

Production of Biodegradable Films as a Renewable Source for Packaging Materials Using Mango Seed Kernel Starch

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Abstract: An underutilized agro-industrial waste, mango seed kernel starch (MSKS), was extracted from *Mangifera indica* seeds and characterized for its physicochemical properties, including amylose content, swelling power, and thermal stability. The extracted starch exhibited a moderate amylose content (31.4%), which is favorable for film formation because it can form strong, continuous networks. The widespread environmental impact of synthetic plastics has prompted the search for sustainable alternatives, with biodegradable polymers emerging as a promising solution. The films were prepared by blending MSKS with polyvinyl acetate (PVAc) at varying ratios (20:80 to 80:20) to enhance mechanical properties and processability. The blends were analyzed using Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), X-ray diffraction (XRD), and thermogravimetric analysis (TGA). FTIR confirmed successful polymer blending, while SEM revealed homogeneous film surfaces with minimal cracks. XRD indicated a semi-crystalline structure, and TGA demonstrated thermal stability up to 350°C, with decomposition primarily occurring between 200–350°C. The research highlights the potential of MSKS as an economical, environmentally friendly substitute for traditional plastics, reducing pollution and promoting sustainable packaging solutions. Future work should concentrate on life cycle assessments (LCA) and industrial-scale production to validate commercial feasibility. The study emphasizes the sustainability and economic viability of MSKS-based films, highlighting waste valorization, reduced carbon footprint, and inherent biodegradability; however, challenges like processing costs and scalability require further optimization. The findings are in line with global efforts to promote circular economy principles and comply with strict regulations like the EU's Packaging and Packaging Waste Regulation (PPWR).

Keywords: Biodegradable films, mango seed kernel starch, sustainable packaging, polyvinyl acetate, waste valorization.

I. Introduction

Background

Many efforts have been exerted to develop starch-based polymers for conserving petrochemical resources, reducing environmental impact, and searching for more applications (Lu, et al., 2009). Biodegradable polymers represent a developing ground. A vast number of biodegradable polymers (e.g. cellulose, chitin, starch, polyhydroxyalkanoates, polylactide, collagen, polycaprolactone, and polypeptides e.t.c) have been synthesized or are formed in a natural environment during the growth levels of organisms (Averous, L. and Boquillon, N. 2012). The pervasive use of synthetic plastics in packaging has led to a global environmental catastrophe, characterized by widespread pollution, ecosystem disruption, and significant contributions to greenhouse gas (GHG) emissions. Conventional plastics, primarily derived from fossil fuels, are designed for durability, persisting in the environment for hundreds to thousands of years, fragmenting into hazardous micro- and nanoplastics that infiltrate ecosystems and food chains (Rahimzadeh & Parsa, 2024; Shen et al., 2024). In 2019, the plastics industry accounted for approximately 3.4% of global GHG emissions, with projections indicating a doubling by 2060 (Akhter et al., 2024). The packaging sector remains a primary culprit, contributing 40% of Europe's plastic demand in 2021, with an average recycling rate of only 40% in the EU in 2022 (Fukuda et al., 2024). This alarming scenario, coupled with increasing consumer demand for eco-friendly products and stringent regulatory pressures like the European Union's Packaging and Packaging Waste Regulation (PPWR), underscores the critical need for biodegradable and compostable alternatives (CDF Corporation, 2024; European Bioplastics, 2025).

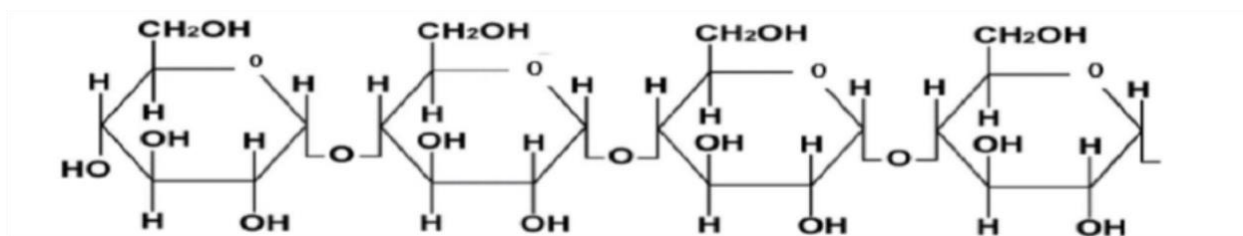
Bioplastics, particularly those derived from renewable biomass, present a viable pathway to mitigating plastic pollution. Among the myriad of natural polymers, starch stands out due to its abundance, biodegradability, low cost, and film-forming capabilities (Kore et al., 2024). Agro- industrial waste streams, such as those from fruit processing, offer an untapped reservoir of starch, representing a sustainable and circular economy approach (Kore et al., 2024). Mango, a widely cultivated tropical fruit, generates substantial waste, including peels and seed kernels, which often go unutilized or are discarded, posing environmental challenges (Al-Saadi et al., 2023). Mango seed kernel starch (MSKS), a major component of this waste, has garnered significant attention as a promising raw material for producing biodegradable packaging films due to its high starch content and inherent biodegradability (Arora et al., 2023; Kore et al., 2024; Md. Amin et al., 2024). This article provides a comprehensive overview of recent advancements (2022-2025) in leveraging MSKS for biodegradable film production, highlighting its potential as a renewable and sustainable packaging solution.

Native Starch Structure

Starch is a natural polymer, an inexpensive and abundant resource, which is biodegradable and can be easily degraded in water being often used as filler for the replacement of petroleum- derived synthetic polymers to reduce environmental pollution. (Elisabeta *et al.*, 2015). Starches have been used to produce biodegradable films to partially or entirely replace petroleum-based plastic polymers because of their low cost and renewability, and it has good mechanical properties (Xu *et al.*, 2005).

Several starches were being used in this synthesis of biodegradable polymer but most are not economically viable, especially in Nigeria, but Mango seed kernel starch is of interest being a waste in some industries and the environment as a whole. It can be hydrolyzed into glucose by microorganisms or enzymes and then further metabolized into CO₂ and H₂O thereby ascertaining its biodegradability. Starch is a polymeric carbohydrate composed of anhydroglucose units. This is not a uniform material and most starches contain two types of glucose polymers: a linear chain molecule termed amylose and a branched polymer of glucose termed amylopectin (Rodriguez *et al.*, 2006).

