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Synthesis and Characterization of Bio-Degradable Plastic by Mucilage of Isabgol Seeds

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Abstract

Aim: This study investigates the synthesis and characterization of biodegradable plastic films using varying ratios (5 wt.% and 10 wt.%) of mucilage extracted from Isabgol seeds, which are rich in polysaccharides and serve as natural binding agents. ***Methods and Statistical Analysis:*** *The mucilage was blended with starch-based plasticizers to form thin films, which were analyzed for their surface morphology (SEM), crystallinity (XRD), and chemical structure (FTIR). XRD results indicated that crystallinity increased at 5 wt.% mucilage but decreased at 10 wt.%, suggesting 5 wt.% as the optimal concentration. FTIR analysis showed vibrational changes corresponding to mucilage content, while mechanical testing revealed that films with 5 wt.% mucilage exhibited superior tensile strength and modulus. Soil degradation tests demonstrated that films decomposed more rapidly in moist clay soil compared to dry soil.* ***Conclusion:*** *the incorporation of 5 wt.% Isabgol mucilage resulted in biodegradable films with enhanced mechanical and degradable properties, supporting their potential as sustainable alternatives to conventional plastics.*

Major Findings: *The study established that 5 wt.% mucilage of Isabgol seeds optimally enhances crystallinity and mechanical strength in starch-based bioplastics. SEM, XRD, FTIR, and tensile tests confirmed improved structural and functional properties. Biodegradation tests showed faster decomposition in moist clay soil, confirming environmental compatibility.*

Keywords: *Biodegradation, Mechanical Strength, Mucilage of Seeds, Plastic*

1.0 Introduction

Much of the plastic waste found in nature consists of conventional, non-biodegradable plastics, and their harmful effects on terrestrial and marine organisms when ingested or entangled are largely documented. Biodegradable and compostable shopping has recently been developed as an alternative to traditional shopping. These plastics are specially designed to break down in composting facilities and produce a product that is non-toxic to soil and crops. Global production of plastics remains at a high level despite the hazardous causes of their use that can degrade many aspects of human life. Biodegradable plastics can completely degrade in landfills,

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sewage, or composter treatment plants by the action of naturally occurring microorganisms. Truly biodegradable plastics leave no toxic, visible or distinguishable residues after following degradation stages. Several countries have banned traditional plastic bags and replaced them with a new generation of bags labeled as biodegradable and compostable[1].

Plants naturally create a variety of polymers such as rubber, starch, cellulose, and storage proteins, all of which are utilized in the production of biodegradable plastics. Most biodegradable and compostable plastics are called bioplastic, and they are generally made from plants (such as bamboo or sugarcane) rather than fossil fuels[2-4]. For these bioplastics to be fairly and effectively biodegradable, their composability needs to be confirmed. In accordance with international standards, ensuring suitability for processing in industrial composting facilities is a priority. Biodegradable plastics represent a promising and innovative solution to the pervasive environmental issues associated with conventional, non-biodegradable plastics. As society grapples with the escalating challenges posed by plastic pollution, the development and adoption of biodegradable plastics have gained significant attention as a potential remedy to mitigate environmental harm. Biodegradable plastics are polymers that can naturally decompose into by-products through the action of microorganisms such as bacteria, fungi, or other living organisms. In contrast to conventional plastics, which endure in the environment for centuries, biodegradable plastics. offer the prospect of reducing the longevity of plastic waste and minimizing its ecological impact[5-7].

Biodegradation is the natural process by which organic substances are broken down into simpler compounds by living organisms, typically microorganisms like bacteria and fungi. This ecological process involves the enzymatic actions of these microorganisms, leading to the decomposition of complex organic molecules into smaller, environmentally benign components. In the context of biodegradable plastics, the material undergoes a Biodegradable materials process when exposed to microbial activities, ultimately transforming into non-toxic by-products, water, carbon dioxide, and biomass[8,9]. Biodegradation plays a crucial role in recycling organic matter and minimizing environmental impact by returning substances to their natural, harmless state. Through enzymatic processes, these organisms metabolize

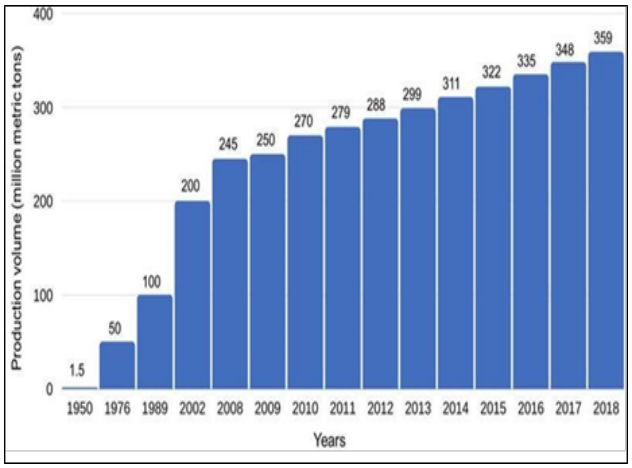


Figure 1. Production of plastic waste worldwide.

