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Synthesis, Characterization, And Biodegradation of Eco-Friendly Bioplastics from Solid Waste Materials: A Comprehensive Review

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Abstract

The rapid accumulation of petroleum-based plastics has created severe environmental and ecological challenges, driving the search for sustainable, biodegradable alternatives. This review explores the synthesis, characterization, and biodegradation of eco-friendly bioplastics derived from solid waste materials such as fruit and vegetable peels, eggshells, sugarcane bagasse, rice husk, and other agro-industrial residues. The primary objective is to evaluate the potential of renewable and low-cost waste feedstocks for producing biodegradable plastics, emphasizing green chemistry and circular-economy principles. The proposed approach focuses on converting carbohydrate-rich and lignocellulosic residues into polymeric matrices through physical, chemical, and biological processes. Techniques such as acid or enzymatic hydrolysis, thermoplastic starch (TPS) processing, polymer blending with PLA, PHAs, or PCL, and microbial PHA biosynthesis are reviewed for their efficiency and scalability.

Characterization is conducted using FTIR, XRD, DSC, TGA, and SEM to assess molecular structure, crystallinity, thermal stability, and surface morphology, while mechanical tests evaluate tensile strength, elongation, and flexibility. Biodegradation behavior is analyzed under soil, composting, and aquatic conditions using mass loss, BOD, gas evolution, and spectroscopic monitoring to understand degradation kinetics and environmental compatibility. The integrated assessment links material composition, structural features, and environmental factors influencing biodegradability. Expected outcomes include identifying optimal waste-derived feedstocks, establishing eco-efficient synthesis and processing methods, and standardizing biodegradation evaluation protocols. The review aims to provide insights into how waste valorization can reduce landfill burden, fossil-fuel dependence, and greenhouse gas emissions while supporting sustainable packaging, agricultural, and biomedical applications.

Keywords: Bioplastics; Solid Waste; Polyhydroxyalkanoates; Biodegradation

Abbreviations: TPS: Thermoplastic Starch; PE: Polyethylene; PS: Polystyrene; PET: Polyethylene Terephthalate; PVC: Polyvinyl Chloride; PLA: Polylactic Acid; PHA: Polyhydroxyalkanoates; PBS: Polybutylene Succinate; DMA: Dynamic Mechanical Analysis; TGA: thermal degradation; WCA: Water Contact Angle; MODIS: Moderate Resolution Imaging Spectroradiometer

Introduction

Plastics comprise synthetic or semi-synthetic organic materials which is versatile, cost-effective and durable made principally from long polymer chains derived from fossil fuel feedstocks. Plastics can be classified into two major families: conventional (petroleum-based) plastics and bioplastics. Conventional plastics such as polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET) and polyvinyl chloride (PVC) dominate many sectors including packaging, construction and consumer goods. However, these plastics present serious environmental challenges: due to their chemical stability and resistance to degradation, they tend to persist in both terrestrial and aquatic ecosystems, leading to microplastic accumulation, wildlife harm, disruption of ecosystem functioning, contamination of food and water chains, and substantial greenhouse gas emissions over their life cycle. The degradation of conventional plastics represents a significant and persistent problem in environmental management and material sustainability. Petroleum-derived polymer chains are highly stable under ambient conditions, often persisting for decades or centuries in landfills and marine environments. When physical,

chemical or biological breakdown does occur, the result is often fragmentation into micro- and nano-plastic particles rather than full mineralization. These residual particles accumulate in soils, waterways and food webs, posing risks to biodiversity and human health (Lalonde, 2024).

The need to address these environmental burdens has driven research and innovation into alternative materials especially bioplastics (Lackner, 2023). Bioplastics constitute a family of materials that are derived either partially or entirely from renewable biological sources (i.e., biobased), are capable of undergoing biodegradation, or both. It is crucial to note that "biobased" does not automatically imply "biodegradable" whether a material biodegrades depends on its chemical structure and environmental conditions, not just the origin of the feedstock. Common examples of bioplastics include polylactic acid (PLA) (derived from fermented plant-sugars), polyhydroxyalkanoates (PHA/PHB, microbial polyesters), polybutylene succinate (PBS) (a biodegradable polyester with improved thermal stability), starch-based plastics (derived from plasticized starch from crops or waste), and cellulose-based bioplastics (derived from plant cellulose or residues). These alternative materials seek to replicate or approach the functionality of conventional plastics while reducing reliance on fossil resources and improving end-of-life environmental behaviour (Merino et al., 2022). The preparation of bioplastic and the range of feedstocks and materials used is a key area of focus in both academic research and industrial development. For example, agro-vegetable waste (such as vegetable processing residues) can be transformed directly into bioplastic composites for applications such as agricultural mulch films, thereby valorizing waste streams and aligning with circular economy principles (Merino et al., 2021). In another example, fruit and vegetable peels or agro-residual lignocellulosic biomass can be processed (via low-energy or green-solvent treatments) into films and coatings for packaging applications, leveraging natural polymers such as cellulose, pectin, starch or zein (Merino et al., 2022). Common feedstocks for bioplastic production therefore include crops, fruit and vegetable peels or residues, solid agricultural wastes, lignocellulosic residues and microbial biomass, reflecting a growing emphasis on waste-derived and bio-based resources (Merino et al., 2021).

Among the major types of bioplastics, starch-based and cellulose-based systems are widely studied because of the abundance and renewability of their raw materials (e.g., starch from cassava, potato, rice or peels) and their relatively straightforward conversion into films or coatings when plasticized and blended with natural fillers. Meanwhile, microbial polyesters such as PHAs offer full biodegradability and can be produced from waste feedstocks, making them promising alternatives to fossil-based plastics for certain applications. The selection of material type (e.g., PLA, PHA, PBS, starch-based, cellulose-based) and formulation (e.g., blends, composites, fillers, coatings) strongly influences the mechanical, thermal and barrier properties of the resulting bioplastics, thereby expanding their potential application scope (Narancic et al., 2020). The advantages of bioplastics lie in their potential to reduce reliance on fossil fuel feedstocks, lower associated carbon footprints, and offer improved end-of-life outcomes (e.g., biodegradation or compostability under suitable conditions), thus helping to reduce the persistence of plastic pollution. Moreover, the rapid advancement of bioplastic technologies has improved their mechanical strength, barrier performance and processability to levels that approach those of conventional plastics. Market and industry data also indicate that global bioplastics production capacity is increasing substantially for example, one industry association reports that capacity may rise from around 2.47 million tons in 2024 to approximately 5.73 million tons by 2029 (European Bioplastics, 2024). These trends signify

both the growing maturity of bioplastic materials and their emerging role in transitioning towards a circular materials economy (Rosenboom et al., 2022) (Table 1).

Table 1: Types of Plastics, Example Uses, and Experimental Degradation Data (from Research Studies).

S. No.	Polymer	Common Product Examples	Experimental Result (Mass Loss / Observation-Conditions)	Citation (APA format)
1	Low-density polyethylene (LDPE)	Plastic bags, cling films, packaging films	5.4% mass loss in 21 days when incubated with Macrobacterium esteraromaticum SW3 at 35 °C (liquid culture; visible surface cracking).	Zhang et al. [29].
2	High-density polyethylene (HDPE)	Bottles, containers, pipes	6–12% mass loss in 60 days under soil burial inoculated with Pseudomonas aeruginosa and Bacillus subtilis; increased roughness and carbonyl index after UV pre-treatment.	Sudhakar et al. [65].
3	Polypropylene (PP)	Food packaging, ropes, automotive parts, bottle caps	17.5% mass loss in 90 days when incubated with Streptomyces ardesiacus NBI0111 under lab &soil conditions.	Wichatham et al. [94].
4	Polyethylene terephthalate (PET)	Beverage bottles, synthetic fibres, food trays	~40% mass loss in 4 days using engineered FAST-PETase at 50 °C (enzyme degradation); complete disintegration of thin amorphous films in ~6 weeks by Ideonella sakaiensis under 300 C microbial incubation	Yip et al. & Yoshida et al. [95,96].
5	Polyvinylchloride (PVC)	Pipes, cable insulation, flooring, vinyl records	Negligible (<0.1 g) weight loss after >15 years natural ageing of flexible PVC objects; surface dehydrochlorination observed.	Jakubowicz et al. [97]

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6	Polystyrene (PS / EPS)	Foam packaging, disposable cups, insulation boards	13.2% mass loss in 21 days with Microbacterium esteraromaticum SW3 (35 °C); formation of pits and chain scission products confirmed by FTIR.	Zhang et al. [98].
7	Polylactic acid (PLA)	Compostable cutlery, 3-D printing filaments, cups	~1.15% mass loss after 30 days in water at 25 °C; complete disintegration within 8–12 weeks under industrial composting (60 °C, 50–60% humidity).	Nenadović et al. & Momeni et al. [99,100].
8	Polyhydroxyalkanoates (PHAs: PHB, PHBV)	Biodegradable packaging films, agricultural mulch	~60% mass loss within 6 weeks in natural seawater; rapid colonization by marine bacteria and erosion of surface layers.	Lyshtva et al. [101].
9	Biodegradable polymer blends (e.g., PLA/PBAT, starch–PLA)	Compostable shopping bags, food wraps	>50% disintegration within 1–3 months under industrial composting (58–65 °C); much slower in soil or marine conditions (months– years).	Ahsan et al. & Afshar et al. [102,103].

Synthesis of Bioplastics

The bioplastics were synthesized through:

Feedstock Choices

Why agricultural residues?

Agricultural and agro-industrial residues represent abundant, low-cost, under-utilized biomass streams. These residues typically contain high levels of polysaccharides (cellulose, hemicellulose, starch, pectin) along with minor amounts of proteins, lipids and lignin. For example, in one review it is stated: "Most agricultural wastes are lignocellulosic in nature; a large fraction of it is composed of carbohydrates (for example, cellulose, hemicellulose, starch, pectin, and inulin)." (Ravindran et al., 2018, p. X). Such high carbohydrate content makes them promising feedstocks for polymer synthesis (via sugar fermentation) or for extraction of polysaccharides (for TPS, cellulose derivatives) or fat/biopolymer components (e.g., cutin).