Starch is the reserved carbohydrate stored as glucose in plants to meet energy needs. It is a natural polymer made up of hundreds of thousands of glucose units linked together by glycosidic bonds. It is the most common carbohydrate in human diets and is contained in large amounts such as yam, cassava, wheat, corn, rice, potatoes, mushrooms, etc. (Alobi *et al.*, 2017). Starch is a white, granular, organic chemical that is produced by all green plants. Starch is a soft, white, tasteless powder that is insoluble in cold water, alcohol, or other solvents. The basic chemical formula of the starch molecule is (C₆H₁₀O₅)_n. Starch is a polysaccharide comprising glucose monomers joined in α 1,4 linkages as shown in scheme 1. The simplest form of starch is the linear polymer amylose while amylopectin is the branched form (Saidu, H. M. and Balarabe S.S. 2023).

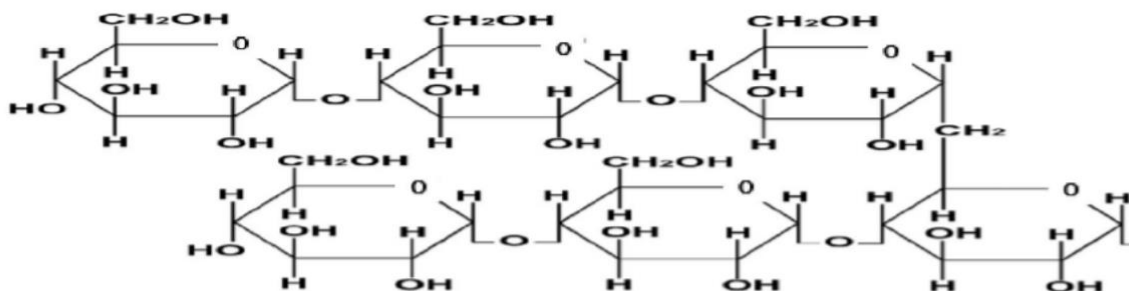


α -1,4^l-linkages scheme 1: structure of a glucose monomer

Amylose

The amylose is mainly a linear polysaccharide composed of D-glucose units linked by α (1 – 4) linkages. These chains are partially ramified with some α (1 – 6) linkages as shown in scheme

1.2. Depending on the botanical source and the extraction process used, amylose molecular weight varies from 10⁵ to 10⁶ gmol⁻¹ with a poly disparity ranging from 1.3 to 2. 1 (Hizukuri *et al.*, 1996). The amylose chain shows a single or double-helical conformation with a rotation on the α (1 – 4) linkages (Valle, *et al.*, 1998). Amylose is a linear portion of starch it is a polymer of glycopyronosyl monomers linked to each other by α (1 – 4) linkages. Amylopectin has the same backbone as amylose, but it's a branched polymer of α (1 – 6) monomer linkages (Cura *et. al*, 1990).



α -1,6^l-linkage scheme 2: structure of a glucose monomer

Biodegradable polymer

Biodegradable simply means capable of undergoing decomposition into carbon dioxide, methane, water, inorganic compounds, and biomass (Averous, L. and Boquillon, N. 2012). They are also polymers or polymer blends, which in addition to processing

properties similar to conventional polymers are susceptible to natural enzyme hydrolysis or other chemical attacks (Sriroth *et al.*, 2019). These are polymers obtained from renewable resources which attracted much attention in recent years. This new interest results from global environmental respect awareness and the fossil depletion problem. Most of the biodegradable polymers have hydrolyzable and/or oxidizable linkage along their main chain. Polymers like poly (vinyl acetate) (PVAc) are known to undergo hydrolysis by side-chain. (Sivalingam *et al.*, 2003). Biodegradable and biocompatible polymers are nowadays gaining importance worldwide in both basic and applied research fields such as pharmacological, biomedical, and environmental applications (Jayachandra *et al.*, 2016).

Improved Mechanical Properties and Biodegradation:

Studies have explored the use of additives and modifications to enhance MSKS-based bioplastics. Research in 2022 demonstrated that adding cellulose to MSKS bioplastics significantly improved their mechanical properties. These bioplastics also showed high biodegradation rates, with 93% to 94% degradation within 30 days, suggesting new opportunities for fast-degrading biomaterials in agricultural applications (Rendón-Villalobo, R. 2022).

Another study from 2024 investigated the incorporation of carboxymethyl cellulose (CMC), chitosan (CS), and nanochitosan (NCS), along with sorbitol as a plasticizer and citric acid (CA) as a cross-linking agent. The addition of CA decreased water uptake and water vapor permeability, while CS and NCS improved mechanical strength. All developed bioplastics showed good antimicrobial activities, highlighting their potential for sustainable food packaging. (Sudha J. *et al.*, 2024).

The development and incorporation of starch nanoparticles (SNPs) from mango kernel starch have shown significant improvements. A 2024 study successfully incorporated 5% SNP concentration into composite films. These films demonstrated enhanced biodegradability, achieving complete degradation within three weeks. They also exhibited increased burst strength and reduced water vapor transmission rates and water solubility. (Akhter, J. M., *et al.* 2024).

Ongoing research continues to refine the extraction and characterization of MSKS from different mango varieties. A 2024 study explored low-cost methods for extracting MSKS from Surjapuri

(X) and Amrapali (Y) varieties using distilled water and alkaline solutions. This research provides insights into variations in starch yield, proximate composition, and physicochemical properties based on extraction methods and mango variety. (Akhter, J. M., *et al.* 2024).

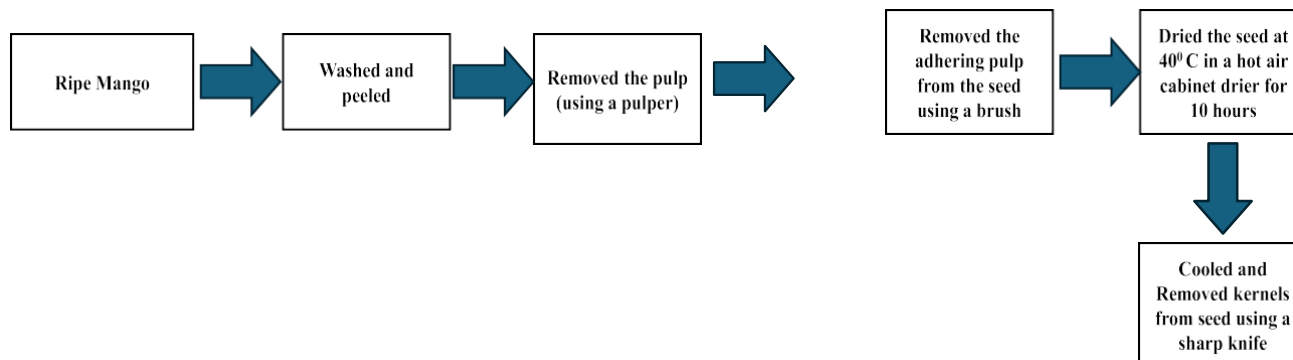
MSKS is also being explored for active edible coatings to extend the shelf-life of fruits. A 2022 study developed mango kernel seed starch-based edible coatings combined with lemongrass essential oil. These coatings were effective in enhancing the storage life of guava fruit by maintaining quality attributes and reducing physiological loss in weight and oxidation rate. (Yadav, A. *et al.*, 2022).