complex molecules into simpler, environmentally safe components. Bio-based materials may not inherently possess biodegradability; this hinges on the specific chemical processes employed during their manufacture and the proportion of bio-based raw materials utilized. Nonetheless, bio-based materials generally exhibit superior environmental performance compared to their fossil-based counterparts. Their usages are expanding across diverse industries, including plastics, chemicals, fashion, and footwear. Enhancing biodegradability is a significant focus, driving innovation towards more sustainable solutions. Notably, the biodegradable plastic sector is experiencing notable growth, spurred by global governmental efforts to mitigate the environmental repercussions of single-use plastics[10].

Figure 1 shows the amount of plastic waste generated from harmful Petro-chemical products which are not degradable by natural means and cause pollution to the environment. Bioplastics represent a transformative approach to plastic production, offering a more environmentally friendly alternative to traditional petroleum-based plastics. These innovative materials are derived from renewable resources, such as plants, bacteria, or other biological matter, and are designed to address the escalating concerns surrounding plastic pollution. These polymers are then processed using techniques like those employed in traditional plastic manufacturing. The resulting bio-plastic products exhibit diverse properties, ranging from rigid structures suitable for packaging to flexible films used in various applications[11]. Considering

its significance, the current work is being started and endeavors have been made to incorporate mucilage of Isabgol seeds mixed with starch to form a biodegradable thin film for its applications in food packing, carry bags, etc.

2.0 Experimental Work

2.1 Materials and Synthesis of Biodegradable Thin Films

The Isabgol seeds (Figure 2a) are soaked in distilled water (Figure 2b) and secrete the mucilage present within the seeds. The soaked seeds are kept for 2-3 hours at room temperature. The heating of these soaked seeds at around 50°C secretes gel, this gel floats above the surface of the water while the seeds get deposited at the bottom of the vessel. Upon heating, the seeds are constantly stirred using a stirrer to separate the mucilage from the seeds. The seeds get deposited at the bottom, and the gel floats above the surface of the water (Figure 2c). 5 wt.% starch solution is prepared separately, and 5 wt.% and 10 wt.% of mucilage are added and stirred continuously at around 70°C for 4 to 5 hours. The clear solution is poured onto a clean and level glass plate and allowed to dry for 5 to 6 days at room temperature. Finally, obtained thin films (Figure 2d) were stored in desiccators for further characterization.

