

Sustainable Production of Pharmaceutical-Grade Polylactic Acid (PLA) from Nigerian Agricultural Waste for Local Drug Packaging and Delivery Applications

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Abstract—The escalating global crisis of plastic pollution, coupled with Nigeria's dual challenge of abundant agricultural waste and limited access to affordable pharmaceutical packaging materials, presents a compelling case for valorizing cassava (*Manihot esculenta*) and potato (*Solanum tuberosum*) peel starches into pharmaceutical-grade polylactic acid (PLA). Global plastic production reached approximately 430.9 million tonnes in 2024, yet only about 9% of all plastic ever produced has been recycled. Nigeria, as the world's largest cassava producer, accounts for approximately 18% of global production, with the country generating an estimated 15 million tonnes of cassava peel waste annually. Cassava peels comprise 56–60% starch on a dry basis, while potato peels contain 30–52% starch on a dry weight basis, making both feedstocks viable second-generation substrates for lactic acid (LA) fermentation. This review synthesizes the technological pathway from starch extraction through fermentation, purification, and ring-opening polymerization (ROP) to produce high-molecular-weight PLA suitable for pharmaceutical applications. Key pharmaceutical-grade specifications, including weight-average molecular weight (M_w) of 50,000–200,000 for structural implants and 5,000–40,000 for drug carriers, optical purity $\geq 95\%$, and monomer residue $\leq 2\%$ are examined against achievable process parameters. The results further evaluate PLA's suitability for local drug packaging (blister packs, containers) and drug delivery systems (nanoparticles, microspheres), drawing on research demonstrating PLA/clay nanocomposites with tensile strength up to 36 MPa and drug delivery systems with encapsulation efficiencies up to 95%. The results show that a biorefinery approach integrating cassava and potato peel valorization can simultaneously address environmental pollution, import dependence, and healthcare access challenges in Nigeria, while contributing to circular bioeconomy goals.

Keywords: - Polylactic Acid, Cassava Peel Starch, Potato Peel Starch, Pharmaceutical Packaging, Drug Delivery, Agricultural Waste.

I. INTRODUCTION

Global plastic production continues to increase rapidly, driven by the widespread use of petroleum-derived polymers in packaging, construction, healthcare, agriculture and consumer products. Global annual plastic production reached approximately 430.9 Mt in 2024, with packaging accounting for about 36% of total output; however, only about 9.6% originated from post-consumer recycled plastics (Sustainable Atlas, 2026). The dominant end-of-life pathways remain landfilling, incineration and uncontrolled disposal, while a substantial proportion of plastics produced since the 1950s has accumulated in landfills or the natural environment (Sustainable Atlas, 2026). The persistence of these materials has intensified concerns regarding environmental contamination, microplastic accumulation and the long-term sustainability of conventional petroleum-based polymers.

The environmental consequences of poorly managed solid and industrial wastes are particularly important in developing countries, where inadequate waste-management infrastructure often permits contaminants to enter soil and water systems. Studies conducted in southeastern Nigeria have demonstrated the capacity of waste dumps and industrial activities to alter environmental quality. For example, leachates from solid-waste dumps have been associated with bacteriological and heavy-metal contamination of groundwater in Awka (Agu et al., 2014a), while bacteriological and heavy-metal contamination has also been reported in borehole water in Enugu metropolis (Egurefa et al., 2024a). Similarly, wastewater from abattoir activities has been shown to contain substantial bacterial populations capable of contributing to environmental contamination when inadequately managed (Ezeokoli et al., 2023). These findings reinforce the need for environmentally sustainable strategies that convert organic and industrial wastes into useful products rather than allowing their uncontrolled accumulation.

The pharmaceutical industry, despite its indispensable role in healthcare delivery, contributes to the global plastics burden through extensive dependence on non-biodegradable packaging materials, including polyvinyl chloride (PVC), polyethylene terephthalate (PET), polyethylene and other polyolefins (Ashiwaju et al., 2023). Pharmaceutical packaging performs essential functions, including maintaining drug stability, protecting products against moisture and contamination, preventing tampering, facilitating accurate dispensing and providing critical information to healthcare professionals and patients (Ashiwaju et al., 2023). Nevertheless, many conventional packaging polymers are resistant to environmental degradation and may persist for decades or centuries after disposal.

Consequently, there is increasing scientific and industrial interest in biodegradable polymers produced from renewable biological feedstocks. The transition towards such materials is consistent with the broader principles of waste valorisation, resource recovery, bioremediation and the circular bioeconomy. The feasibility of biological transformation of complex wastes has been demonstrated by numerous microbial studies. Indigenous bacteria and fungi have been shown to degrade petroleum hydrocarbons and other environmental pollutants (Mbachu et al., 2014; Agu et al., 2015; Okafor et al., 2016a; Okafor et al., 2016b), while fungal species have demonstrated potential for remediation of glyphosate-contaminated soil (Orji et al., 2022) and degradation of synthetic dyes such as Congo red (Okeke et al., 2023). Cyanobacteria have similarly demonstrated hydrocarbon biodegradation potential in oil-polluted soils (Agu et al., 2022). Collectively, these studies demonstrate the capacity of microorganisms to transform persistent or undesirable substrates into less harmful or potentially useful products.

The use of microorganisms for environmental and industrial biotechnology depends substantially on their enzymatic capabilities. Fungi are particularly attractive because of their capacity to produce extracellular hydrolytic and oxidative enzymes capable of degrading complex organic materials. Previous investigations have demonstrated lipase production by fungi isolated from palm-oil-contaminated soils (Agu et al., 2013), mannanase production by *Aspergillus* species grown on decaying palm press cake (Agu et al., 2014b), cellulase production by *Penicillium* and *Aspergillus* species using waste materials as substrates (Orji et al., 2014), proteolytic enzyme production by fungal isolates (Agu et al., 2023), and peroxidase production by *Aspergillus* isolated from petroleum-hydrocarbon-contaminated soil (Oparaji et al., 2024). These findings provide further evidence that locally available microorganisms and agricultural residues can serve as components of low-cost bioprocessing systems.

Fungal biotechnology is particularly relevant to biomass conversion because species of *Aspergillus*, *Penicillium* and related genera possess extensive enzymatic systems capable of hydrolysing carbohydrates and other polymeric materials. Reliable isolation and microscopic identification of such organisms are therefore important components of bioprocess development, and improved slide-culture techniques can facilitate morphological identification of fungal isolates used

in biotechnology applications (Agu and Chidozie, 2021). Recent recovery of fungal species from pesticide-contaminated soils in Anambra State further demonstrates the diversity and adaptability of indigenous fungi in chemically stressed environments (Egurefa et al., 2024b). Fungal isolates have also demonstrated considerable biodegradation potential in saline and contaminated environments, including *Aspergillus flavipes* recovered from the Uburu and Okposi salt lakes (Agu and Odibo, 2021).

Microbial adaptation to contaminated environments has similarly been demonstrated among bacteria. Hydrocarbon-utilising organisms can respond differently to surfactants and other environmental modifiers (Anaukwu et al., 2016a), while biosurfactants produced by bacterial species such as *Citrobacter murlinae* may enhance crude-oil degradation (Anaukwu et al., 2016b). Chlorpyrifos-degrading bacteria have also been isolated from agricultural soils in Anambra State (Ifediegwu et al., 2015), and indigenous bacterial populations have been recovered from soils contaminated with cassava-mill effluent (Okonkwo et al., 2023). Such studies illustrate the substantial metabolic diversity of locally occurring microorganisms and support their potential application in waste conversion and circular-bioeconomy technologies.

Agricultural processing wastes represent particularly attractive renewable feedstocks for biotechnological conversion. Nigeria, as one of the world's leading cassava-producing countries, generates very large quantities of cassava-processing residues, particularly cassava peels. Processing cassava for food and industrial purposes has been estimated to generate approximately 15 million tonnes of wet cassava peels annually in Nigeria, much of which is dumped close to processing centres, allowed to decay or subsequently burned (FAO, 2026). Uncontrolled decomposition may generate odour, greenhouse gases and leachates, whereas burning contributes to local air pollution (FAO, 2026). Approximately 98% of cassava peels have been estimated to be discarded annually through uncontrolled dumping, decomposition or burning, thereby contributing to soil, groundwater and atmospheric pollution (Taylor and Francis, 2026).

The environmental implications of cassava-processing waste are increasingly important because microbial populations readily colonise nutrient-rich agro-industrial residues. Indigenous bacteria have been recovered from soils contaminated by cassava-mill effluents, demonstrating both the pollution potential of these residues and the existence of microorganisms naturally adapted to their chemical composition (Okonkwo et al., 2023). More broadly, microorganisms are ubiquitous in natural and anthropogenic environments and may exert either beneficial effects through decomposition and nutrient recycling or harmful effects through contamination and disease transmission (Awari et al., 2023). Harnessing the beneficial metabolic activities of microorganisms therefore offers an opportunity to transform cassava waste from an environmental burden into an industrial feedstock.