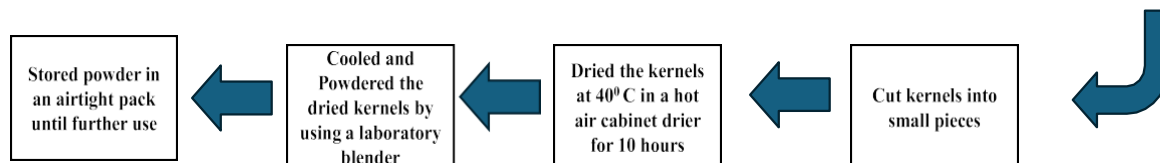
II. Methodology

A specie of mango (*Mangifera indica*) seed kernel was sourced in one of the local markets named Naibawa Yan Lemo, Kano State Nigeria.

Sample Extraction and Preparation

The kernel of the mango seeds samples was cut into small pieces and steeped in 0.16% aqueous solution of sodium hydrogen sulfite for 24 hours for preservation. The solution was decanted, and the samples were ground in a blender. The ground slurry was screened through muslin cloth where it was left and washed thoroughly with distilled water. After 1 hour the supernatant was then decanted from the filtrate and allowed the starch layer to settle and re-suspended again in distilled water followed by centrifuging at 2800 rpm for about 5min. The upper non-white layer of the residue was scraped off and the white layer was re-suspended in distilled water and centrifuged. This was repeated four more times and finally, the starch was then collected and dried at 50°C for 6 hours in an oven. The extracted starch was then mixed with glycerol in different blends and then transferred to a high-speed mixer to prepare the thermoplastic starch at 78°C. The thermoplastic and the reactive agent (hydrogen peroxide) were then melted together at different ratios of each blend varying the polyvinyl acetate to get the biopolymer.





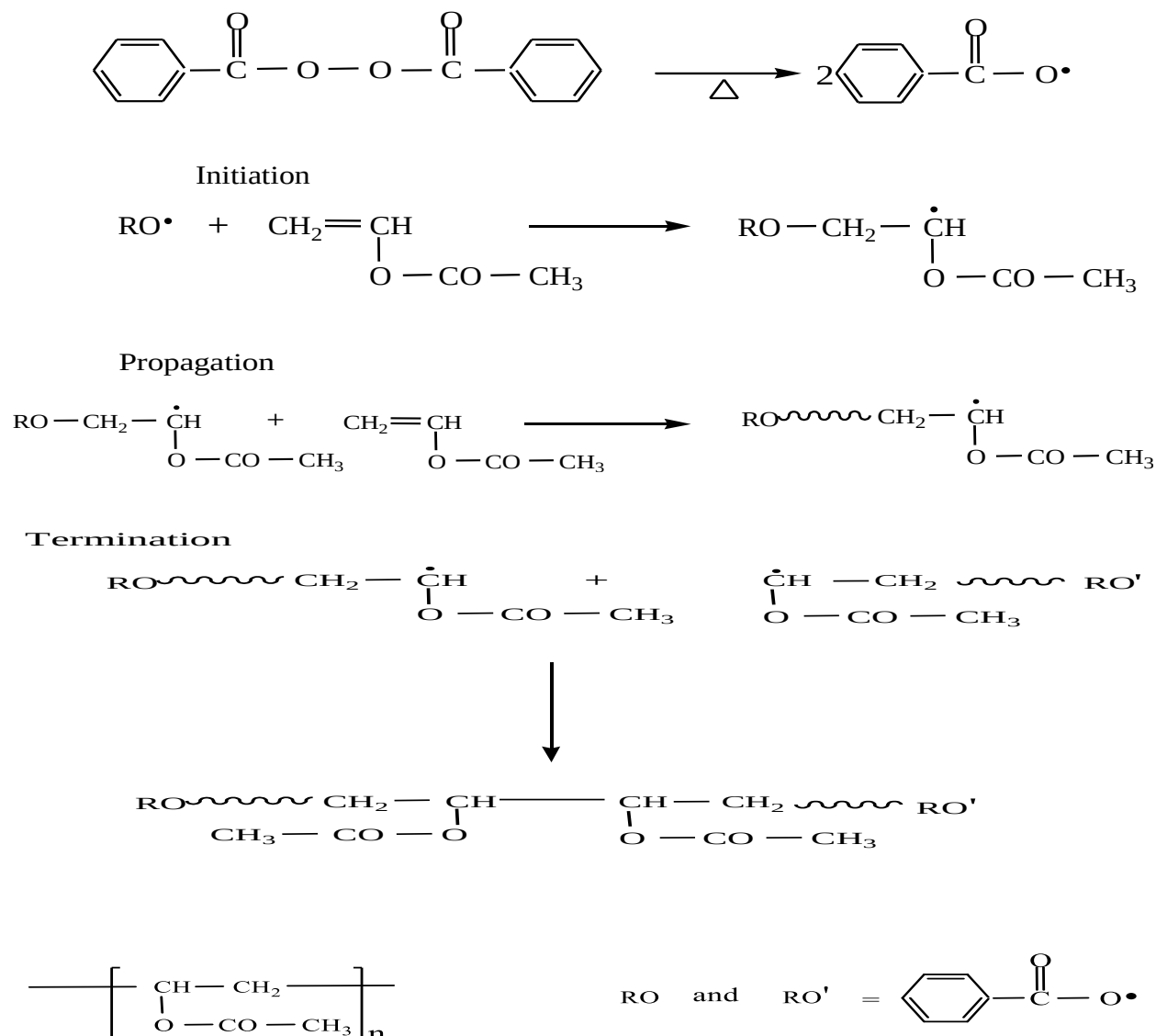
Mango Seed Powder Extraction Process

Physicochemical Characterization

Thorough characterization of extracted MSKS is essential to understand its suitability for film formation and to guide subsequent modifications. Key properties investigated include amylose content, gelatinization temperature, crystallinity and granule morphology (Akhter et al., 2024; Md. Amin et al., 2024). MSKS typically exhibits a moderate to high amylose content (e.g., 31.4% reported for some varieties), which is favorable for film formation due to amylose's ability to create strong, continuous networks upon retrogradation (Ahmad et al., 2022; Kore et al., 2024).

