAINING INSTITUTE

FACULTY OF TEXTILE, APPAREL AND FASHION TECHNOLOGY

DEPARTMENT OF TEXTILE TECHNOLOGY

SCHOOL OF GRADUATE STUDIES A MASTER'S THESIS ON:

DEVELOPMENT AND CHARACTERIZATION OF BIOPLASTIC SYNTHESIZED FROM AVOCADO SEED AND CASSAVA STARCH WITH INTEGRATED ORANGE PEEL

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Addis Ababa, Ethiopia



FEDERAL INSTITUTE OF TECHNOLOGY

SCHOOL OF GRADUATE STUDIES

DEPARTMENT OF TEXTILE TECHNOLOGY

DEVELOPMENT AND CHARACTERIZATION OF BIOPLASTIC SYNTHESIZED FROM AVOCADO SEED AND CASSAVA STARCH WITH INTEGRATED ORANGE PEEL

A THESIS PROPOSAL (PART-II) SUBMITTED TO FEDERAL TVET INSTITUTE FACULTY OF TEXTILE TECHNOLOGY

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IN PARTIAL FULFILLMENT FOR THE DEGREE MASTER OF SCIENCE

IN TEXTILE TECHNOLOGY

BY: ANBESAW MUKET

ADVISOR: DR. FETENE FUFA (PhD)

Declaration

I undersigned and declare that this thesis titled “Develop and characterize bio plastic synthesize from avocado seed and cassava starch with orange peel integration” is my original work carried out under the supervision of Anbesaw Muket. It has not been presented for a degree in this or any other university and all sources of materials used for the thesis have been fully acknowledged.

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ANBESAW MUKET	_____	_____

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge

Name of advisor	Signature	Date
DR: FETENE FUFA (PhD	_____	_____

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ABSTRACT

In this study, cassava starch-avocado seed starch-pectin (CS/AS-pectin) bio plastic films were systematically developed, and the C-1 formulation—consisting of 70% cassava starch, 30% avocado seed starch, 20% glycerol, and pectin—was identified as the optimal composition based on a comprehensive evaluation of mechanical performance, water interaction behavior, structural integrity, and biodegradability. Mechanical characterization revealed that C-1 had a tensile strength of 6.75 MPa, an elongation at break of 32.5%, and a Young's modulus of 180 MPa, indicating a well-balanced combination of strength and flexibility, most likely due to synergistic interactions between the crystalline regions of cassava starch and the amorphous domains of avocado starch, which were further stabilized by glycerol and pectin as a plasticizing and network-forming agent. Water absorption and solubility analyses revealed increased moisture resistance (55% water uptake, 16% solubility), which can be attributed to increased hydrogen bonding, improved polymer chain packing, and pectin's network-compacting effect, which reduces water penetration while preserving film integrity. Biodegradation experiments conducted under soil burial circumstances revealed that about 50% of the material deteriorated over 28 days, demonstrating ecologically responsible disintegration without jeopardizing functional stability during service life. FTIR spectroscopy confirmed strong polymer-polymer and polymer-plasticizer interactions, indicating the formation of a cohesive molecular network, while SEM imaging revealed a smooth, uniform, and dense morphology with minimal phase separation, which was consistent with the mechanical and barrier properties. Overall, these findings establish C-1 as a very promising biodegradable material for sustainable packaging applications such as food wrap, fresh produce wrapping, and eco-friendly consumer items. Furthermore, the formulation provides a solid foundation for future enhancements such as Nano fillers, advanced plasticizers, or industrial production scaling strategies, indicating its potential for practical implementation in the emerging field of environmentally friendly bio plastics.

Key words: Cassava starch; Avocado seed starch; Orange peel pectin; Starch-based composites; Biodegradable films; Mechanical characterization; FTIR and SEM analysis

ABBREVIATIONS

AS — Avocado Seed Starch

CS — Cassava Starch

OPP — Orange Peel Pectin

CS/AS — Cassava–Avocado Starch Blend

CS–AS–P — Cassava–Avocado–Pectin Composite

BP — Bio-plastic

CBF — Composite Bio-plastic Film

FTIR — Fourier Transform Infrared Spectroscopy

SEM — Scanning Electron Microscopy

UTM — Universal Testing Machine

UV–Vis — Ultraviolet–Visible Spectrophotometry

TS — Tensile Strength

EB — Elongation at Break

YM — Young's Modulus

WA — Water Absorption

WS — Water Solubility

Gly — Glycerol (Plasticizer)

MPa — Megapascal

% — Percentage

mm — Millimeter

cm^{-1} — Wavenumber (FTIR unit)

ASTM — American Society for Testing and Materials

CHAPTER 1

1. INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Conventional plastics that are chemically altered consist of long-chain synthetic polymers, which are assembled into a variety of shapes and strengths to produce materials with a high molecular weight and extended durability. [1]

The market for plastic products is growing these days. Conventional plastics are required in such vast quantities and are preferred over other materials because of their exceptional long-term qualities, which include resistance to chemical reactions, particularly those caused by enzymes. However, because of the rise of plastic waste that raises environmental concerns, using conventional plastics for short-lived applications is not sustainable. This results from the fact that plastics are made from crude oil, a fossil fuel that is not renewable and hence pollutes the environment heavily.[2]

The original products may stay in our landfills for hundreds or even thousands of years since the plastics that do remain in them breakdown very slowly. The negative environmental effects of plastics made from petrochemicals are becoming more widely known. Many studies have been carried out to manage plastic waste on Earth by identifying environmentally suitable plastic substitutes. Bio-plastic are this environmentally beneficial substitute. [3]

Bio-plastic are defined as polymers that are bio based, biodegradable, and/or compostable by the European Bio-plastic Organization (EBO). Under either naturally occurring or artificially induced conditions, these bio-plastic break down primarily into carbon dioxide, water, and inorganic biomass due to the action of microorganism enzymes. [4]

Polymeric materials composed of or developed from biological products derived from biomass are referred to as bio based (Figure 1). The polymers are either generated by microbes through fermentative processes (e.g., polyhydroxyalkanoates, or PHA) using an appropriate carbon source, or they are directly extracted from the biomass (e.g., starch, cellulose). Moreover, plant

biomass can be chemically or biologically catalyzed to create the building blocks of other polymers, such as polyolefins and polylactide (PLA). [5]

Plastic that decomposes biologically Natural substances including water, carbon dioxide, and compost are produced via the chemical process of biodegradation, which is carried out by ambient microorganisms (no artificial additives are required). The substance, the application, and the surrounding environmental factors (such as location or temperature) all affect the biodegradation process. [6]

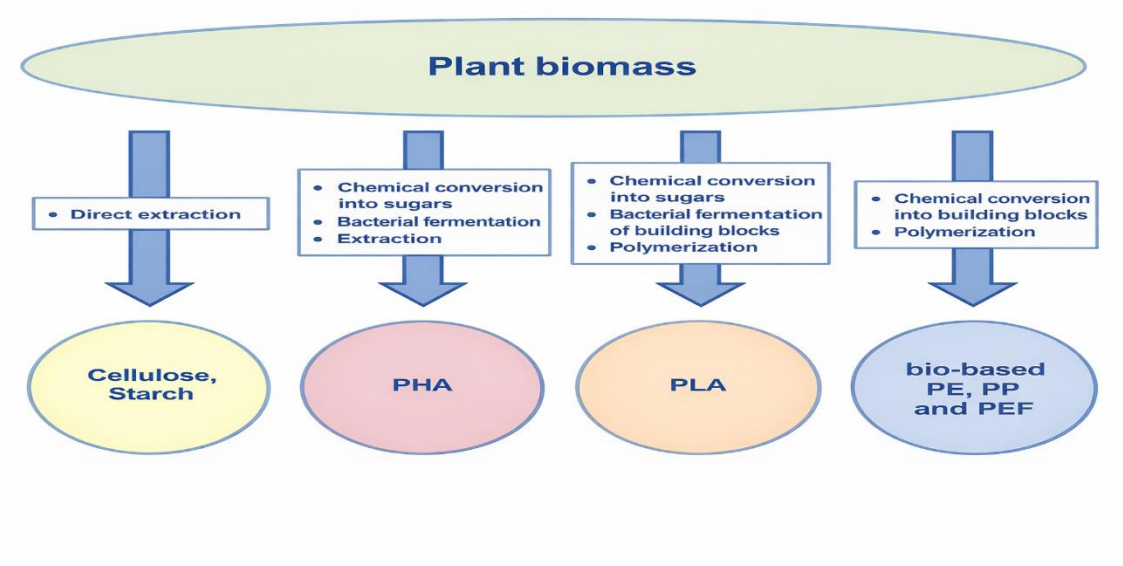


Figure 1 Classification framework of bioplastics based on source, biodegradability, and production pathway, illustrating the relationship between bio-based and biodegradable polymer categories.

Plants as a Source of Bio-plastic

Starch is the primary plant source utilized in the creation of bio-plastic. The naturally occurring polymer known as starch is made up of two different kinds of polymers called amylose and amylopectin.[7] Natural biodegradable polymers like starch have the potential to take the role of manmade polymers in short-term uses like cutlery and disposable packaging. Given that it is a cheap, plentiful, and renewable resource, biodegradable films made of it are frequently used for a variety of purposes. For example, avocado seeds, which are typically thrown away, contain about 30% starch. Therefore, it could be a source of starch.[4]

The starch that is suitable for making biodegradable plastics is includes. Using cassava starch. Tapioca starch. Red bean starch, corn starch. Among the many researchers, plastic that has tensile strength that meets SNI standards is from corn starch. However, the weakness of corn starch is less elastic than plastics from other starches. [8]

Other additives including cross-linking agents, nanoparticles, and other functional additives suited to a given use, like antimicrobial agents that aim to get rid of food preservatives, are also frequently included. Alternatively, because man-made polymer fibers are expensive and have environmental problems, natural polymers may eventually take their place.[9]

Another blending agent used is plasticizer. The plasticizer used in making this biodegradable plastic is glycerol. Glycerol is a neutral viscous liquid with a sweet taste and colorless, with a melting point of 20°C and a boiling point of 290°C. Glycerol is a good type of solvent because it can dissolve easily in water and alcohol, but not in oil. Glycerol is found in many animal and vegetable fats as glycerol esters of palmitic and oleic acids.[8]

1.2 STATEMENT OF THE PROBLEM

The environmental, health, and economic challenges posed by conventional plastics have reached critical levels. Derived from non-renewable fossil fuels, traditional plastics contribute significantly to global pollution, with over 400 million tons produced annually and less than 10% recycled.[10] This has led to the accumulation of plastic waste in landfills and natural ecosystems, where non-biodegradable plastics persist for centuries, breaking down into micro plastics that infiltrate food chains and pose risks to human health.[11] Furthermore, the reliance on fossil fuels for plastic production exacerbates climate change, with the sector accounting for approximately 6% of global oil consumption.[12]

In Ethiopia, growing concerns about plastic pollution have led to policy interventions targeting single-use plastic bags. Current regulations aim to **restrict or phase out single-use plastic bags** to reduce environmental degradation and promote sustainable consumption. However, the effectiveness of these policies remains limited by enforcement challenges and lack of sustainable material alternatives.[13]

In response, there is an urgent need to develop sustainable alternatives such as bio plastics, which are derived from renewable resources and offer biodegradability. Cassava, a widely

available and high-starch crop, has been extensively studied for its potential in bio plastic production due to its excellent film-forming properties and low cost.[14] Similarly, pectin, a natural polysaccharide extracted from orange peel—a common agro-industrial waste—has shown promise as a bio plastic component due to its biodegradability, mechanical strength, and ability to form flexible films.[15] Additionally, avocado seeds, an underutilized byproduct of the food industry, represent another sustainable source of starch for bio plastic applications.

This study investigates the extraction and characterization of starch from cassava and avocado seeds, combined with pectin from orange peel, to develop eco-friendly bio plastics. By leveraging these renewable and waste-derived materials, the research aims to address the dual challenges of plastic pollution and agricultural waste management. The findings will contribute to the development of sustainable materials, support circular economy principles, and align with global sustainability goals,[16] such as the United Nations Sustainable Development Goals (SDGs) 12 (Responsible Consumption and Production) and 13 (Climate Action).[17]

1.3 OBJECTIVE

1.3.1 General objectives

- Develop and characterize bio plastic synthesize from avocado seed and cassava starch with orange peel integration

1.3.2 Specific objectives

- To synthesize bio plastic films from cassava starch, avocado seed starch, and orange-peel derivatives using controlled formulation parameters.
- To characterize the mechanical, physicochemical, and microstructural properties of the developed bio plastics using standardized analytical techniques.
- To assess the water-interaction behavior and biodegradability of the bio plastics through absorption, solubility, and soil-burial tests.
- To optimize the composite formulation and identify suitable application areas based on performance outcomes.