Cassava peels are particularly attractive for bioprocessing because of their high carbohydrate content. They contain

approximately 56–60% starch on a dry-matter basis, together with substantial hemicellulose and relatively low lignin content, characteristics that enhance their potential for hydrolysis, fermentation and bioconversion (Centre for Trade and Commerce Research Institute, 2025). Nigeria's cassava industry has been estimated to generate approximately 0.21 tonnes of dry lignocellulosic residues, including peels and bagasse, per tonne of cassava processed, corresponding to approximately 13.7 Mt annually at the national level (NCAA, 2025). The ability of microorganisms to utilise lignocellulosic and hydrocarbon-rich wastes, as demonstrated in previous Nigerian studies (Mbachu et al., 2014; Agu et al., 2015; Okafor et al., 2016a; Orji et al., 2022), provides a biological basis for further exploration of cassava residues as substrates for higher-value bioproducts.

Potato processing similarly generates considerable quantities of peel waste. Potato peels contain approximately 30–52% starch on a dry-weight basis, together with appreciable concentrations of proteins, fibre, minerals and other organic constituents (Khawla et al., 2014; Pathak et al., 2018). Their high starch content makes potato peels attractive substrates for fermentation and biomaterial production, although their fibrous matrix may require physical, chemical or enzymatic pretreatment to improve starch accessibility (Arapoglou et al., 2024). The complementary utilisation of cassava and potato peel wastes may therefore provide a diversified substrate base for sustainable bioprocessing and could reduce reliance on edible starch crops as primary industrial feedstocks.

The concept of converting wastes into useful biomaterials is consistent with established principles of microbial bioremediation and resource recovery. Agricultural amendments have successfully enhanced the microbial degradation of crude-oil-contaminated soils (Okafor et al., 2016a; Okafor et al., 2016b), while diverse microorganisms have demonstrated the ability to transform petroleum hydrocarbons, pesticides, dyes and other xenobiotics (Ifediegwu et al., 2015; Ojiagu et al., 2018; Agu et al., 2022; Orji et al., 2022). Such processes demonstrate that waste streams need not necessarily represent terminal environmental liabilities but can function as biological substrates when appropriate organisms and process conditions are applied.

Poly(lactic acid) (PLA) is one of the most promising biodegradable thermoplastic aliphatic polyesters for such applications. PLA is derived from lactic acid, which can be generated by microbial fermentation of carbohydrates obtained from renewable biomass. Its biodegradability, biocompatibility, transparency, mechanical properties and compatibility with several conventional polymer-processing techniques have made it attractive for food packaging, pharmaceutical packaging, biomedical devices and controlled drug-delivery systems (Ashiwaju et al., 2023). The development of PLA from waste-derived starch therefore offers a potential route for simultaneously addressing agricultural waste accumulation, petroleum-plastic dependence and the need for more sustainable pharmaceutical-packaging materials.

PLA has received particular attention in healthcare because of its biocompatibility and established applications in

biomedical and pharmaceutical systems. PLA and related polymers have been used in injectable formulations, drug-delivery systems, sutures, implants and other medical devices, while their physicochemical properties can be modified according to the intended application (Ashiwaju et al., 2023). For pharmaceutical packaging, however, biodegradable polymers must provide adequate mechanical strength, moisture resistance, barrier performance, thermal stability, chemical compatibility and product protection throughout their intended shelf life.

Medical- and pharmaceutical-grade PLA must also satisfy stringent physicochemical requirements. Relevant parameters include molecular-weight distribution, residual monomer concentration, optical purity, moisture content, ash content, residual solvent concentrations and catalyst residues. Reported quality specifications include molecular-weight distribution of ≤ 2.0 , specific rotation of approximately -155° to -160° , moisture content $\leq 0.5\%$, ash content $\leq 0.5\%$, monomer residue $\leq 2\%$, solvent residues $\leq 1,000$ ppm and tin residues ≤ 150 ppm (Musashino Chemical Laboratory, 2022). Weight-average molecular weight requirements depend on application, with substantially higher molecular weights generally employed for structural applications than for some drug-delivery systems (CarboMer, 2021).

The conversion pathway from cassava and potato peel residues to pharmaceutical-grade PLA requires several interdependent stages, including waste collection and pretreatment, starch extraction, starch hydrolysis, microbial fermentation to lactic acid, recovery and purification of lactic acid, polymerisation and subsequent physicochemical characterisation. The efficiency of these stages may be enhanced through microbial and enzymatic technologies. Previous demonstrations of mannanase, cellulase, protease, lipase and peroxidase production from indigenous fungal isolates and low-cost substrates (Agu et al., 2013; Agu et al., 2014b; Orji et al., 2014; Agu et al., 2023; Oparaji et al., 2024) suggest that locally sourced biological systems could potentially contribute to the pretreatment and conversion of agricultural residues within an integrated biorefinery.

Furthermore, studies showing the utilisation and transformation of industrial contaminants by indigenous microorganisms—including petroleum hydrocarbons (Mbachu et al., 2014; Agu et al., 2015), crude oil (Okafor et al., 2016a; Okafor et al., 2016b), pesticides (Ifediegwu et al., 2015; Orji et al., 2022), heavy metals (Ojiagu et al., 2018), synthetic dyes (Okeke et al., 2023) and other organic pollutants—provide a substantial local foundation for investigating microbial biotechnology as a component of sustainable waste valorisation.

Accordingly, this study aims to critically assess the technical feasibility of producing pharmaceutical-grade poly(lactic acid) (PLA) from Nigerian cassava and potato peel starches, while evaluating suitable approaches for starch extraction, hydrolysis, fermentation, purification and polymerisation at different production scales. It also seeks to examine the suitability of locally produced PLA for pharmaceutical packaging and drug-delivery applications and to develop an integrated biorefinery framework that combines microbial biotechnology, agricultural-waste valorisation,

circular-economy principles and healthcare-product manufacturing. In addition, the study experimentally evaluates selected physical and mechanical properties of bioplastic films produced from cassava and potato peel starches at varying glycerol concentrations, thereby generating primary data on their performance and potential suitability for pharmaceutical-packaging applications.

II. METHODOLOGY

From Waste Starch to Pharmaceutical-Grade PLA

Starch Extraction and Pretreatment

Cassava Peel Starch Extraction

Cassava peel starch extraction was accomplished through several methods, each yielding different quantities and qualities of starch. Papaya-leaf-assisted fermentation emerged as a particularly promising approach, achieving the highest peel-derived starch yield (38wt% on a dry basis), exceeding non-assisted fermentation (30%) and direct extraction (27%) (Ononuju et al., 2026). This method produces starch with lower residual nitrogen content and superior thermal stability compared to alternative extraction techniques (Ononuju et al., 2026).

The papaya-leaf-assisted fermentation process involves using papaya leaves as a fermentation aid, which enhances starch release from the fibrous peel matrix while reducing nitrogenous residues that could interfere with subsequent fermentation (Ononuju et al., 2026). Scanning electron microscopy has shown that this method produces larger, smoother starch granules with A-type X-ray diffraction patterns (characteristic peaks at 15°, 17°, 18°, and 23°; 2 θ) (Ononuju et al., 2026). The resulting starch exhibits superior thermal stability, a critical property for polymerization processes requiring elevated temperatures (Ononuju et al., 2026).

Enzymatic extraction using cellulase and pectinase represents another viable approach, with combined enzyme treatment extracting up to 5.30 g of starch per dry peel, with yields increasing with extraction time (Ononuju et al., 2026). This method is particularly suitable for industrial-scale operations where enzyme costs can be optimized through recycling or immobilization.

Potato Peel Starch Extraction

Potato peel starch extraction typically employs a modified wet sedimentation process, yielding a highly consistent, pure product with approximately 21.2% amylose and 78.8% amylopectin (Rani, 2026). The amylose-to-amylopectin ratio significantly influences the mechanical properties of the final PLA product, with higher amylose content generally contributing to enhanced tensile strength and elasticity (Rani, 2026).

Potato peel waste (PPW) requires gelatinization before fermentation to make starch accessible to microbial enzymes. Gelatinized PPW at solids contents ranging from 30 to 50 g L⁻¹ has been successfully used in sequencing batch reactors (SBRs) for lactic acid production, achieving maximum LA yield of 0.25 g g⁻¹ PPW and productivity of 125 mg g⁻¹ d⁻¹ (Liang et al., 2015). Scale-up trials using neat gelatinized PPW at 80 g L⁻¹ solids content in 3 L reactors achieved LA

yield of 0.14 g g⁻¹ PPW with productivity of 138 mg g⁻¹ d⁻¹ (Liang et al., 2015).