Synthesis of Polyvinyl Acetate by Suspension Polymerization

The Polyvinyl acetate was synthesized by additional polymerization using benzoyl peroxide as an initiator at 60 °C the reaction was terminated after one hour the resulting polymer was purified in n-hexane and air-dried. The molecular weight was found to be 1133 gmol⁻¹. Lyoo *et. al*, (1998) has suggested that increasing initiator concentration increases the percentage conversion. The reaction scheme is outlined in scheme 3.



Scheme 3: Polymerization of Vinyl acetate monomer by chain-growth polymerization. (Srivastava *et al*, 2006)

Suspension Polymerization of Vinyl Acetate (VAc)

Sodium carboxymethyl cellulose (CMC) (0.166 g) suspension agent was dissolved in 90 ml of distilled water under a nitrogen atmosphere and constantly stirred in a 250 ml three-neck round bottom flask fitted with a rubber septum.

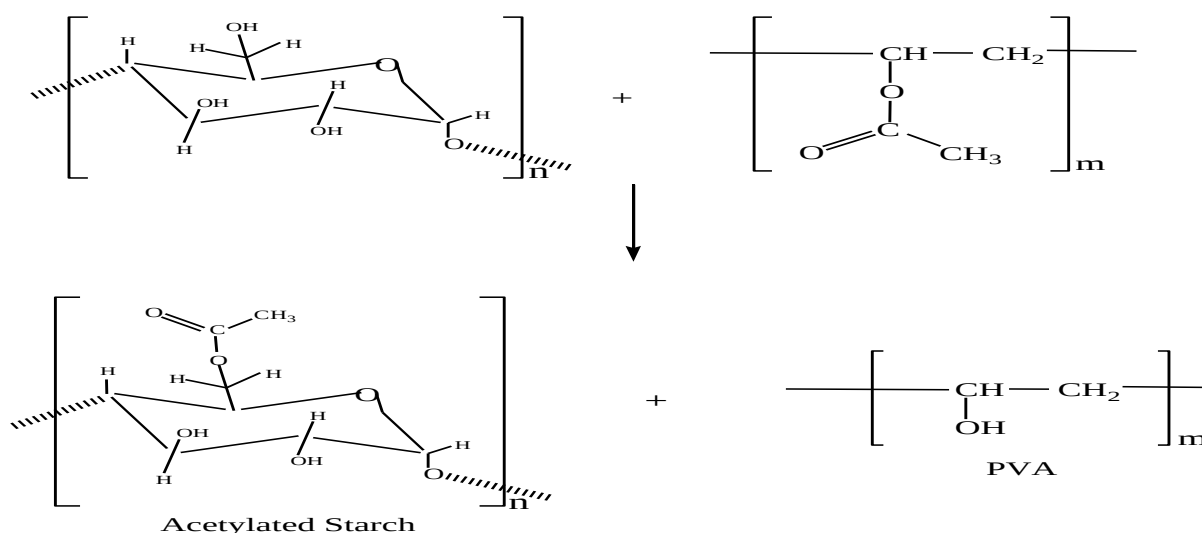
After degassing, 50 ml of Vinyl acetate monomer and 0.5 g benzoyl peroxide was added at once, at a fixed polymerization temperature of 60 °C. The reaction mixture was stirred for 1 hour. The poly(vinyl acetate) was filtered and washed with warm water to remove the residual suspension agent, and then purified in n-hexane to remove unreacted monomers. (Lyoo *et. al*, 1998).

Reactive Blending of PVAc With Native Starch

This reaction gives chance for transesterification between two polymers resulting in the acetylation of some -OH groups in the starch repeat units with simultaneous formation of the hydroxyl group on poly(vinyl acetate) as shown in scheme 4.

Morphological image of the Starch/PVAc blend micrograph analysis is an important factor in observing the physical structure of the blended films. The blended films seem to be homogeneously prepared. The micrographs revealed that the phase structures in the starch/PVAc blends films are different as the magnification increases. The appearance of the starch showed the presence of many large size granules. The SEM reveals that the surface was smooth with no evidence of crack. Upon magnification, some granules appeared to be either round or oval.

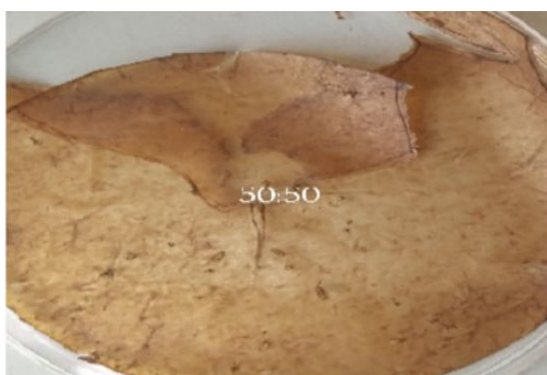
Scheme II



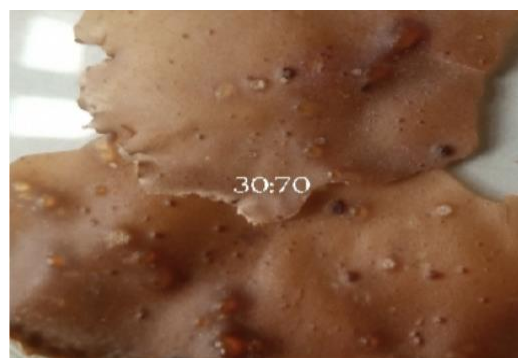
Scheme 4: Chemical reaction during native starch/ PVAc blending (Victoria & Patricia, 2005).

Preparation of PVAc / Starch Blends

The synthesized PVAc from suspension polymerization and native cassava starch blends were prepared with ratios of 20:80, 40:60, 50:50, and 80:20. These were achieved by dissolving the weight percent of PVAc in acetone, and weight percent of starch in DMSO then, these solutions were mixed and stirred vigorously at room temperature. The dissolved solution was cast onto a glass plate and allowed to dry in a vacuum oven at 30 °C, the same procedure was used for PVAc/starch-g-oleic acid. However, PVAc/Starch, 20:80 ratio was found to be highly brittle (non-film forming) and hence couldn't be characterized. (Byun *et. al*, 2012).