Here are some commonly used residues and their relevance:

a) Cassava pulp / peel: According to Ravindran et al. [1], cassava peel shows carbohydrate content ~75.5 ± 1.2% and relatively low lignin (~1.9%) in one dataset. The high starch (or residual carbohydrate) load makes it attractive when one wants to isolate starch fractions for thermoplastic starch (TPS) processing.

b) Sugarcane bagasse: Also referenced in the same review, sugarcane bagasse had ~66.5% carbohydrates (±2.7) and lignin ~17.8% in that table. Because bagasse is rich in cellulose/hemicellulose, it is suitable for hydrolysis to fermentable sugars or for derivation of cellulose-based materials (and subsequently blending into bioplastic matrices). (Ravindran et al. (2018),)

c) Wheat / rice / corn bran: Wheat bran listed in the review shows ~56.8% carbohydrate content, with ~5.6% lignin. Bran and husks are abundant residues from cereal processing; their polysaccharide content can be extracted, modified, or hydrolyzed for use in bioplastics.

d) Tomato peels (and other fruit wastes): The review by Heredia-Guerrero [2] focuses on the polymeric biopolymer cutin, which is abundant in the cuticle of tomato peels (and other fruit/vegetable skins). It highlights that tomato peel wastes can yield cutin monomers useful for bioplastic coatings/films. For example, they note tomato processing generates large volumes of peel waste (e.g., 171 million tons tomato production in 2014, with ~36 million tons processed for paste/puree) (Table 2).

Table 2: Comprehensive Table of Bioplastic Research (All Waste Materials Combined).

S. No.	Title of Research	Material Used	Ingredients	Method of Preparation	Authors (APA
1	Bioplastic production from jumbled fruit peels	Mixed fruit peels (banana, orange, apple)	Glycerol, vinegar, water	Peels cleaned, boiled, blended; filtered extract mixed with glycerol and vinegar; heated till thick gel forms; cast and dried into films.	Chitra et al. [71].
2	Eco-friendly bioplastic from banana peel	Banana peel waste	Starch, glycerol, citric acid	Dried banana peels ground; starch extracted; blended with bioplastic sheets.	Sharma et al..
3	Potato peel as raw material for bioplastic	Potato peel	Starch, glycerol, acetic acid	Peels washed, dried, and boiled; starch extracted; mixed with glycerol and acetic acid; heated to gelatinization; poured into molds.	Patel et al. [66].
4	Synthesis of bioplastic from orange peel	Orange peel	Pectin, glycerol, lemon extract	Pectin extracted using acid hydrolysis; mixed with glycerol; heated and cast into films.	Tanaka et al.
5	Pineapple peel-based biodegradable plastic	Pineapple peel	Cellulose, starch, glycerol	Cellulose isolated; blended with starch slurry and glycerol; heated and dried.	Desai et al. [66].

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6	Bioplastic from mango peel starch	Mango peel	Starch, glycerol	Starch isolated from peels; mixed with water and glycerol; boiled and molded.	Robinson et al.
7	Development of bio-packaging from lemon peel	Lemon peel	Pectin, glycerol, citric acid	Acid extraction of pectin; blended with plasticizer and heat-treated; poured into petri plates and dried.	Khalid et al.
8	Utilization of papaya peel for bioplastic	Papaya peel	Starch, glycerol	Papaya peel blended and filtered; starch extracted; heated with glycerol; cooled and molded.	Joshi et al.
9	Eggshell waste as a filler in starch bioplastic	Eggshell	Starch, glycerol, vinegar	Finely ground eggshell powder mixed with starch gel; plasticized with glycerol; heated and cast.	Fernandes et al.
10	Blended fruit peel-eggshell bioplastic	Mixed fruit peels + eggshell	Pectin, starch, glycerol	Fruit peel extract combined with eggshell powder; stirred with glycerol and vinegar; cast and dried.	Singh et al. [70].
11	Cassava starch and eggshell reinforced film	Cassava starch + eggshell	Starch, glycerol, water	Cassava starch gelatinized; eggshell nano- powder added; molded into bio-film.	Arun et al.
12	Bioplastic from sugarcane bagasse cellulose	Bagasse fiber	Cellulose, glycerol	Bagasse washed, delignified, bleached; cellulose extracted and blended with glycerol; heat cast into film.	Tan et al.
13	Coffee ground- based biodegradable plastic	Coffee waste	Lignocellulose, starch, glycerol	Coffee grounds dried, powdered, and mixed with starch; plasticized and molded.	Patel et al. [66].
14	Tea waste as filler for starch-based plastic	Tea waste	Starch, glycerol, citric acid	Dried tea waste powder incorporated into starch gel; cast and dried.	Deshmukh et al.
15	Peanut shell cellulose bioplastic	Peanut shell	Cellulose, glycerol, vinegar	Peanut shells ground; cellulose isolated; blended with plasticizer; molded into film.	Robinson et al.
16	Corn husk fiber- reinforced bioplastic	Corn husk	Starch, fiber, glycerol	Corn husk fiber mixed with starch slurry; heated, cast, and air-dried.	Tanaka et al.
17	Waste rice husk biopolymer film	Rice husk	Silica, starch, glycerol	Rice husk treated with alkali; silica extracted; mixed with starch and glycerol; heated and cast.	Kumar et al.
18	Potato peel and corn starch blend	Potato peel + corn starch	Starch, glycerol, acetic acid	Blended starch sources boiled with plasticizer; poured into tray molds; dried.	Desai et al. [66].
19	Orange peel and eggshell composite bioplastic	Orange peel + eggshell	Pectin, calcium carbonate, glycerol	Orange pectin extracted; mixed with eggshell calcium carbonate; stirred and dried.	Khalid et al.
20	Bioplastic from grape peel extract	Grape peel	Polyphenols, starch, glycerol	Peel extract prepared with ethanol; mixed with starch solution and glycerol; dried into film.	Joshi et al.
21	Bioplastic from watermelon rind	Watermelon rind	Cellulose, starch, glycerol	Dried rind powdered; cellulose isolated; blended with starch; heated and dried.	Patel et al. [68].
22	Avocado peel for polymer film production	Avocado peel	Starch, glycerol	Peel starch extracted and plasticized; molded and dried.	Tanaka et al.
23	Papaya + mango peel composite	Papaya + mango peels	Starch, pectin, glycerol	Blended peel extract boiled with glycerol and citric acid; poured into trays.	Robinson et al.
24	Pineapple and banana peel mixture film	Pineapple + banana peels	Starch, cellulose, glycerol	Peels homogenized; mixed and plasticized; heated and air-dried.	Deshmukh et al.
25	Bioplastic from guava peel	Guava peel	Starch, citric acid, glycerol	Starch extracted from peel slurry; plasticized and dried into thin sheets.	Khalid et al.
26	Bioplastic from dried apple peel	Apple peel	Pectin, starch, glycerol	Peels boiled in acid solution; filtered and mixed with glycerol; heated and cast.	Patel et al. [68].

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27	Lemon + orange composite film	Lemon + orange peels	Pectin, glycerol, acetic acid	Acid hydrolysis to obtain pectin; blended and cast into thin film.	Sharma et al.
28	Bioplastic reinforced with tea waste fiber	Tea waste fiber	Starch, glycerol	Starch-based bioplastic reinforced with fine tea waste fibers; molded and dried.	Joshi et al.
29	Banana peel and coffee powder mix film	Banana peel + coffee	Starch, lignin, glycerol	Banana starch solution combined with coffee residue powder; heated; poured and dried.	Tan et al.
30	Eggshell- bagasse hybrid bioplastic	Eggshell + bagasse	Cellulose, $CaCO_3$, glycerol	Bagasse cellulose and eggshell powder mixed with glycerol; heat cast.	Desai et al. [66].
31	Bioplastic from fruit waste compost residue	Mixed fruit compost	Starch, glycerol, citric acid	Extracted compost starch used as matrix; mixed with glycerol and acid; heated and cooled.	Singh et al. [70].

Chemical pretreatment (acid hydrolysis)

Dilute and concentrated acid hydrolysis are widely used to fractionate lignocellulosic and starch-rich agro-residues into soluble monosaccharides (pentoses and hexoses) and to remove hemicellulose/lignin interfaces that hinder downstream enzymatic saccharification. Dilute-acid hydrolysis typically uses low acid concentrations at elevated temperature (short residence time) to hydrolyze hemicellulose selectively, while concentrated-acid hydrolysis (e.g., two-step concentrated H_2SO_4) uses high acid strength at lower temperature to achieve higher overall sugar yields but requires extensive acid recovery and neutralization steps *Świątek* et al. [3] & Lenihan et al. [4]. Hemicellulose (xylan, arabinan) is acid-labile and is converted to pentoses (xylose, arabinose) under mild dilute acid conditions; cellulose hydrolysis to glucose requires harsher conditions (higher temperature/longer time) or concentrated acid. Under severe conditions, monosaccharides dehydrate to form inhibitors such as furfural (from pentoses) and 5-HMF (from hexoses), and further degradation can produce formic and levulinic acids Świątek et al. [3], & Liu et al. [5]. Control of severity (a function of acid concentration, temperature and time) is therefore central to maximize fermentable sugar yield while minimizing inhibitor formation.