1.4 SIGNIFICANCE OF THE STUDY

This work is important for several reasons, including how it advances sustainable materials and addresses environmental issues:

Addresses growing demand for sustainable alternatives: Because traditional plastics rely on non-renewable resources, produce pollution, and generate trash, they present serious environmental issues. This research investigates a unique bio-plastic material that may be produced using renewable resources, thereby providing a more environmentally friendly option.

Utilizes waste materials: The study encourages resource recovery and lessens dependency on virgin resources by combining avocado seed and orange peel, which are frequently regarded as waste materials.

Potential for improved sustainability: If well optimized, the created bio-plastic may provide advantages for the environment over conventional plastics:

- **Biodegradability**: May help lessen the amount of plastic trash that ends up in landfills and pollution.
- **Reduced environmental impact**: The manufacture of bio-plastic may have a lower environmental footprint in terms of pollution generation and resource usage than that of regular plastics.

Advances knowledge in bio-plastic development: This research contributes to the expanding field of bio-plastic by:

- The produced bio-plastic might benefit the environment more than traditional plastics if it is properly optimized:
- Biodegradability: May contribute to a reduction in the quantity of plastic waste that pollutes and ends up in landfills.
- Diminished environmental impact: Compared to the production of ordinary plastics, the production of bio-plastic might have a smaller environmental impact in terms of resource use and pollution generation.

Informs future research and development: The findings of this study can inform future research efforts in several ways:

- Directing more optimization: determining possible areas where the qualities or manufacturing techniques of the bio-plastic might be enhanced.
- Promoting the investigation of related bio-plastic: Providing impetus for studies on the utilization of other discarded or underutilized materials to produce bio-plastic.
- Aiding in the creation of sustainable materials: Contributing significant insights to the expanding corpus of studies aimed at identifying environmentally friendly substitutes for conventional plastics

1.5 SCOPE OF THE PAPER

The goal of this project is to solve the environmental issues related to traditional plastics by developing and characterizing a novel bio-plastic material. The scope includes utilizing leftover orange peel in combination with starches from avocado seeds and cassava, two easily obtained and renewable resources, to create bio-plastic. To attain targeted functionality and resource consumption efficiency, the study will involve creating and adjusting the composition of the bio-plastic. The mechanical qualities (strength, flexibility) and biodegradability of the produced bio-plastic will be assessed under controlled circumstances. Finally, considering the sustainability of bio-plastic in comparison to conventional plastics, the research will investigate possible uses for bio-plastic based on its attained qualities. By making use of waste materials and underutilized resources, this research seeks to aid in the creation of sustainable alternatives while providing insightful information about the characteristics and possible uses of these bio-plastic.

1.6 LIMITATIONS OF THE STUDY

Due to financial and laboratory facility limitations, this research study on the creation of bio-plastic from cassava and avocado seed starches with orange peel integration may run into difficulties. Here are a few examples of possible drawbacks.

1. Limited Access to Specialized Equipment:

- Advanced characterization techniques: In-depth examination of the content and microstructure of the bio-plastic may not be possible without sophisticated equipment such as advanced microscopy or high-performance chromatography. This might make it harder to comprehend how formulation and properties relate to one another.

- Pilot-scale processing: Because pilot-scale equipment is not readily available, the research may be restricted to lab-scale bio-plastic manufacturing. This limits the capacity to evaluate possible obstacles and refine production parameters for later, larger-scale production.

2. Budget Constraints:

Restricted investigation of other formulations: Financial limitations may make it impossible to investigate a wider variety of bio-plastic formulations with varied ratios and extra ingredients. This can make it more difficult to determine which formulation is best for a certain application.

3. Time Constraints:

Time and money restrictions may put a limit on how long biodegradation tests conducted under controlled settings can last. This might make it more difficult to comprehend the bio-plastic's biodegradation behavior in its whole over an extended period.

CHAPTER 2

2. LITREATURE REVIEW

2.1 INTRODUCTION

Petrochemical-based polymers, including polyethylene terephthalate (PET), polybutylene terephthalate (PBT), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC), are extensively utilized in daily applications due to their versatility, low cost, lightweight nature, and favorable thermal properties. These materials are commonly employed in the manufacture of single-use products such as beverage containers, disposable cutlery, food packaging, and retail carry bags. Despite their widespread use, petrochemical-derived plastics pose significant environmental concerns, primarily due to their substantial carbon footprint and persistence in ecosystems. Their economic viability, mechanical durability, and low density render them superior to traditional materials such as metals, wood, and paper in many industrial applications. Consequently, these synthetic polymers play a critical role across multiple sectors, including packaging, automotive, construction, and consumer goods.[18]

However, their non-biodegradability and reliance on fossil feedstocks necessitate the development of sustainable alternatives to mitigate long-term ecological impacts.

Bio-plastic is the term for plastic made from living things, including microbes, plants, and animals. This kind of plastic is distinct from polymers made from fossil fuels in numerous respects. Another name for bio-plastic made from biomass is bio-based plastic. Since they come from renewable resources and can break down through direct hydrolysis, they are often biodegradable. Today, a vast array of oil-based polymers is used as packaging materials in numerous industries. Because plastic created from fossil fuels is non-degradable and difficult to recycle, it is a major contributor to solid waste. This makes plastic leftovers one of the most significant concerns facing the modern world. Nowadays, bio-plastic plastics made from living things—have been produced by scientists to combat the waste of non-degradable plastic.

Bio-based polymers have been widely used for packaging in a variety of industries in recent years. The variety of disposable possibilities provided by bio-based polymers has incentivized researchers to promote ecological growth.[19]

2.1.1 BIODEGRADABLE POLYMERS

Both environmental degradation and recycling of these bio-plastic are highly feasible. Three phases make up the environmental breakdown of polymers: (1) Bio deterioration: Microorganisms grow within or on the surface of polymers, changing its chemical, physical, and mechanical properties; (2) Bio-fragmentation: Microorganisms act on the larger polymer units, breaking them down into smaller units called oligomers and monomers; and (3) Assimilation: Following the breakdown of polymers into smaller unit monomers, a significant amount of carbon, energy, and nutrient sources are released, which are then used by the microorganisms and transformed into water, carbon dioxide, and biomass.[20]

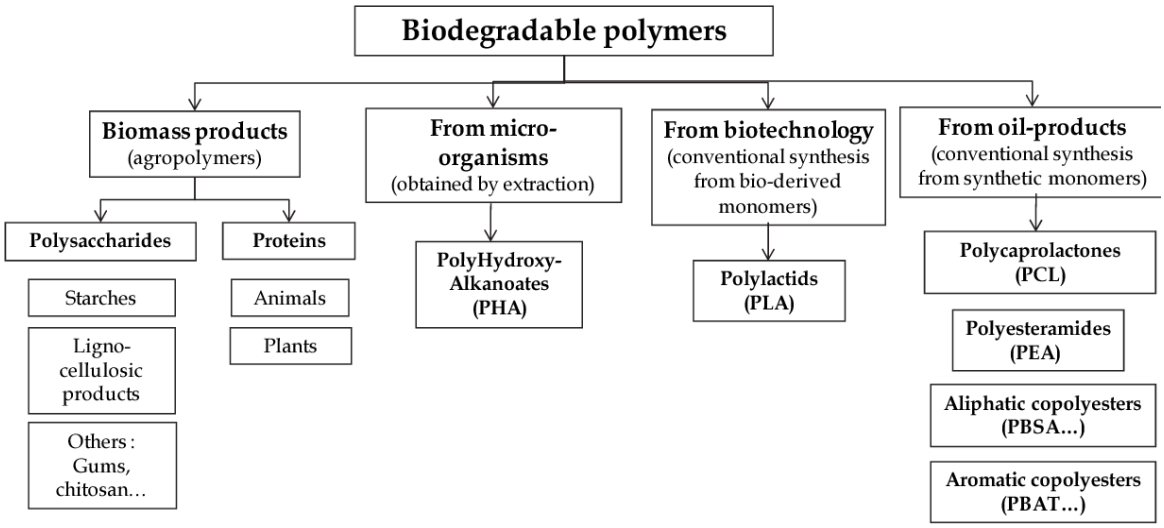


Figure 2 Systematic classification of biodegradable polymers according to origin and synthesis route, including agro-polymers, microbial polymers, chemically synthesized bio-based polymers, and fossil-derived biodegradable polymers.

Various biodegradable polymers have been proposed to be classified differently. Our suggestion is to categorize the biodegradable polymers based on how they were made (fig. 2): There are four types of polymers: (i) those made from biomass, such as agro-polymers made from agro-resources like starch or cellulose; (ii) those made by microbiological production, like polyhydroxyalkanoates (PHAs); (iii) those made chemically and conventionally from monomers made from agro-resources like polylactic acid (PLA); and (iv) those made from fossil resources. The first three categories (i–iii) are the only ones that come from sustainable sources. These biodegradable polymers can be further divided into two groups: biodegradable polyesters, or biopolyesters (categories ii–iv), and agro-polymers (category i).[19]

2.1.2 BIO-PLASTIC BASED ON POLYSACCHARIDES:

2.1.2.1 STARCH

Starch is a widely distributed, naturally occurring substance made up of the glucose polymers amylose and amylopectin. The usefulness and potential applications of starch are influenced by its physicochemical qualities, which are largely determined by the ratio of amylose to amylopectin. Though the branching structure of amylopectin typically results in a film with low mechanical qualities, this can be enhanced by introducing plasticizers like sorbitol and glycerol. A higher amylose concentration increases the strength of the film.[21]

Since the benefits are the main needs of a package, biopolymers made from starch are the most appropriate substitute for certain commercial uses. They also have superior biodegradability, renewability, and good oxygen barrier qualities.[22]

Many reports on the successful synthesis of bio-plastic from starch have been documented. Current reports on the synthesis of bio-plastic are presented in Table 1. Although strategies have shown a great impact on the successful synthesis of bio-plastic.[23]

Example of the current reports on the synthesis of bio-plastic

Type of carbohydrate	Raw material	Results
Cassava starch	Cassava starch, fiber, chitosan, and polystyrene foam	Foam tray from cassava starch with fiber and chitosan had the same mechanical properties as polystyrene foam
	Tapioca starch, cornstarch, polylactide, and methylene diphenyl diisocyanate (MDI), glycerol	The effect of adding MDI increased the tensile strength of bioplastics and great thermal properties. When without adding MDI, bioplastic surfaces were evenly distributed. On the contrary, the addition of MDI allowed the formation of aggregates on bioplastics surface

Cassava starch, polyvinyl alcohol (liquid), talc powder, glycerin, urea, and water	Biodegradability of bioplastic is slower than that of paper, which is because the paper is more organic than bioplastics Bio plastics from cassava starch had the highest tensile strength than polyvinyl alcohol and paper.
Cassava starch, glycerol, yerba mate extract	The addition of yerba mate extract accelerated the biodegradability of bioplastic in the soil
Cassava starch, glycerol, and water	The mechanical properties of bioplastics were influenced by glycerol and starch content. Glycerol content improved the elongation but it decreased the tensile strength and Young's modulus. Conversely, starch content increased the tensile strength and Young's modulus. Bioplastics with higher glycerol and starch content had a tensile strength of 7.0 MPa and elongation of 132.1%
Tapioca starch, glycerol, potassium hydroxide, sodium hydroxide, sodium chloride, acetic acid, sulfuric acid, and Cellulose Nanofibers	The addition of cellulose nanofibers as a reinforcing component increased tensile strength, thermal stability, absorption properties, and crystallinity
Cassava starch, sorbitol, lowdensity polyethylene (LDPE) and montmorillonite (MTT)	Additional LDPE provided good mechanical properties. LDPE allowed uniform and homogeneous morphologies compared to MTT