50:50 Starch/PVAc



30:70 Starch/PVAc

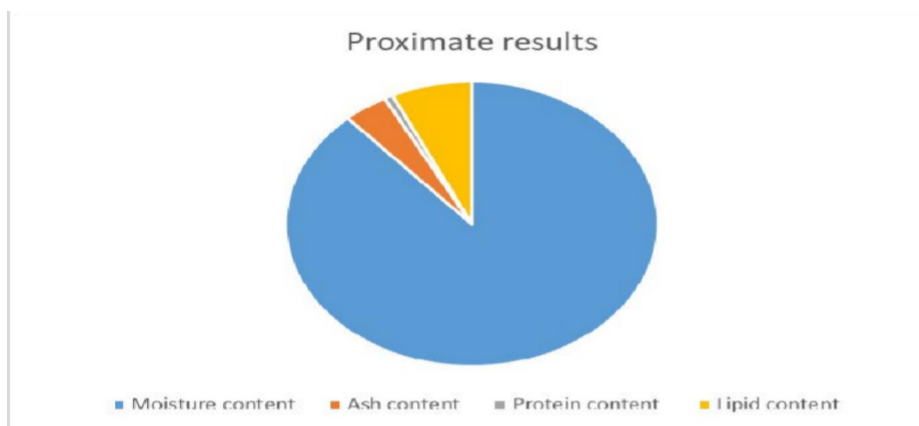
III. Results and Discussion

Proximate Analysis of the mango starch extracted.

The table below shows the proximate analysis of the mango seed kernel starch extracted. Table 1: Proximate

Parameter	Percentage composition (%)
Moisture content	4.79
Ash content	0.21
Protein content	0.04
Lipid content	0.38

All values are averages of triplicate determinations expressed on a dry weight basis.



Other physicochemical parameters include are Table 2: Turbidity

Turbidity/NTU	Time/hr
1.61	0
2.53	24

2.51	48
2.42	72
2.31	96
2.33	120
2.40	144

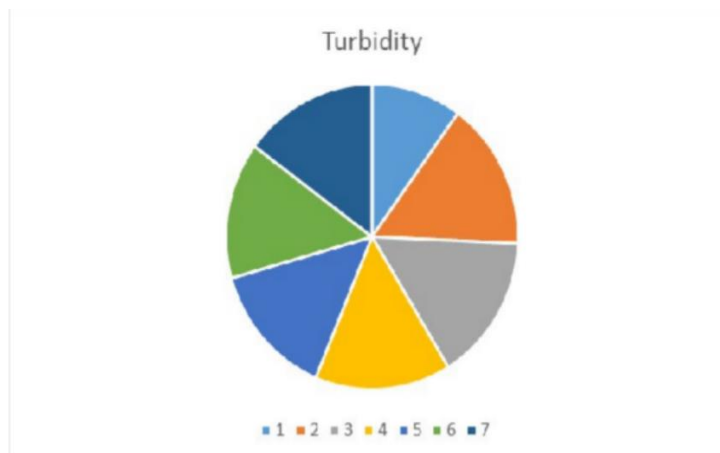
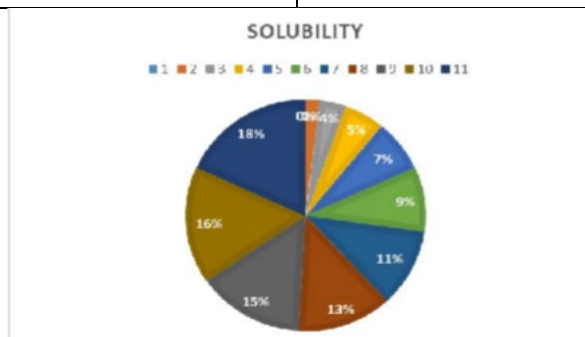
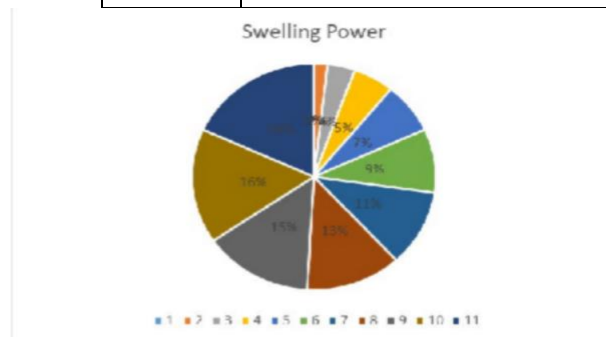


Table 3: Swelling Power

S/N	Temperature (°C)	Swelling Power	Solubility (%)
1	0	3.7760	0.1590
2	10	3.2755	0.1840
3	20	3.7695	0.1793
4	30	3.0395	0.1304
5	40	3.4065	0.1432
6	50	4.0190	0.1983
7	60	6.9395	0.0383
8	70	5.3995	0.4415
9	80	4.7095	0.3562
10	90	1.0662	0.2963
11	100	6.0205	0.2935



FTIR – Analysis

The FTIR – Spectra for starch (figure 4.3), polyvinyl acetate (figure 4.4), and all the prepared polymer blends of PVAc/Starch (figure 4.5) were acquired using FTIR – 8400S (SHIMADZU, Japan) at a frequency range 4000 – 400 cm^{-1} . The spectra obtained were analyzed for the presence/absence of key functional groups by comparison with a standard FTIR correlation table.