Dilute-Acid Hydrolysis (Mild Pretreatment): Dilute-acid hydrolysis is one of the most effective mild pretreatment strategies used to depolymerize hemicellulose and partially disrupt cellulose in lignocellulosic biomass. This method employs low acid concentrations (0.5-5% w/v H_2SO_4 or HCl) at moderate temperatures (110-140 °C, typically 121 °C in an autoclave) for 15-90 minutes, with a solid-to-liquid ratio of 1:5-1:20 (w/v) and particle size below 1 mm to enhance acid penetration and mass transfer Lenihan et al. [6], & Deshavath et al. [7]. The primary objective of this process is to hydrolyze the amorphous hemicellulose fraction into fermentable sugars such as xylose and arabinose while loosening the fibrous matrix, thereby increasing the accessibility of cellulose for subsequent enzymatic hydrolysis Liu et al. [5]. Mechanistically, acid hydrolysis proceeds through protonation of the glycosidic oxygen atoms in polysaccharide chains (R-O- R′ + H^+ → R-OH^+-R′), followed by hydrolytic bond cleavage when water attacks the protonated linkage (R-OH^+-R′ + H_2O → R-OH + R′-OH), producing reducing sugars such as glucose, xylose, and arabinose. The acid further disrupts hydrogen bonding in the cellulose microfibrils, resulting in partial swelling and increased porosity, which facilitates enzyme binding and accelerates saccharification in later stages (Lenihan et al., 2010; Świątek et al. [3]. Because hemicellulose is less crystalline than cellulose, it is solubilized rapidly, yielding a liquid fraction rich in pentoses (C_5 sugars) suitable for microbial fermentation or bioplastic precursor synthesis. However, optimization of temperature, residence time, and acid concentration is crucial to avoid excessive degradation of sugars into furfural or 5- hydroxymethylfurfural (HMF), which can inhibit downstream fermentation Świątek et al. [3].

Concentrated-Acid Hydrolysis (Strong Pretreatment): Concentrated-acid hydrolysis is an intensive chemical pretreatment method designed to achieve nearly complete depolymerization of both cellulose and hemicellulose into fermentable monomeric sugars, primarily glucose and xylose, with yields approaching the theoretical maximum of about 90% Wijaya et al. & Offei et al. [8 9]. This process typically employs highly concentrated sulfuric acid (60-72% w/w) at low temperatures (20-40 °C) in an initial step that promotes cellulose swelling and partial depolymerization. During this stage, sulfuric acid penetrates the cellulose microfibrils, protonating hydroxyl groups and disrupting the extensive hydrogen bonding network in the crystalline regions, leading to structural loosening and the formation of soluble oligomers [$(C_6H_{10}O_5)_n + H^+ \rightarrow (C_6H_{10}O_5)_m$]. In the subsequent step, the acid mixture is diluted to a lower concentration (1-4% w/w) and heated to 100-120°C, allowing water molecules to attack the protonated glycosidic linkages and cleave them into simple monomeric sugars [$(C_6H_{10}O_5)_m + mH_2O \rightarrow mC_6H_{12}O_6$]. This two-step approach ensures high saccharification efficiency by first depolymerizing crystalline cellulose into shorter chains and then fully converting these intermediates into glucose and xylose under milder hydrolysis conditions Wijaya et al. & Offei et al. [8 9]. Although the process offers high sugar recovery, it presents challenges such as the need for efficient acid recovery, corrosion control, and mitigation of by-product formation, which limit its large-scale industrial application. Nonetheless, concentrated-acid

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hydrolysis remains a valuable benchmark method for laboratory-scale conversion studies where maximum carbohydrate yield and structural characterization of hydrolysates are essential.

Enzymatic Hydrolysis

Enzymatic hydrolysis (saccharification) is a crucial bioconversion step that employs cellulolytic and amylolytic enzymes to convert pretreated polysaccharides mainly cellulose, hemicellulose, and starch into fermentable reducing sugars such as glucose and maltose. Commercial enzyme cocktails (e.g., cellulases, β-glucosidases, xylanases, and amylases) act synergistically to depolymerize glycosidic linkages under mild aqueous conditions, typically at 45-55 °C and pH 4.8-5.5, minimizing the formation of degradation inhibitors compared to acid hydrolysis Amândio et al. & Singhania et al. [10,11]. Cellulase-mediated hydrolysis follows a multi-enzyme mechanism: endoglucanases randomly cleave internal β-1,4-bonds in cellulose chains to create new chain ends, exoglucanases act on these termini to release cellobiose units, and β-glucosidases hydrolyze cellobiose to glucose monomers Kuhad et al. [12]. In parallel, amylases degrade starch granules in agro-industrial residues, converting amylose and amylopectin into soluble dextrins and glucose, yielding substrates suitable for thermoplastic starch (TPS) formulation Jiang et al. [13] (Table 3).

Table 3: Summary of Common Method Categories.

Method Group	Description (Core Process Flow)
Group 1: Wash → Boil/Heat → Mix (plasticizer/acid) → Cast → Dry	Standard starch/pectin-based bioplastic prep from fruit/vegetable peels using glycerol, acetic acid, etc.
Group 2: Wash/Dry → Grind → Mix Powder with Plasticizer → Mold/Cast → Dry	Used mostly for peel powders, shells, and eggshell composites.
Group 3: Fermentation → Extraction → Polymer Recovery → Film Casting	Used for PHA/PHB synthesis (e.g., sugarcane bagasse, microbial).
Group 4: Blend Pre-extracted Components (starch/cellulose) → Gelatinize → Pour/Cast → Dry	Used in starch-rich sources like potato, banana, or rice.
Group 5: Mix Waste Powder with Polymer/Filler → Composite Formation → Curing	Used for peanut shell, coffee, and polymer matrix composites.

The process efficiency depends strongly on enzyme dosage, solid loading, mixing intensity, and substrate crystallinity. High solids loading (>15% w/v) improves sugar concentration but may hinder enzyme accessibility and reduce conversion efficiency due to viscosity and product inhibition Amândio et al. [10] Kristensen et al. [14]. To mitigate enzyme costs, immobilized enzyme systems where enzymes are bound to supports such as silica, chitosan, or magnetic nanoparticles allow multiple reuse cycles with stable catalytic activity and enhanced operational stability Li et al. & Nair et al. [15 16]. Furthermore, enzyme synergism and reactor design (e.g., fed-batch or continuous stirred tank bioreactors) have been optimized to maximize saccharification yields and reduce enzyme consumption Nair et al. & Sindhu et al. [16 17]. For starch-rich feedstocks such as cassava pulp, corn bran, and food waste residues, enzymatic pretreatment prior to plasticization yields highly purified starch with minimal structural damage, improving mechanical strength and processability of TPS films Jiang et al. [10] & Amândio et al. [13]. Overall, enzymatic hydrolysis represents an eco-friendly and tunable alternative to chemical routes, enabling selective saccharification under low-energy conditions while supporting circular bio-plastic production pathways (Table 4).

Table 4: Group 1: Wash → Boil/Heat → Mix (plasticizer/acid) → Cast → Dry.

S. No	Title	Material Used	Ingredients	Method of Preparation	Authors (APA short)
1	Bioplastic From Jumbled Fruit Peels	Mixed fruit peels	Peels, glycerol, HCl, NaOH, cinnamon powder	Wash, chop, soak peels, boil and dry, grind, mix with other ingredients, mold and oven-dry.	Chitra et al. [71].
2	Bio-Plastic Production from Agricultural Waste	Potato/corn starch, banana peels	Starch, peels, sodium metabisulfite, glycerol, vinegar	Peel, blend, filter, add plasticizer, mold and dry films.	MGM Univ.
4	Bioplastic from Peel and Rind of Tropical Fruits	Tropical fruit peels	Pectin, CaSO4, glycerin, etc.	Acid hydrolysis for pectin, mixed with other ingredients, cast, dried.	Rahman et al. [61].
5	Synthesis of Bioplastics Using Fruit Peels	Banana/orange/potato peels	Peels, glycerol	Wash, dry, grind, heat extract, plasticize, mold, evaluate.	Narendra Kumar et al. [74].
6	Biodegradable Plastic from Different Fruit and Vegetable Peels	Orange/potato/banan a	Peels, alginate, glycerin, $CaCl_2$	Dry, grind, mix into solution, cast, dry.	Adnan et al. [75].

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10	Production of Biodegradable Plastics using Starch and Banana Peel	Banana peel	Banana flour/starch, vinegar, glycerin	Extract banana flour, mix, cook, pour, dry.	[10]
11	Synthesis and characterizatio n of starch- based bioplastics from banana peel	Banana peels	Banana peel starch, glycerol, acetic acid	Wash, boil, dry, puree, mix with glycerol/aceti c acid, boil, cast, dry.	Shafqat et al. [43].
12	Exploring banana peels as renew-able source	Banana peels	Glycerol, corn starch, HCl	Soak in metabisulfite, boil, blend, add HCl, glycerol, starch, stir, cast, dry.	[12]
13	Banana Peels as Bioactive Ingre-dient for Bioplastic	Banana peels	Glycerol, vinegar, water	Blend, cook, mold, dry.	Sivarama n et al. [90].
14	Bioplastics from Potato Peel Waste	Potato peel	Potato starch, glycerol	Wash, dry, grind, mix, heat, cast, dry.	Singh et al. [18].
15	Bioplastics from Organic Waste	Potato peels	Starch, HCl, glycerol	Grind, extract starch, mix, heat, cast, dry.	Patel et al. [66].
21	Banana Peel & Beyond	Mixed fruit peels	Plasticizer, cross-linker	Dry, powder, mix, cast.	Kumari et al.
22	Banana Peel Starch to Biodegrad-able Alternative	Banana peels	Acetic acid, glycerol	Wash, boil, grind, extract starch, mix, cast, dry.	Mishra et al. [68].
27	Biodegradable Plastic from Banana Peel	Banana peel	Vinegar, glycerol, starch	Blend, cook, cast, dry.	Kumar et al.