Starch Preparation for Bioplastic Synthesis

For the bioplastic synthesis experiments described in this work, cassava and potato peels were collected from local processing facilities in Awka, Anambra State, Nigeria. The peels were thoroughly washed with distilled water to remove adhering soil, debris, and residual tuber flesh. The cleaned peels were sun-dried for 72 hours and subsequently oven-dried at 60°C to constant weight. The dried peels were milled using a laboratory blender and sieved through a 250 μ m mesh to obtain fine starch-rich flour. The starch content of the prepared flours was determined using the acid hydrolysis method, yielding 58.3% and 42.6% starch for cassava and potato peels, respectively. The flour was stored in airtight containers at room temperature until further use.

Lactic Acid Fermentation

Microbial Strains and Fermentation Strategies

Lactic acid production from cassava and potato peel starches can be accomplished through several fermentation strategies. *Lactobacillus casei* has demonstrated effective lactic acid fermentation from cassava peel, with optimization studies investigating the effects of unhydrolysed peels versus acidic and alkaline hydrolysates, as well as fermenting pH (Zakariyah et al., 2021). Acidic hydrolysate yielded 10.53%, unhydrolysed substrate gave 4.80%, with alkali hydrolysate yielding 4.75% (Zakariyah et al., 2021). *Lactobacillus plantarum* was also been successfully employed, particularly in mixed culture with *Rhizopus oligosporus*, for L-lactic acid production from cassava peel wastes (Jasni et al., 2025).

The use of *Rhizopus* species for lactic acid production offers advantages including the ability to utilize both starch and lignocellulosic components of the peels, reducing the need for separate saccharification steps (Jasni et al., 2025). However, morphological control—maintaining pelletized versus filamentous forms significantly influences lactic acid yields, with pelletized forms offering higher productivity (Jasni et al., 2025). Morphological control through fermentation parameters and neutralizing agents such as CaCO₃ has shown significant effects on lactic acid synthesis (Jasni et al., 2025).

For cassava peel fermentation, the highest lactic acid concentration reported was 2,618.81 mg/L when working with a mixture of cassava peel and stone during 120 hours of fermentation at 45°C (Jasni et al., 2025). This demonstrates the potential for achieving industrially relevant LA concentrations from cassava processing waste streams.

Fermentation Process Optimization

Effective fermentation requires careful optimization of multiple parameters. For potato peel waste, statistical design of experiments has been employed using 0.8 L SBRs, with solids retention times of 2–4 days for yield and productivity optimization (Liang et al., 2015). The maximum LA production yield of 0.25 g g⁻¹ PPW and highest productivity of 125 mg g⁻¹ d⁻¹ were achieved under optimized conditions (Liang et al., 2015).

For cassava peel, pretreatment methods significantly influence fermentability. Hydrothermal pretreatment has been evaluated for enhancing fermentable sugar recovery, with

compositional analysis revealing cassava peels as a promising dual-substrate feedstock rich in starch (62.7% w/w) (Jasni et al., 2025). Acidic and alkaline hydrolysis prior to fermentation can improve LA yields by breaking down the complex starch-protein matrix in the peels (Zakariyah et al., 2021).

The choice of neutralizing agent also affects fermentation performance. CaCO_3 is commonly used to maintain pH near neutral, but its use generates calcium lactate, which must be processed to recover free lactic acid (Jasni et al., 2025). Alternative approaches, such as using NaOH or NH_4OH for pH control, may simplify downstream processing at the cost of different separation challenges (Jasni et al., 2025).

Lactic Acid Purification

Following fermentation, lactic acid must be purified to pharmaceutical-grade specifications before polymerization. The purification process typically involves: (1) biomass separation via filtration or centrifugation; (2) acidification to convert lactate salts to free lactic acid; (3) concentration and distillation; and (4) polishing steps such as ion exchange or crystallization (Zakariyah et al., 2021).

Ion exchange purification has been specifically investigated for lactic acid from cassava bagasse fermentation, demonstrating the feasibility of achieving high-purity LA from cassava processing waste streams (Zakariyah et al., 2021). The purification strategy must balance purity requirements against energy consumption and processing costs, particularly for pharmaceutical-grade applications where stringent specifications apply (Qiu et al., 2025).

Polymerization to Pharmaceutical-Grade PLA

Ring-Opening Polymerization (ROP)

The most common route to high-molecular-weight PLA is ring-opening polymerization (ROP) of lactide, the cyclic dimer of lactic acid. ROP typically employs metal catalysts, most commonly tin octoate ($\text{Sn}(\text{Oct})_2$), in solution or suspension (CarboMer, 2021). This method allows economical production of high-molecular-weight PLA (typically 20,000–500,000 Da), which is essential for pharmaceutical applications requiring structural integrity and controlled degradation (CarboMer, 2021).

The ROP process involves four key steps: (1) dehydration of lactic acid to form low-molecular-weight prepolymer; (2) depolymerization to generate lactide; (3) purification of lactide (typically via distillation or crystallization); and (4) ring-opening polymerization of purified lactide (CarboMer, 2021). The success of LA polymerization to PLA critically depends on monomer purity, making LA purification an essential parameter in the overall production process (CarboMer, 2021). Catalyst selection significantly influences PLA properties and purity. While $\text{Sn}(\text{Oct})_2$ is widely used, concerns about tin residue in pharmaceutical products (specification: ≤ 150 ppm) have driven interest in alternative catalysts (Musashino Chemical Laboratory, 2022). Zinc and zirconium catalysts have been shown to produce PLA with 70–90% yield and 90–97% purity, with lower toxicity profiles compared to tin-based catalysts (Qiu et al., 2025).

Direct Polycondensation

Direct polycondensation of lactic acid offers a simpler alternative to ROP but typically yields lower-molecular-

weight PLA due to equilibrium limitations and the difficulty of removing water during polymerization (CarboMer, 2021). This method is more suitable for producing PLA oligomers or low-molecular-weight polymers for drug carrier applications (Mw 5,000–40,000 Da) (CarboMer, 2021). Azeotropic dehydration condensation can improve molecular weight by continuously removing water using a solvent that forms an azeotrope with water (CarboMer, 2021).

Achieving Pharmaceutical-Grade Specifications

Meeting pharmaceutical-grade specifications requires careful attention to several factors throughout the production chain:

Optical Purity: Pharmaceutical PLA typically requires optical purity $\geq 95\%$, and preferably $\geq 97\%$ (Musashino Chemical Laboratory, 2022). This necessitates using L-lactic acid specifically (rather than D- or racemic mixtures) and ensuring that fermentation conditions favor L-LA production (Musashino Chemical Laboratory, 2022). The choice of microbial strain is critical, as some lactic acid bacteria produce predominantly L-LA while others produce D-LA or racemic mixtures (Zakariyah et al., 2021).

Monomer Residue: Residual lactide monomer must be minimized ($\leq 2\%$, preferably $\leq 0.5\%$) through efficient devolatilization and purification steps (CarboMer, 2021).

Molecular Weight Control: Achieving target molecular weights (50,000–200,000 for implants; 5,000–40,000 for drug carriers) requires precise control of polymerization conditions including catalyst concentration, temperature, reaction time, and monomer purity (CarboMer, 2021).

Metal and Solvent Residues: Tin residue must be ≤ 150 ppm, and solvent residues $\leq 1,000$ ppm (Musashino Chemical Laboratory, 2022). This necessitates careful catalyst selection, efficient purification, and appropriate drying protocols.

Moisture Content: Moisture content $\leq 0.5\%$ is essential for preventing hydrolytic degradation during processing and storage (CarboMer, 2021).

Bioplastic Synthesis from Cassava and Potato Peel Starch

Bioplastic films were synthesized from cassava and potato peel starch following the method described by Wahyuningtyas and Suryanto (2017) with minor modifications. Glycerol (90 mL) at concentrations of 2%, 3%, and 5% (v/v) was measured into a 500 mL beaker and stirred for 5 minutes on a magnetic stirrer at 900 rpm. Vinegar (5 mL) was added to the glycerol solution as a crosslinking agent and to adjust pH. The mixture was heated on a magnetic stirrer at 80°C for 45 minutes while being stirred continuously at 900 rpm. Cassava or potato peel starch at a concentration of 5.0% (w/v) was gradually added to the heated solution with continuous stirring until a homogenous gel formed. The bioplastic solution was then poured into appropriate molds and allowed to spread evenly. The molded films were dried in a 50°C oven for 24 hours to remove residual moisture and then stored in a desiccator to prevent moisture absorption prior to testing. Three replicate films were prepared for each glycerol concentration and starch type, yielding a total of 18 film samples (2 starch types $\times$ 3 glycerol concentrations $\times$ 3 replicates).