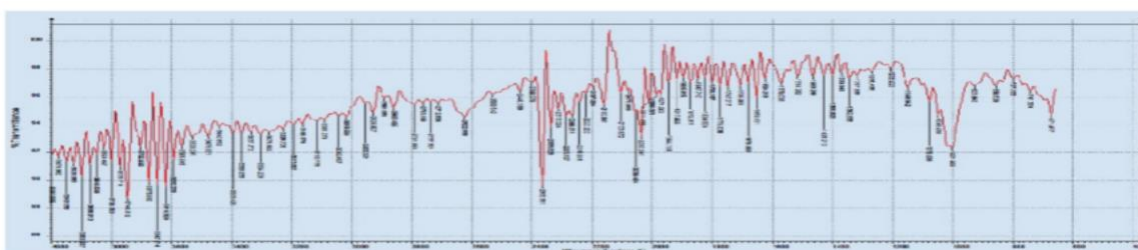


Figure 1: FTIR spectrum of the Mango starch

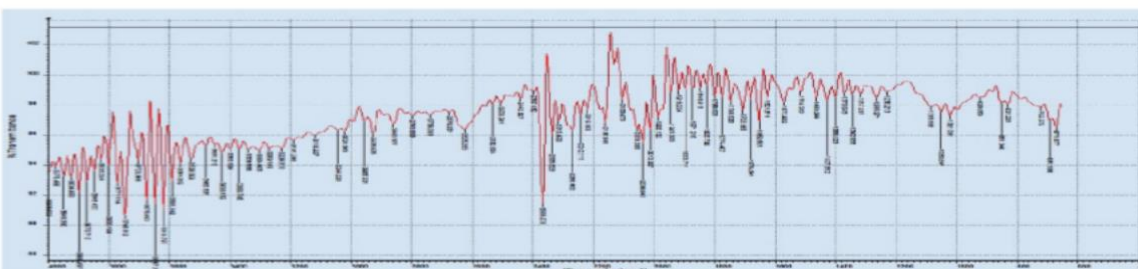


Figure 2: FTIR spectrum of Vinyl acetate

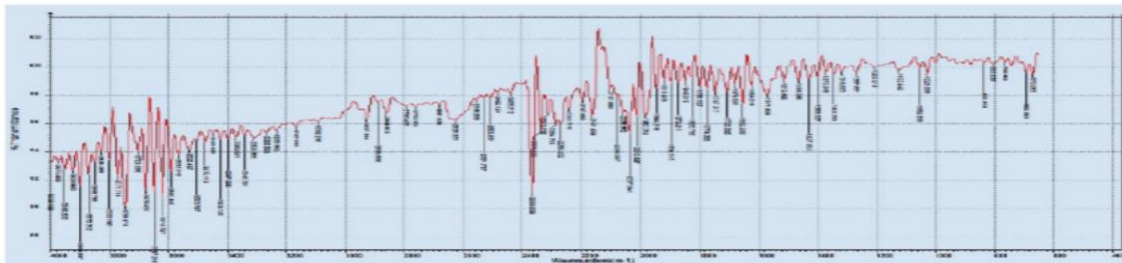
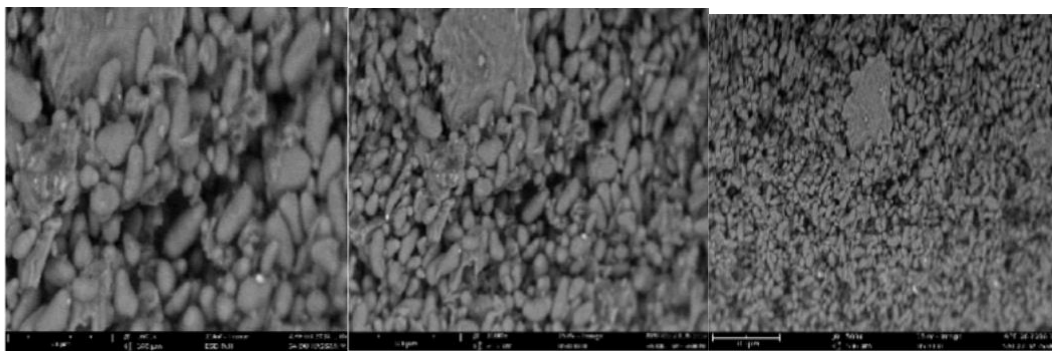


Figure 3: FTIR spectrum of Starch/PVAc 30:70 ratio

Scanning Electron Microscopy (SEM)

Scanning electron microscopy was used to evaluate the miscibility, roughness, and compatibility of the starch, polyvinyl acetate, and polymer blends through morphological analysis. The surface analysis of the extracted starch was performed at different magnifications. The SEM image in figure 4.6 shows that of mango starch granules which have an oval shape with pores on the surface. The pores also depend on the starch origin which may be more or less deep, sometimes they form channels in the interior of the granules. (Ferraz et al., 2019).

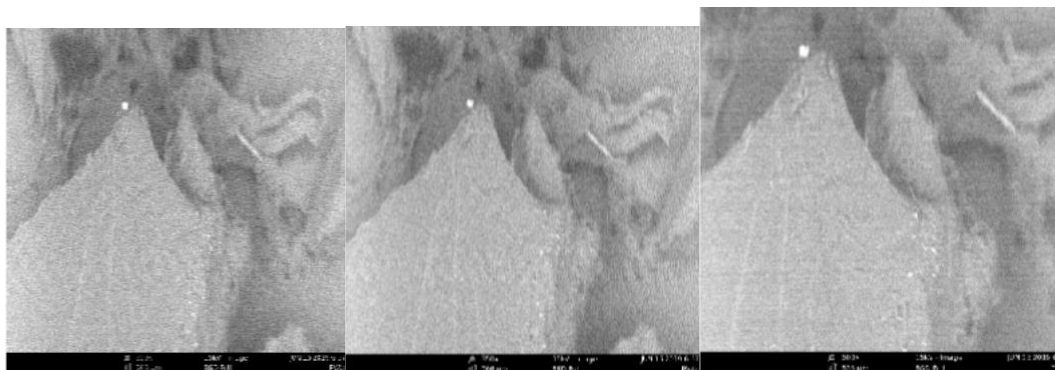


Magnification at 50µm

Magnification at 80µm

Magnification at 100µm Figure 4: SEM

Morphology of the Mango seed kernel starch at 3 different magnifications

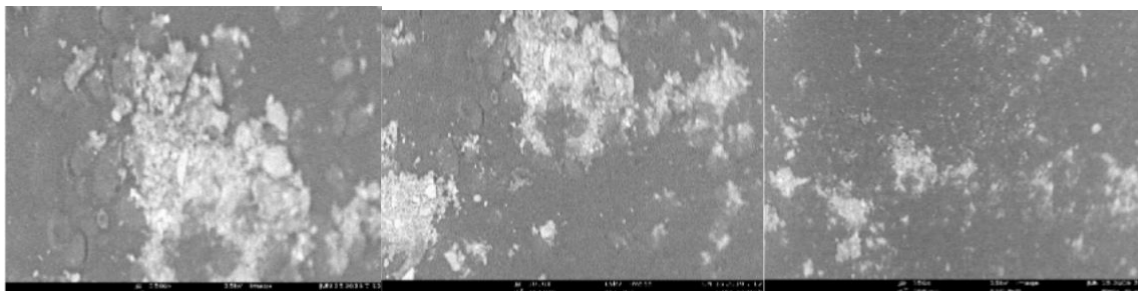


Magnification at 50µm

Magnification at 80µm

Magnification at 100µm Figure 5: SEM

Morphology of the PVAc at 3 different magnifications



Magnification at 50µm

Magnification at 80µm

Magnification at 100µm Figure 6: Micrographs

of starch/PVAc blend 70/30 films at different magnifications

X-RAY Diffraction (XRD)

The x-ray diffraction was used to ascertain the crystallinity of the starch, polyvinyl acetate and the polymer film produced. The X-ray diffraction pattern was obtained from starch as a powder containing 16% moisture with the operating parameters of the