	Tapioca starch, zinc oxide as repair agents, glycerol, Escherichia coli, and staphylococcus aureus	The addition of 2% ZnO increased tensile strength and elongation. The thickness of biofilms that met Japanese Industrial Stan
Potato starch	Potato starch, yam starch, hydrochloric acid, and sodium hydroxide	Bioplastics made from potato starch and yam starch had a tensile strength of 0.6 MPa and 1.9 MPa. They experienced 50% of weight loss at temperatures of 250ºC and 310ºC. Biodegradation in the soil takes 1 week
Cassava peel	Cassava peel, sorbitol, and microcrystalline cellulose (MCC)	The effect of additional microcrystalline cellulose increased tensile strength. Bioplastics with the addition of 6% MCC had the highest tensile strength values. However, the addition of MCC decreased elongation, density, and water absorption
Avocado seed	Avocado seed, microcrystalline cellulose, glycerol, hydrochloric acid, potassium hydroxide, Sodium hypochlorite, sugar palm fibers, and water	Bioplastics from avocado seeds with the addition of microcrystalline cellulose obtained the best mechanical properties with a ratio of 7: 3 ratio with 2.74 MPa tensile strength and an extension of 3.61%. Bioplastic surface morphology is uneven and hollow
Durian seed	Durian seeds, ultrapure water, chitosan, acetic acid (0.1%), and lime water	Bioplastic from durian seeds had a tensile strength of 0.1158 MPa compared to the standard value, elongation of 2.1875%, and Young's modulus of 4.1515 MPa. The test results of bioplastics mechanical properties compared to bioplastic

		moderate are still far from the standard
Cornstarch	Cornstarch, sodium benzoate, dimethylsulfoxide, and photosensitizer	The best condition was obtained by adding 0.75% of sodium benzoate. The surface morphology is uniform and homogeneous
	Cornstarch, glycerol, and sorbitol	Bioplastics by casting method had a lower thickness and had a greater tensile strength compared to that by pressing and blowing method
	Cornstarch, polylactide, lysine diisocyanate (LDI)	Cornstarch decreased the thermal stability of bioplastic. LDI increased the temperature of thermal degradation (compared to bioplastic without LDI) and decreased biodegradability. LDI allowed a homogeneous surface morphology
	Cornstarch, potassium hydroxide, formaldehyde, resorcinol, and Saccharum spontaneum L. (SS	Addition of SS as an amplifier improved mechanical properties and thermal stability. Biopolymer degradation time with the amplifier requires 60 days
	Cornstarch, taro starch as, glycerol, and distilled water	Taro starch improved mechanical properties and thermal stability
	Cornstarch, banana pseudostem fiber (BSF), and glycerol	10% of BSF increased tensile strength and Young's modulus. The surface morphology of the fill particle in the aggregate bioplastic matrix

	Cornstarch, polydimethylsiloxane (PDMS), and Acetoxypolysiloxane (Acetoxy-PDMS; Elastosil E43)	Bioplastic prepared with PMDS has good elongation and tensile strength compared to that without PMDS. SEM Surface morphology was uniform and homogeneous
	Cornstarch, glycerol, white vinegar, titanium dioxide nanoparticles (TiO2) as reinforcing agents	TiO2 increased the tensile strength of bioplastics from 3.55 to 3.95 MPa, decreased elongation from 88 to 62%, and increased decomposition temperature. Morphology was a homogeneous surface with fewer cracks
	Cornstarch, distillers dried grain (DDGS), and phenolic resin	DDGS and phenolic resins improved mechanical properties. 25% of DDGS concentration gave good tensile strength. Up to 75% of DDGS increased biodegradability from 0 to 38% and reduced surface hardness
	Cornstarch, polypropylene (PP), calcium carbonate, Maleic anhydride grafted polypropylene (MAPP), Curauá fibers (CF), and potassium hydroxide	The addition of CF increased hardness, tensile strength, and Young's modulus, as well as decreased bio composite extension. Bioplastic had a homogeneous surface with the addition of CF and MAPP

Table 1 Summary of reported starch-based bio-plastic formulations and their corresponding mechanical, thermal, and biodegradation performance characteristics.

2.1.2.2 Avocado seed starch

The avocado fruit, also called the butter pear or alligator pear, is distinguished by having just one seed, which makes up 16% of the fruit weight and is protected by a hard shell. Although some research has indicated that avocado seeds can be used as a raw material for the manufacture of

oil and pigment, they are typically thrown away as byproducts in the environment. Depending on the cultivar, an avocado seed's starch content can amount to 74.47% of its dry weight.



Figure 3 Raw avocado seed used as a starch source for bio-plastic precursor extraction.

Chemical, enzymatic, and physical techniques can be used to modify starch to enhance functional qualities. The hydroxyl moieties in starch are esterified, resulting in the replacement of these hydroxyl moieties with acetyl groups and the acetylation reaction. The interactions between the amylopectin outer chains and the amylose chains are lessened because of this structural alteration. Because of this, acetylated starches are more stable, resistant to retro gradation, and capable of forming a paste at a lower temperature of gelatinization. The distribution of the acetyl groups, degree of substitution (DS), and starch supply all affect the functional characteristics of acetylated starch; these factors may also be connected to the swelling power (SP) and degree of gelatinization of the starch granule. Acetylated starches are mostly utilized as gelling agents, thickeners, and stabilizers.[24]

2.1.2.2.1 Starch Extraction of Avocado Seed Starch

After being thoroughly cleaned and chopped into small pieces, the avocado pits were immersed in distilled water containing 0.2% v/v sodium metabisulfite for a whole day while kept chilled. The raw material was crushed in an industrial mixer for five minutes with a 0.2% (v/v) sodium metabisulfite solution to extract the starch. The mixture was sieved through 200 meshes (0.074 mm) after homogenization. After re suspension in 0.2% sodium metabisulfite solution (v/v) after 24 hours of decantation, the supernatant was removed after centrifuging at 1105 g for 12 minutes.

The residue's surface was cleared of the mucilage that had developed there. After being dried for 12 hours at 40 °C in an oven, the starch residue was refrigerated and kept in a clean container. [25]

2.1.2.3 Cassava starch

Cassava starch is a carbohydrate extracted from the roots of the cassava plant (Manihot esculenta), a staple crop widely grown in tropical and subtropical regions. Known for its resilience in poor soil conditions and drought resistance, cassava is a critical food security crop, particularly in developing countries.[26]

Cassava is one of the carbohydrates crops those accounts for 10% of total carbohydrate crop consumption in the world after maize, wheat, rice, and potato. Cassava has been used for **4F** sectors, including food for humans, feed for animals, fuel for renewable energy, and factories using cassava materials.[27]



Figure 4 Cassava root tuber serving as the primary commercial starch feedstock for bio-plastic production.

The starch derived from its roots is a fine, white powder with a neutral taste and excellent functional properties, making it a valuable ingredient in both food and non-food industries.

In the food sector, cassava starch is commonly used as a thickening, binding, and stabilizing agent in products such as soups, sauces, baked goods, and gluten-free foods. Its ability to form clear, viscous gels and its compatibility with other ingredients make it a popular choice for food manufacturers.[28] beyond food, cassava starch is utilized in industries such as paper

production, textiles, adhesives, and biodegradable plastics, owing to its adhesive and film-forming capabilities.[29]

With increasing global interest in sustainable and renewable resources, cassava starch is also being explored for eco-friendly applications, including bio plastics and biofuels.[30] its affordability, versatility, and abundance position it as a key commodity in addressing both industrial and environmental challenges. As a result, cassava starch continues to play a significant role in global agriculture, food security, and industrial innovation.

2.1.2.3.1 Extraction of starch from cassava

Cassava tubers without visible defects are washed, peeled, rinsed with distilled water and grated. Distilled water is then added to the whole, which is crushed and macerated for 10 to 15 minutes. The liquid phase is separated from the tuber pulps by filtration. This operation is repeated 5 times until the liquid flowing out of the filtration is clear. The collected liquid called ―starch milk‖ is then decanted for 6 hours. The supernatant is removed and the deposited sediment is dried at 30°C in oven for 72 hours. The lumps obtained are then crushed and sieved. The powder starch is obtained and ready for use as a bio plastic feedstock.[31]

2.1.2.4 Orange peel

In addition to vitamins, orange peels also include soluble sugars, starch, hemicellulose, cellulose, pectin, lignin, ash, fat, protein, and trace amounts of acids including citric, malic, and malonic acid, which make up roughly 3.35% of the peel structure.



Figure 5 Orange peel biomass utilized as a pectin source for bio-plastic composite formulation.

2.1.2.4.1 Composition

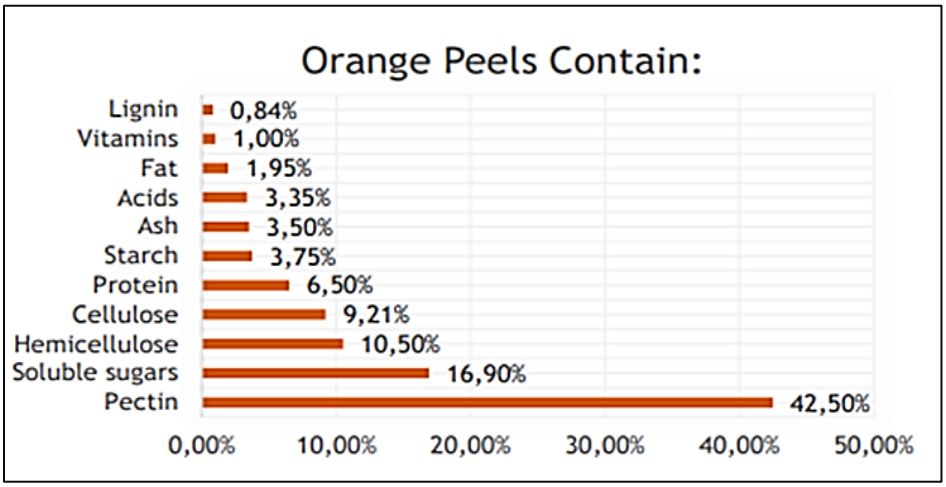


Figure 6 Major compositional fractions of orange peel, highlighting pectin, cellulose, hemicellulose, and minor constituents relevant to bio-polymer applications.

Pectin

Pectin is a structural member of the galacturonic acid-rich polysaccharide family and is employed as a gelling agent in the food industry. It can be utilized in sweets, fillings, and juice beverages as a kind of stabilizer [32]. About 43 percent of the pectin found in orange trash is present.

The many carbohydrates that make up orange peel pectin include rhamnose, galactose, arabinose, and pectic acid. Flavonoids, phenolic acids, and citric acid are among the other substances that are present in trace amounts. Depending on the oranges' origin, the extraction technique, and the purification step, orange peel pectin's precise makeup can change.[33]

Orange peel has a high cellulose content, which can be used to produce glucose and eventually biodegradable plastics. This presents a possible source of bio-plastic. Furthermore, lignin and hemicellulose fractions can be added to or modified to improve the qualities of bio-plastic.[34]

CHAPTER 3

3 MATERIALS AND METHODOLOGY

The methodology describes how to integrate orange peel with cassava and avocado seed starches to create and define bio-plastic. Researchers and business experts in this subject can use the flow chart as a reference because it offers a clear and simple description of the procedure.

