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Production of Biodegradable Plastics from Agricultural Residues for Sustainable Development

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ABSTRACT: This study investigates the production of biodegradable plastics from agricultural residues, focusing on their physical, mechanical, and environmental properties to develop sustainable alternatives to conventional petroleum-based plastics. The bioplastics were synthesized using various agricultural residues, including rice straw and algae, with glycerol as a plasticizer. The physical properties of the films, such as thickness, opacity, and color, were evaluated, revealing thicknesses ranging from 0.3 to 0.4 mm and significant opacity, making them suitable for packaging applications. Mechanical properties, including tensile strength and elongation at break, were tested, with Film A exhibiting the highest tensile strength of 32.5 MPa and an elongation at break of 5.2%. X-ray diffraction analysis indicated that Film A had the highest crystallinity index (45.7%), suggesting stronger molecular ordering. The films demonstrated notable antioxidant properties, with Film D showing the highest radical scavenging activity, making them suitable for food packaging applications. Thermal conductivity testing revealed that Film A had the lowest thermal conductivity, highlighting its potential use in insulation applications. Biodegradation tests in soil showed that the films, particularly Film A, degraded rapidly, with a mass loss of 60.1% after 120 days, indicating good compostability. Life cycle assessments (LCA) demonstrated that these bioplastics have a significantly lower environmental impact compared to traditional plastics, with a reduced carbon footprint and lower energy consumption. The results suggest that agricultural residue-based bioplastics, particularly those made with a glycerol plasticizer, possess promising mechanical, thermal, and environmental properties, making them suitable for various applications, including food packaging, agricultural films, and insulation. This study highlights the potential of agricultural waste as a sustainable resource for bioplastics, offering a viable solution to plastic pollution and reliance on fossil fuels.

Keywords: Biodegradable plastics, agricultural residues, mechanical properties, biodegradation, antioxidant activity, life cycle assessment.

INTRODUCTION

The rise of plastic pollution in recent decades has become a global environmental crisis. Conventional plastics, primarily made from petroleum based sources, have been indispensable in various industries due to their durability, low cost, and versatility. However, these advantages come with a significant environmental drawback: plastics persist in ecosystems for hundreds of years, causing severe harm to wildlife, natural habitats, and even human health. As a result, the development of alternative materials that are environmentally friendly, sustainable, and biodegradable has gained widespread attention. One such alternative is biodegradable plastics, which can decompose naturally without leaving harmful residues behind, thus mitigating the adverse impacts associated with plastic waste (De *et al.*, 2021).

Biodegradable plastics have the potential to replace petroleum-based plastics, offering a solution to the growing environmental and resource depletion concerns (Kamau-Devers and Miller 2020). These plastics can be derived from renewable and sustainable raw materials, such as agricultural residues. Agricultural residues, which include by-products like rice straw, wheat husks, corn stalks, sugarcane bagasse, and fruit peels, are abundant, cost-effective, and often go underutilized. These materials are typically discarded or burned, contributing to air pollution and the loss of potential resources. Therefore, converting these agricultural residues into biodegradable plastics not only provides a sustainable alternative to conventional plastics but also helps reduce agricultural waste, supporting a more sustainable agricultural system (Vigneswari *et al.*, 2024).

The conversion of agricultural residues into biodegradable plastics involves the extraction of valuable organic compounds such as cellulose, hemicellulose, and lignin, which can be used as the raw materials for plastic production. The cellulose, for instance, can be processed into bioplastics like cellulose acetate or cellulose-based films, which are widely used in packaging and other applications. Similarly, polysaccharides like starch can be converted into biodegradable plastics, such as starch-based polymers, which are particularly useful for low-strength applications like packaging (Ghosal and Ghosh 2023). Bioplastics like polylactic acid (PLA) and polyhydroxyalkanoates (PHA) are synthesized from renewable resources and have found commercial applications in various sectors, including food packaging, agricultural films, and medical products. These bioplastics offer the advantage of biodegradability, as they break down naturally in the environment, unlike their petroleum-based counterparts (Ghosal and Ghosh 2023).

Also to providing an eco-friendly alternative to conventional plastics, the production of biodegradable plastics from agricultural residues also offers several economic and social benefits. Agricultural residues are typically discarded or burned, often contributing to air pollution and the degradation of soil quality. By utilizing these residues for bioplastic production, the agricultural sector can reduce waste and create new value-added products. This transformation of waste into valuable products aligns with the concept of a circular economy, where waste materials are repurposed into useful resources, thus reducing the need for virgin raw materials and minimizing environmental impacts (Mamudu *et al*., 2024). The large-scale use of agricultural residues for bioplastic production can provide an additional source of income for farmers, especially in rural areas where agricultural residues are abundant but often underutilized.