The degree of crystallinity was estimated quantitatively as described by Andrade et al.,

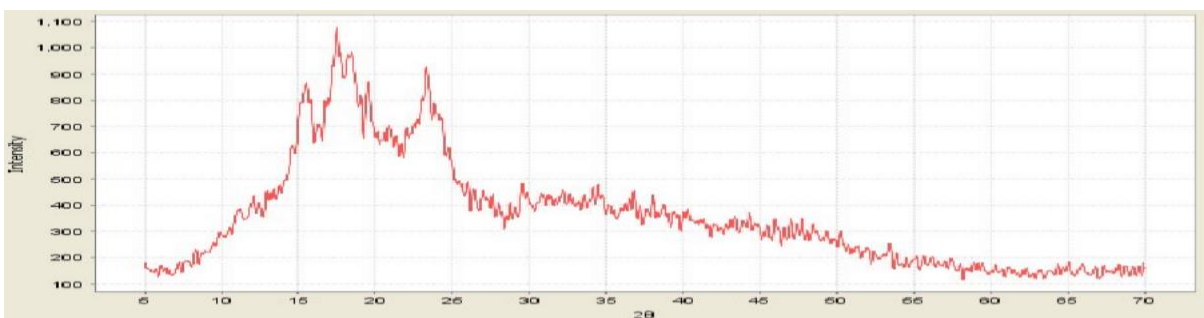


Figure 7: XRD of the starch

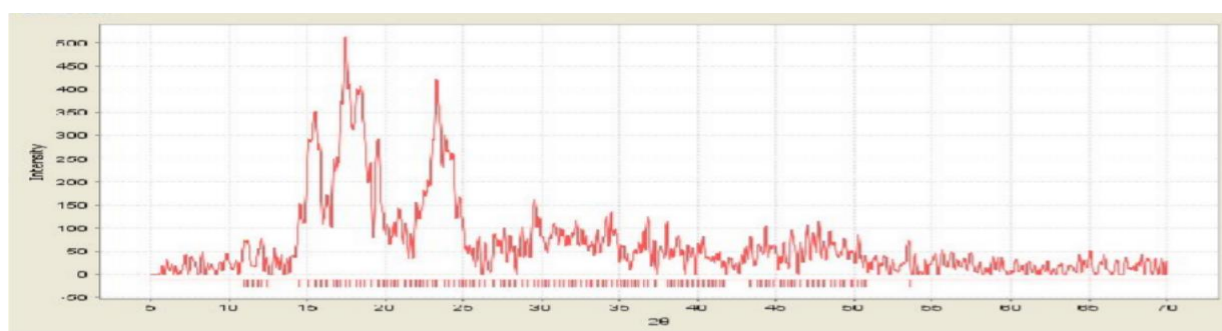


Figure 8: XRD of the Polyvinyl acetate (PVAc)

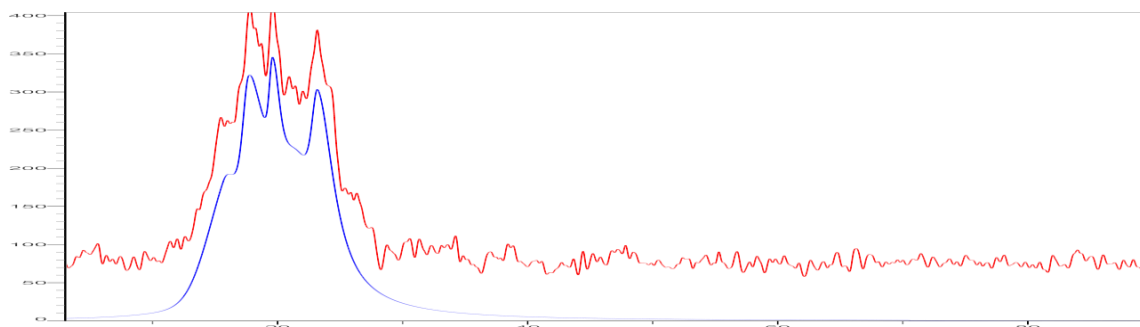


Figure 9: XRD of the polymer film produced in the ratio of 70/30 blend

The most prominent peaks are often observed at around 2θ values of 15°, 19°, and 26°. These peaks correspond to the typical crystalline regions of the A-type polymorph of starch. XRD pattern showed sharp peaks (representing crystalline regions) superimposed on a broad background (due to the amorphous regions). Crystalline Peaks: These are typically sharp and occur at specific diffraction angles (2θ). In starches, common diffraction peaks were found around 15°, 18°, 19°, and 26°. While the amorphous background, is often observed between 10° and 30°, indicating the presence of amorphous regions. The intensity of this hump can give insights on the degree of disorder in the starch structure.

Thermogravimetric analysis (TGA)

Thermogravimetric analysis (TGA) is a very useful technique in determining the content of starch and other components. TGA analysis in mango starch provides insights into the thermal stability and decomposition behavior of the starch sample. The TGA generally shows a characteristic multi-step weight loss, which is attributed to moisture loss, decomposition of organic matter (including amylose and amylopectin) and complete degradation and carbonization at higher temperatures. In the initial mass loss occurs in this range (50 °C–150 °C) and is attributed to the evaporation of physically absorbed water (moisture content). This is typical for starch materials, as they are hygroscopic. The mass loss in this range indicates the amount of water content in the mango starch. If the mass loss is significant, it means the starch is retaining a lot of moisture, which can affect its processing and applications. For most starches, this weight loss typically ranges between 5-15%, depending on the relative humidity and how the sample was prepared or stored. The second major mass loss occurs in this range, representing the decomposition of starch's primary organic components: amylose and amylopectin. This is the most significant mass loss phase in starch. Starch decomposes into

smaller fragments and volatile products in this temperature range 200 °C–350 °C. Beyond 350 °C, the remaining carbonaceous material decomposes. The TGA curve flattens out when almost no mass loss is detected, indicating the residual char left after complete thermal degradation. This phase is often attributed to the carbonization of the residual material left after the volatile organic matter has been decomposed. The temperature at which the first noticeable degradation occurs (after moisture loss) provides insights into the thermal stability of the starch. If the mango starch shows a higher onset temperature compared to other starches, this suggests better thermal stability. This temperature at which the maximum rate of weight loss occurs during the main decomposition phase. For starch, this usually falls between 250 °C and 320 °C. The TGA curve shows that mango starch has a slow rate of weight loss and retains more mass at higher temperatures, it indicates a higher thermal stability. This could be due to the unique composition of mango starch compared to conventional starch sources (corn, cassava, potato).