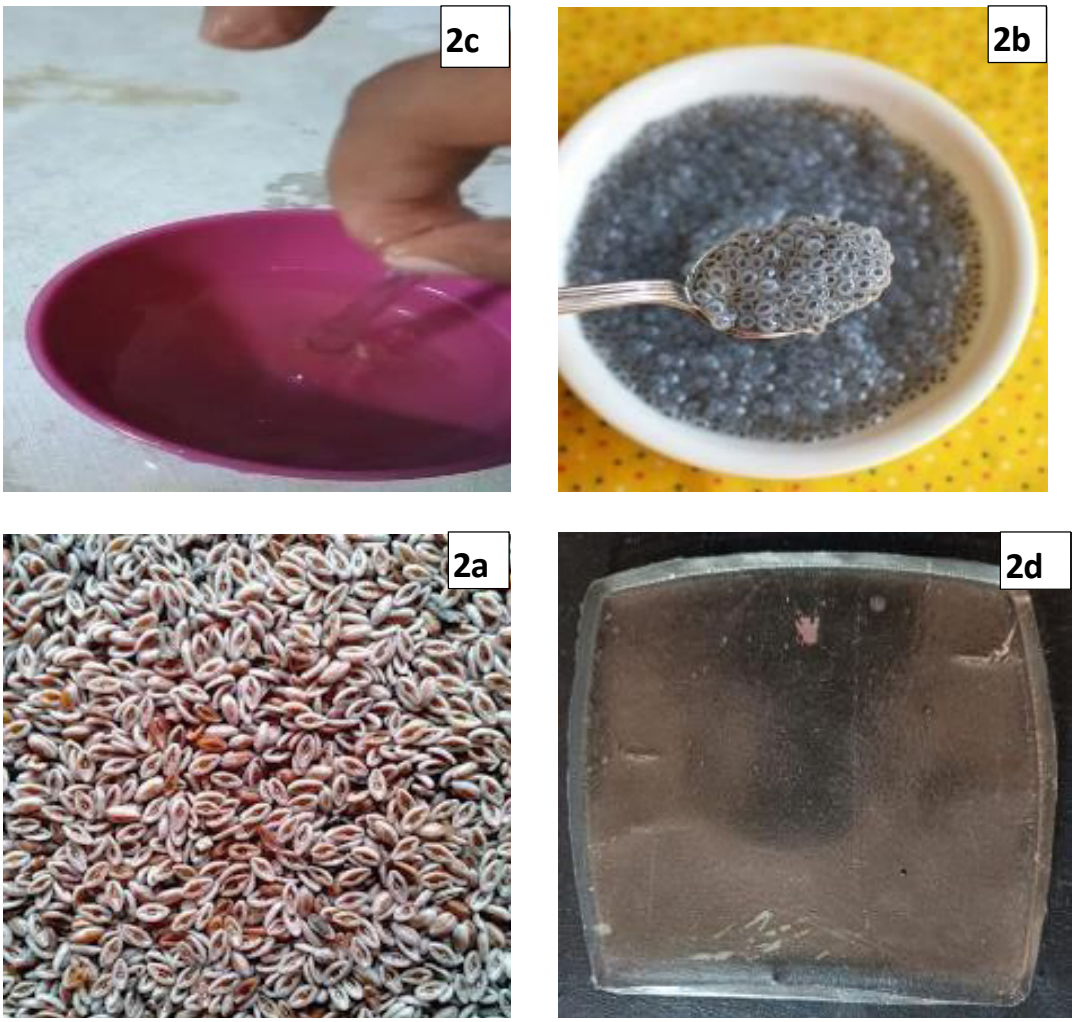


Figure 2. **2(a).** Isabgol seeds, **2(b).** Seeds soaked in distilled water, **2(c).** Mucilage separation upon heating and **2(d)**. Mucilage film.

2.2 Instrumentation

The XRD studies of the films were made with an X-ray source with CuKα radiation of wavelength 1.5406 Å. The surface morphology of these polymer films was observed using a JEOL 840, resolution at 20 Kv, 10 nm Scanning Electron Microscope (SEM). The samples were gold-coated using the sputter coater at 10 mA current under 10^{-2} torr vacuum for 3 minutes before imaging. Fourier Transform Infrared (FTIR) spectra of these films were recorded using Thermo–Nicolet 6700. The measurements were taken over a wave number range of 400 – 4000 cm^{-1}.

3.0 Results and Discussion

3.1 XRD Studies

X-ray diffraction is most useful for the determination of the nature of the sample, phase identification, quantitative identification of the mixture of phases, percentage of crystallinity, etc. As shown in Figure 3, all the synthesized samples exhibit a characteristic semicrystalline peak 2θ = 19.88°, indicating the presence of both amorphous and crystalline regions within the films. Additionally, the appearance of Bragg-like reflections at 2θ = 29.63° and 47.74° in all samples suggests the nucleation of a crystalline phase, likely facilitated by the molecular interactions between the starch matrix and the mucilage components. These secondary peaks may correspond to the ordering of polysaccharide chains due to the addition of mucilage, which contains monosaccharide units like xylose, arabinose, and galactonic acid that can promote structured interactions. Quantitative analysis of the XRD data revealed that the sample with 0 wt.% mucilage exhibited a crystallinity of 56.28%. Interestingly, this value increased to 60.04% with the addition of 5 wt.% mucilage, suggesting enhanced molecular ordering and stronger intermolecular hydrogen bonding facilitated by the mucilage. However, at 10 wt.% mucilage, the crystallinity dropped to 55.63%, indicating a possible oversaturation effect, where excess mucilage disrupts the uniform crystalline lattice, leading to a more amorphous structure.

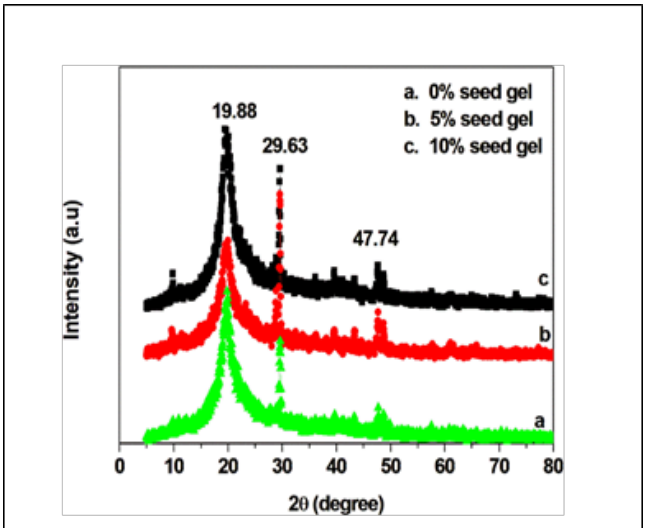


Figure 2. XRD pattern of synthesized biodegradable film samples.

