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Development of biodegradable film from pineapple waste as alternative of conventional plastic

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Abstract
Plastic pollution has emerged as a serious global environmental concern. The excessive use of conventional plastics, particularly in single-use applications, poses a long-term threat due to their non-biodegradable nature. As a solution, research on biopolymer-based packaging materials has gained significant attention. In the present study, cellulose was extracted from pineapple peel waste generated during fruit processing and blended with polylactic acid (PLA) to develop an eco-friendly, sustainable, and biodegradable packaging film. The developed film exhibited satisfactory mechanical properties, low water solubility, and 47% biodegradation within five weeks (based on a soil-burial test). The study demonstrates that agro-waste can be effectively utilized to develop a sustainable alternative to conventional plastics.

Keywords: Pineapple peel, cellulose, polylactic acid, biopolymer, biodegradable, sustainable packaging

1. Introduction

Plastic has become an integral part of modern life due to its lightweight, durable, inexpensive, and versatile nature. It has revolutionized sectors such as food packaging, storage, transportation, and industrial applications. However, plastics are now a major global environmental threat. Worldwide plastic production exceeds 350 million tons annually, and nearly 2,50,000 tons of plastic waste is estimated to float in oceans (Shaikh *et al.*, 2021) [17]. Plastic waste contributes to soil, water, and air pollution and negatively impacts biodiversity. Most conventional plastics, derived from petroleum-based polymers such as polyethylene, polypropylene, and polystyrene, take hundreds of years to degrade. Consequently, single-use plastics have become a major environmental and societal concern (Mangaraj *et al.*, 2019) [11]. To address this challenge, the development of biodegradable and bio-based packaging materials is crucial. Utilizing agricultural waste is an effective and eco-friendly approach toward sustainable development (Qu *et al.*, 2021; Selani *et al.*, 2014) [14, 16]. The fruit and vegetable processing industry generates large amounts of bio-waste, which, if properly utilized, can support the "waste-to-wealth" concept. Pineapple (*Ananas comosus* L.) is a major tropical fruit with a global production of 28.65 million tons, including 2.4 million tons from India (Mala *et al.*, 2024) [10]. Nearly 60% of pineapple mass becomes waste during processing, of which peel contributes about 29-40%. The peel contains significant amounts of cellulose (18-25%), hemicellulose (20-30%), and lignin (15-20%) (Chaudhary *et al.*, 2019) [3], making it a promising and low-cost raw material for biopolymer production. Pineapple peel has been extensively explored for biotechnological applications, including the production of biofuels, organic acids, vinegar, enzymes (notably bromelain), and animal feed, largely due to its high fermentable sugar and moisture content (Gil and Maupoey, 2018; Roda *et al.*, 2016) [4, 15]. It also serves as an excellent substrate for microbial fermentation and enzyme production. Beyond biochemical applications, the lignocellulosic structure of pineapple peel makes it a viable alternative to traditional fiber sources in the development of biopolymers, paper, and composite reinforcement materials, offering a sustainable replacement for wood pulp (Sibaly & Jeetah, 2017) [18]. Additionally, the presence of functional groups such as-OH and-COOH enables its use as a bio-adsorbent for environmental applications, particularly in the removal of dyes and heavy metals from wastewater (Chan *et al.*, 2016; Gogoi *et al.*, 2018) [2, 5].

Cellulose is the most abundant natural polymer, composed of β-D-glucose units. Its crystalline structure offers mechanical strength, chemical stability, and renewability. It is environmentally friendly and, when blended with biopolymers such as PLA, starch, or chitosan, enhances mechanical strength and moisture-barrier properties of films.

Polylactic acid (PLA) is a bio-based and biodegradable thermoplastic polymer produced from renewable resources such as corn starch, sugarcane, or cassava. It is transparent, non-toxic, and suitable for food-contact applications, making it widely used in the packaging industry. However, pure PLA is brittle and has high moisture permeability, which limits its use. Incorporating natural fillers such as cellulose improves interfacial bonding, mechanical strength, flexibility, and barrier properties (Qin *et al.*, 2016) [13].

Biodegradable packaging is safer for the environment than conventional plastics. It enhances food quality and shelf life by offering moisture and oxygen barrier properties. Active packaging, containing natural antioxidants or antimicrobial agents, further improves food safety (Ibrahim *et al.*, 2010) [7]. Aim of the present study was to developed a biodegradable sheet which can be a sustainable alternative of conventional plastic by utilizing the agricultural waste pineapple peel cellulose and poly lactic acid.