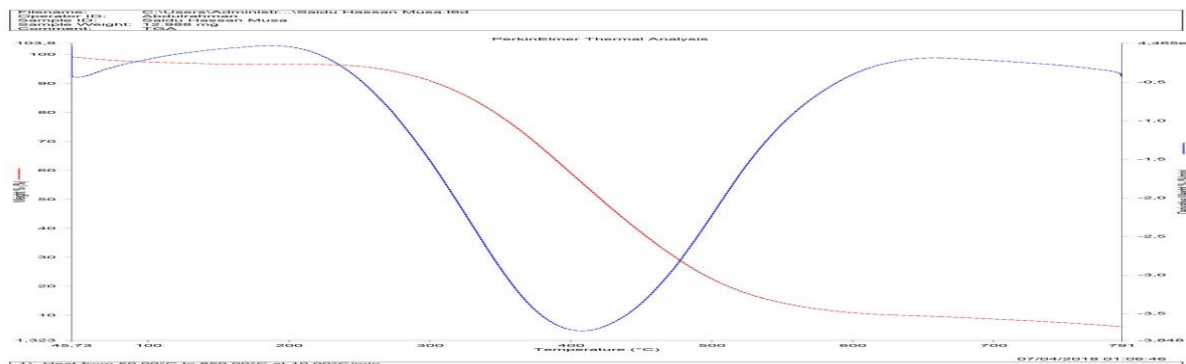


Figure 10: Thermogravimetric degradation of the MSKS/PVAc

Sustainability and Economic Viability Sustainability/Scalability

The potential for large-scale production of MSKS-based films is inherently linked to the abundant availability of mango seed kernels. Mango is one of the most widely cultivated tropical fruits globally, leading to the generation of massive quantities of agro-industrial waste, particularly peels and seeds. These kernels are often discarded or underutilized, representing an enormous, readily accessible, and non-food competing biomass source. Unlike bioplastics derived from dedicated food crops, MSKS production does not compete for agricultural land or resources, making its supply chain inherently more sustainable and scalable. Research has shown that starch can be effectively extracted from various mango cultivars (Rodrigues, A. A. M., et al., 2020). The use of MSKS for biodegradable films aligns strongly with the principles of sustainable development and circular economy.

Waste Valorization: It transforms an agricultural waste product into a valuable resource, reducing landfill burden and creating value from underutilized biomass (Arora et al., 2023; Kore et al., 2024).

Reduced Carbon Footprint: Replacing petroleum-based plastics with bio-based alternatives reduces reliance on fossil fuels and potentially lowers GHG emissions over the product life cycle (Akhter et al., 2024).

Biodegradability: The inherent ability of MSKS films to decompose naturally minimizes long-term environmental pollution (Ahmad et al., 2022).

However, a holistic sustainability assessment requires Life Cycle Assessment (LCA) studies. Currently, detailed LCA studies specifically for MSKS packaging films, evaluating their environmental impacts from raw material extraction to end-of-life, are an area requiring further dedicated research (EnPress Publisher LLC, 2024). Existing LCA studies often focus on mango waste disposal or general starch extraction, not the specific film product.

Economic Viability

The economic viability of MSKS films is primarily driven by the low cost of the raw material. Mango seed kernels are often discarded or used minimally, presenting a virtually free or very inexpensive feedstock (Arora et al., 2023; Kore et al., 2024). This gives MSKS films a potential cost advantage over bioplastics derived from dedicated crops (e.g., corn starch) or complex fermentation processes. This is significantly bolstered by the low cost, or even negative cost (due to disposal expenses), of its primary raw material. Mango seed kernels are typically considered waste, meaning their acquisition cost for industrial processing can be minimal to non-existent. This provides a substantial cost advantage over conventional plastics derived from fossil fuels or bioplastics that rely on cultivated crops. By valorizing this agricultural waste, industries can transform a disposal burden into a valuable resource, creating new revenue streams and contributing to a circular economy. While initial investments in processing equipment and infrastructure for large-scale extraction and film production would be necessary, the ongoing operational costs, particularly for raw materials, are projected to be significantly lower. Furthermore, the increasing global demand for sustainable and eco-friendly packaging, coupled with stringent environmental regulations, creates a growing market willing to absorb the costs associated with novel biodegradable alternatives. Recent studies, such as those exploring enhanced mechanical properties and biodegradation through additives (Saidu H. M. and Balarabe S. S. 2023). However, the overall economic competitiveness also depends on:

Processing Costs: The energy and chemical inputs for extraction, modification, and film formation. Advances in green extraction methods (UAE, MAE) aim to reduce these costs (Md. Amin et al., 2024).

Production Scale: As discussed, scaling up from laboratory to industrial production requires significant investment in infrastructure and technology, which can initially increase per-unit costs.

Market Demand and Pricing: While there is a growing consumer willingness to pay a premium for sustainable products, biodegradable films still face price competition from mature and cheap conventional plastics (European Bioplastics, 2025). The long-term economic viability hinges on technological advancements, policy support, and increasing consumer awareness that drives demand. Despite the current challenges, the valorization of mango waste positions MSKS as a highly promising and economically attractive renewable source for the packaging industry.

IV. Conclusion

This research successfully demonstrates the significant potential of mango seed kernel starch (MSKS) as a renewable and sustainable raw material for producing biodegradable packaging films. Addressing the global environmental crisis caused by persistent synthetic plastics, the study highlights the effective valorization of agricultural waste by transforming discarded mango seed kernels into a valuable resource.

Physicochemical characterization confirmed MSKS's suitability for film formation, revealing its favorable amylose content, enhanced thermal stability (up to 350°C), and a balanced semi- crystalline structure that contributes to both mechanical integrity and biodegradability. The successful production of homogeneous MSKS/polyvinyl acetate (PVAc) blends was achieved, though specific ratios, such as the 20:80 PVAc:Starch blend, were found to be brittle and non- film-forming, underscoring the importance of optimal blend compositions.

The development of MSKS-based films offers substantial environmental benefits, including waste valorization, reduced carbon footprint by replacing fossil fuel-based plastics, and inherent biodegradability, aligning strongly with circular economy principles. Economically, the low cost of mango seed kernels presents a significant advantage. However, challenges related to processing costs, production scale, and market competition necessitate further optimization. Future work must focus on comprehensive Life Cycle Assessments (LCA) and integrated strategies involving technological advancements, policy support, and consumer engagement to facilitate widespread commercialization and foster a more sustainable packaging future.

V. Acknowledgement

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