This variation in crystallinity has important implications for the material's mechanical and barrier properties. Notably, the crystallinity of the 5 wt.% mucilage film (60.04%) closely matches that of High-Density Polyethylene (HDPE), a common synthetic polymer used in domestic packaging such as juice and milk bottles. HDPE's performance is largely attributed to its high crystallinity, which imparts rigidity, durability, and low permeability. The fact that our biopolymer film achieves comparable crystallinity suggests it may offer similar functional characteristics, particularly in non-load-bearing domestic applications. However, while this preliminary comparison indicates promise, more rigorous validation is necessary to confirm its practical utility as an HDPE alternative. This includes comprehensive evaluation of additional parameters such as thermal stability (e.g., TGA/DSC analysis), water vapor and oxygen permeability, impact resistance, and long-term durability under real-world conditions. Future studies should also examine its behavior under varying environmental stresses, including temperature, humidity, and microbial exposure, to fully establish its feasibility for packaging or household use. Nonetheless, the structural similarity in crystallinity marks a strong step toward the development of sustainable and functional biodegradable plastics.

The percentage of the degree of crystallinity (Xc) was determined from the ratios of the area under the crystalline peak and the respective halos using the method[8,9].

$$X_c = \frac{A_c}{A_c + A_a} \times 100 \quad (2)$$

Where A_c and A_a are the area of crystalline and amorphous (halo) regions, respectively.

3.2 SEM Studies

The film morphologies of 0 % mucilage and 5 wt.% mucilage is shown in Figure 4. Both samples have a surface of uniform and homogenous surface but with various degrees of harshness. They don't show attributable crystalline region morphology, so the semi-crystallinity of these samples is possibly sub-microscopic in nature. They exhibit uniformly distributed microporous structures. This shows that the interface similarity between the segments is one of the fundamental factors influencing the performance of blends.

3.3 FTIR Studies

The FTIR spectra of all the samples are shown in Figure 5. The absorption band in the region 3498 cm^{-1} - 3996 cm^{-1} is due to the intermolecular hydrogen-bonded O-H

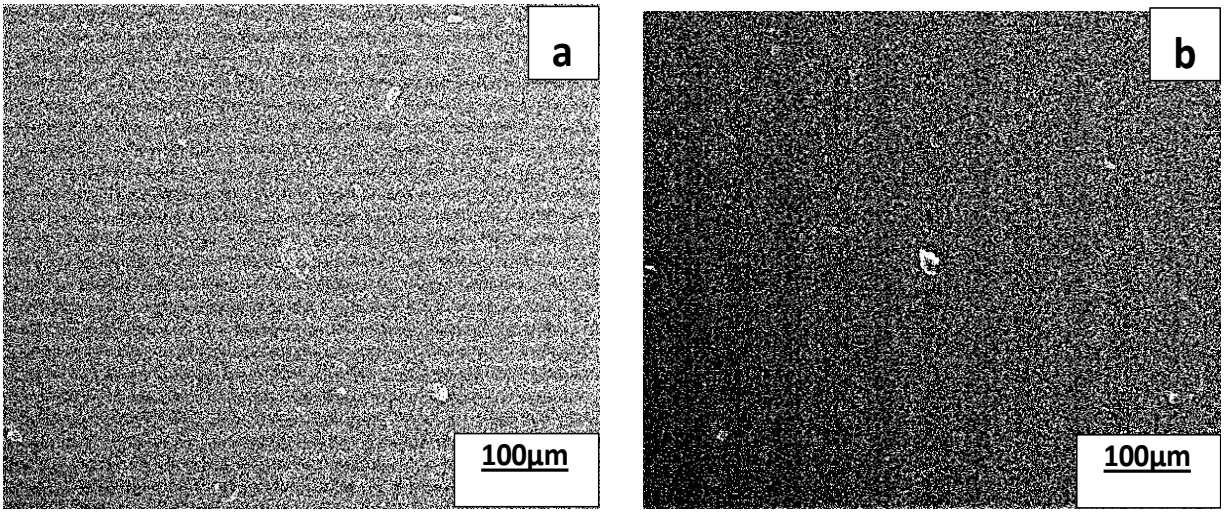
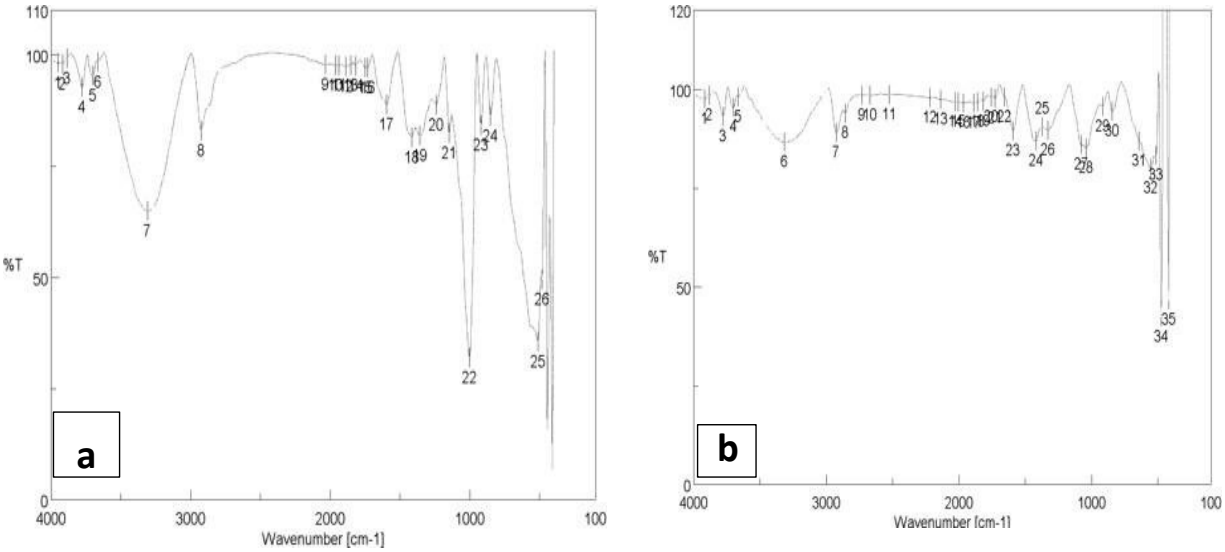