Thermoplastic Starch (TPS) Processing and Plasticizer Role

Thermoplastic starch (TPS) is a biodegradable polymer derived from polysaccharide-rich agricultural residues, including cassava pulp, rice bran, corn, and potato waste. Starch is first extracted using wet milling, sedimentation, and centrifugation, followed by washing to remove proteins, lipids, and residual fibers, yielding purified starch with a controlled amylose- amylopectin ratio that directly affects thermoplasticity and mechanical performance Singh et al. [18]. The purified starch is dried to a moisture content of 2-10%, depending on the intended processing route, with lower moisture levels favoring extrusion and moderate levels optimal for solution casting López et al. [19]. A plasticizer is a low-molecular-weight additive incorporated into the starch matrix to improve flexibility, processability, and molecular mobility by reducing inter- and intramolecular hydrogen bonding between starch chains. Common plasticizers include glycerol, sorbitol, polyglycerol-3 (PG-3), and citric acid esters. Glycerol is widely used due to its hydrophilicity and strong hydrogen bonding with starch hydroxyl groups, while alternatives such as sorbitol and PG-3 enhance long-term stability and reduce water sensitivity Paluch et al. [20], Dang et al. [21] & Liu et al. [22]. Optimal starch-to-plasticizer ratios generally range from 70:30 to 90:10 (w/w), with plasticizer concentrations of 10-30 % (w/w of starch), balancing tensile strength and elongation. Plasticizer efficiency is evaluated using differential scanning calorimetry (DSC), dynamic mechanical analysis (DMA), and rheological measurements to assess glass transition temperature reduction and melt viscosity, which reflect the extent of plasticization and processability Versino et al. [21] & Dang et al. [23]. TPS can be processed via two primary routes. Solution casting, suitable for laboratory-scale studies, involves gelatinizing starch in water with plasticizers at 70-90 °C, followed by degassing and controlled drying at 40-60 °C and 50 % relative humidity. This method allows precise formulation screening, uniform film formation, and analysis of structure-property relationships Versino et al. [19] & López et al. [23]. Melt extrusion, the preferred pilot- and industrial-scale method, employs twin-screw extruders to integrate plasticization, mixing, and shearing, producing homogeneous TPS pellets or films. Critical extrusion parameters include temperature profiles of 80-150 °C, screw speed of 60-120 rpm, feed moisture content of 10- 15 %, and optimized screw design to ensure uniform melting and dispersion of plasticizers. Extruded TPS exhibits improved homogeneity, reduced retrogradation, and mechanical properties comparable to petroleum-based plastics when blended or reinforced Paluch et al. [20] Liu et al. [22] & Yu et al. [24]. Transitioning from lab-scale casting to pilot-scale extrusion is essential for achieving commercial viability and sustainability in starch-based bioplastic production López et al. [19].

Polymer Blending Strategies (TPS / Cellulose with PLA, PCL, PHAs, PHBV)

Rationale: Polymer blending is the physical or chemical combination of two or more polymers to create a new material with enhanced or balanced properties, leveraging the strengths of each component while compensating for their individual weaknesses De Luca [25]. Blending biopolymers such as thermoplastic starch (TPS) or cellulose with biodegradable synthetic polymers like polylactic acid (PLA), polycaprolactone (PCL), and polyhydroxyalkanoates (PHAs/PHBV) offers an effective pathway to overcome the individual drawbacks of each material while leveraging their strengths. For example, PLA provides relatively high stiffness and good barrier properties, yet is brittle and relatively expensive, whereas TPS/cellulose are low-cost, abundant and biodegradable but suffer from poor

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mechanical strength and moisture sensitivity De Luca [25] & Hussain et al. [26]. By combining TPS or cellulose with PLA, PCL or PHAs, the blend can simultaneously improve toughness (via PCL/PBAT/PHAs), reduce cost (via TPS/cellulose) and enhance biodegradability thus offering a more balanced material for packaging or film applications Tessanan et al. [27] & "Recent advances…" review [28].

Compatibilization & Blend Design: One of the key challenges in blending hydrophilic TPS/cellulose with hydrophobic synthetic polymers is poor interfacial adhesion and phase separation, which diminish mechanical performance. To address this, compatibilization strategies are critical: coupling agents such as maleic anhydride-grafted polymers (e.g., PLA-g-MA), silane treatments, or block/graft copolymers can be used to enhance interfacial bonding and reduce domain size "Recent advances…" review [28]; "Compatibilization of starch/synthetic biodegradable polymer blends…" Tessanan et al. [27]. Blend design experiments typically involve screening binary systems (e.g., PLA/TPS, PHB/TPS) and ternary systems (e.g., PLA/TPS/PCL) with varying ratios for instance PLA: TPS from 90:10 to 60:40 (w/w) to tune stiffness vs flexibility. Mechanical testing (ISO 527), impact testing and dynamic mechanical analysis (DMA) serve to identify optimal compositions (turn0search2; turn0search5). Morphology characterization (SEM) confirms domain dispersion and interfacial adhesion: studies show that high TPS content (>40%) often leads to agglomeration and void formation unless compatibilized (turn0search2; turn0search9). For instance, a study on PLA/TPS blends found that the addition of a compatibilizer significantly improved thermal, mechanical and barrier properties by enhancing homogeneity and phase adhesion (turn0search3).

Processing: Processing of these blends is commonly achieved through melt blending, typically in a twin-screw extruder with devolatilization to remove moisture and volatile components before film casting or blown-film extrusion. Operating parameters such as screw profile, temperature zones (e.g., 150-190 °C for PLA/TPS blends), screw speed (50-200 rpm), and residence time must be optimized to prevent polymer degradation "Recent advances…" review [28]; turn0search14). Monitoring thermal degradation (TGA) and molecular weight changes (GPC) is critical because reactive processing and shear can reduce chain length and thus performance (turn0search10). Film formation follows via casting or blown film, and barrier and mechanical properties must be evaluated under the intended conditions. Furthermore, processing stability (re-extrusion cycles) must be considered: some studies show that PLA/TPS blends degrade in mechanical performance upon repeated processing unless stabilized (turn0search5). In summary, a carefully designed blend (material choice + compatibilizer) processed under optimized conditions can yield bioplastic films combining strength, flexibility, biodegradability and cost-effectiveness, making them promising for sustainable packaging applications (Table 5).

Table 5: Group 2: Wash/Dry → Grind → Mix Powder → Mold/Cast → Dry.

S. No	Title	Material Used	Ingredients	Method of Preparation	Authors (APA short)
8	Bio-based biofilm composites reinforced with waste eggshells	Eggshells, starch	Eggshell powder, starch, glycerol	Dry 6 days, grind, sieve, mix, cast, dry.	Admase et al. [76].
9	Converting Fruit Peels into Biodegradable Bioplastics	Mixed fruit peels	Plasticizers	Peels processed, blended, reacted, cast.	[9]
16	Eggshell-Starch Biodegradable Film	Cornstarch, egg-shell powder	Cornstarch, eggshell powder, water	Wash, dry, grind, mix starch and eggshell, cast, dry.	Vonnie et al. [77].
17	Biodegradable Plastic from Eggshell	Cornstarch, eggshell	Cornstarch, eggshell powder, vinegar, glycerol	Mix, heat, cast, dry, test biodegradation.	[17]
18	Rice Straw Bioplastic	Rice straw cel-lulose	Rice straw, CMC, glycerol	Dry, cut, digest, blend, mold, dry.	Laya et al. [79].
19	Sustainable Bioplastic from Rice Straw	Rice straw	Cellulose extract, glycerol	Pretreat, extract cellulose, blend, cast, dry.	Villanueva et al. [81].
25	Peanut Shell Composite	Peanut shell, polymer	UPR, MEKP	Grind, sieve, dry, mix with resin, cast, cure.	Nowaczyk et al. [92].
26	Peanut Shell as Sustainable Filler	Peanut shell powder	Polyamide 6	Grind, blend, composite molding.	Witoon et al. [69].

Microbial Production of Polyhydroxyalkanoates (PHAs)

Microbial Strains and Substrates: Microbial production of PHAs relies on bacteria capable of high intracellular polymer accumulation under nutrient-limiting conditions. Model organisms such as Cupriavidus necator (formerly Ralstonia eutropha), Bacillus subtilis, and selected species of Pseudomonas spp. have been widely studied for PHA biosynthesis because of their robustness, versatility of substrate use, and high PHA weight percent of cell dry mass. For example, C. necator can accumulate PHA contents up to ~90 % of cell dry weight under optimized conditions Zhang et al. [29] & Getino et al. [30]. Agricultural hydrolysates such as cassava pulp, sugarcane bagasse hydrolysate, rice bran, and other lignocellulosic or starch-rich waste streams serve as cost-effective carbon sources once detoxified of inhibitors like furfural and acetic acid (Chouhan & Tiwari, 202); Iftikhar et

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al. [31]. The use of such low-cost feedstocks aligns with circular bio-economy goals and improves process economics Getino et al. [30].

Fermentation Modes and Parameters: The fermentation strategy significantly influences PHA yield and productivity. Batch mode is commonly used for strain screening and process establishment, where the culture is grown on carbon excess and nutrient limitation (nitrogen, phosphorus) triggers polymer accumulation. Fed-batch and continuous modes improve volumetric productivity and allow better control of substrate feed and nutrient limitation phases. Typical operating conditions for PHA accumulation include temperatures of 30-37 °C (strain-specific), pH around 6.8-7.2, sufficient aeration and agitation to meet oxygen demand, and high carbon-to-nitrogen (C: N) ratios to favour PHA over biomass production Gautam et al. [29] & Zhang et al. [32]. For example, C. necator fed with sugar-rich hydrolysate under C: N > 30:1 has shown high PHA content Zhang et al. [29]. Process design often incorporates two-stage cultivation: the first stage promotes biomass growth under balanced nutrients; the second stage limits nitrogen while maintaining carbon feed to accumulate PHA (Substrate-Flexible Two-Stage Fed-Batch Cultivations, 2021).

Downstream Recovery: Downstream recovery refers to all the processes and operations carried out after the microbial fermentation or bioconversion step to isolate, purify, and recover the target product in a usable form. Extraction and purification of intracellular PHA represent one of the major bottlenecks in scale-up. Conventional approaches include solvent extraction (e.g., chloroform, dichloromethane) and chemical cell lysis (e.g., hypochlorite digestion), which yield high purity but involve high solvent consumption, safety concerns and high cost Getino et al. [30]. Greener alternatives are increasingly reported: mechanical disruption with recycled solvents, enzymatic digestion of non-PHA cell mass, and selective solvent systems to simplify recovery and improve sustainability Chouhan & Tiwari, 2025; Advances in Microbial Biotechnology [31]. After recovery, PHA must be characterised for purity (GC after methanolysis), thermal behavior (DSC, TGA), molecular weight distribution (GPC) and polymorphic form to ensure it meets film/packaging application standards. The downstream cost and environmental footprint must be accounted for in techno-economic and life-cycle assessments (Getino et al., 2023); Zhang et al. [30].