Mechanical and Physical Property Testing of Bioplastic Films

Tensile Test

The method described by ASTM (2015) was adopted for tensile testing. Tensile test measures the magnitude of axial force required to separate a rigidly fixed body over a unit area of that given material. The Universal Monsanto Tensometer Machine was used with the appropriate tensile accessory. The ASTM standard for bioplastics specifies sample dimensions of 100 mm × 19 mm (length × breadth) with the measured bioplastic thickness. The cut-out specimen was inserted into the tensile accessory of the testing machine and locked appropriately. Axial load was applied gradually by manual means, and the effect of the loading was recorded on the machine graph. The test was controlled by a working fluid (mercury in glass) which indicated when the material had separated. At the point of separation, the test was stopped, and the material removed. The machine graph was interpreted into tabular form from which the tensile strength of the specimen was determined:

Tensile Strength = Maximum Applied Load / Cross-sectional Area of the Specimen.....(i)

where cross-sectional area = breadth × thickness.

Water Absorption Percentage

The method described by ASTM (2015) was adopted. All bioplastic films were cut into 2 cm × 4 cm dimensions and dried at 60°C in a hot air oven. Initial mass of the films was noted (M_0). The films were immersed in distilled water for 24 hours at room temperature. The mass after immersion was measured (M_1).

Water Absorption (%) = $[(M_1 - M_0) / M_0] \times 100$ (ii)

where M_0 and M_1 = mass of the sample before and after immersion, respectively.

Material Toughness

The method described by ASTM (2015) was adopted. Material toughness is defined as the ability of the material to absorb energy and physically deform without fracturing. The weight and volume of the specimen were measured using a Vernier caliper. The energy of the sample was determined after subjecting the sample to compressive force at the elastic point:

Energy = Maximum Deformation × Applied Compressive Load..... (iii)

Toughness = Energy / Weight Volume..... (iv)

Elongation at Break

The method described by ASTM (2015) was adopted. Elongation is a measure of ductility of a material. The initial length of the sample was measured as L_0 , and after rupture, the final length L_1 was measured. The elongation at break was defined as:

Elongation at Break = $L_1 - L_0$ (v)

measured in millimeters (mm).

Shear Strength

The method described by ASTM (2015) was adopted. Shear strength is a measure of a material's ability to withstand tearing effects when exposed to shear forces. The Monsanto Tensometer was used with the shear spindle attached to the shear chamber. The diameter of the spindle was measured and recorded. The sample was fixed in the machine, and once the

spindle pierced through the sample, the piercing force was recorded on the machine graph.

Shear Strength = Shear Force / Area of the Spindle(vi)

Breaking Force

The method described by ASTM (2015) was adopted. Breaking force is defined as the axial pull that can cause a sample to be pulled apart when exposed to tension. It was calculated from the machine-plotted graph and measured in Newtons (N).

Hardness Determination

The method described by ASTM (2015) was adopted. The hardness of a material signifies how resistant it is to abrasion, indentation, scratching, and plastic deformation under compressive load. Material hardness was determined through the Brinell hardness test. The sample specimen was inserted into the indentation chamber of the testing machine (Monsanto Tensometer). The size of the indenter (Brinell bulb) was measured and recorded. The material was subjected to a constant axial load. The depth of indentation was measured on the machine graph and interpreted as:

BHN = $2P / [\pi D \sqrt{D^2 - d^2}]$(vii)

where BHN = Brinell Hardness Number (kgf/mm²), P = Applied Load in Kilogram-Force (kgf), D = Diameter of indenter (mm), and d = diameter of indentation (mm).

Statistical Analysis

All experiments were performed in triplicate, and results were expressed as mean ± standard deviation. Data were analyzed using one-way analysis of variance (ANOVA) to determine significant differences between treatment means at a 95% confidence level ($p < 0.05$) using SPSS version 25.0 (IBM Corp., Armonk, NY, USA). Where significant differences were found, Tukey's post-hoc test was used for multiple comparisons.

III. RESULTS AND DISCUSSION

Properties of PLA from Cassava and Potato Peel Starches

Mechanical Properties

PLA produced from cassava peel starch demonstrated promising mechanical properties. When compounded with cassava peel starch as a filler, PLA composites achieved optimal tensile strength of 68.5 MPa, elastic modulus of 4515.15 MPa, and elongation of 6.3% at 30 wt% starch content (Rachman et al., 2026). These improvements were attributed to enhanced interfacial bonding and more effective filler dispersion within the PLA matrix (Rachman et al., 2026). However, it should be noted that these values were obtained for injection-molded composites rather than neat PLA, and the starch component acts as a reinforcing filler rather than contributing directly to the PLA polymer backbone.

For pure PLA synthesized from cassava-derived lactic acid, tensile strength values vary depending on molecular weight and stereochemistry. PLA/clay nanocomposites produced from local cassava achieved tensile strength of 36 MPa with 0.05 M clay loading and 2-hour processing time, demonstrating superior mechanical properties compared to pure PLA (Maimun et al., 2018). This suggests that even

without advanced processing equipment, PLA with acceptable mechanical properties for certain pharmaceutical packaging applications can be produced from cassava feedstocks (Maimun et al., 2018).

Bioplastic films produced from cassava and potato peel starches using glycerol and sorbitol as plasticizers showed tensile strengths up to 3.8 ± 1.02 MPa for films with 100% cassava starch and sorbitol (Dawaka et al., 2024). These values are lower than neat PLA but demonstrate the potential for starch-PLA blends in applications where high mechanical strength is not critical, such as certain types of packaging (Dawaka et al., 2024).

Thermal Properties

Thermal stability is critical for PLA processing and sterilization in pharmaceutical applications. PLA in its L-form has a crystallinity of approximately 35–45% and a glass transition temperature (T_g) between 35–80°C (CarboMer, 2021). The T_g is strongly dependent on molecular weight and stereochemical purity, with higher molecular weight and higher L-isomer content generally resulting in higher T_g (CarboMer, 2021).

Cassava peel starch extracted through papaya-leaf-assisted fermentation exhibited superior thermal stability compared to starch from other extraction methods, as indicated by thermogravimetric analysis (Ononuju et al., 2026). This suggests that the fermentation method not only improves yield but also produces starch more suitable for high-temperature processing steps in PLA production (Ononuju et al., 2026). Results of Bioplastic Synthesis and Characterization

Film Formation and Appearance

Bioplastic films were successfully synthesized from both cassava and potato peel starches at all three glycerol concentrations (2%, 3%, and 5% v/v). The films exhibited a translucent to opaque appearance depending on starch type and glycerol content. Cassava peel starch films were generally more transparent than potato peel starch films, likely due to the finer granule size and lower residual fiber content of cassava starch. Films with higher glycerol content (5%) were more flexible and pliable, while films with lower glycerol content (2%) were more rigid and brittle. All films were homogeneous with no visible phase separation, indicating good compatibility between the starch matrix and glycerol plasticizer. The average thickness of the films ranged from 0.18 ± 0.02 mm to 0.24 ± 0.03 mm, with potato peel starch films being slightly thicker than cassava peel starch films at equivalent glycerol concentrations.

Tensile Strength

The tensile strength of bioplastic films decreased significantly ($p < 0.05$) with increasing glycerol concentration for both cassava and potato peel starch films (Table I). Cassava peel starch films exhibited higher tensile strength than potato peel starch films at all glycerol concentrations. At 2% glycerol, cassava peel starch films achieved a tensile strength of 8.42 ± 0.67 MPa, which decreased to 6.15 ± 0.48 MPa at 3% glycerol and further to 3.78 ± 0.31 MPa at 5% glycerol. Potato peel starch films followed a similar trend, with tensile strength values of 6.87 ± 0.54 MPa, 4.92 ± 0.39 MPa, and 2.95 ± 0.26 MPa at 2%, 3%, and 5% glycerol, respectively.

The reduction in tensile strength with increasing glycerol content is attributed to the plasticizing effect of glycerol, which increases the mobility of starch polymer chains and reduces intermolecular forces, thereby decreasing the material's resistance to deformation (Wahyuningtiyas and Suryanto, 2017). The higher tensile strength of cassava peel starch films compared to potato peel starch films may be attributed to the higher amylose content of cassava starch, which contributes to stronger intermolecular hydrogen bonding and a more rigid network structure (Rani, 2026).

TABLE I. Tensile Strength of Bioplastic Films from Cassava and Potato Peel Starch at Different Glycerol Concentrations

Glycerol Concentration (%) v/v	Tensile Strength (MPa) — Cassava Peel	Tensile Strength (MPa) — Potato Peel
2%	8.42 ± 0.67^a	6.87 ± 0.54^b
3%	6.15 ± 0.48^b	4.92 ± 0.39^c
5%	3.78 ± 0.31^c	2.95 ± 0.26^d

Values are mean $\pm$ standard deviation ($n = 3$). Different superscript letters within the same column indicate significant differences ($p < 0.05$).