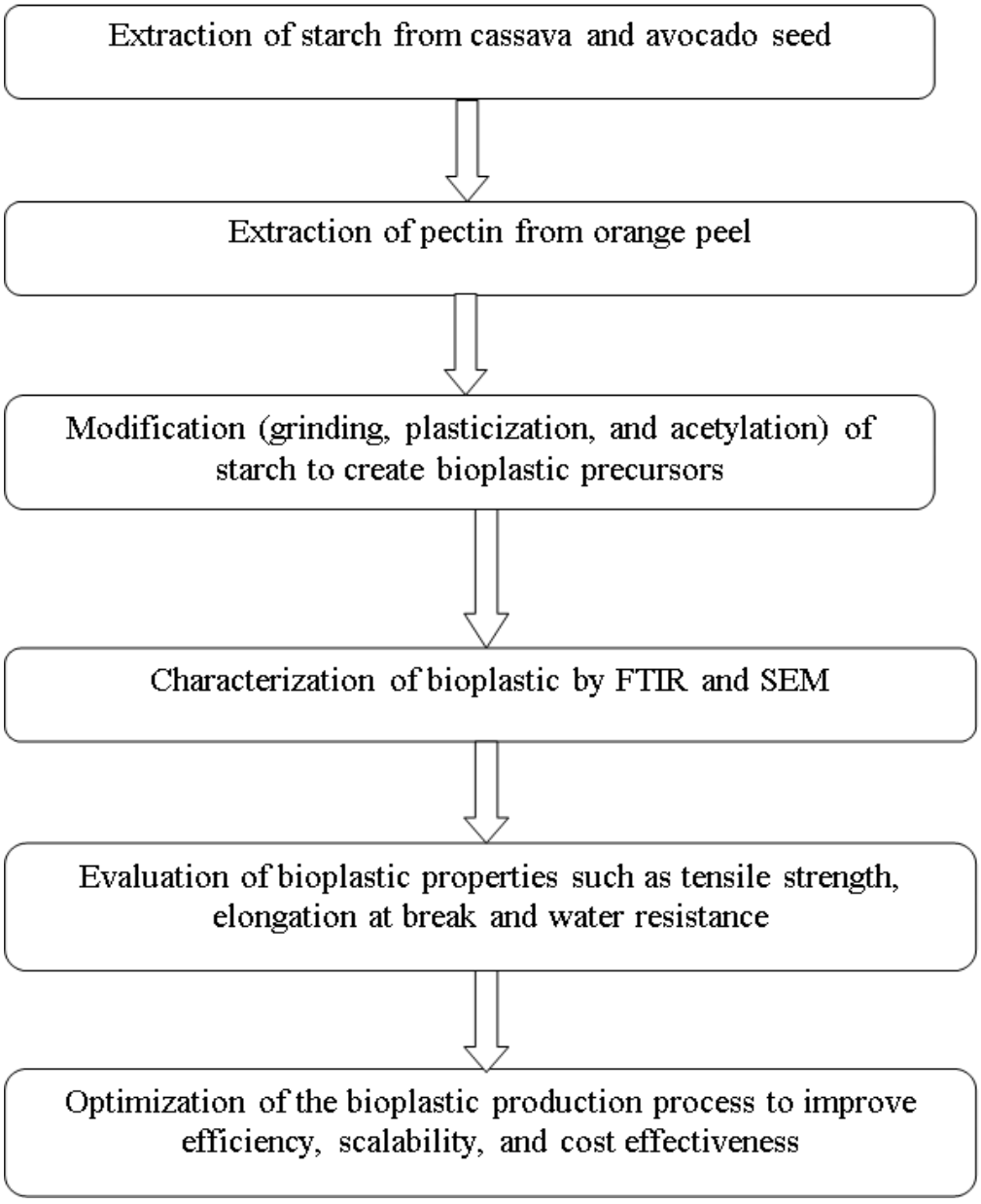


Table 2 Overall material preparation and experimental methodology flow sequence for composite bio-plastic development.

Materials and Equipment Table

Category	Item	Specifications/Details
Materials	Cassava starch	Extracted from cassava root
	Avocado seed starch	Extracted from avocado seeds
	Orange peel pectin	Extracted from orange peels
	Glycerol	Plasticizer, 99% purity
	Distilled water	Solvent
Equipment	Weighing balance	Precision ±0.001 g
	Magnetic stirrer/hot plate	For mixing and heating
	Casting Molds	Flat glass plates or Teflon Molds
	Oven	For drying films at 50–60°C
	FTIR spectrometer	For structural analysis
	Tensile testing machine	ASTM D882 standard for mechanical properties
	Water vapour permeability setup	ASTM E96 or ISO 2528 standard
	Scanning Electron Microscope (SEM)	For surface and cross-sectional morphology analysis
	Soil burial setup	For biodegradability testing
	pH meter	For pectin extraction
	Grinder/blender	For grinding avocado seeds and orange peels
	Sieve	For starch extraction (e.g., 100–200 mesh)
	Beakers, flasks, and stirrers	For mixing and preparation

Table 3 Materials, chemicals, and analytical equipment used in bio-plastic production and characterization.

3.1 CASSAVA STARCH EXTRACTION

The extraction process of cassava starch is according to research that has been done previously by Natalia and Muryeti. [35] The cassava is cleaned from the cassava roots and removing the outer skin (A) and washed with clear washing water (B), after that cutting fresh cassava roots into small chunks (C). The cassava is mashed using a blender until it becomes porridge (D). The cassava slurry is then finely filtered and allowed the starch to settle for a period, (E) typically at room temperature for about 24 hours. After the precipitation period, the resulting cassava precipitate, namely primarily starch is separated from the water. The separated starch is then dried to remove excess moisture. The dried starch precipitate is filtered to achieve a particle size of 100 meshes. (F)



A



B



C



D





E F

Figure 7 Stepwise cassava starch extraction process including washing, peeling, size reduction, slurry formation, sedimentation, and drying.

3.2 AVOCADO STARCH EXTRACTION

The extraction process of avocado seed starch is according to research that has been done previously by jamenez, [36] After being thoroughly cleaned (A) and chopped into small pieces(B), the avocado pits were immersed in distilled water containing 0.2% (v/v) ascorbic acid for 24 hours while kept chilled. The soaked pits were then crushed in an industrial mixer for five minutes with a 0.2% (v/v) ascorbic acid solution to extract the starch(C). The resulting mixture was homogenized and sieved through a 200-mesh (0.074 mm) screen to separate the starchy liquid from fibrous material(D). The filtrate was allowed to settle for 24 hours, after which the supernatant was carefully decanted to isolate the starch sediment (E). To remove any mucilage formed on the surface of the residue, the starch was washed multiple times with distilled water and allowed to settle again. Finally, the purified starch was dried in an oven at 40 °C for 12 hours, (F) refrigerated, and stored in a clean, airtight container for further use.







A B C



D



E



F

Figure 8 Avocado seed starch extraction workflow showing pretreatment, grinding, sieving, sedimentation, purification, and low-temperature drying stages.

3.2.1 DETERMINATION OF AMYLOSE AND AMYLOPECTIN OF THE EXTRACTED STARCH

Amylose content of starch was determined following a reported method K.J Kumar and as per equation (6). Starch, 0.1 g, was weighed and mixed with 9 ml of 0.1 N NaOH solutions and 1 ml of 95% ethanol.)e starch suspension in the solution was continuously stirred and boiled for 10 min. starch suspension was then transferred to a beaker and diluted with 50 ml of distilled water. A 5 ml aliquot of the starch suspension was added to the volumetric flask. 5 ml solution was then diluted to 100 ml with 1 ml of 1 N acetic acid and 2 ml of iodine solution and mixed well. Solution was scanned using a UV-Vis spectrophotometer at 620 nm wavelength to determine the absorbance of the starch suspension solution. Amylopectin content in starch was also determined by subtracting the amylose percentage.

$$Am(\%) = 3.06 * A * 20, \quad (6)$$

$$Ap(\%) = 100 - Am(\%), \quad (7)$$

Where Am =amylose content, A = absorbance, Ap = amylopectin content, and 3.06 is the conversion factor.

Amylose and amylopectin levels, as well as granule size, have a substantial impact on starch characteristics such as water absorption, gelatinization, pasting behavior, and susceptibility to enzyme assault. UV-vis spectrophotometry is often used to assess amylose content by measuring the absorbance of a reference sample at 620 nm. This approach yielded an amylose content of 17 ± 0.03% in avocado starch and an amylopectin concentration of 83.2 ± 0.11% by difference, consistent with recent findings Luiss Chel. Cassava starch, derived from the cassava root,

comprises around 25 ± 0.05% amylose and 75 ± 0.05% amylopectin. The observed variation in amylose and amylopectin content in both starches could be significantly influenced by factors such as botanical genotype, soil type, climatic conditions, and harvesting time, highlighting the importance of environmental and genetic factors in starch composition and functional properties.

3.3 PECTIN EXTRACTION

Dried orange peel is first ground into small pieces (A). This powdered peel is then mixed with distilled water and a small amount of dilute hydrochloric acid to create an acidic environment, which is essential for pectin extraction.[37] The mixture is subsequently heated on a hot plate while being stirred continuously. After heating, the mixture is filtered to separate the liquid (containing the extracted pectin) from the solid residue. Ethanol is then gradually added to the liquid, causing the pectin to precipitate out as a jelly-like substance. The precipitated pectin is collected, washed with ethanol to remove any impurities, and finally dried in an oven at a low temperature. The yield of pectin is then calculated based on the weight of the dried pectin obtained.

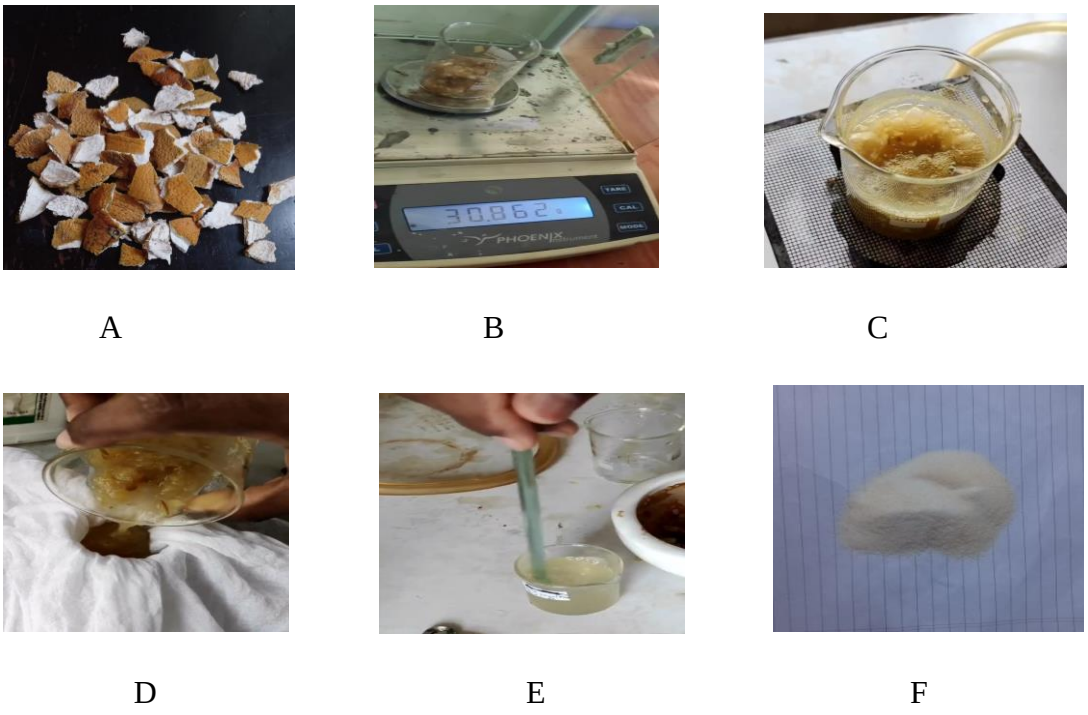


Figure 9 Acid-assisted pectin extraction process from orange peel followed by filtration, alcohol precipitation, and drying.

3.4 BIO PLASTIC PRODUCTION

Bio plastic formulations were created by changing the cassava starch (CS) to avocado seed starch (AS) ratios in five groups: 100/0, 0/100, 70/30, 50/50, and 30/70. Each starch ratio was created at three different glycerol levels (20%, 25%, and 30%), resulting in 3.0 g, 3.75 g, and 4.5 g of glycerol per batch. All formulations used a constant 3 g of pectin as a co-polymer and 200 mL of water as the processing medium. The A- and B-series reflect pure cassava and avocado starch baselines, respectively, whereas the C-, D-, and E-series assess mixed-starch interactions under the same plasticizer and pectin conditions. This organized architecture enables a systematic study of how starch composition and glycerol concentration affect film development and performance.