2. Materials and Methods

2.1 Raw materials and chemicals

Pineapple peels were collected from a local fruit processing unit after that and proceed to extract cellulose. Major chemicals used Dichloromethane, Pineapple peel cellulose and polylactic acid (PLA) of analytical grade.

2.2 Preparation of biodegradable sheet

The PLA-PPF films were prepared using a modified casting technique. An aqueous solution was made by dissolving Poly lactic acid (PLA) in dichloromethane (DCM) at varying concentrations (80%, 85%, and 90% wt.%), followed by the slow addition of extracted pineapple peel cellulose (10%,15 and 20 wt.%) into the PLA solution while stirring continuously on a hot plate at 30-35 °C. The mixture was stirred until it became homogeneous. The warm mixture was cast onto a flat surface, forming films with a thickness of approximately 0.3-0.35 mm. The films were dried at room temperature or in an oven set at 30-35 °C for 24 hours after that carefully removed for further characterization and application. The independent parameter are shown in the table 1

Table1: Independent parameters for development of sheet

Constant Parameter				
DCM(ml)	**100 ml**			
Independent Parameter	**Code**	**Coded Level**		
		-1	**0**	**+1**
Cellulose (%)	X_1	10	15	20
PlA (%)	X_2	80	85	90

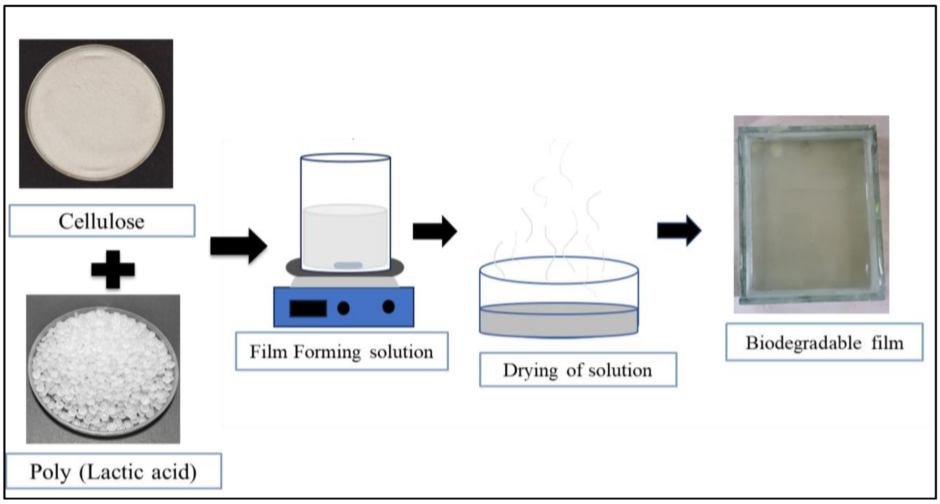

Fig 1: Development of biodegradable sheet

2.3 Film Thickness

The thickness of the developed bio-nanocomposite films was measured using a digital vernier calliper (0.01 mm least count). For each film, average of the readings was taken at three random points (Yadav *et al.*, 2020) [19].

2.4 Mechanical properties of the developed films

The film samples will be cut into rectangular strips with a length of 80 mm and a width of 20 mm. A 25 kg load cell and an A/TG probe will be used for the measurements. The test was conducted with pre-test, test, and post-test speeds of 0.8 mm s^{-1}, 0.8 mm s^{-1}, and 10.0 mm s^{-1}, respectively.

The tensile strength and elongation at break of the films will be calculated using the formulas provided by (Alves *et al.* 2015) [1].

$$\text{TS (MPa)} = \frac{\text{Maximum load (N)}}{\text{Initial cross section area (mm}^2)} \qquad (1)$$

2.5 water solubility

The film samples were cut into rectangular pieces (2×2 cm^2) and weighed (up to three decimal places). The samples were then put in petri dishes and 20 ml distilled water was put into them. After leaving the samples undisturbed for 24 h, the weight was again taken preceded by quick wiping with filter paper (to remove excess water) (Harussani *et al.*, 2021) [6]. The swelling ratio was then calculated using the following formula

$$S.R.(\%) = \frac{(\text{Final weight} - \text{Initial weight})}{\text{Initial weight}} \times 100 \quad (2)$$

2.6 Biodegradation test

A simple soil burial test was used to assess the biodegradability of the bioplastic samples. Bioplastic samples (5×5 cm) were buried in natural soil in plastic containers at a depth of 5 cm below the soil's top surface and incubated at room temperature without any enzyme activity or composting substances (Kumar *et al.*, 2021) [9]. The weight loss (percent) of the samples at 7 days interval safter soil burial was used to determine the degree of biodegradability *of* the bioplastics. The samples were cleaned by wiping lightly with tissue to remove soil debris from the surface of the samples after each interval of soil burial, then, dried at room temperature in a desiccator till they attained a consistent weight. The weight change (loss) before and after burial was measured and compared to determine biodegradability. Equation (3) is used to compute the weight losses in the buried samples. (Onovo *et al.*, 2022) [12]

$$\text{Weight Loss}(\%) = \frac{(W_1 - W_0)}{W_0} \times 100 \quad (3)$$

where wo and $w1$ are weights of the samples before and after burial.