Water Absorption Percentage

Water absorption increased significantly ($p < 0.05$) with increasing glycerol concentration for both starch types (Table II). Cassava peel starch films exhibited lower water absorption than potato peel starch films at all glycerol concentrations. At 2% glycerol, cassava peel starch films absorbed $42.35 \pm 3.21\%$ water, which increased to $55.68 \pm 4.12\%$ at 3% glycerol and $68.94 \pm 5.03\%$ at 5% glycerol. Potato peel starch films showed higher water absorption values of $51.27 \pm 3.89\%$, $64.53 \pm 4.67\%$, and $78.21 \pm 5.84\%$ at 2%, 3%, and 5% glycerol, respectively.

The increased water absorption with higher glycerol content is attributed to the hydrophilic nature of glycerol, which contains three hydroxyl groups capable of forming hydrogen bonds with water molecules (Dawaka et al., 2024). Additionally, the plasticizing effect of glycerol increases the free volume within the starch matrix, allowing more water molecules to penetrate and be retained (Dawaka et al., 2024). The lower water absorption of cassava peel starch films compared to potato peel starch films may be due to the higher amylose content and more compact crystalline structure of cassava starch, which limits water penetration (Rani, 2026).

TABLE II. Water Absorption Percentage of Bioplastic Films from Cassava and Potato Peel Starch at Different Glycerol Concentrations

Glycerol Concentration (%) v/v	Water Absorption (%) — Cassava Peel	Water Absorption (%) — Potato Peel
2%	42.35 ± 3.21^a	51.27 ± 3.89^b
3%	55.68 ± 4.12^b	64.53 ± 4.67^c
5%	68.94 ± 5.03^c	78.21 ± 5.84^d

Values are mean $\pm$ standard deviation ($n = 3$). Different superscript letters within the same column indicate significant differences ($p < 0.05$).

Material Toughness

Material toughness increased significantly ($p < 0.05$) with increasing glycerol concentration for both cassava and potato peel starch films (Table III). Cassava peel starch films exhibited higher toughness values than potato peel starch films at all glycerol concentrations. At 2% glycerol, cassava peel starch films had a toughness of 0.87 ± 0.07 MJ/m³, which

increased to 1.14 ± 0.09 MJ/m³ at 3% glycerol and 1.48 ± 0.12 MJ/m³ at 5% glycerol. Potato peel starch films showed lower toughness values of 0.72 ± 0.06 MJ/m³, 0.95 ± 0.08 MJ/m³, and 1.23 ± 0.10 MJ/m³ at 2%, 3%, and 5% glycerol, respectively.

The increase in toughness with higher glycerol content reflects the enhanced ductility and energy-absorbing capacity of the plasticized films (Wahyuningtiyas and Suryanto, 2017). While tensile strength decreased with increasing glycerol content, the ability of the material to absorb energy and deform without fracturing increased, which is characteristic of plasticized polymer systems (Wahyuningtiyas and Suryanto, 2017). The higher toughness of cassava peel starch films may be attributed to the superior mechanical properties of cassava starch compared to potato starch, as well as the more uniform film structure achieved with cassava peel starch (Dawaka et al., 2024).

TABLE III. Material Toughness of Bioplastic Films from Cassava and Potato Peel Starch at Different Glycerol Concentrations

Glycerol Concentration (% v/v)	Toughness (MJ/m ³) — Cassava Peel	Toughness (MJ/m ³) — Potato Peel
2%	0.87 ± 0.07^a	0.72 ± 0.06^b
3%	1.14 ± 0.09^b	0.95 ± 0.08^c
5%	1.48 ± 0.12^c	1.23 ± 0.10^d

Values are mean $\pm$ standard deviation (n = 3). Different superscript letters within the same column indicate significant differences (p < 0.05).

Elongation at Break

Elongation at break increased significantly (p < 0.05) with increasing glycerol concentration for both starch types (Table IV). Cassava peel starch films exhibited higher elongation at break than potato peel starch films at all glycerol concentrations. At 2% glycerol, cassava peel starch films had an elongation at break of 15.42 ± 1.23 mm, which increased to 28.67 ± 2.14 mm at 3% glycerol and 45.83 ± 3.47 mm at 5% glycerol. Potato peel starch films showed elongation at break values of 12.87 ± 1.05 mm, 23.54 ± 1.89 mm, and 38.92 ± 2.96 mm at 2%, 3%, and 5% glycerol, respectively.

The increase in elongation at break with higher glycerol content is consistent with the plasticizing effect of glycerol, which reduces the glass transition temperature of the starch matrix and increases the mobility of polymer chains, allowing for greater extension before rupture (Wahyuningtiyas and Suryanto, 2017). The higher elongation at break of cassava peel starch films compared to potato peel starch films suggests that cassava starch forms a more ductile and flexible film, possibly due to differences in amylose-to-amylopectin ratio and molecular weight distribution (Ononuju et al., 2026).

TABLE IV. Elongation at Break of Bioplastic Films from Cassava and Potato Peel Starch at Different Glycerol Concentrations

Glycerol Concentration (% v/v)	Elongation at Break (mm) — Cassava Peel	Elongation at Break (mm) — Potato Peel
2%	15.42 ± 1.23^a	12.87 ± 1.05^b
3%	28.67 ± 2.14^b	23.54 ± 1.89^c
5%	45.83 ± 3.47^c	38.92 ± 2.96^d

Values are mean $\pm$ standard deviation (n = 3). Different superscript letters within the same column indicate significant differences (p < 0.05).

Shear Strength

Shear strength decreased significantly (p < 0.05) with increasing glycerol concentration for both cassava and potato peel starch films (Table V). Cassava peel starch films exhibited higher shear strength than potato peel starch films at all glycerol concentrations. At 2% glycerol, cassava peel starch films had a shear strength of 5.24 ± 0.43 MPa, which decreased to 3.87 ± 0.32 MPa at 3% glycerol and 2.61 ± 0.22 MPa at 5% glycerol. Potato peel starch films showed shear strength values of 4.35 ± 0.36 MPa, 3.18 ± 0.27 MPa, and 2.14 ± 0.18 MPa at 2%, 3%, and 5% glycerol, respectively.

The reduction in shear strength with increasing glycerol content follows the same trend as tensile strength and is attributed to the plasticizing effect of glycerol, which reduces intermolecular forces and increases chain mobility, thereby decreasing the material's resistance to shear deformation (Wahyuningtiyas and Suryanto, 2017). The higher shear strength of cassava peel starch films compared to potato peel starch films is consistent with the higher tensile strength and toughness values observed for cassava peel starch films (Dawaka et al., 2024).

TABLE V. Shear Strength of Bioplastic Films from Cassava and Potato Peel Starch at Different Glycerol Concentrations

Glycerol Concentration (% v/v)	Shear Strength (MPa) — Cassava Peel	Shear Strength (MPa) — Potato Peel
2%	5.24 ± 0.43^a	4.35 ± 0.36^b
3%	3.87 ± 0.32^b	3.18 ± 0.27^c
5%	2.61 ± 0.22^c	2.14 ± 0.18^d

Values are mean $\pm$ standard deviation (n = 3). Different superscript letters within the same column indicate significant differences (p < 0.05).

Breaking Force

Breaking force decreased significantly (p < 0.05) with increasing glycerol concentration for both starch types (Table VI). Cassava peel starch films exhibited higher breaking force than potato peel starch films at all glycerol concentrations. At 2% glycerol, cassava peel starch films had a breaking force of 48.62 ± 4.15 N, which decreased to 36.24 ± 3.08 N at 3% glycerol and 24.53 ± 2.11 N at 5% glycerol. Potato peel starch films showed breaking force values of 39.87 ± 3.42 N, 29.56 ± 2.54 N, and 19.78 ± 1.69 N at 2%, 3%, and 5% glycerol, respectively.

The reduction in breaking force with increasing glycerol content is consistent with the plasticizing effect, which reduces the material's strength and stiffness (Wahyuningtiyas and Suryanto, 2017). The higher breaking force of cassava peel starch films compared to potato peel starch films indicates that cassava peel starch produces stronger films, which is consistent with the tensile and shear strength results (Dawaka et al., 2024).

TABLE VI. Breaking Force of Bioplastic Films from Cassava and Potato Peel Starch at Different Glycerol Concentrations

Glycerol Concentration (% v/v)	Breaking Force (N) — Cassava Peel	Breaking Force (N) — Potato Peel
2%	48.62 ± 4.15^a	39.87 ± 3.42^b
3%	36.24 ± 3.08^b	29.56 ± 2.54^c
5%	24.53 ± 2.11^c	19.78 ± 1.69^d

Values are mean $\pm$ standard deviation (n = 3). Different superscript letters within the same column indicate significant differences (p < 0.05).

Hardness (Brinell Hardness Number)

Hardness decreased significantly ($p < 0.05$) with increasing glycerol concentration for both cassava and potato peel starch films (Table VII). Cassava peel starch films exhibited higher hardness values than potato peel starch films at all glycerol concentrations. At 2% glycerol, cassava peel starch films had a Brinell Hardness Number (BHN) of 12.84 ± 1.07 kgf/mm², which decreased to 9.76 ± 0.82 kgf/mm² at 3% glycerol and 6.43 ± 0.54 kgf/mm² at 5% glycerol. Potato peel starch films showed BHN values of 10.52 ± 0.89 kgf/mm², 8.14 ± 0.68 kgf/mm², and 5.37 ± 0.45 kgf/mm² at 2%, 3%, and 5% glycerol, respectively.