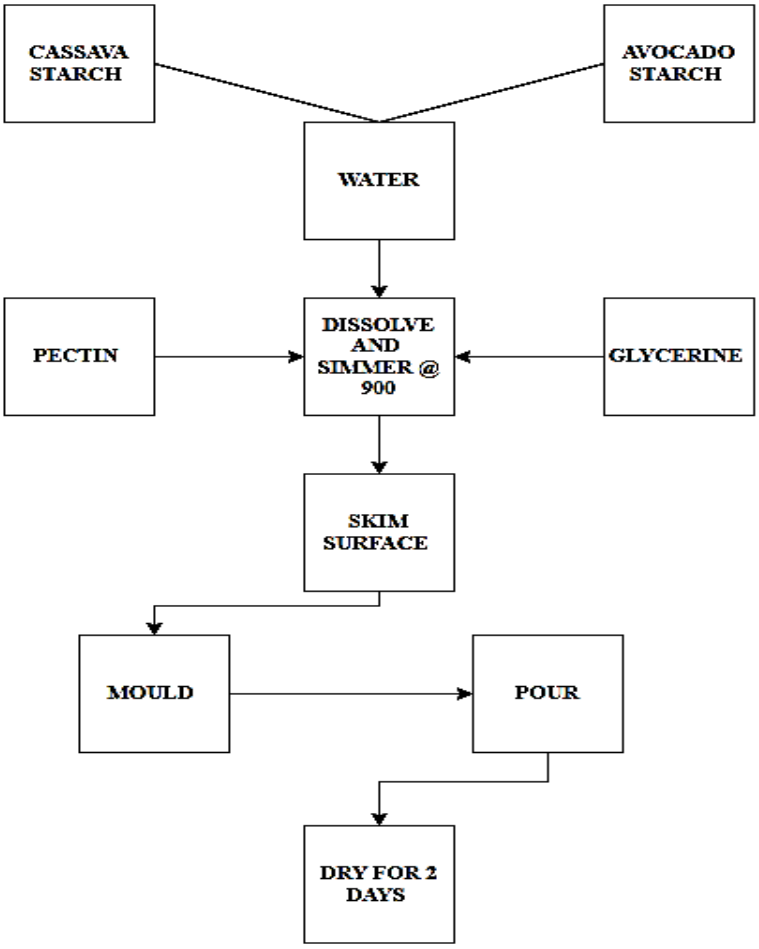


Figure 10 Process flow chart of composite bio-plastic film production from cassava starch, avocado seed starch, and orange peel pectin.

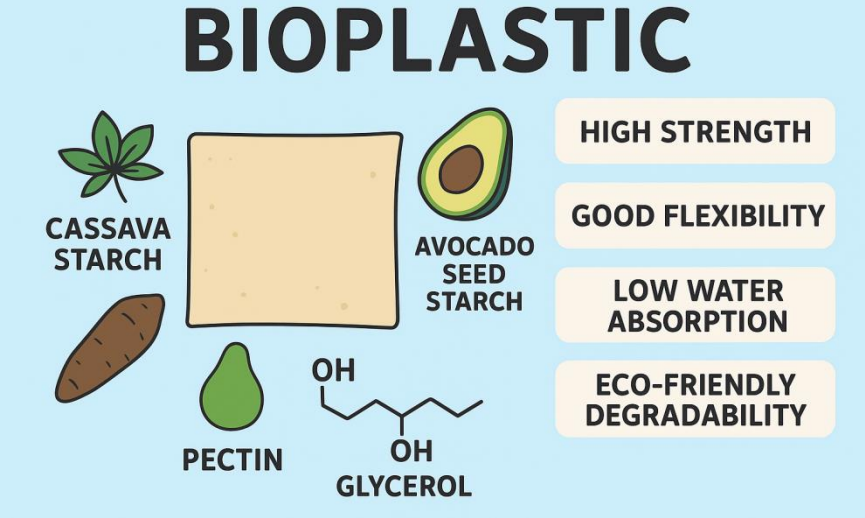


Figure 11 Conceptual model of the starch–pectin–plasticizer bio-plastic composite structure.

3.5 EXPERMENTAL DESIGN

Run	CS/AS (%)	Glycerol (%)	Gly (g)	Pectin (g)	Water (mL)
A-1	100/0	20	3	3	200
A-2	100/0	25	3.75	3	200
A-3	100/0	30	4.5	3	200
B-1	0/100	20	3	3	200
B-2	0/100	25	3.75	3	200
B-3	0/100	4.5	4.5	3	200
C-1	70/30	20	3	3	200
C-2	70/30	25	3.75	3	200
C-3	70/30	30	4.5	3	200
D-1	50/50	20	3	3	200
D-2	50/50	25	3.75	3	200
D-3	50/50	30	4.5	3	200
E-1	30/70	20	3	3	200
E-2	30/70	25	3.75	3	200
E-3	30/70	30	4.5	3	200

Table 4 Experimental design matrix showing cassava/avocado starch ratios, glycerol levels, pectin content, and processing water volume for all formulations.

Variables: Cassava starch, glycerol, Avocado seed starch and orange peel pectin are varied to study their effects on bio plastic properties.

Response Variables to Measure

After preparing the bio plastic films, evaluate the following properties for each experiment:

* Tensile Strength (MPa).
* Elongation at Break (%).
* Water solubility and absorption (%).
* Biodegradability (% weight loss over time).

3.5 CHARACTERIZATION AND EVALUATION OF BIO PLASTIC

Functional Groups Analysis

3.5.1 FTIR

The FTIR (fingerprint) is a characterization based on the vibrations of atoms or molecules by passing infrared radiation through a material or sample in which the energy corresponds to the wave frequency. The absorbance bands of the functional groups in the material are used to identify the substance properties.[38]



Figure 12 FTIR spectroscopy setup used for functional group and molecular interaction analysis of bio-plastic films.

3.5.2 SEM

SEM analysis technique allows examining of changes in the morphology of materials at the micro scale. In order to perceive monitoring and the changes in the structure of the samples, images from the SEM were used. All samples were subsequently submitted for SEM.[39]

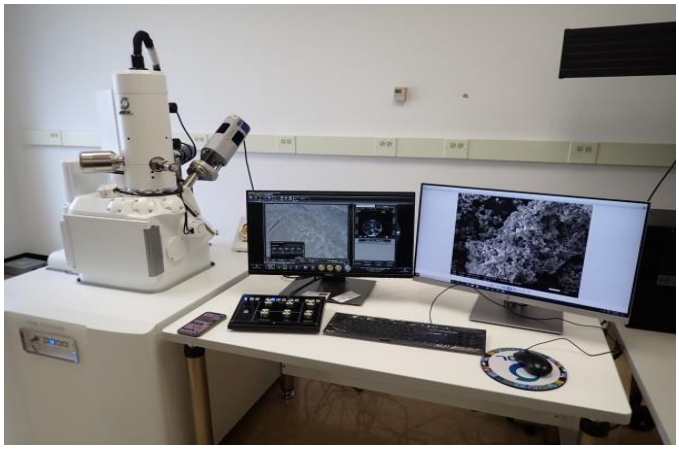


Figure 13 Scanning Electron Microscopy (SEM) system used for microstructural and surface morphology characterization of bio-plastic samples.

3.5.3 Biodegradability

A soil-burial degradation test was used to assess biodegradation behavior. 20 x 20 mm bio plastic specimens were oven-dried to a consistent mass and their initial weight was noted before burial. To monitor the pace of degradation, samples were inserted into biologically active soil at a depth of around 8 cm and removed at prearranged intervals.

In order to evaluate microbial degradation, specimens were carefully cleaned after recovery, re-dried to a consistent mass, and the amount of mass loss was measured.

$$\text{Microbial Resistance (\%)} = \frac{\text{Final Mass} - \text{Initial Mass}}{\text{Initial Mass}} \times 100$$

was used to compute microbial resistance in addition to mechanical and visual deterioration, offering an additional indicator of material stability under soil microbial activity. Once the samples showed significant or total mass loss, overall biodegradability was assessed.[40] [41][42][43]

3.5.4 Mechanical properties

In accordance with ASTM D-882, mechanical properties were assessed. A Universal Testing Machine (UTM) with a crosshead speed of 8 mm min^{-1} was used to evaluate bio plastic samples that were 8 cm by 10 cm and had a thickness of less than 1 mm. Young's modulus, tensile strength, and elongation were calculated in accordance with ASTM D5336 using the formulas.[44]

3.5.4.1 Tensile-Strength (MPa)

The tensile test is performed by drawing the test object from two directions, increasing the length while decreasing the diameter. The amount of load and length increase is measured during the test. Tensile strength refers to the greatest load that a material can withstand.[45] [46]

$$TS = \frac{Fmax}{A0}$$

Where: TS = tensile-strength, F_{max} = maximum force, A_0 = initial surface width

3.5.4.2 Elongation (%)

Percentages are computed by comparing the length of the film upon break to the length of the film before being tugged by the Tensile Strength Elongation Tester. The Elongation Percentage formula may be used to compute the mathematical elongation.[47]

$$\text{Elongation Percentage } (\%) = \frac{(L1 - L0)}{L0} * 100\%$$

Where: L_1= the final length of the test object, L_0= the initial length of the test object

3.5.4.3 Young's modulus

Measures the stiffness of the material, calculated from the initial linear portion of the stress-strain curve. $E = \frac{\sigma}{\varepsilon}$

where σ is stress and ε is strain in the elastic region.

3.5.5 Water resistance

Water resistance refers to the ability of a material to resist the penetration or absorption of water. In the context of bio plastics, water resistance is a critical property because it determines how well the material can withstand exposure to moisture or water without losing its structural integrity, mechanical properties, or functionality.

3.5.5.1 Water Absorption Test:

The bio plastic films' moisture absorption characteristics were assessed in accordance with ASTM D570 to ascertain their hydrophilicity and water-uptake behavior. Prior to testing, all samples were oven-dried at 50 °C for 24 hours, chilled in a desiccator, and weighed to establish the initial dry mass (W_i). The dried films were then cut into predetermined dimensions of 20 mm × 20 mm and fully immersed in distilled water at ambient temperature for a 24-hour soaking period. After immersion, the samples were removed, carefully wiped with a soft towel to eliminate surface moisture without causing structural damage, and promptly reweighed to determine the wet mass (W_f). Water absorption (%) was determined using the expression:

$$\text{Microbial Resistance (\%)} = \frac{\text{Final Mass} - \text{Initial Mass}}{\text{Initial Mass}} \times 100$$

This method provides a quantitative measure of the water uptake capacity of bio plastics and allows assessment of how variations in cassava starch–arrowroot starch ratios and glycerol concentrations across the 15 formulations influence moisture sensitivity, swelling behavior, and the overall suitability of the films for applications requiring controlled hydrophilicity.[48]

3.5.5.2 Water solubility

The durability and resistance to dissolution of the bio plastic sheets in aquatic conditions were evaluated by measuring their water solubility. Circular film samples (diameter: 6 cm) were initially oven-dried at 105 °C for 6 hours to acquire the initial dry mass (mi). The dried films were then submerged in 40 mL of distilled water at 25 °C with gentle agitation for 24 hours. After immersion, the un-dissolved sections of the films were carefully filtered and oven-dried again at 105 °C until a consistent weight (mf) was attained. The water solubility (%) was computed using the following formula:

$$\text{WS} = \frac{\text{mi} - \text{mf}}{\text{mi}} * 100$$

This method gives a quantitative assessment of the fraction of the bio plastic film lost to water dissolution. Applying this method to all 15 ratios.[49]

CHAPTER 4

4. RESULT AND DISCUSSION

This section presents and critically evaluates characteristics of bio plastics made from cassava and avocado seed starch, as well as glycerin and pectin. Mechanical performance, structural characterization (FTIR and SEM), biodegradability, and water interaction qualities (absorption and solubility) are all discussed. The emphasis is on comprehending how starch composition and plasticizer concentration affect molecular interactions, microstructure, and functional behavior. This section contributes to the design and development of ecologically friendly bio plastic materials by linking formulation factors with reported mechanical, structural, and degradation responses.

4.1 FTIR

The bio plastic's FTIR spectrum displays typical cassava starch-based polymer characteristics, including modest peak shifts consistent with glycerol-starch interactions.