Figure 4. SEM images of **(a)** 0% mucilage, **(b)** 5 wt.% mucilage.



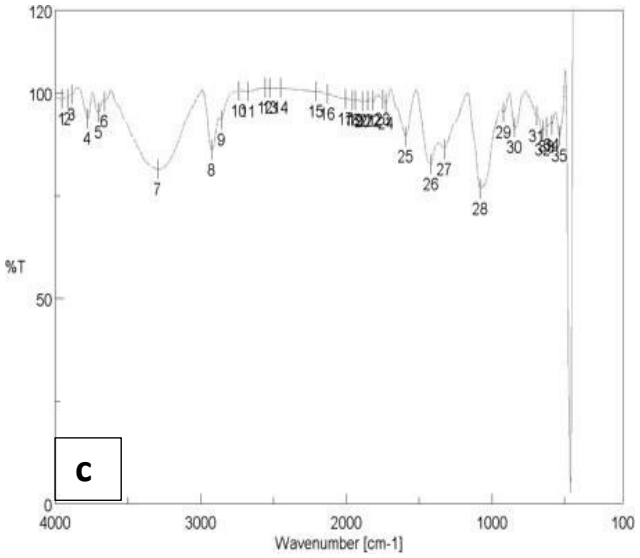


Figure 5. FTIR images of (**a**) 0% mucilage, **(b)** 5 wt.% mucilage (**c**) 10 wt.% mucilage.

stretching frequency of starch-mucilage-based samples, which is shifted to 3496 cm^{-1} - 3585 cm^{-1}, and 3762 cm^{-1} in the 5 wt.% as well as in 10 wt.% seed gel. The C-H, OCH, and CCH asymmetric bending vibration of a methyl group in CH_3O in 5wt.% exhibited absorption at 1500 cm^{-1} - 1450 cm^{-1}. All these changes in the FTIR spectra are clear indications of the complexation of seed gel into the starch polymer matrix[12].

3.4 Mechanical Property Studies

The load versus displacement and stress-strain curves of the reported samples are shown in Figure 6. The tensile strength and modulus of 0% mucilage are 18.312MPa and 0.745GPa, respectively. This value increases to 30.661MPa and 0.982 GPa for 5 wt.% mucilage sample, however, it decreases to 23.19 MPa and 0.654 GPa for 10 wt.% mucilage of seeds. This clearly shows that 5 wt.% mucilage sample exhibits 13.15 times more than that of 10 wt.% mucilage sample. Hence, it is more suitable for higher load-bearing applications. As the density of the gel increases, the tensile strength of the bio-plastic decreases. The Yield strength and Peak load are used to determine the load-bearing capacities of the specimen.