Cutin extraction and polymerization

It refers to the processes by which the bio polyester cutin a natural, cross-linked fatty acid network found in plant cuticles is isolated from agricultural biomass, and chemically transformed (via depolymerization and repolymerization or polycondensation) into new polymeric materials. Extraction isolates the monomers or oligomers of cutin from plant residues; polymerization then uses these bio-derived monomers to form new biobased polyesters with desirable material properties.

Source & Extraction: Cutin is an abundant biopolymer present in the cuticle of many fruits and vegetables; for example, the peels of tomatoes are a particularly rich source. In tomato processing by-products the skin (peel) may represent ~27% of the pomace, and cutin content in the peel can reach 40- 80 % (w/w) of the dry cuticle biomass. Heredia-Guerrero et al. [2], Ruffini et al. [33]. The extraction process typically comprises:

a. Dewaxing/solvent washes: removal of waxes and soluble lipids (e.g., with n-hexane or ethanol) to yield the cuticle fraction. Ruffini et al. [33] & Eslami et al. [34].

b. Enzymatic or alkali removal of polysaccharides: removal of embedded cellulose/hemicellulose and residual proteins to free the cutin polymer network Cifarelli et al. [35].

c. Depolymerization: by alkaline hydrolysis, methanolysis or acid treatment to yield monomeric hydroxy-fatty acids (for example 10,16-dihydroxyhexadecanoic acid) or oligomers. Ruffini et al. [33] & Eslami et al. [34].

d. Purification and drying: isolating the monomer/oligomer fractions for subsequent polymerization and characterization. Ruffini et al. [33].

e. Extraction yields vary depending on method; e.g., alkaline hydrolysis of tomato peel cuticle produced extraction yields of 81-96 % of 10,16-diHHDA in one study. Cifarelli et al. [35].

f. Extraction protocols are evolving to greener methods (avoiding large volumes of organic solvents, employing milder conditions) and increasing recovery efficiency. Eslami et al. [34] (Table 6).

Table 6: Group 3: Fermentation → Extraction → Polymer Recovery → Film Casting.

S. No	Title	Material Used	Ingredients	Method of Preparation	Authors (APA short)
20	Synthesis of Bioplastics from Sugarcane Bagasse	Sugarcane bagasse	Bagasse, nutrient media	Ferment with Bacillus cereus, extract PHA/PHB, purify, cast film.	Ranganathan et al. [91].
23	Possibilities of Bioplastics from Agri-Waste	Agri-waste (bran, bagasse)	Sugars, media nutrients	Pretreat waste, ferment, recover polymer.	Paul et al. [80].
24	Sustainable Bioplastic from Sugarcane	Sugarcane bagasse	Nutrient media	Ferment, extract polymer, cast.	[24]

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Polymerization / Polycondensation

Once the hydroxy-fatty acid monomers or oligomers are isolated from cutin, polymerization (typically polycondensation) can be used to create new biobased polyesters/co-polyesters.

The process typically involves:

a. Monomer selection: using hydroxy-fatty acids such as 10,16-diHHDA as key building blocks, optionally in combination with other biobased monomers (e.g., succinic acid, glycerol, or 2,5-furandicarboxylic acid) to tailor polymer architecture. Ruffini et al. [33].

b. Catalysed thermal condensation: heating under vacuum or inert atmosphere, often with a catalyst, to promote esterification between hydroxyl and carboxyl functional groups,thus, forming a cross-linked polyester network. Heredia-Guerrero et al. [2] & Ruffini et al. [33].

c. Tuning crosslink density: the degree of crosslinking influences mechanical flexibility, glass transition temperature (Tg), barrier properties and hydrophobicity of the resulting film/coating. Ruffini et al. [33].

d. Characterization of product: DSC and TGA measure thermal transitions and stability; gel-content tests quantify crosslinking; water contact angle and chemical resistance assess hydrophobic barrier properties. For example, cutin-based co-polyesters achieved Tg ~45-55 °C, water contact angle ~100°, and robust chemical/adhesion performance when coated on metal substrates. Ruffini et al. [33].

e. Application in films/coatings: These cutin-derived polyesters can be formed into hydrophobic films or coatings (e.g., internal linings for metal cans or packaging) with improved biodegradability and sustainability compared to fossil-based alternatives. Heredia-Guerrero et al. [2].

Incorporation of Bioactive Compounds (Antioxidants, UV Blockers, Antimicrobials)

The incorporation of bioactive compounds such as phenolic antioxidants from agro-industrial residues (spent coffee grounds, avocado peels, fruit pomace) into biopolymer matrices has emerged as a promising strategy to enhance the functionality of biodegradable films for food packaging applications. These bioactives provide oxidative stability, UV-blocking capability, and antimicrobial activity, thereby converting conventional bioplastics into active packaging systems Merino et al. [6], Lee et al. [36] & Bhattarai et al. [37]. Extraction of phenolic- rich fractions can be achieved via solvent extraction using ethanol, water, or their mixtures, as well as advanced green techniques such as microwave-assisted extraction, ultrasound-assisted extraction, or supercritical CO_2 extraction. The choice of extraction method influences the yield, composition, and bioactivity of the extracts, including total phenolic content, radical scavenging potential (DPPH, ABTS), and antimicrobial efficacy Bhattarai et al. [6] & Merino et al. [37] & Rostami et al. [38].For incorporation, three main strategies are employed: (1) direct blending into the polymer melt or solution when the bioactive compounds are thermally stable, which allows uniform distribution within the matrix; (2) encapsulation using carriers such as cyclodextrins, nanoemulsions, liposomes, or polysaccharide microcapsules to protect thermally labile compounds during extrusion or processing, ensuring controlled release and retention of functionality; and (3) surface coating or impregnation of the polymer film, enabling localized functionalization and tunable release kinetics Bhattarai et al. [38], & Rodrigues et al. [39]. The impact of bioactive incorporation is evaluated through a combination of analytical and functional tests: antioxidant capacity is measured using DPPH, ABTS, or FRAP assays; antimicrobial activity is assessed via inhibition zone or microbial growth reduction tests; UV- blocking efficiency is quantified spectrophotometrically; and migration studies ensure food- contact safety Merino et al. [6] & Lee et al. [36]. Additionally, the mechanical (tensile strength, elongation at break) and barrier properties (water vapor permeability, oxygen transmission rate) of the films are monitored, as bioactive addition can alter polymer network interactions Rostami et al. [38] & Rodrigues et al. [39]. Overall, the integration of phenolic extracts and other bioactives into biopolymer films provides a dual advantage: valorization of agro-wastes and the production of functional, sustainable active packaging materials suitable for modern food preservation challenges (Table 7).

Table 7: Group 4: Blend Extracted Starch/Cellulose → Gelatinize → Pour → Dry.

S. No	Title	Material Used	Ingredients	Method of Preparation	Authors (APA short)
3	Production of Bioplastic from Waste Agricultural Biomass	Bean peel, plantain peel	Water	Wash, dry, grind, cellulose extraction, conversion.	[3]
7	Tropical Fruit Peel Pectin Film	Tropical fruit pectin	$CaSO_4$, glycerol	Pectin extracted, mixed, cast, dry.	Rahman et al. [61].
28	Bioplastic from Coffee Grounds	Coffee grounds	Agar, glycerin, water	Mix, heat, whisk, pour into mold, set/cool.	[28]
29	Spent Tea Leaf- Based Film	Tea leaves	Bioplastic matrix	Dry, grind, mix, cast.	Melikoglu et al [84].

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Analysis of Bioplastics

Physical Characterization of Bioplastic Materials

The physical analysis of bioplastic materials is essential to determine their suitability for application (e.g., packaging, films, structural parts). Key properties such as thickness, density, water absorption/solubility, mechanical strength (tensile, elongation, modulus) and barrier behaviour (moisture uptake, permeability) provide insight into performance under service conditions Saharan & Kharb [40]. Poor physical performance (e.g., high water uptake, low tensile strength) may limit utility or durability of the bioplastic.

Proposed Tests

Thickness and density: Thickness refers to the average distance between the two major surfaces of a film or sheet of bioplastic. It is important because it influences mechanical behaviour, barrier properties (e.g., permeability), optical clarity, and overall consistency of film production. Density (mass per unit volume) ofa bioplastic film or sheet provides insight into the material's compactness, void content, and filler dispersion. It affects mechanical strength, permeability, and sometimes biodegradation behaviour. Choubey [41]. Use a micrometer or thickness gauge (often with 0.001 mm resolution). Measure film thickness using micrometer; density by displacement or gravimetric methods.

Moisture content / water absorption / solubility: Moisture content is the proportion of water naturally present in the bioplastic film under defined conditions. Water absorption refers to the uptake of water when the film is immersed or exposed to humid conditions often expressed as % increase in weight. Solubility refers to the portion of the film that dissolves in water (or solvent) under defined condition expressed as % of initial mass. These are critical because many bioplastics (especially starch- or cellulose-based) are hydrophilic, and high water uptake or solubility may degrade mechanical/physical performance or reduce service life Choubey et al. [41] & Wardana [42].For example, in a study by Jain et al. [43] bioplastics from soybean agro-waste exhibited water absorption up to 112.6 % (potato starch variant) and 118.1 % (corn-starch variant), signifying very high hydrophilicity.

Elongation at break, Young's modulus: Elongation at break means Strain (often in %) at the instant of failure (how much the film stretches) Young's modulus: Measure of stiffness slope of stress-strain curve in linear elastic region (MPa or GPa). These parameters reflect mechanical durability, flexibility and stiffness of bioplastic films key to applications like packaging, bags or structural parts Gurunathan [44]

Mechanical Tensile Testing: "Tensile testing, also known as tension testing, is a fundamental materials science test in which a sample is subjected to a controlled tension until failure. Properties that are directly measured via a tensile test are ultimate tensile strength, maximum elongation and reduction in area." (IJREAM, 2023). Mechanical Testing (Tensile Tests) characterized mechanical behavior by applying uniaxial force on specimens and recording stress-strain responses. This provided Young's modulus, tensile strength, and elongation at break, essential metrics for assessing if bioplastics meet physical demands of intended applications such as packaging. The authors used tensile testing to compare synthesized materials with conventional plastics, optimize formulations, and evaluate the effects of plasticizers, blending, and fillers. Measures elasticity, tensile strength, and elongation to compare with conventional polymers Shafqat et al. [45].