3. Results and Discussion

The present work aims at the development of biodegradable composite films reinforced with natural fiber at different loading levels. As shown in table 2, films containing 10%, 20%, and 30% fiber were successfully prepared and visually examined. The sheet exhibited a smooth and transparent appearance, whereas the incorporation of fiber resulted in a gradual change in color and surface texture with increasing fiber concentration. Films with 10% fiber showed good dispersion of fibers within the polymer matrix, while 20% fiber-loaded films exhibited a slightly rough surface, indicating enhanced fiber-matrix interactions. At 30% fiber content, the films appeared more opaque and comparatively rough, which may be attributed to increased fiber agglomeration at higher loading levels.

The addition of fiber significantly influenced the structural and functional properties of the developed films. Increasing fiber concentration improved the rigidity and compactness of the film matrix due to the formation of hydrogen bonding between the hydroxyl groups of the fiber and the polymer chains. However, at higher fiber loading (30%), reduced flexibility and uneven distribution of fibers were observed, suggesting a critical threshold for effective reinforcement.

3.1 Thickness of the developed film

The thickness of the developed PLA-pineapple peel cellulose composite films ranged from 0.306 to 0.348 mm, as shown in Table 2. A gradual increase in thickness was observed with increasing cellulose content, which can be attributed to the higher solid content and reduced flowability of the casting solution at higher fiber loadings. Similar trends have been reported in natural fiber-reinforced biopolymer films, where increased filler concentration contributes to a denser film structure. The uniform thickness of the films indicates effective casting and homogeneous dispersion of cellulose within the PLA matrix.

Table 2: Physical and mechanical properties of PLA-cellulose film

Property	10%	15%	20%
Tensile strength (MPa)	35.24	38.21	40.07
Thickness (mm)	0.306	0.321	0.348
Water solubility, %	8.65	7.42	6.18

3.2 Mechanical properties of the developed film

The tensile strength of the films increased with increasing cellulose content, ranging from 35.24 MPa to 40.07 MPa. The improvement in tensile strength can be attributed to strong interfacial interactions between PLA and cellulose fibers, mainly through hydrogen bonding between hydroxyl groups of cellulose and ester groups of PLA. The reinforcement effect of cellulose restricted polymer chain mobility, resulting in enhanced load-bearing capacity (Karim *et al.*, 2022) [8]. The results indicate that pineapple peel cellulose effectively acts as a reinforcing agent in PLA-based films.

3.3 Water solubility

Water solubility of the developed films decreased with increasing cellulose concentration. The film containing 10% cellulose showed the highest water solubility (8.65%), whereas films with 15% and 20% cellulose exhibited lower solubility values. The reduction in solubility is attributed to the formation of a compact polymer-fiber network, which limits water penetration and dissolution. Lower water solubility is desirable for food packaging applications, as it enhances moisture resistance and dimensional stability of the film.

3.4 Biodegradation behavior

Soil-burial tests demonstrated progressive degradation of the material over time. During the first week, slight surface roughness with minor edge degradation was observed. By the third week, visible cracks and color changes appeared, indicating the initiation of polymer matrix breakdown. After five weeks, a major portion of the film had degraded, leaving only small traces. Overall, 47% biodegradation was recorded within five weeks, confirming the eco-friendly and biodegradable nature of the PLA-cellulose composite film. The presence of cellulose accelerated microbial activity, enhancing the degradation rate of the film in soil.

4. Conclusion

Cellulose was successfully extracted from pineapple peel waste and utilized for the development of biodegradable PLA-based composite films. The incorporation of pineapple peel cellulose improved mechanical strength, reduced water solubility, and enhanced biodegradability of the films. The developed films showed up to 40.07 MPa tensile strength and 47% biodegradation within five weeks, indicating their strong potential as a sustainable alternative to conventional plastic packaging. This study supports the waste-to-wealth concept by valorizing agricultural waste into value-added biodegradable packaging materials. Further incorporation of natural antioxidants or antimicrobial agents may enable the development of active food packaging systems.

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