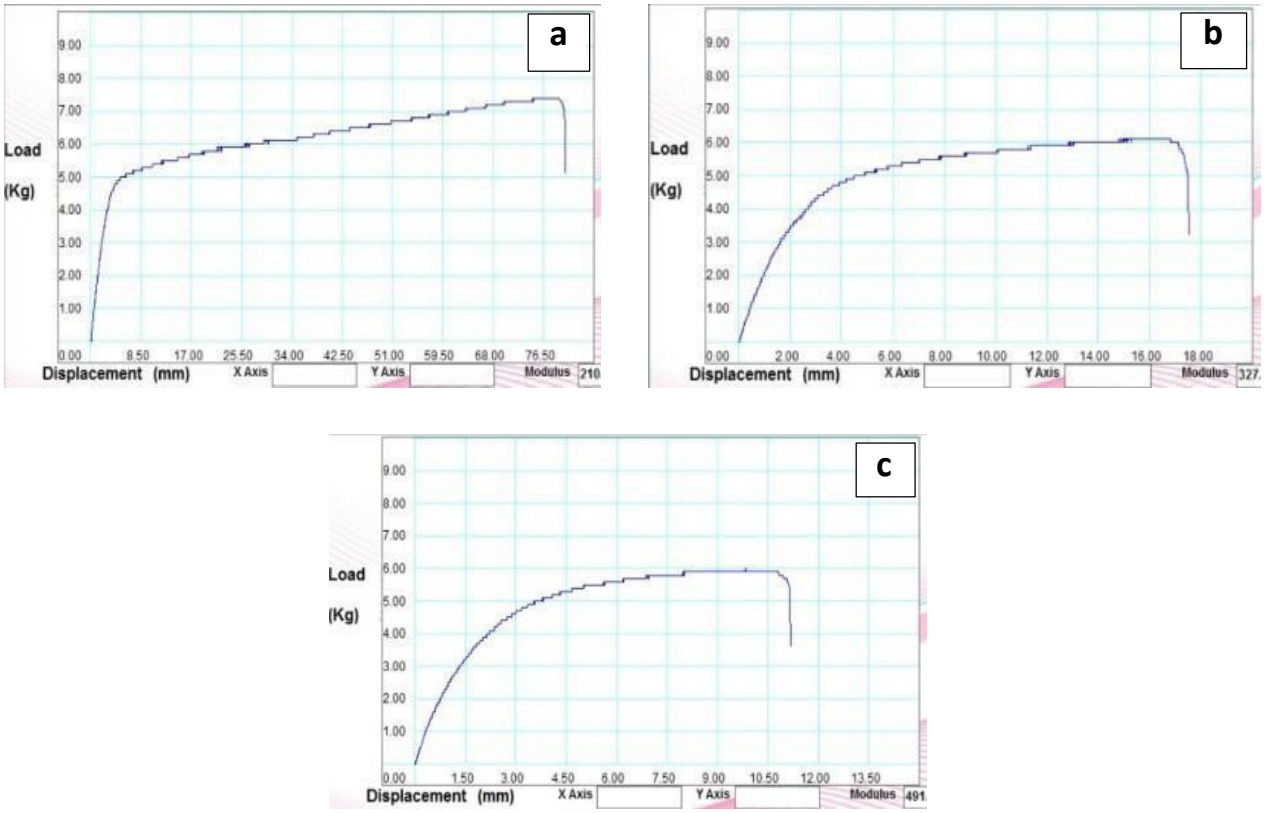


Figure 6. Load v/s displacement graph for **(a)** 0% mucilage, **(b)**5 wt.% mucilage, **(c)** 10 wt.% mucilage.

Table 1. Tensile strength and modulus

Sample	Tensile Strength (MPa)	Modulu s (GPa)	Peak load (kN)	Peak load (kg)
0% seed gel	18.312	0.745	0.0632	7.6
5 wt. % seed gel	30.661	0.982	0.0768	7.8
10 wt. % seed gel	23.192	0.654	0.0578	5.9

The tensile strength of HDPE is around 30 MPa. Hence, 5 wt.% mucilage sample could prove as an alternative for HDPE[13,14].

3.6 Soil Degradation Test

Biodegradation of the synthesized films was assessed by burying 1 cm × 1 cm samples in two types of soil- red soil and clay-rich moist soil as illustrated in Figures 7a and 7b (sample preparation) and Figures 7c and 7d (burial conditions). The study was conducted over a 30-day period, during which samples were periodically removed at 10-day intervals (Day 0, Day 10, Day 20, and Day 30), washed gently, and dried for measurement. A clear deformation and shrinkage in the specimen shape