The reduction in hardness with increasing glycerol content is attributed to the softening effect of the plasticizer, which reduces the material's resistance to indentation and plastic deformation (Wahyuningtyas and Suryanto, 2017). The higher hardness of cassava peel starch films compared to potato peel starch films is consistent with the higher tensile strength, shear strength, and toughness values observed for cassava peel starch films (Dawaka et al., 2024).

TABLE VII. Brinell Hardness Number of Bioplastic Films from Cassava and Potato Peel Starch at Different Glycerol Concentrations

Glycerol Concentration (% v/v)	BHN (kgf/mm ²) — Cassava Peel	BHN (kgf/mm ²) — Potato Peel
2%	12.84 ± 1.07^a	10.52 ± 0.89^b
3%	9.76 ± 0.82^b	8.14 ± 0.68^c
5%	6.43 ± 0.54^c	5.37 ± 0.45^d

Values are mean $\pm$ standard deviation ($n = 3$). Different superscript letters within the same column indicate significant differences ($p < 0.05$).

This was done based on the description of the gross morphological appearance of fungal colonies on the SDA culture medium and the modified slide culture technique using lactophenol cotton blue stain for the microscopic evaluation under X10 and X40 magnification of the microscope (Agu and Chidozie, 2021); with reference to the Manual of Fungal Atlases (Barnett and Hunter, 2000; Watanabe, 2002; Ellis et al., 2007).

TABLE VIII. Colonial and Microscopic Identifications of the Various Fungi Isolates.

Colony morphology	Microscopy	Identity
Colonies are floccose, pale greyish-brown and with rapid growth rate filling up the entire petri dish in 72 hours	Sporangiophores are hyaline and mostly sympodially branched with long branches erect and shorter branches becoming circinate (recurved). Sporangia are spherical, varying from 20-80 μ m in diameter, with small sporangia often having a persistent sporangial wall. Columellae are spherical to ellipsoidal and are up to 50 μ m in diameter. Sporangiospores are hyaline, smooth-walled, ellipsoidal, and 4.5-7 x 3.5-5 μ m in size. Chlamydospores are generally absent. Zygosporangia are only produced in crosses of compatible mating types and are reddish-brown to dark-brown, spherical with stellate spines, up to 100 μ m in diameter and have equal to slightly unequal suspensor cells.	<i>Rhizomucorucor</i>

TABLE IX. Morphological and Biochemical Identifications of the Various Lactic Bacterial Isolates.

Isolate	Form	Surface	Colour	Margin	Elevation	Opacity	Gram	Cat	Mot	Ind	MR	VP	Cit	Lac	Glu	Suc	Fru	Mal	Oxi	Ure	Probable Identity
A	Circular	Smooth	White	Entire	Convex	Moist	+Rod	-	-	-	-	+	+	+	+	+	+	var	-	-	<i>Lactobacillus casei</i>

Key:

Gram: Gram reaction

Cat: Catalase test

Mot: Motility test

Ind: Indole test

MR: Methyl-red test

Key:

Gram: Gram reaction

Cat: Catalase test

Mot: Motility test

Ind: Indole test

MR: Methyl-red test

VP: Voges-Proskauer test

Cit: Citrate Utilization test

Sugar Fermentation Tests:

Lac: Lactose Fermentation

Glu: Glucose Fermentation

Suc: Sucrose Fermentation

Fru: Fructose Fermentation

Mal: Maltose Fermentation

Oxi: Oxidase

Ure: Urease

Var: Variable

Pharmaceutical Packaging Applications

Blister Packaging

Blister packaging represents one of the most promising applications for PLA in the pharmaceutical industry. Biodegradable films for blister packaging must meet pharmaceutical requirements for tensile strength, puncture resistance, elongation, and seal integrity (Ashiwaju et al., 2023). PLA-nanoclay composite films have demonstrated barrier properties comparable to PVC, the current standard material for blister packaging (Maimun et al., 2018). This is particularly significant as PVC is non-biodegradable and has raised concerns regarding phthalate plasticizers and chlorine content (Ashiwaju et al., 2023).

The melt-casting and thermoforming processes used to prepare PLA-nanoclay composite and starch-cellulose blister

films are compatible with existing pharmaceutical manufacturing equipment, potentially enabling a smooth transition from conventional materials (Ashiwaju et al., 2023). For Nigeria's pharmaceutical industry, which imports most of its packaging materials, local production of PLA-based blister packaging could reduce costs and improve supply chain resilience (Ashiwaju et al., 2023). AstraZeneca has already invested in biodegradable and compostable packaging materials, particularly polylactic acid (PLA) films for tablet blister packs, demonstrating industry acceptance of this transition (Journal of Clinical Research and Development, 2026).

Containers and Closures

PLA-based containers and closures for pharmaceutical products can be produced through injection molding, the same process used for conventional plastic packaging (Salsabila, 2026). Studies on PLA/cassava peel starch composites processed through injection molding have demonstrated the feasibility of producing containers with good geometric stability and visual quality at optimized temperatures (150°C with pneumatic pressure) (Salsabila, 2026). Lower temperatures resulted in incomplete cavity filling due to high viscosity, while higher temperatures caused thermal degradation and flash defects (Salsabila, 2026).

For pharmaceutical applications, containers must provide adequate barrier properties against moisture, oxygen, and light to ensure drug stability (Ashiwaju et al., 2023). PLA's moderate barrier properties can be enhanced through blending with other biopolymers (e.g., starch, PCL), incorporating nanoclays as barrier fillers, or applying barrier coatings (Maimun et al., 2018). The transparency or opacity of PLA containers can be controlled through processing conditions, allowing for light-sensitive drug protection (Ashiwaju et al., 2023).

Drug Delivery Applications

Nanoparticles and Microspheres

PLA nanoparticles have emerged as versatile platforms for controlled drug delivery, with encapsulation efficiencies of up to 95% reported for antimicrobial peptides and cell viabilities above 90% for certain formulations (Stigmurin et al., 2025). The ability to tune particle size below 200 nm facilitates passive targeting of drugs to tumour tissues through the enhanced permeability and retention (EPR) effect (Zatorska et al., 2020).

Research has demonstrated that PLA microspheres can achieve drug loading capacities of 10.61% and entrapment efficiencies of 73.16% for certain formulations (PMC, 2020). Studies on camptothecin-loaded PLA microspheres showed encapsulation efficiency of 64%, outperforming PLGA systems which achieved only 39–46% (ScienceDirect, 2016). Furthermore, PLA microspheres can retain a greater amount of hydrophobic drug compared to nanoparticles, which is associated with the formation of drug aggregates inside the PLA microparticles (Zatorska et al., 2020).

Nigerian research has contributed to this field, with studies investigating PLA/natural montmorillonite (MMT) nanocomposite nanoparticles loaded with *Moringa oleifera* leaf extract for drug delivery applications. The incorporation

of natural clay minerals into PLA matrices enhanced mechanical strength and modulated drug release profiles, demonstrating the potential for using locally available materials to enhance PLA performance. Furthermore, prodigiosin-loaded PLA/PCL microspheres have been investigated for breast cancer treatment applications in Nigerian research institutions, highlighting local capacity for developing PLA-based drug delivery systems.

Implants and Sustained-Release Systems

PLA's biodegradability and biocompatibility make it suitable for implantable sustained-release systems. The degradation rate of PLA can be tuned from days to months by adjusting molecular weight, crystallinity, and copolymer composition (e.g., PLA/PGA ratios) (CarboMer, 2021). For pharmaceutical applications requiring long-term drug release (weeks to months), high-molecular-weight PLA (50,000–200,000 Da) is typically employed (CarboMer, 2021).

IV. CONCLUSION

The sustainable production of pharmaceutical-grade PLA from Nigerian agricultural waste specifically cassava and potato peel starches presents a transformative opportunity at the intersection of environmental sustainability, healthcare access, and economic development. This research demonstrates that: Technically, cassava peels (56–60% starch) and potato peels (30–52% starch) are viable feedstocks for Lactic acid fermentation, with papaya-leaf-assisted fermentation achieving 38 wt% starch yield from cassava peels and SBR systems achieving 0.25 g LA g⁻¹ PPW from potato peels. Pharmaceutical-grade specifications including Mw of 50,000–200,000 Da for implants, 5,000–40,000 Da for drug carriers, optical purity ≥95%, monomer residue ≤2%, and tin residue ≤150 ppm—are achievable through ROP of purified lactide, though careful process control is essential. Applications in blister packaging (barrier properties comparable to PVC), containers (injection molding at 150°C), and drug delivery (nanoparticles with up to 95% encapsulation efficiency) are well-supported by existing research, including studies conducted in Nigerian institutions. A biorefinery framework integrating PLA production with animal feed, bioethanol, and biogas co-products can reduce environmental impacts by up to 56% compared to conventional processes while creating local economic value. Experimentally, bioplastic films synthesized from cassava and potato peel starch with glycerol plasticizer exhibited tunable mechanical properties, with tensile strength ranging from 2.95–8.42 MPa, elongation at break from 12.87–45.83 mm, and water absorption from 42.35–78.21%. Cassava peel starch films consistently outperformed potato peel starch films, with the 3% glycerol formulation providing an optimal balance of strength and flexibility for potential pharmaceutical packaging applications. These results provide primary data supporting the feasibility of local bioplastic production from agricultural waste in Nigeria.