Water Contact Angle and Gas Permeability: Water Contact Angle (WCA) Measurement quantified surface wettability by measuring the angle formed between a water droplet and the bioplastic surface. This indicates hydrophilicity or hydrophobicity, influencing barrier properties and moisture resistance. "The permeability of a polymer is defined as the rate at which it is penetrated by various gases. gas permeation is the passage of a permeant through a polymer material." Jung, Kim [36] Authors applied WCA to understand surface energy and predict water vapor permeability, informing material suitability for food packaging or moisture-sensitive applications. Evaluate surface hydrophobicity and oxygen/water vapor barrier properties critical for packaging applications (Merino et al., 2021).

Morphology / surface structure / porosity: Morphology addresses the microstructure of the film surface smoothness/ roughness, filler dispersion, porosity, voids, cracks and influences mechanical, barrier and degradation behaviour Amin & Chowdhury [46]. Using SEM or optical microscopy to assess the homogeneity, pore structure, filler dispersion, surface cracks. For example, in composite films with TiO_2 and corn starch, SEM revealed changes in surface roughness and morphology which correlated with mechanical behaviour Amin & Chowdhury [46] (Table 8).

Table 8: Group 5: Mix Waste Powder + Polymer Matrix → Composite Curing.

S. No.	Title	Material Used	Ingredients	Method of Preparation	Authors (APA short)
30	Coffee Grounds Review	Coffee grounds	Lipid/cellulose components	Extract via solvent or acid, blend, process to bioplastic/ bio-composite.	Johnson et al. [83].
31	Peanut Hull- Based Biodegradable Products	Peanut hulls	Starch, agar, glycerol	Powder hulls, mix, refrigerate, dry.	Choudhury et al. [62].

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Chemical Characterization of Bioplastic Materials

Understanding the chemical structure, functional groups, crystallinity, thermal behaviour and morphology at the micro/nano scale is crucial. These structural features govern relationships such as filler-matrix interaction, polymer chain mobility, crystallinity vs amorphous content, and thereby affect mechanical, thermal and degradation behaviour Kharb & Saharan [47]. Without such analysis, it is difficult to interpret why a material behaves as it does or how to tailor it. These analyses allow one to interpret why a material behaves the way it does (for example, why a film with low crystallinity might absorb more water or degrade faster) and thus tailor the formulation to meet targeted properties or end-of-life behaviour.

Fourier Transform Infrared Spectroscopy (FTIR): "Fourier transform infrared (FTIR) spectroscopy probes the vibrational properties of amino acids and cofactors, which are sensitive to minute structural changes." Burton [14]. it is used extensively to identify chemical functional groups and verify molecular interactions. This technique works by passing infrared light through the sample and measuring the absorbance at various wavelengths, which correspond to vibrational modes of specific chemical bonds such as O-H, C=O, and C-H. Authors employed FTIR to confirm the presence of key biopolymer components like cellulose, starch, and pectin, to detect plasticizer incorporation, and to monitor chemical modifications or cross-linking during synthesis. Detects characteristic molecular vibrations by infrared light absorption, confirming functional groups like hydroxyl, ester, and carbonyl. It validates polymer chemical structures and tracks degradation-induced bond cleavage (Merino et al., 2021).

Solid-State Nuclear Magnetic Resonance (NMR): "Solid-state nuclear magnetic resonance spectroscopy is an atomic-level method used to determine the chemical structure, three-dimensional structure and dynamics of solids and semi-solids." (Reif, Ashbrook, Emsley, & Hong, 2021) spectroscopy served as a powerful tool for elucidating detailed molecular structures and quantifying polymer components. NMR exploits the magnetic properties of nuclei such as ^13C under a strong magnetic field to generate spectra revealing chemical environments. The authors used solid-state NMR, specifically cross-polarization magic angle spinning (CP-MAS) techniques, to distinguish and quantify different polysaccharides (cellulose, hemicellulose, starch) and lignin content, crucial for correlating composition with mechanical and biodegradation properties. Reveals molecular environments and compositional proportions of cellulose, starch, and lignin (Merino et al., 2021).

X-Ray Diffraction (XRD): "Solid-state nuclear magnetic resonance spectroscopy is an atomic-level method used to determine the chemical structure, three-dimensional structure and dynamics of solids and semi-solids." (Reif, Ashbrook, Emsley, & Hong, 2021). It was employed to investigate crystallinity and phase composition. By directing X-rays onto a crystalline sample, diffraction patterns are produced according to Bragg's law, revealing information about crystalline structures and the degree of order in polymer chains. The authors leveraged XRD to assess changes in crystallinity due to processing and plasticization, which directly influence mechanical strength and biodegradability, as amorphous regions degrade faster than crystalline ones. Determines crystallinity and phase structure affecting strength and degradation (Merino et al., 2021).

Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC): "Solid-state nuclear magnetic resonance spectroscopy is an atomic-level method used to determine the chemical structure, three-dimensional structure and dynamics of solids and semi- solids." (Reif, Ashbrook, Emsley, & Hong, 2021).TGA measured thermal stability by gradually heating samples and recording mass loss. This technique delineates decomposition temperatures and stages, crucial for understanding processing limits and durability. The authors used TGA to evaluate the effect of plasticizers, fillers, or blending on thermal properties, ensuring materials withstand manufacturing conditions and perform robustly during use. "Solid-state nuclear magnetic resonance spectroscopy is an atomic-level method used to determine the chemical structure, three-dimensional structure and dynamics of solids and semi- solids." (Reif, Ashbrook, Emsley, & Hong, 2021) (DSC) identified thermal transitions such as glass transition temperature (Tg), melting point (Tm), and crystallization behavior by measuring heat flow associated with these events during controlled heating or cooling. DSC provided insights into the thermal properties governing the flexibility, processability, and stability of the bioplastics. Authors included DSC data to complement TGA findings and to tailor processing parameters accordingly. Analyse thermal decomposition and phase transitions to determine processing windows and stability Agarwal et al. [48].

Scanning Electron Microscopy (SEM): "The scanning electron microscope (SEM) uses a focused beam of high-energy electrons to generate a variety of signals at the surface of solid specimens. The signals that derive from electron-sample interactions reveal information about the sample including external morphology (texture), chemical composition, and crystalline structure and orientation." (Swapp, n.d.). Scanning Electron Microscopy (SEM) offered high- resolution imaging of the bioplastic surface morphology and cross-sectional microstructures by scanning with an electron beam, which interacts with the sample to produce secondary electrons detected to form detailed images. Authors utilized SEM to visualize polymer network homogeneity, filler dispersion, fibre alignment, surface roughness, and degradation-induced surface erosion or microbial colonization, linking morphology with performance and biodegradation. Visualizes morphology, surface structure, and degradation changes (Widantha et al., 2025).

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Biological Characterization of Bioplastics

The drive towards developing bioplastics stems significantly from the need for improved end-of-life behaviour particularly biodegradation and compostability compared to traditional petroleum-based plastics. However, literature emphasises that biodegradability is highly variable, and depends on multiple interacting factors such as polymer chemistry (type of bioplastic), degree of crystallinity, environmental conditions (moisture, temperature, microbial community), and the test method used for assessment Onovo [50] & Ajala [51]. For instance, in a soil burial study of a starch-based bioplastic bag, a 74 % weight reduction was achieved over 120 days, whereas an oxo-LDPE control showed only ~3 % reduction under the same conditions, underscoring the influence of material chemistry and microbial dynamics BMC Microbiology [52]. These findings reveal that performing a reliable biodegradation analysis requires linking the rate and extent of degradation to the material's structure and properties (e.g., crystallinity, water-uptake behaviour) and to the specific conditions under which degradation occurs (e.g., soil temperature, nutrient availability). Without this integrated understanding, it is difficult to interpret why certain bioplastic formulations degrade faster or slower, or to predict real-world end-of-life performance. Moreover, recent studies highlight that the biological fate of bioplastics includes not just weight loss but also the dynamics of microbial communities, fragment formation (micro- and nanoplastics), and eco-toxicological implications. For example, a review of biodegradable and bio-based plastic microplastics found that some bioplastic-derived micro-particles can still exert ecotoxicity (e.g., oxidative stress, biomarker effects) in various organisms, meaning that biodegradation alone is not sufficient; the nature of residuals and by-products also matters Ecotoxicity of Biodegradable Microplastics [53]. The interplay between physical/structural properties (e.g., high crystallinity may slow degradation), environmental context (e.g., nutrient limited soils reduce microbial action), and end-of-life pathways (soil burial, composting, aquatic) underscores the need for a comprehensive biological/biodegradation assessment in your study.

Proposed Tests

Soil Burial / Composting Test: Soil burial or composting tests evaluate the biodegradability of bioplastic materials under controlled terrestrial conditions. The test simulates natural or industrial composting, where microbial communities in soil or compost degrade the polymer over time, producing CO_2, water, and biomass Onovo [51]. Mass loss, mechanical property changes (e.g., tensile strength), surface erosion, and chemical changes are typical metrics. SEM or optical microscopy can be used to observe surface morphology and degradation patterns. For instance, Onovo et al. [51] reported 46-63 % mass loss of starch-based films after 30 days, whereas other studies showed 37 % mass loss after 120 days, highlighting variability due to soil type, temperature, and microbial activity. Specimens of the developed bioplastic will be buried in a defined soil or compost matrix (e.g., 25-30 °C, ~60 % water-holding capacity, inoculated with active microbial consortium) for set intervals (e.g., 2, 4, 8, 12 weeks). Measurements will include mass loss (%), mechanical property change (e.g., tensile strength), visual/SEM inspection for cracks or surface erosion, and optionally gas evolution (CO_2 / CH_4) for aerobic/anaerobic conditions. For example, in a soil burial study a mass loss of 46 %-63 % was achieved in 30 days for starch-based films Onovo et al. [51], while another soil study reported 37 % mass loss after 120 days (2016).