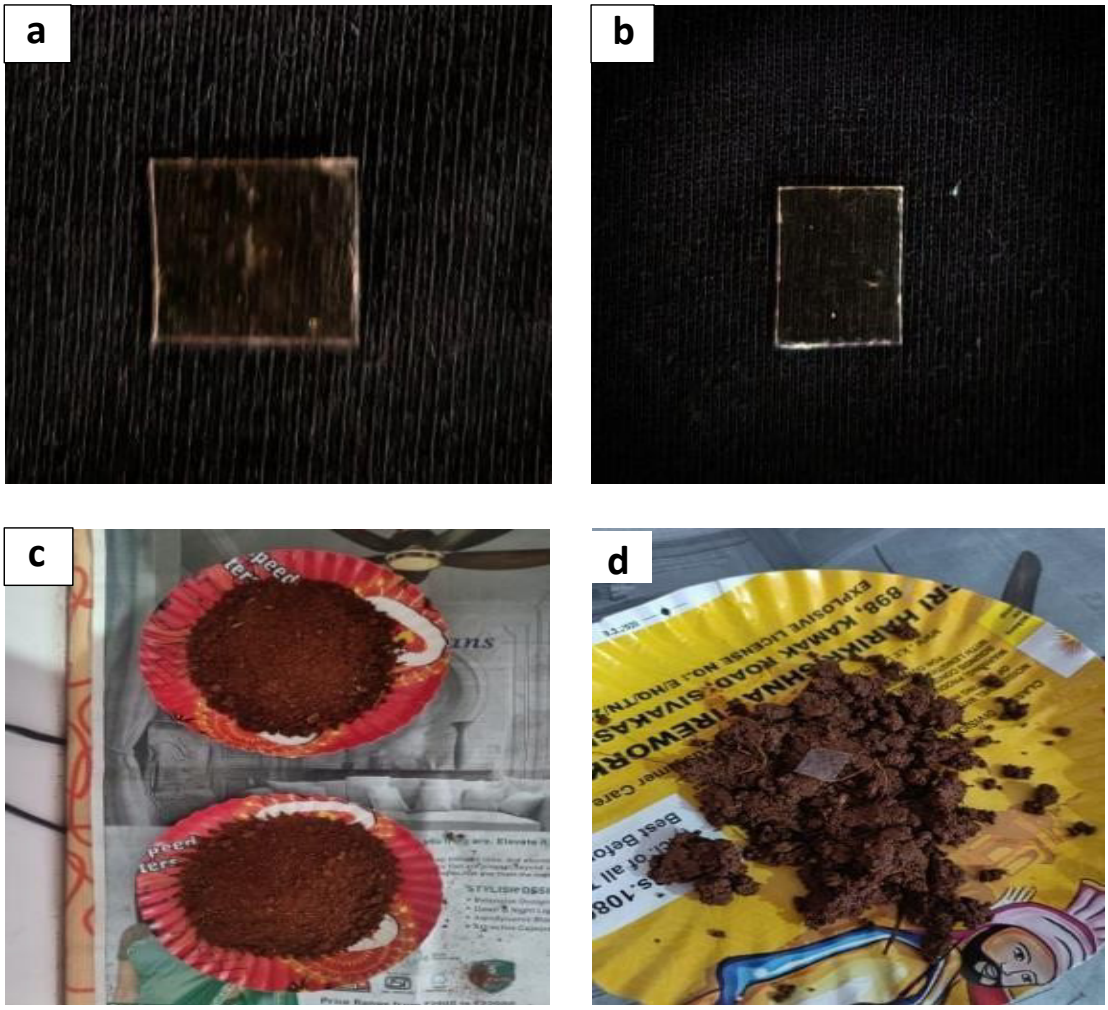


Figure 7. Cut samples to be immersed in the soil.

were observed over time. The physical degradation was accompanied by gradual disintegration, indicating microbial activity. Quantitatively, the mass loss was used as an indicator of biodegradation. The samples buried in clay soil showed a mass reduction of 18.4% after 10 days, increasing to 47.6% by Day 30, while those in red soil showed a slightly lower degradation profile with 12.2% mass loss after 10 days and 35.8% after 30 days. The

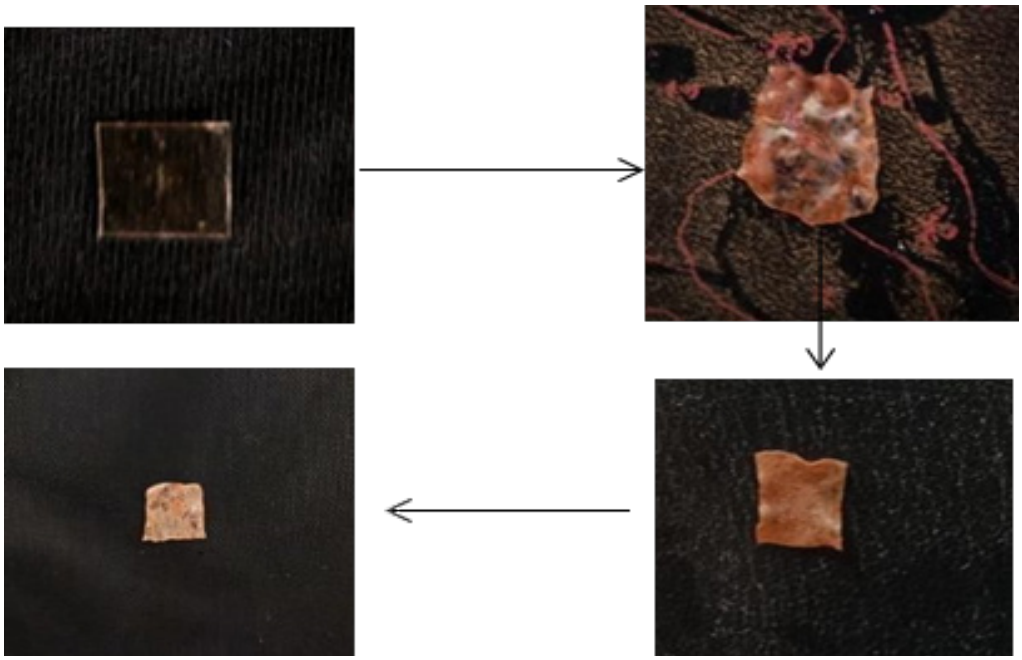


Figure 8. Degradation timeline of 5 wt.% mucilage sample in dry soil (day 1 to day 13).