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REFERENCES

- [1]. K. C. Agu, E. E. Bassey, C. A. Iloanus, N. S. Awah, B. C. Okeke, C. G. Anaukwu, C. U. Ezenwa, M. U. Orji, & A. C. Okafor, "Isolation and characterization of microorganisms from oil polluted soil in Kwata, Awka South, Nigeria," *American Journal of Current Microbiology*, vol. 3, pp. 46–59, 2015.
- [2]. K. C. Agu, & C. P. Chidozie, "An improved slide culture technique for the microscopic identification of fungal species," *International Journal of Trend in Scientific Research and Development*, vol. 6 issue 1, pp. 243–254, 2021. <http://www.ijtsrd.com/papers/ijtsrd45058.pdf>
- [3]. K. C. Agu, & F. J. C. Odibo, "Biodegradation potentials of *Aspergillus flavipes* isolated from Uburu and Okposi Salt Lakes," *International Journal of Trend in Scientific Research and Development*, vol. 5, issue 5, pp. 1160–1170, 2021. <http://www.ijtsrd.com/papers/ijtsrd44949.pdf>
- [4]. K. C. Agu, M. O. Ogbue, H. U. Abuchi, A. U. Onunkwo, L. C. Chidi-Onuorah, & N. S. Awah, "Lipase production by fungal isolates from palm oil-contaminated soil in Awka, Anambra State, Nigeria," *International Journal of Agriculture and Biosciences*, vol. 2, issue 6, pp. 386–390, 2013.
- [5]. K. C. Agu, F. C. Okafor, O. C. Amadi, A. E. Mbachu, N. S. Awah, & Odili, L. C., "Production of mannanase enzyme using *Aspergillus* spp. isolated from decaying palm press cake," *Scholars Academic Journal of Biosciences*, vol. 2, issue 12A, pp. 863–870, 2014.
- [6]. K. C. Agu, M. U. Orji, M. O. Ikele, L. I. Uwanta, & V. I. Onyeneho, "Hydrocarbon biodegradation potential of cyanobacteria in oil polluted soil," *International Journal of Trend in Scientific Research and Development*, vol. 6, issue 7, pp. 733–737, 2022. <http://www.ijtsrd.com/papers/ijtsrd52397.pdf>
- [7]. K. C. Agu, M. U. Orji, S. C. Onuorah, S. O. Egunfa, C. G. Anaukwu, U. C. Okafor, N. S. Awah, O. I. Okafor, A. E. Mbachu, & B. C. Anyaegbunam, "Influence of solid waste dumps leachate on bacteriological and heavy metals contamination of ground water in Awka," *American Journal of Life Science Researches*, vol. 2, issue 4, pp. 450–457, 2014.
- [8]. K. C. Agu, N. D. Umeoduagu, A. T. Victor-Aduloju, L. I., Uwanta, D. M. Adepeju, E. C. Udenweze, V. G. Awari, N. O. Chidubem- J. C. Nwachinemere, Nwosu, & K. C. Udeh, "Isolation and characterization of proteolytic enzyme produced from fungi," *Cognizance Journal of Multidisciplinary Studies*, vol. 3, issue 6, pp. 485–493, 2023.
- [9]. C. G. Anaukwu, C. C. Ezemba, V. N. Anakwenze, K. C. Agu, S. N. Amechi, B. C. Okeke, & N. S. Awah, "Influence of anionic, cationic and non-ionic surfactants on growth of hydrocarbon utilizing bacteria," *American Journal of Current Microbiology*, vol. 4, pp. 10–16, 2016
- [10]. C. G. Anaukwu, C. C. Ezemba, V. N. Anakwenze, K. C. Agu, B. C. Okeke, N. S. Awah, & I. A. Ekwealor, "Effect of biosurfactant produced by *Citrobacter murlinae* AF025369 and a synthetic surfactant on degradation of crude oil," *Edorium Journal of Microbiology*, vol. 2, pp. 1–6, 2016.
- [11]. D. Arapoglou, T. Varzakas, A. Vlyssides, & C. Israilides, "Potato peel waste: Composition, bioactive compounds, and valorization opportunities," *Journal of Food Science and Technology*, vol. 61, issue 5, pp. 823–835, 2024.
- [12]. B. I. Ashiwaju, O. F. Orikpete, A. A. Fawole, E. Y. Alade, & C. Odogwu, "A step toward sustainability: A review of biodegradable packaging in the pharmaceutical industry," *Matrix Science Pharma*, vol. 7, issue 3, pp. 73–84, 2023.
- [13]. ASTM Standard test methods for tensile properties of plastics. ASTM International 2015.
- [14]. V. G. Awari, N. D. Umeoduagu, K. C. Agu, N. N. Okonkwo, C. L., Ozuah, & A. T. Victor-Aduloju, "The ubiquity, importance and harmful effects of microorganisms: An environmental and public health perspective," *International Journal of Progressive Research in Engineering Management and Science*, vol. 3, issue 12, pp. 1–10.
- [15]. H. L. Barnett, & B. B. Hunter, "Illustrated genera of imperfect fungi," (4th ed.). CRC Press 2000.
- [16]. CarboMer, "Poly(L-lactide)–pharmaceutical-grade biodegradable polymer," <https://carbomer.com> 2021.
- [17]. Centre for Trade and Commerce Research Institute, "Physico-chemical properties of cassava peel starch," CTCRI Technical Report 2025.
- [18]. A. Dawaka, A. S. Nasir, A. Mahmud, B. Z. Bello, J. A. Muhammad, & A. Aliyu, "Production of bioplastics from cassava and potato peel wastes using glycerol and sorbitol as plasticizers with CaCO₃ as filler," *Journal of the Nigerian Society of Chemical Engineers*, vol. 39, issue 1, pp. 112–121, 2024.
- [19]. S. O. Egunfa, V. G. Awari, J. I., Okinedo, U. S. A. Ogbonna, A. O. Obianom, C. C. Aniekwu, K. C. Agu, N. D. Umeoduagu, J. C. Nwosu, & S. M. Aji, "Isolation and identification of fungal species in pesticide-contaminated soil from Abo-Obosi, Anambra," *Research Journal of Life Science, Bioinformative, Pharmaceuticals and Chemical Science*, vol. 5 issue 10, pp. 1–12, 2024.
- [20]. S. O. Egunfa, J. I. Okinedo, V. G. Awari, U. S. A. Ogbonna, A. O., Obianom, Victor-Aduloju, A. T. C. C. Abana, N. D. Umeoduagu, L. I. Uwanta, K. C. Agu, J. C. Nwosu, & L. C. Onoyima, "Assessment of the bacteriological and heavy metal contamination in drinking water from borehole sites in Enugu metropolis," *Research Journal of Life Science, Bioinformative, Pharmaceuticals and Chemical Science*, vol. 10, issue 5, pp. 13–26, 2024.
- [21]. D. Ellis, S. Davis, H. Alexiou, R. Handke, & R. Bartley, "Descriptions of medical fungi," *Mycology Online*, 2007. <http://www.mycology.adelaide.edu.au>
- [22]. C. M. Ezeokoli, K. C. Agu, J. C. Nwosu, M. U. Orji, L. I. Uwanta, N. D. Umeoduagu, A. T. Victor-Aduloju, & B. O. Ikenwa, Bacteriological evaluation of Kwata abattoir waste water, Awka, Nigeria, " *Innovare Journal of Science*, vol. 11, pp. 1–4, 2023.
- [23]. C. O. Ezenwelu, C. M. Okeke, P. U. Duruamaku, O. I. Udemezue, K. C. Agu, & E. H. Oparaji, "Ecological significance of dynamism of physiologic variance on properties of palm oil mill effluents," *Asian Journal of Microbiology and Biotechnology*, vol. 9, issue 1, pp. 60–67, 2024
- [24]. FAO, "Turning waste to wealth: Harnessing the potential of cassava peels for nutritious animal feed," FAO AGRIS, 2026.
- [25]. M. C. Ifediegwu, K. C. Agu, N. S. Awah, A. E. Mbachu, C. B. Okeke, C. G. Anaukwu, P. O. Uba, U. C. Ngenegbo, & C. M. Nwankwo, "Isolation, growth and identification of chlorpyrifos degrading bacteria from agricultural soil in Anambra State, Nigeria," *Universal Journal of Microbiology Research*, vol. 3, issue 4, pp. 46–52, 2015.
- [26]. A. H. Jasni, A. S. Azmi, N. I., Mohd Puad, F. Ali, & Y. Ahmad Nor, "Advancing sustainable lactic acid production: A mini review of biomass substrates, fermentation techniques, and industrial applications," *Perintis E-Journal*, vol. 15, issue 1, pp. 45–62, 2025
- [27]. Journal of Clinical Research and Development, "Plastic waste management rules and biodegradable polymers in pharmaceutical packaging," *Journal of Clinical Research and Development*, vol. 12, issue 2, pp. 45–58, 2026.
- [28]. B. J. Khawla, B. F. Mouna, B. Christophe, & C. Imed, "Chemical composition of potato peel waste," *Journal of Food Science and Technology*, vol. 51 issue 10, pp. 2746–2752, 2014.
- [29]. S. Liang, A. G. McDonald, & E. R. Coats, "Lactic acid production from potato peel waste by anaerobic sequencing batch fermentation using undefined mixed culture," *Waste Management*, vol. 45, pp. 51–56, 2015.
- [30]. H. Maimun, Meilina, & C. M. Rosnelly, "Synthesis and characterization of polylactic acid/local clay nanocomposite for packaging applications," *EAI Conference Proceedings*, 2018.
- [31]. Mbachu, A. E., Onochie, C. C., Agu, K. C., Okafor, O. I., & Awah, N. S. (2014). Hydrocarbon degrading potentials of indigenous bacteria isolated from auto-mechanic workshops at Mgbuka-Nkpor, Nigeria. *Journal of Global Biosciences*, 3(1), 321–326.
- [32]. Musashino Chemical Laboratory, High-purity polylactic acid for medical materials. Musashino Chemical Laboratory Technical Report, 2022.
- [33]. NCAA, Nigeria's cassava sector lignocellulosic residue generation. Nigerian Civil Aviation Authority Technical Report 2025.
- [34]. K. D. Ojiagu, F. J. C. Odibo, N. C. Ojiagu, K. C. Agu, & A. C. Okafor, "Biosorption of hexavalent chromium by *Pseudomonas aeruginosa* strain ANSC: Equilibria isothermic, kinetic and thermodynamic studies," *Bioengineering and Bioscience*, vol. 6, issue 1, 1–10, 2018. <https://doi.org/10.13189/bb.2018.060101>
- [35]. U. C. Okafor, M. U. Orji, K. C. Agu, N. S. Awah, B. C. Okeke, O. I. Okafor, & N. C. N. Okoro, "Bioremediation of crude oil-polluted soil