Aquatic / Marine Environment Test (if relevant): This test evaluates the degradation of bioplastics in aquatic environments such as seawater, freshwater, or sediments. Films are submerged at the water-sediment interface, and degradation is monitored via mass loss, chemical functional-group changes (e.g., via FTIR), and visual fragmentation. This test is crucial because biodegradation rates in aquatic systems often differ significantly from terrestrial soils due to lower microbial activity, temperature variation, and salinity effects (Phosri, et al., 2022). For bioplastic films likely to enter marine/estuarine environments, submersion in seawater (or sand-seawater interface) with monitoring of weight loss, chemical-group changes (via FTIR), and visual fragmentation will be undertaken. This adds relevance for end-of-life in aquatic settings where degradation kinetics differ.

Anaerobic Digestion / Biogas Test: Anaerobic digestion tests assess biodegradation under oxygen-free conditions. Bioplastics are incubated with anaerobic microbial consortia, often in bioreactors or digestion vessels. Biogas production (CH_4, CO_2), chemical oxygen demand (COD) reduction, and polymer structural changes are measured to determine the rate and extent of degradation (Di et al., 2024). This method is particularly relevant for industrial composting and biogas recovery

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applications. If relevant (e.g., for biodegradable packaging) an anaerobic digestion set-up will measure CH_4/CO_2 production, COD reduction, and polymer structural changes. Reviews highlight that many bioplastics show inconsistent degradation under anaerobic conditions, so this test is essential for industrial composting/AD relevance (Miksch, et al., 2020).

Fragmentation / Micro-particle Release & Kinetics: This test evaluates the formation of micro- and nano-fragments as bioplastics degrade, which is important for environmental safety and degradation kinetics. Periodic sampling allows monitoring of functional-group changes (via FTIR), particle size distribution (via microscopy), and degradation kinetics (e.g., first-order decay modeling). For example, PLA-starch blends were observed to release micro- particles (1-25 μm) within a week under composting conditions, and first-order kinetic modeling quantified degradation rates Biodegradation behavior and modelling [52]. Periodic sampling of degraded material will include chemical analyses (e.g., FTIR to detect functional-group changes), microscopy to detect micro-particle or nano-fragment release, and degradation kinetics modelling (e.g., first-order decay modelling as used for PLA-starch blends) (Biodegradation behaviour and modelling…, 2017) [55].

Microbial Community/Enzymatic Tests and Eco-toxicity Screening: This approach evaluates biodegradation mediated by specific microbial communities or enzymes (e.g., cellulase, lipase) and assesses ecological impact of degradation by-products. Microbial community shifts are often studied via 16S rRNA sequencing, while ecotoxicity tests monitor the effects of residual fragments on soil or aquatic organisms. This helps determine not only degradation efficiency but also environmental safety BMC Microbiology, & Ecotoxicity [52,53]. Where feasible, assess changes in soil microbial community composition using 16S rRNA sequencing as in BMC Microbiology [52] and screen for eco-toxicological effects of residual fragments (e.g., using the recent micro-plastics/bioplastic review) Ecotoxicity [53]. These metrics will provide insight into not just how much degradation occurs, but how and whether by-products may pose ecological risks (Table 9).

Table 9: Comparative Summary Table of Bioplastic Preparation Methods (31 Studies).

Method Type	Representative Studies (APA short)	Feedstock k Used	Process Characteristics	Advantages	Limitations / Challenges	Applications
1. Simple Starch- Gelatinization	Chitra et al. [71]. Sharma et al. 2021; Patel et al. [66]. Robinson et al. 2020; Joshi et al. 2022	Fruit peels (banana, potato, mango, mixed)	Heat starch slurry with glycerol, cast, and air-dry	Easy, reproducible, low-cost	Moderate tensile strength, water sensitivity	Edible films, soft packaging
2. Acid- Aided Pectin Extraction	Tanaka et al. 2020; Khalid et al. 2019; Sharma et al. 2020; Khalid et al. 2021	Citrus and guava peels	Acid hydrolysis, gelation, casting	Good gel strength, water resistance	Brittle films under dry conditions	Edible coatings, thin films
3. Eggshell-Reinforced Starch Films 4 Cellulose-Fiber- Based Composites	Fernandes et al. 2021; Singh et al. [70]. Arun et al. 2020; Khalid et al., 2020; Desai et al. [66]. Tan et al. 2021; Robinson et al. 2021; Deshmukh et al. 2020; Kumaret al. 2020; Tanaka et al. 2019	Starch/pe ction + eggshell Bagasse, coffee, tea, rice husk, peanut shell	Incorporate $CaCO_3$ filler during gelatinization Alkali delignification→ Plasticization → Casting	High strength, improved barrier property Excellent rigidity and durability	Reduced flexibility Energy- intensive; darker color	Packaging, semi- rigid films Rigid container s, trays
5. Multi- Waste Hybrid Blends	Desai et al. [66]; Sharma et al. 2020; Tan et al. 2022; Robinson et al. 2022; Singh et al. [70].	Mixed peels, composted residues	Blend multiple starch or pectin sources	Synergistic flexibility and biodegrade ability	Requires optimization for ratios	General packaging, thin films
6. Fiber- Reinforce d Specialty Films	Joshi et al. 2020; Deshmukh et al. 2021; Khalid et al. 2020	Tea, coffee, fruit fiber composites	Add fiber Filler to starch matrix	Enhanced texture and color	Slight opacity	Bio-tableware, eco-films

Significance / Background

Bioplastics have emerged as a sustainable alternative to petroleum-based plastics due to their renewable origins, biodegradability, and potential to mitigate environmental pollution. Their use in packaging (both flexible and rigid) is expanding rapidly because they can provide comparable barrier and mechanical properties while significantly lowering fossil-carbon dependency and lifecycle emissions Ghasemlou et al. [56] & Ibrahim et al. [57]. Increasing consumer awareness and stricter environmental regulations have further driven the transition toward renewable packaging materials. In agricultural applications, bioplastics such as starch- based and PLA-PBAT blends are used to produce biodegradable mulch films that reduce soil contamination, minimize plastic waste, and improve soil health. These materials can be tailored to degrade at controlled

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rates and serve as carriers for agrochemicals or beneficial microorganisms Nanda et al. [58]. In the biomedical field, polymers like PLA, PHA, and PCL are valued for their biocompatibility and biodegradability, enabling applications in sutures, drug-delivery systems, scaffolds, and temporary implants Ibrahim et al. [57] & Nanda et al. [58]. Their capacity to degrade harmlessly in vivo provides safer, eco-conscious alternatives to conventional medical materials. Further, automotive and consumer product sectors utilize bioplastic composites reinforced with natural fibers, offering lightweight, durable components that lower greenhouse gas emissions and enhance end-of-life management options Ibrahim et al. [57] & Nanda et al. [58]. Likewise, circular-economy research now focuses on transforming agricultural and food residues into bioplastic feedstocks, reducing waste generation and dependence on virgin biomass Senila et al. [59] & Yadav et al. [60]. Collectively, these applications demonstrate that bioplastics are crucial in advancing sustainable material innovation and aligning product lifecycles with global circular-economy objectives.

Knowledge Gaps / Rationale

Despite these advantages, several scientific and practical limitations hinder the widespread adoption of bioplastics and justify targeted research. First, environmental trade-offs vary significantly among production pathways. Life-cycle assessments reveal that certain bioplastic processes (especially fermentation and purification in PLA production) can still exhibit high energy and greenhouse gas footprints if not optimized Senila et al. [59] & Yadav et al. [60]. Therefore, comprehensive environmental analyses are essential to identify truly sustainable synthesis routes. Second, biodegradability claims are often misunderstood; many "biodegradable" plastics require controlled industrial composting to degrade effectively. The lack of infrastructure and standardized labeling leads to confusion and potential contamination of recycling streams Basit et al. [61] & Nizamuddin et al. [62]. Understanding real-world degradation behavior under soil and compost conditions remains a critical gap.

Third, mechanical and thermal limitations of certain bioplastics, such as neat PLA or starch blends, restrict their use in high-performance applications. While additives and reinforcements can improve these properties, they sometimes reduce biodegradability or recyclability Abe et al. [58] & Nanda et al. [63]. Moreover, feedstock competition between food and bioplastic crops raises sustainability concerns. Using agricultural residues or food waste as feedstocks could address this issue but introduces challenges in preprocessing and conversion efficiency Senila et al. [59]. Finally, emerging studies show that bioplastic degradation products can still yield micro- or nano-scale fragments with potential ecotoxic effects Piao et al. [64]. This underscores the need to examine degradation pathways and byproducts in environmental matrices. These gaps form the scientific rationale for the present research, aimed at developing improved, environmentally sustainable bioplastic materials with validated degradation behavior and minimized ecological risk.

Biodegradation of Bioplastics

Biodegradation is a critical parameter determining the environmental sustainability of bioplastics, referring to the biological conversion of polymeric materials into simpler compounds such as carbon dioxide, methane, water, and biomass under natural conditions Chamas et al. [65] & Dilkes-Hoffman et al. [66]. The extent and rate of biodegradation depend on polymer chemistry, crystallinity, molecular weight, additives, and environmental factors such as temperature, humidity, oxygen availability, and microbial population Tokiwa et al. [67] & Nascimento et al. [68]. To comprehensively evaluate biodegradation behavior, multiple complementary analytical techniques are employed, each addressing distinct mechanistic aspects of degradation kinetics, mineralization, and structural transformation.

Mass Loss Determination

mass loss refers to the reduction in sample mass due to volatilisation or decomposition. Mass loss analysis provides a direct measure of polymer decomposition through quantifying the reduction in sample mass over a defined incubation period in soil, compost, or marine environments Chamas et al. [66]. During degradation, polymer chains undergo hydrolysis and microbial enzymatic cleavage, leading to volatilization and physical fragmentation. Periodic weighing at predetermined intervals (e.g., 2, 4, 8, 12 weeks) allows assessment of degradation rate constants and correlation with environmental parameters such as temperature and moisture (Kale et al., 2021). Studies using PLA and starch-based composites have reported up to 70 % mass loss after 12 weeks in controlled composting at 58 °C, demonstrating enhanced microbial assimilation (Nogueira et al., 2022; Merino et al., 2021). This quantitative approach forms a baseline for comparing biodegradability among formulations and environments.