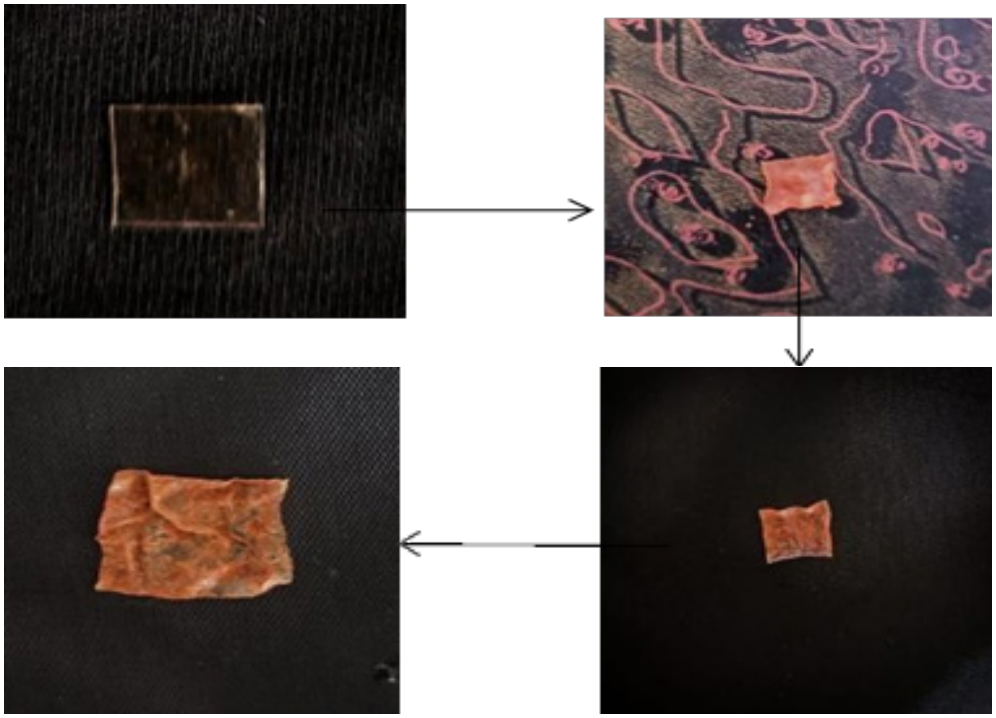


Figure 9. Degradation timeline of 5 wt.% mucilage sample in clay soil (day 1 to day 13).

degradation timeline of 5 wt.% mucilage sample in dry soil and clay soil (Day 1 to Day 13) is demonstrated in Figures 8 and 9, respectively.

This difference can be attributed to the higher moisture content and microbial load in clay soil, which enhances the enzymatic breakdown of the biopolymer matrix. Microbial degradation is known to play a key role in decomposing bioplastics such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), and starch-based films through hydrolysis and enzymatic cleavage of polymer chains. The mucilage-based films developed in this study follow a similar degradation pattern, with surface erosion and loss of structural integrity being more rapid in microbial-rich, moist environments. The results confirm that the developed films are biodegradable under natural soil conditions, and the degradation rate is significantly influenced by the type of soil. Further microbial analysis and kinetic modeling of degradation could provide deeper insights into the degradation mechanism and rate constants[15].

4.0 Conclusion

A fast-biodegradable, non-toxic, and environmentally friendly plastic film was successfully synthesized using 5 wt.% mucilage extracted from isabgol seeds with starch as the base polymer. SEM analysis confirmed the uniform surface morphology of the films, while XRD results indicated an increase in crystallinity at 5 wt.% mucilage, establishing it as the optimum composition. FTIR studies revealed notable vibrational changes with varying mucilage content, indicating successful interaction between starch and mucilage molecules. Mechanical testing showed that films with 5 wt.% mucilage exhibited improved tensile strength and modulus, making them mechanically viable for light-duty applications. Soil degradation tests demonstrated that the films degraded more rapidly in moisture-rich clay soil than in dry soil, highlighting their potential as eco-friendly materials for single-use or short-lifecycle products. To enhance the impact and applicability of this research, future studies should focus on optimizing the mucilage extraction and blending process to further improve mechanical strength and flexibility. Additionally, incorporating natural additives or crosslinkers may enhance durability and barrier properties. Long-term performance testing under real-world conditions such as food packaging, agricultural mulch films, and disposable carry bags, is also recommended. Finally, a deeper investigation into microbial degradation pathways and environmental safety assessments will be essential to validate these materials for commercial and regulatory acceptance.

5.0 References

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