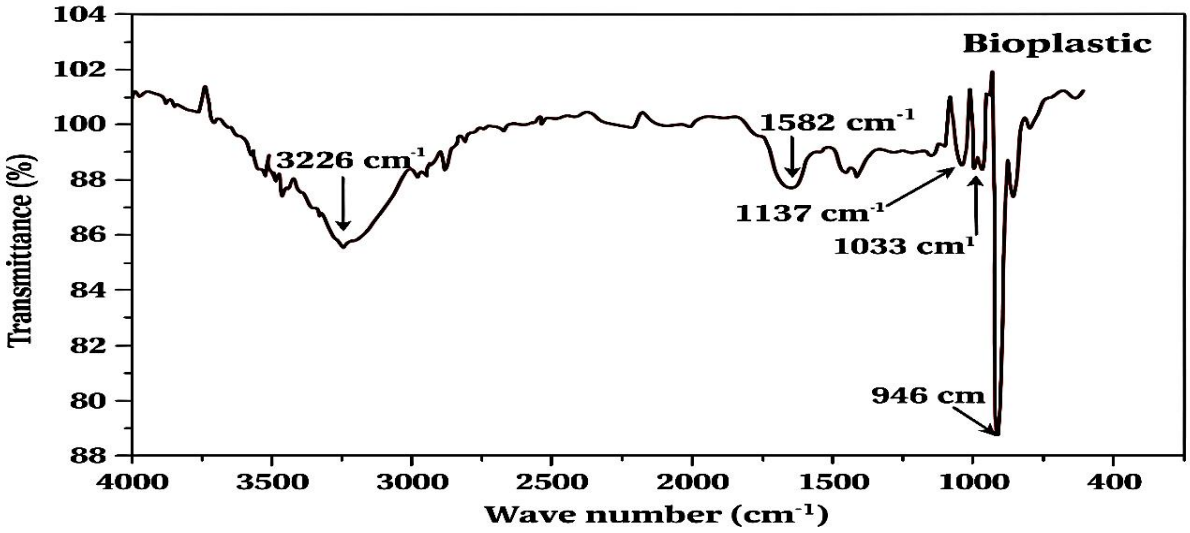


Figure 14 FTIR spectrum of cassava-starch-based bio-plastic film showing characteristic polysaccharide absorption bands.

Extensive hydrogen bonding within the biopolymer matrix is shown by a wide absorption about ~3226 cm^{-1}. A moderate band at ~1582 cm^{-1} shows water absorption and slight hydroxyl group deformation. The peaks at ~1137 cm^{-1} and ~1033 cm^{-1} are attributable to C-O-C and C-O

stretching of polysaccharide rings, indicating the maintained starch structure. The strong signal at ~946 cm^{-1} indicates glycosidic C-H deformation, indicating an intact α-1,4/α-1,6 linkage structure. Overall, the spectrum demonstrates the effective creation of a starch-glycerol bio plastic with conventional polysaccharide signatures and modest spectral alterations associated with plasticization.

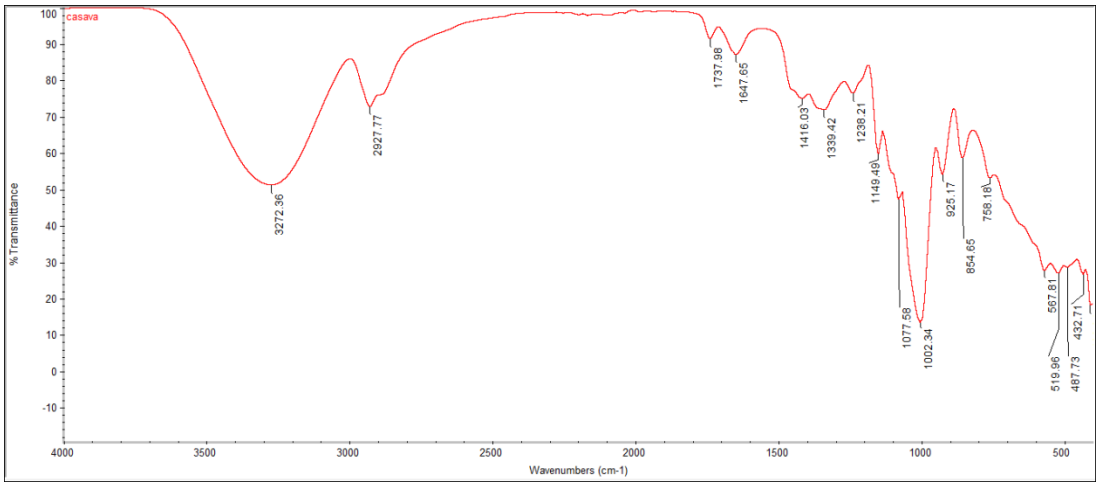


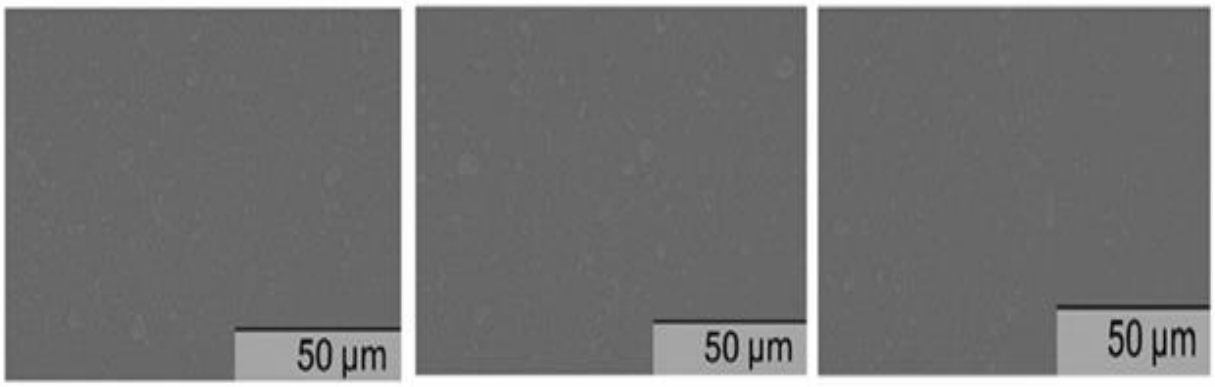
Figure 15 FTIR spectrum of cassava–avocado starch–pectin composite bio-plastic demonstrating enhanced intermolecular bonding features.

FTIR examination (Figure 15) demonstrates the effective integration of cassava starch, avocado seed contents, and orange-peel pectin into the composite films. The wide O-H stretch at ~3272 cm^{-1} shows substantial hydrogen bonding among starch hydroxyls, pectin, and glycerol, whereas the aliphatic C-H band at ~2928 cm^{-1} confirms the presence of the polymeric backbone and plasticizer. The carbonyl vibration at ~1738 cm^{-1} is related to ester groups in pectin (and small lipid residues). The neighboring bands at ~1648 cm^{-1} and ~1416 cm^{-1} reveal carboxylate/water interactions, implying partial de-esterification and ionic character of pectin within the matrix. Strong C-O-C/C-O absorptions in the 1150-1000 cm^{-1} area confirm the polysaccharide glycosidic structure. These spectrum signatures together imply molecular-level compatibilization (hydrogen bonding and ionic interactions) between starch and pectin, which contributes to the composite's mechanical integrity and altered water-interaction behavior.

4.2 SEM

Three SEM micrographs (50 µm scale) for the optimized sample reveal uniform, compact, and homogenous film surfaces with no notable fractures, holes, or phase-separation domains, indicating a well-integrated polymer matrix. The faint distributed micro-features observed on the

surfaces indicate adequate starch-biopolymer dispersion and gelatinization during film production. Overall smoothness and minimum surface imperfections indicate good intermolecular compatibility, effective plasticizer dispersion, and a stable structural morphology that is suitable for mechanical performance and regulated water interaction.



C-1 **C-2** **C-3**

Figure 16 SEM micrograph of optimized bio-plastic formulation (C-1) showing dense, uniform, and low-porosity morphology.

4.3 Mechanical Properties

Sample	Cassava/Avocado	Gly (%)	TS (MPa)	El (%)	Modulus (MPa)
A-1	100/0	20	7.50	25.0	210.0
A-2	100/0	25	5.75	32.5	140.0
A-3	100/0	30	4.00	47.5	80.0
B-1	0/100	20	5.50	55.0	140.0
B-2	0/100	25	4.25	75.0	100.0
B-3	0/100	30	2.75	120.0	52.5
C-1	70/30	20	6.75	32.5	180.0
C-2	70/30	25	5.00	45.0	120.0
C-3	70/30	30	3.65	65.0	72.5
D-1	50/50	20	6.00	42.5	162.5
D-2	50/50	25	4.65	60.0	110.0
D-3	50/50	30	3.25	90.0	65.0

E-1	30/70	20	5.75	52.5	145.0
E-2	30/70	25	4.00	70.0	102.5
E-3	30/70	30	2.80	110.0	57.5

Table 5 Mechanical performance results of bio-plastic films including tensile strength, elongation at break, and Young's modulus.

The starch composition and glycerol concentration had a significant impact on the mechanical performance of bio plastic sheets (Table 5). Pure cassava starch films (A-series) had the maximum tensile strength (7.50 MPa for A-1) and modulus (210 MPa), indicating a dense polymer network and strong hydrogen bonding inside the cassava starch matrix. However, these films were rather brittle, as seen by their modest elongation at break (El: 25%). Increasing glycerol content from 20% to 30% gradually reduced TS (4.00 MPa for A-3) and modulus (80 MPa) while significantly increasing elongation (47.5%), demonstrating glycerol's plasticizing effect, which improves chain mobility, flexibility, and ductility at the expense of mechanical strength.

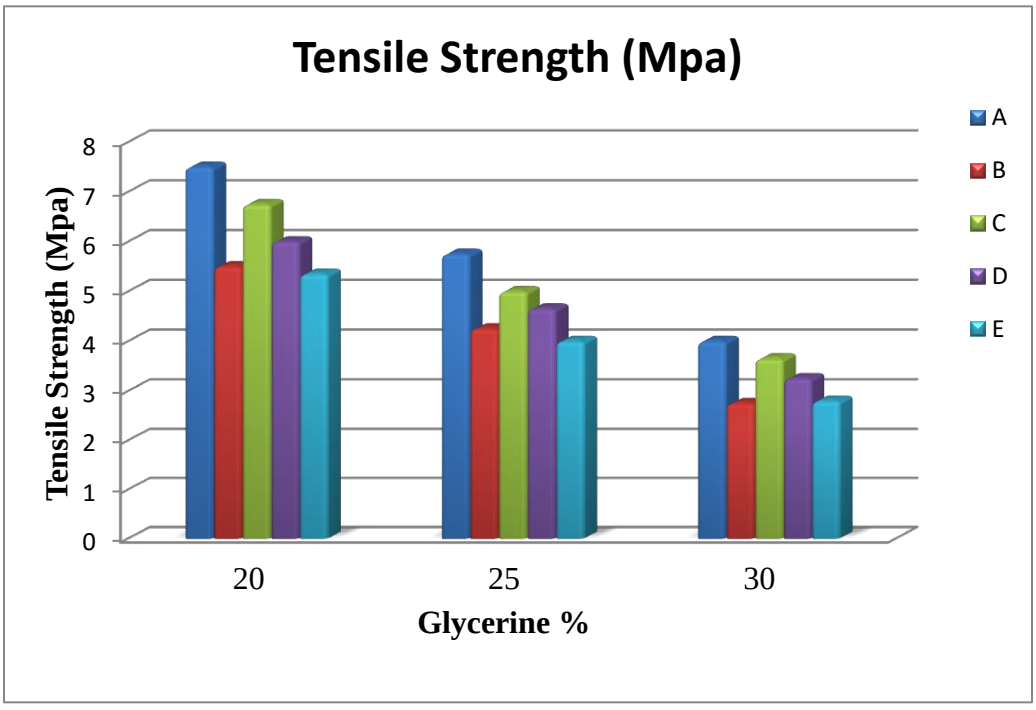


Figure 17 Comparative tensile strength results of all bio-plastic formulations under ASTM D882 testing conditions.