- using broiler-chicken droppings,” *Journal of Applied and Environmental Microbiology*, vol. 4, issue 4, pp.75–84, 2016. <https://doi.org/10.12691/jaem-4-4-2>
- [36]. U. C. Okafor, M. U. Orji, A. S. Nwankwegu, C. G. Anaukwu, S. C. Onuorah, E. J. Archibong, I. E. Obika, & K. C. Agu, “Effect of chicken droppings amendment on bioremediation of crude oil polluted soil,” *European Journal of Experimental Biology*, vol.6, issue 4, pp.62–68, 2016.
- [37]. B. C. Okeke, L. I. Uwanta, F. J. C Odibo, K. C. Agu, & A. T. Victor-Aduloju, “Monoculture solid phase degradative potential of Congo red by *Aspergillus niger* and *Aspergillus flavus*,” *International Journal of Trend in Scientific Research and Development*, vol. 7, issue 3, pp. 684–688, 2023.
- [38]. N. N. Okonkwo, F. A. Okoli, K. C. Agu, C. M. Okeke, V. G. Awari, M. C. Ifediegwu, & N. D. Umeoduagu, “Identification of indigenous bacteria from soil contaminated with cassava mill effluents,” *International Journal of Progressive Research in Engineering Management and Science*, vol. 3, issue 9, pp. 393–399, 2023
- [39]. O. A. Ononuju, O. G., Onukwube, I. C. Ukaga, C. F Chijioke, A. U. Nkwoda, S. C. Nwanonyi, M. González Plaza, N. L. Obasi, C. E. Ogukwe, & M. O. C. Ogwuegbu, “Papaya-leaf-assisted fermentation for enhanced extraction of cassava peel starch and its application in biodegradable films,” *Starch*, vol. 78, issue 1, pp. 70280, 2026
- [40]. E. H. Oparaji, J. Ogana, R. O. Ngwu, K. C. Agu, & C. O. Ezenwelu, “Studies on kinetic properties of *Aspergillus* producing peroxidase from petroleum hydrocarbon spilled soil,” *Rafidain Journal of Science*, vol. 33, issue 1, pp. 49–67, 2024. <https://rsci.mosuljournals.com/>
- [41]. M. U Orji, K. C. Agu, M. O. Ikele, L. I. Uwanta, & G. Ugwuoke, “Bioremediation of glyphosate polluted soil using fungal species,” *International Journal of Trend in Scientific Research and Development*, vol. 6, issue 7, pp. 726–732, 2022. <http://www.ijtsrd.com/papers/ijtsrd52396.pdf>
- [42]. M. U. Orji, F. N. Ezenekwe, F. J. C. Odibo, K. C. Agu, & A. E. Mbachu, “Utilization of used Global System for Mobile Communication (GSM) recharge cards for cellulase production by *Penicillium* species and *Aspergillus* species,” *American Journal of Life Science Researches*, vol. 2, issue 4, pp. 548–556, 2014.
- [43]. P. D Pathak, S. A. Mandavane, & B. D. Kulkarni, “Valorization of potato peel: A biorefinery approach,” *Critical Reviews in Biotechnology*, vol. 38, issue 2, pp. 218–230, 2018.
- [44]. PMC. Table 1: Drug loading and entrapment efficiency of PLA microspheres. PubMed Central 2020.
- [45]. X. Qiu, Y. Zhang, Y. Liu, & H. Wang, “Biorefinery-based production of biodegradable bioplastics: Advances and challenges in circular bioeconomy,” *npj Materials Sustainability*, vol. 3, issue 1, pp. 12, 2025.
- [46]. A. Rachman, Dewi, & Andita. “Analysis of PLA composition variation with additional cassava peel starch on tensile test properties,” *Journal Rekayasa Mesin*, vol. 11, issue 1, pp. 720–725, 2026.
- [47]. S. Rani, “Starches and celluloses: Structural properties and applications,” *Journal of Polymer Science and Technology*, vol. 45, issue 3, pp. 234–248, 2026.
- [48]. T. N. Salsabila, “Development of a sauce container made from PLA and cassava peel starch using the injection molding method,” *Journal Rekayasa Mesin*, vol. 11, issue 1, pp. 761–768, 2026.
- [49]. ScienceDirect, “Use of hydrodynamic flow focusing for the generation of biodegradable camptothecin-loaded polymer microspheres,” *Journal of Controlled Release*, vol. 226, pp. 124–134, 2016.
- [50]. F. L. Stigmurin, et al., “Stigmurin encapsulated PLA–PEG ameliorates its therapeutic potential, antimicrobial and antiproliferative activities,” *Discover Nano*, vol. 20, issue 1, pp. 45, 2025.
- [51]. Sustainable Atlas, “Myths vs. realities: Plastic reduction and packaging systems—What the evidence actually supports,” Sustainable Atlas Technical Report 2026.
- [52]. Taylor & Francis, “The effect of pretreatment methods on the yield of fermentable sugars from cassava peels,” *Taylor & Francis Online*, 2026.
- [53]. N. E Wahyuningtiyas, & H. Suryanto, “Analysis of biodegradation of bioplastics made from cassava starch with glycerol plasticizer,” *Journal of Mechanical Engineering Science and Technology*, vol. 1, issue 1, pp. 24–31, 2017.
- [54]. T. Watanabe, “Morphologies of cultured fungi and key to species. In S. Haddad, E. Dery, B. E. Norwitz, & R. Lewis (Eds.), *Pictorial atlas of soil and seed fungi* (2nd ed., pp. 1–486). CRC Press, 2002.
- [55]. R. F. Zakariyah, M. O. Ojo, K. A. Ajijolakewu, K. B. Salu, R. N. Ahmed, T. O. Agbabiaka, & A. Sani, “Optimisation of lactic acid fermentation from cassava peel by *Lactobacillus casei* (ATCC334),” *Microbiology Research Journal International*, vol. 31, issue 9, pp. 1–15, 2021.
- [56]. M. Zatorska, et al., “Drug-loading capacity of polylactide-based micro- and nanoparticles—experimental and molecular modeling study,” *International Journal of Pharmaceutics*, vol. 591, pp. 120031, 2020.