Biological Oxygen Demand (BOD) Measurement

Biological Oxygen Demand (BOD) is the dissolved oxygen consumed by microorganisms during the oxidation of reduced substances in waters and wastes." It quantifies oxygen consumption during microbial degradation, reflecting metabolic activity on the bioplastic Penn, Pauer, & Mihelcic [69]. It serves as an indirect indicator of microbial metabolic activity and the extent of organic carbon conversion to CO_2. Elevated BOD values during incubation indicate active biodegradation of polymer fragments. In bioplastic assessment, BOD tests are often paired with carbon dioxide evolution analysis to determine the degree of mineralization Lucas et al. [67] & Nascimento et al. [70]. For instance, PHA and PBAT- based films exhibited high BOD values in inoculated seawater, suggesting substantial microbial utilization of degradation intermediates (Martinaud et al., 2024). Thus, BOD data provide an eco-physiological metric of bioplastic biodegradability under realistic conditions.

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Gas Evolution Analysis

Gas evolution analysis primarily measuring CO_2 and CH_4 emissions is a key method to confirm mineralization and to distinguish aerobic from anaerobic degradation pathways. The evolved gases are typically quantified via gas chromatography (GC) or infrared gas analysis Nanda et al. [58]. In aerobic composting tests, a stoichiometric correlation between CO_2 evolution and theoretical carbon content is used to determine the percentage of biodegradation (ASTM D5338; ISO 14855). Under anaerobic digestion, CH_4 and CO_2 evolution reveal methanogenic degradation potential (Hermann et al., 2022). Recent studies demonstrated that PLA-PBAT blends reached 80 % mineralization after 90 days under controlled composting conditions, confirming nearly complete bioconversion (Nascimento et al. [67]. Gas evolution results thus serve as a definitive indicator of environmental mineralization.

Spectroscopic Monitoring (FTIR and Complementary Techniques)

Fourier Transform Infrared Spectroscopy (FTIR) is extensively used to monitor chemical changes in polymer functional groups during degradation. The method detects alterations in characteristic absorption peaks corresponding to ester carbonyls, hydroxyls, and aliphatic C- H bonds, which signify chain scission or oxidation (Prasad et al., 2024). Progressive attenuation of C=O and C-O-C bands, along with the emergence of new -OH and COOH peaks, indicates oxidative depolymerization and hydrolysis of ester linkages (Merino et al., 2021; Cazón et al., 2021). FTIR time-series spectra, combined with thermogravimetric and differential scanning calorimetry (DSC) data, provide molecular-level insights into the degradation mechanism, crystallinity changes, and chemical transformations (Martinaud et al., 2024). The use of complementary Raman and UV-Vi's spectroscopy further refines the detection of oxidative intermediates, confirming progressive molecular breakdown.

Surface Morphology Analysis via SEM

Scanning Electron Microscopy (SEM) enables visualization of surface erosion, crack formation, and microbial colonization during and after degradation. SEM imaging operates by directing a focused beam of electrons on the sample surface to generate topographical contrast, revealing microscale structural deterioration (Erdman, Bell, & Reichelt, 2019). Comparative SEM micrographs before and after soil burial tests have shown pronounced pitting, biofilm formation, and surface porosity in starch-PLA composites, signifying microbial activity (Merino et al., 2021; Yadav et al. [60]. SEM evidence corroborates mass loss and FTIR findings, illustrating the morphological manifestation of chemical degradation.

Integrated Multimodal Assessment

Integrating these techniques mass loss quantification, BOD measurement, gas evolution, FTIR spectroscopy, and SEM imaging yields a comprehensive understanding of bioplastic degradation kinetics and mechanisms (Martinaud et al., 2024; Merino et al., 2021). The combination allows researchers to correlate macroscopic weight changes with molecular-level transformations and microbial interactions. Such multimodal approaches align with standardized protocols (ASTM D5988, ISO 17556) ensuring reproducibility and comparability of biodegradability data across laboratories (Haider et al., 2019). These evaluations ensure that newly developed bioplastics meet environmental performance standards and regulatory biodegradability criteria, supporting their responsible deployment in packaging, agriculture, and biomedical applications.

Discussion

The synthesis of bioplastics from various waste materials such as fruit and vegetable peels, eggshells, agricultural residues, and lignocellulosic biomass represent an emerging and sustainable alternative to petroleum-derived plastics. Across the 31 reported studies analysed, the core strategies for bioplastic fabrication revolve around three main biochemical foundations: starch gelatinization, pectin gelation, and cellulose or calcium carbonate reinforcement, each contributing unique structural and mechanical properties.

Fruit-Based Starch and Pectin-Derived Bioplastics

Fruit peel wastes are among the most commonly investigated feedstocks for bioplastic preparation due to their high content of starch, pectin, cellulose, and polyphenolic compounds.

Mixed Fruit and Individual Peel Systems

Chitra et al. (2022) produced a gelatinized biopolymer film using blended banana, orange, and apple peels. Their method involved cleaning, boiling, blending, and filtering the peel extract, followed by heating with glycerol and vinegar until a gel-like matrix was formed. The mixture was then cast into trays and air-dried to form translucent, flexible films. The acid component (vinegar) aided in mild hydrolysis of polysaccharide chains, enhancing uniformity and cohesion. Sharma et al. (2021) adopted a similar approach with banana peel starch, demonstrating improved film flexibility and homogeneity when citric acid was used as a natural cross-linker. Patel et al. (2020) and Tanaka et al. (2020) extended this to potato and orange peels, respectively, highlighting starches and pectin's capability to form semi-crystalline thermoplastics upon heating. Desai et al. [71] and Robinson et al. (2020) utilized pineapple and mango peel starch, respectively, showing that blending cellulose and starch from the same waste increased tensile strength and surface smoothness. Similarly, Khalid et al. (2019) extracted pectin from lemon peel through acid hydrolysis, yielding films with excellent gel consistency and reduced water absorption. Joshi et al. (2022) further reported papaya peel- based bioplastics of high biodegradability within 20 days in soil environments. Overall, the acid-assisted heating-casting-drying approach was a unifying technique for these fruit-derived materials. It is simple, cost-effective, and reproducible, producing uniform films suitable

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for packaging or edible applications. The key difference across studies lies in the plasticizer-acid combination and the starch or pectin content of the feedstock.

Eggshell-Reinforced Bioplastic Composites

The inclusion of eggshell powder ($CaCO_3$) as a reinforcement agent has gained significant attention for improving film strength and reducing hydrophilicity. Fernandes et al. (2021) demonstrated that incorporating finely ground eggshell into starch-glycerol matrices increased tensile strength and hardness by over 25%. The calcium carbonate acted as a nucleating agent, promoting ordered polymer alignment. Singh et al. [72] blended mixed fruit peel extract with eggshell powder and glycerol, producing denser, less porous bioplastics with slower biodegradation rates, extending usability. Similarly, Arun et al. (2020) developed cassava starch-eggshell films, where nano-sized eggshells acted as a bio-filler improving thermal stability. Desai et al. [71] innovatively combined bagasse cellulose with eggshell $CaCO_3$, demonstrating synergistic reinforcement cellulose providing structural rigidity, while $CaCO_3$ reduced hydrophilic swelling. Khalid et al. (2020) explored orange peel pectin-eggshell composites, where Ca^{2+} ions enhanced cross-linking between pectin molecules, improving tensile resistance. Collectively, these findings underscore that eggshell-reinforced starch or pectin films yield superior mechanical properties while maintaining biodegradability, making them suitable for semi-rigid packaging applications.

Cellulosic and Fibrous Agricultural Waste Bioplastics

Fibrous agricultural residues such as sugarcane bagasse, coffee, tea, rice husk, corn husk, and peanut shells are rich in cellulose, hemicellulose, and lignin. These materials require chemical pretreatment for polymer extraction. Tan et al. (2021) extracted cellulose from sugarcane bagasse using delignification and bleaching, blending it with glycerol to produce biodegradable films with high tensile strength. Patel et al. [73] used spent coffee grounds mixed with starch, forming lignocellulosic composites with improved rigidity. Deshmukh et al. (2020) treated tea residues similarly, using citric acid and glycerol to produce films with natural coloration and good thermal stability. Kumar et al. (2020) worked on rice husk-derived silica-starch films, exploiting the amorphous silica structure to enhance stiffness, while Tanaka et al. (2019) incorporated corn husk fibers into starch matrices to create flexible yet resilient biofilms. Robinson et al. (2021) and Witoon et al. [74] used peanut shell powder as a filler in polymeric films, obtaining high-strength composites with reduced plasticizer dependency. Despite requiring energy-intensive alkali pretreatment, these methods produced strong, water-resistant films, optimal for rigid applications (e.g., trays, biodegradable containers). Their main limitations were darker coloration, less flexibility, and slower biodegradation.

Hybrid and Multi-Waste Bioplastic Systems

Hybrid systems combining two or more waste materials were introduced to balance flexibility, strength, and sustainability. Desai et al. (2022) used blended starch from potato and corn peels, showing synergistic gelatinization and enhanced film transparency. Sharma et al. (2020) mixed lemon and orange peels, demonstrating that pectin blends improve elasticity and color uniformity. Tan et al. (2022) combined banana peel starch with coffee residue, achieving a unique texture and enhanced structural rigidity due to lignin-rich coffee residues. Robinson et al. (2022) mixed papaya and mango peels, while Singh et al. [75] developed starch-based films using composted fruit residues-showing high biodegradability and waste recovery efficiency. Other notable studies such as Deshmukh et al. (2021) (pineapple-banana) and Joshi et al. (2020 (starch films reinforced with tea waste fiber) illustrated that combining multiple biopolymers can significantly reduce brittleness without synthetic additives [76-116]. Hence, multi- waste hybridization provides balanced film flexibility and mechanical strength, representing a practical circular-economy approach for food and agricultural industries.

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