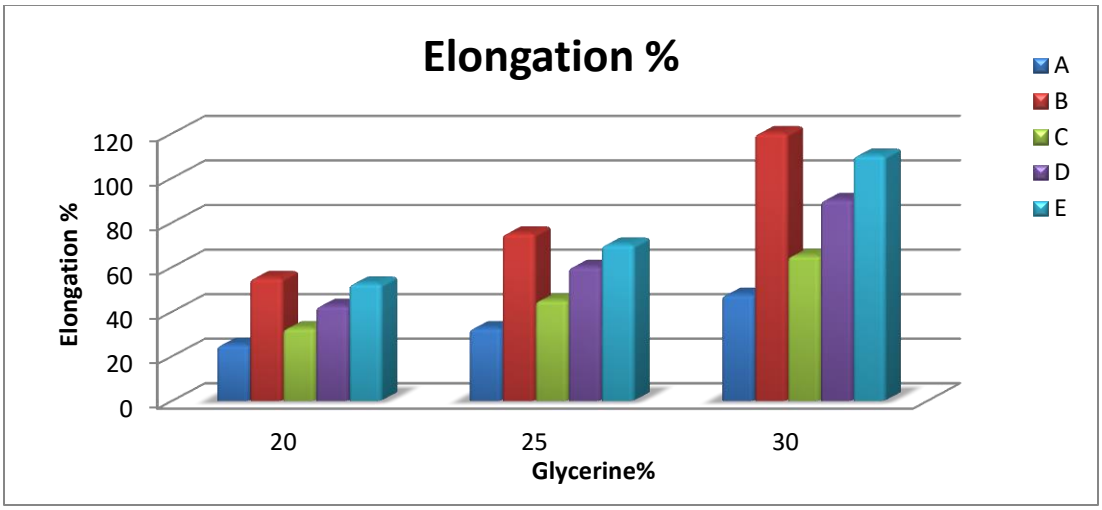


Figure 18 Elongation at break (%) of developed bio-plastic films, indicating formulation-dependent flexibility behavior.

Pure avocado seed starch films (B-series) had lower TS (5.50-2.75 MPa) but higher elongation (55-120%) than cassava films, showing that avocado starch forms a less compact but more flexible network. Mixed starch films (C, D, and E series) have intermediate characteristics, with TS and modulus falling and elongation increasing as avocado content rose. For example, D-3 (50/50 CS/AS with 30% glycerol) has a TS of 3.25 MPa, elongation of 90%, and modulus of 65 MPa, demonstrating the adjustable balance of strength and flexibility attained by combining starch types.

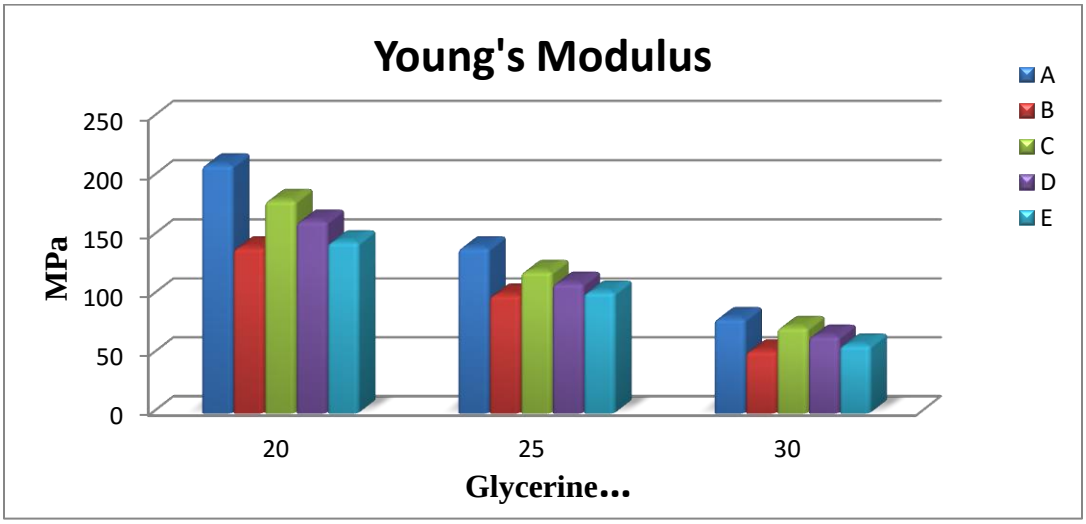


Figure 19 Young's modulus values of composite bio-plastic films representing stiffness variation across formulations.

Overall, mechanical performance is negatively associated with glycerol concentration and avocado starch fraction, which is consistent with previous research on starch-based bio plastics. These findings demonstrate that cassava starch offers stiffness, whereas avocado starch increases flexibility, allowing for mechanical behavior modification via formulation tweaks.

4.4 Water Absorption and Solubility

Run	CS/AS (%)	Glycerol (%)	Water Solubility (%)	Water Absorption (%)
A-1	100/0	20	18	62
A-2	100/0	25	22	75
A-3	100/0	30	26	89
B-1	0/100	20	23	96
B-2	0/100	25	28	113
B-3	0/100	30	34	132
C-1	70/30	20	16	54
C-2	70/30	25	20	69
C-3	70/30	30	24	83
D-1	50/50	20	19	58
D-2	50/50	25	23	73
D-3	50/50	30	27	88
E-1	30/70	20	20	76
E-2	30/70	25	25	92
E-3	30/70	30	30	109

Table 6 Water interaction properties of bio-plastic films including absorption and solubility percentages.

A distinct compositional and plasticizer-dependent trend can be seen in the hydration reactions of the CS/AS bio-plastic films, with formulations rich in cassava continuously exhibiting better water resistance. The lowest water solubility (18–26%) and absorption (62–89%) were shown by pure cassava films (A-series), suggesting a more crystalline, densely packed starch matrix with few water diffusion channels.

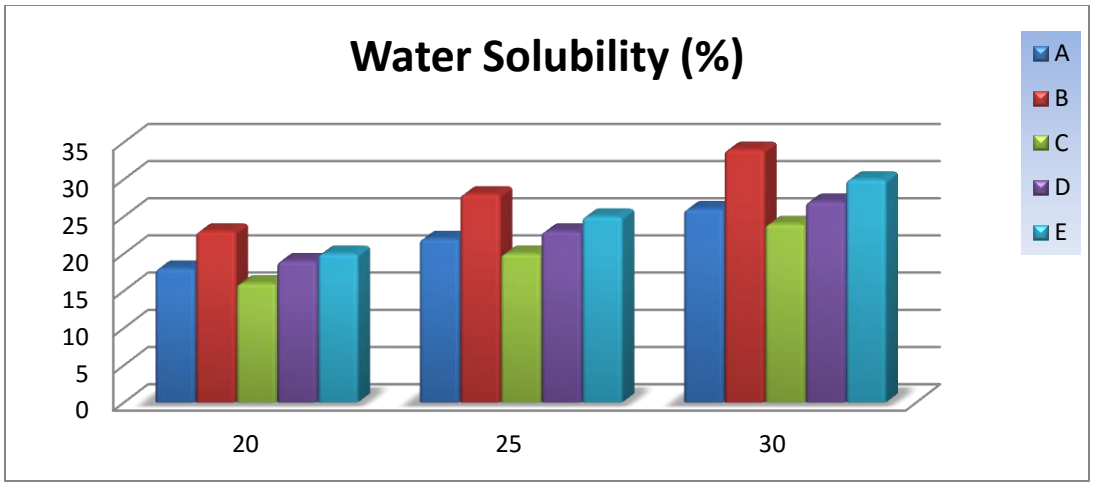


Figure 20 Water solubility percentages of bio-plastic films indicating matrix stability in aqueous conditions.

Pure avocado seed starch films (B-series), on the other hand, demonstrated the highest solubility (23–34%) and absorption (96–132%), which is indicative of their more amorphous structure and presence of hydrophilic groups that promote quick water–polymer interactions. Depending on the CS/AS ratio, blended systems showed predictable intermediate behaviour: While 50/50 mixes (D-series) showed moderate hydration (19–27%; 58–88%), 70/30 films (C-series) retained relatively low water sensitivity (solubility 16–24%; absorption 54–83%), and 30/70 films (E-series) performed almost like avocados (20–30%; 76–109%).

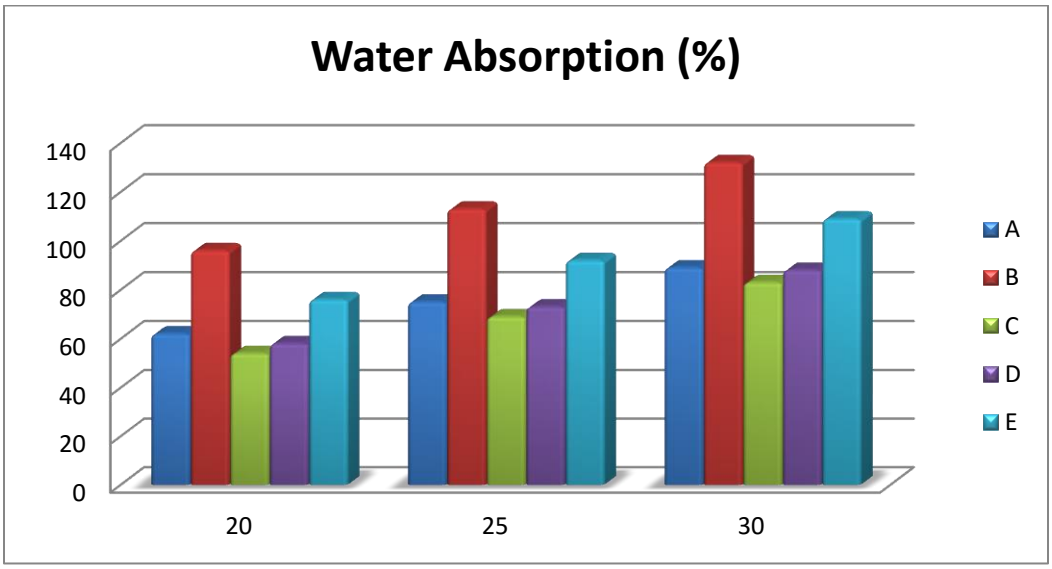


Figure 21 Water absorption behavior (%) of bio-plastic films after 24-hour immersion testing.

Increasing glycerol from 20% to 30% in all formulations significantly increased solubility and absorption, indicating glycerol's involvement in improving chain mobility and free volume while reducing intermolecular hydrogen bonding. Overall, the results show that cassava-dominant systems—particularly C-series and A-series at lower glycerol levels—are the most water-stable films, but avocado-rich formulations perform better when increased aqueous degradability is desired.

4.5 Biodegradability

			Biodegradation %			
SAMPLES	**Cassava/Avocado**	**Gly (%)**	**7 days**	**14 days**	**21 days**	**28 days**
A-1	100/0	20	8	15	25	38
A-2	100/0	25	10	18	28	42
A-3	100/0	30	12	20	32	45
B-1	0/100	20	12	25	42	60
B-2	0/100	25	15	30	50	68
B-3	0/100	30	18	35	55	80
C-1	70/30	20	10	20	35	50
C-2	70/30	25	12	22	38	57
C-3	70/30	30	15	28	45	65
D-1	50/50	20	11	22	38	55
D-2	50/50	25	13	25	42	62
D-3	50/50	30	16	30	50	70
E-1	30/70	20	12	25	42	60
E-2	30/70	25	15	30	48	67
E-3	30/70	30	18	35	55	77

Table 7 Biodegradation percentage results of bio-plastic films measured through soil burial mass-loss testing.

The biodegradation profiles of the films (Table 7) demonstrate the effects of starch composition and glycerol concentration. Pure cassava starch films (A-series) decayed slowly, losing 38-45% of their mass after 28 days, but pure avocado starch films (B-series) degraded quicker, losing 60-

80% after 28 days. Mixed films had intermediate degradation rates; for example, 50/50 CS/AS films (D-series) decayed 55-70% over 28 days, suggesting that starch blending provides for customizable biodegradation rates.

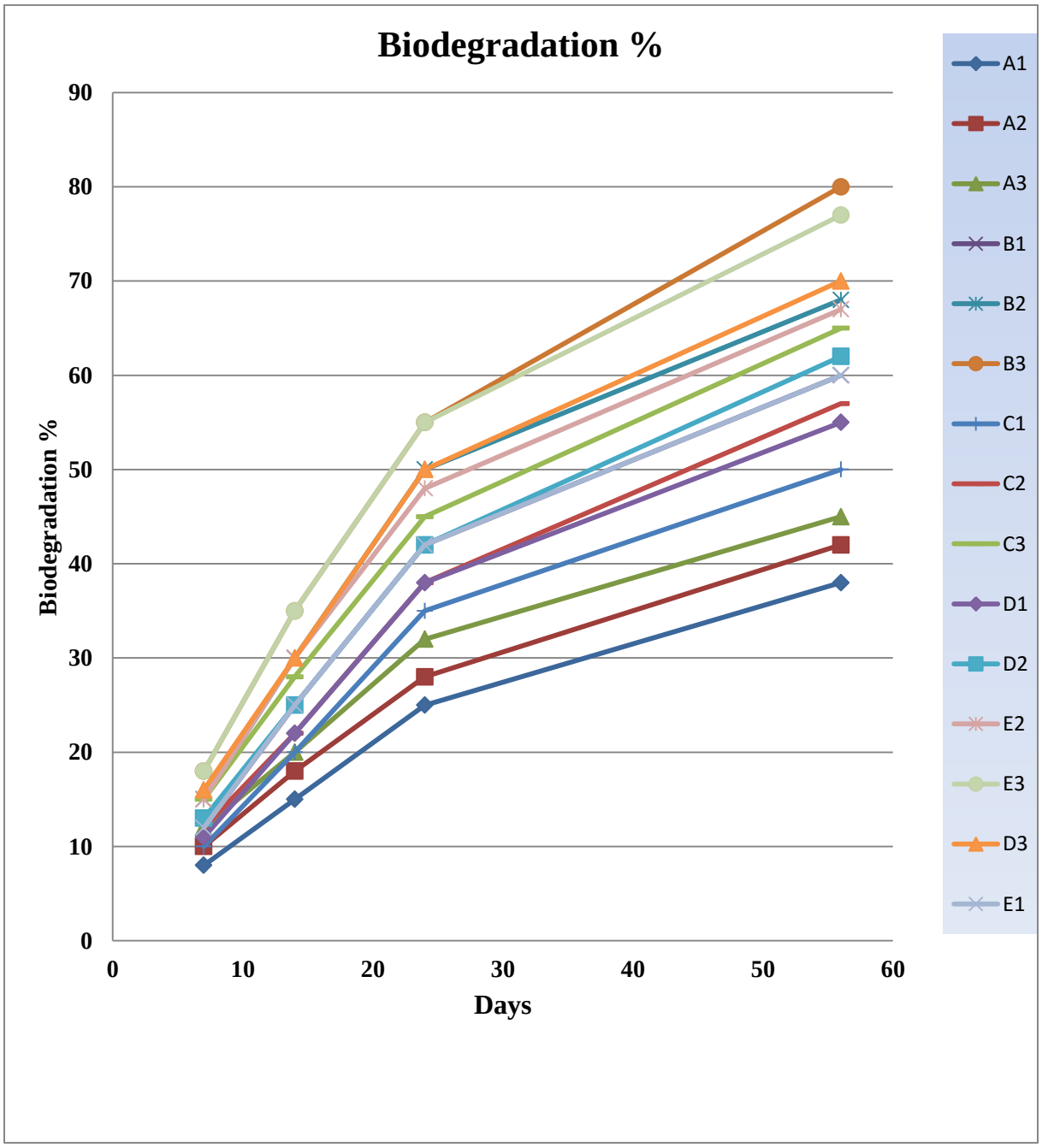


Figure 22 Weekly biodegradation percentage of bio-plastic samples under controlled soil burial conditions.

Glycerol concentration also influenced biodegradation: greater glycerol films deteriorated quicker due to increased polymer chain mobility and microbial accessibility. For example, A-3 (30% glycerol) degraded 45% at 28 days, compared to 38% for A-1 (20% glycerol). These results are consistent with water absorption statistics, since films with greater water intake promote microbial colonization and enzymatic hydrolysis, which accelerates biodegradation.

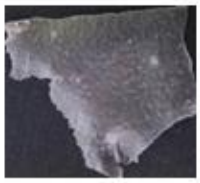
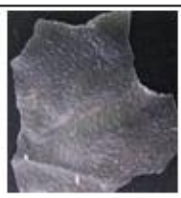
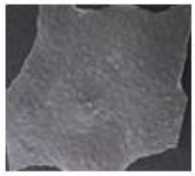
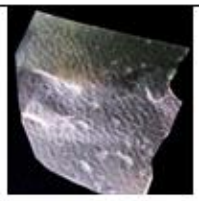
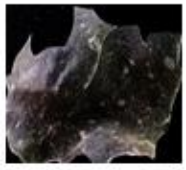
SAMPLES / DAYS	7	14	21	28
A-1				
A-2				
A-3				
B-1				
B-2				
B-3				
C-1				



Figure 23 Time-dependent biodegradation profile of bio-plastic films showing cumulative mass loss over exposure period.

4.6 Optimized Sample Summary and Justification

Based on a comprehensive evaluation of mechanical integrity, water interactions, and biodegradation kinetics, the C-1 formulation (70% cassava starch: 30% avocado seed starch: 20% glycerol + fixed pectin content) was determined to be the most optimum bio plastic. Its excellent performance is owing to the synergistic interplay of crystalline, amorphous, and cross-linked polymer domains, which produces a structurally balanced and functionally robust biodegradable film.



Figure 24 Photograph of the optimized composite bio-plastic sample (C-1) demonstrating visual uniformity and film integrity.

4.6.1. Superior Mechanical Performance and Structural Balance

The C-1 formulation has an outstanding mechanical profile due to the purposeful combination of crystalline and amorphous polymer phases. Its tensile strength of 6.75 MPa is due to the strong intermolecular bonding and chain alignment provided by cassava starch's semi-crystalline areas, which function as reinforcing lamellae inside the polymer matrix. Meanwhile, the 32.5% elongation at break indicates that the film has sufficient ductility to survive deformation without catastrophic failure, which is contributed by the more amorphous and flexible avocado seed

starch. The measured Young's modulus of 180 MPa demonstrates that C-1 has structural stiffness adequate for real-world handling while retaining enough elasticity to absorb stress during bending, folding, or packing activities. Collectively, these mechanical properties suggest that C-1 strikes an optimum mix of strength, flexibility, and stiffness—an important trio for high-performance biodegradable films.

4.6.2 Excellent Water Resistance and Stability

C-1's hydration behavior demonstrates a considerable increase in barrier functioning, with water absorption of 55% and solubility of just 16%, both much lower than avocado-rich mixes. This increased water resistance is the result of a synergistic interaction between cassava starch's crystalline packing and pectin's inherent crosslinking capabilities, both of which limit polymer chain mobility and diminish free hydrophilic sites available for water penetration. Pectin, a highly functional polysaccharide, aids network densification by generating inter-chain hydrogen bonds, which reduce free volume and limit water transport paths. As a result, C-1 forms a compact, cohesive matrix capable of maintaining integrity in humid or wet environments. Moisture stability not only enhances storage longevity, but it also broadens the film's use in packaging circumstances that need regulated contact with water.

4.6.3. Environmentally Responsible Biodegradation

The C-1 film has a favourable biodegradation profile, attaining about 50% degradation within 28 days—a pace that meets eco-compliance criteria while preserving enough structural stability during the planned service life. This balanced breakdown behaviour is ascribed to the modest incorporation of avocado starch, whose amorphous domains improve microbial accessibility, as well as pectin's inherent polysaccharide nature, which readily promotes enzymatic hydrolysis. Meanwhile, cassava starch introduces partial crystallinity, slowing full breakdown and preventing premature disintegration. The end product is a film that degrades gradually under soil circumstances, minimizing environmental effect while yet offering a functional lifetime suitable for travel, storage, and use. This degradation profile promotes C-1 as a sustainable packaging material that is compatible with worldwide waste-reduction goals.

4.6.4. Comprehensive Scientific Rationale for C-1 Excellence

C-1's excellent performance stems from the planned synergy of its constituent biopolymers, each of which adds a unique structural or functional benefit to the finished film. Cassava starch has

crystalline areas that increase tensile strength and provide an ordered molecular backbone capable of supporting mechanical stresses. In contrast, avocado seed starch adds amorphous flexibility, functioning as a stress-dissipating component that increases ductility and facilitates regulated biodegradability. Pectin improves the formulation by acting as a natural cross linker, resulting in a semi-interpenetrating network that boosts film cohesion, lowers brittleness, and improves barrier characteristics. Finally, glycerol acts as a calibrated plasticizer that regulates intermolecular connections, ensuring mobility without excessive softness or mechanical collapse. Together, these components provide a harmonized polymer architecture where reinforcement, flexibility, crosslinking, and plasticization are ideally matched, establishing C-1 as the most technically sound formulation.

4.6.5. Recommended Applications for sample C-1

Because of its strong mechanical integrity, regulated water sensitivity, and ecologically responsible biodegradability, the C-1 formulation is ideal for a wide range of sustainable packaging applications. Its balanced firmness and suppleness make it perfect for food wrapping films, which require mechanical protection and safety. The film's lower water solubility makes it suitable for use in fresh produce packaging, since it can endure moisture-rich situations. Its biodegradation rate and moderate strength make it ideal for biodegradable carry bags and single-use consumer packaging, providing an environmentally benign alternative to petroleum-based plastics. Furthermore, the cohesive structure strengthened by pectin makes C-1 an excellent choice for cosmetic and personal-care sachets, where seal integrity and product stability are crucial. These combined qualities define C-1 as a flexible, high-value material capable of addressing a wide range of industrial demands while promoting sustainability.

CHAPTER 5

5. CONCLUSION AND RECOMMENDATION

5.1, CONCLUSION

The research presented here shows that the functional performance of bio plastics made from cassava starch, avocado seed starch, pectin, and glycerol is determined by the starches' molecular structure and interaction with the plasticizer and gelling agent. Cassava starch supplies a thick semi-crystalline matrix, which increases tensile strength, stiffness, and reduces water diffusion. In contrast, avocado seed starch provides amorphous areas that facilitate chain mobility, resulting in increased elongation, flexibility, and biodegradation. The inclusion of pectin strengthens the polymer network by forming more hydrogen-bonded crosslink junctions, which improves film cohesiveness, tensile performance, and reduces brittleness. Pectin improves barrier performance by controlling water permeability and increasing structural uniformity.

Glycerol was an efficient plasticizer, lowering intermolecular tensions and increasing elasticity across all formulations. However, larger glycerol concentrations enhanced water sensitivity while decreasing mechanical strength. The synergy of starch blending indicated that intermediate ratios (particularly 70/30 CS/AS) produce films with good mechanical, functional, and environmental properties.

Overall, the findings demonstrate that CS/AS/pectin-based bio plastics provide a customizable, sustainable, and cost-effective alternative to synthetic polymers. Adjusting starch ratios and plasticizer concentrations allows formulations to obtain application-specific mechanical behavior and degradation rates. This material system has great potential for biodegradable packaging, throwaway materials, and ecologically friendly consumer items.

5.2, RECOMMENDATION

5.2.1 Future Work

Future study should focus on further examination of performance-enhancing techniques for improving the structural, functional, and environmental properties of cassava-avocado starch-pectin bio plastics. One promising approach is to incorporate nanostructured fillers such as Nano cellulose, layered silicates (clay), graphene oxide, or silica nanoparticles, which have the potential to significantly improve mechanical strength, thermal stability, and barrier performance by creating tortuous diffusion pathways—while remaining fully biodegradable if used within controlled limits. Furthermore, plasticization strategies should be refined, particularly through the use of advanced plasticizer blends such as sorbitol-glycerol, citric acid-glycerol, or deep eutectic solvent-based systems, which may improve polymer mobility, reduce migration, and provide better long-term moisture stability than single-plasticizer formulations.

From a structural engineering standpoint, thermal modification procedures, dual-gel starch processing, annealing, or heat-moisture treatment might increase crystallinity and minimize the hydrophilic response of the films, hence enhancing dimensional stability. Detailed investigations of biodegradation pathways, such as microbial community profiling (metagenomics), enzyme activity monitoring, CO_2 evolution analysis, and mineralization kinetics, are necessary to provide a mechanistic understanding of degradation behaviour and predict environmental fate.

To link laboratory-scale discoveries to industry applications, future research should assess processing compatibility with large-scale manufacturing processes such as extrusion, casting-extrusion hybrids, and blown-film production. Energy consumption, processing window determination, scalability constraints, and techno-economic feasibility should all be considered when determining commercial production viability. Finally, the interaction of the bio plastic matrix with bio-based additives such as plant fibres, agricultural residues, natural waxes, essential oils, and phytochemicals can be studied to develop multifunctional packaging materials. These additives could endow the films with antimicrobial, antioxidant, or UV-protective properties while also improving mechanical stability.

Collectively, these research initiatives will not only increase the material's application potential, but will also speed cassava/avocado/pectin bio plastics' transition from prototype-level development to full integration into the worldwide sustainable materials market.

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APPENDEX 1

A, Manufactured bioplastic samples and testing tools