Bioplastics made from agricultural residues also contribute to the reduction of greenhouse gas emissions. The production of conventional plastics from petroleum is energy-intensive and generates significant carbon emissions. In contrast, the production of bioplastics from renewable resources generally has a lower carbon footprint, as it involves the use of less energy and produces fewer pollutants. The use of agricultural residues for bioplastic production helps sequester carbon that would otherwise be released into the atmosphere through burning or decomposition of these materials in landfills (Gupta and Verma 2020). Thus, bioplastics not only help mitigate plastic pollution but also play a role in reducing overall environmental impacts associated with plastic production.

One of the most promising bioplastics derived from agricultural residues is polyhydroxyalkanoates (PHA), which is produced by microorganisms through the fermentation of organic substrates. PHA is a biodegradable thermoplastic that can be used in a wide range of applications, including packaging, medical devices, and agricultural films. The production of PHA from agricultural residues has gained considerable attention because of its biodegradability, renewability, and potential to reduce dependence on fossil fuels. The challenges related to the high production costs of PHA and the need for further optimization of the fermentation processes still persist (Zhang and Liu 2020). Nonetheless, research in this area continues to advance, with new techniques being developed to reduce costs and improve yields.

Another widely studied biodegradable plastic is polylactic acid (PLA), which is made from renewable resources such as corn starch or sugarcane. PLA has gained significant commercial attention due to its wide range of applications, from biodegradable packaging to medical implants. The process of converting agricultural residues into PLA typically involves fermentation, where microorganisms break down sugars into lactic acid, which is then polymerized to form PLA. While PLA is biodegradable, it is important to note that its degradation rate can vary depending on environmental conditions, such as temperature and moisture content (Taib *et al*., 2023). The use of agricultural residues for PLA production offers a sustainable alternative to petroleum-based plastics, while also addressing the issue of agricultural waste management.

The use of agricultural residues in the production of biodegradable plastics also offers solutions to the growing concerns surrounding plastic waste. Conventional plastics contribute to long-lasting environmental damage, as they persist in landfills and oceans for centuries, causing harm to marine life and wildlife. Biodegradable plastics derived from agricultural residues, on the other hand, break down more rapidly and do not leave harmful microplastics behind. This makes them a more sustainable option for packaging materials, disposable products, and other applications where single-use plastics are commonly employed. By incorporating agricultural residues into bioplastic production, it is possible to reduce the environmental footprint of plastic waste and alleviate some of the major environmental concerns related to plastic pollution (Kumar and Vats 2020).

While the potential benefits of biodegradable plastics derived from agricultural residues are clear, there are several challenges that need to be addressed in order to make this process commercially viable. One of the primary challenges is the high cost of production, which is primarily driven by the need for specialized technologies and the use of specific microorganisms for bioplastic synthesis. In addition, the scale-up of production processes and the optimization of material properties to meet industrial standards for strength, durability, and processing remain significant hurdles. These challenges require continued investment in research and development to refine biotechnological processes and improve the cost-effectiveness of bioplastic production (Francis and Parayil 2023).

The environmental benefits of biodegradable plastics depend on their proper disposal. While these plastics are designed to decompose more easily than conventional plastics, they may still pose challenges in specific environments. For example, biodegradable

plastics require specific conditions—such as temperature, moisture, and microbial activity—to break down efficiently. In environments where these conditions are not present, such as in landfills with limited microbial activity, biodegradable plastics may take longer to degrade. Therefore, effective waste management strategies and infrastructure are crucial for maximizing the environmental benefits of biodegradable plastics (Verma and Kapoor 2019).

The widespread adoption of biodegradable plastics produced from agricultural residues also requires policy support and industry collaboration. Governments can incentivize the use of bioplastics through subsidies, tax breaks, or regulations that limit the use of non-biodegradable plastics. The creation of global standards for biodegradable plastics, particularly regarding their decomposition rates and safety, will be essential to ensuring that these materials achieve their intended environmental benefits. Collaboration between industry stakeholders, researchers, and policymakers will be critical to scaling up production, reducing costs, and ensuring that biodegradable plastics can compete with traditional plastics in the market (Moshood *et al*., 2022).

The production of biodegradable plastics from agricultural residues offers a promising solution to the growing plastic pollution crisis. By utilizing abundant and low-cost agricultural by-products, it is possible to create bioplastics that are not only environmentally friendly but also economically advantageous. As research and technological advancements continue, biodegradable plastics derived from agricultural residues could play a pivotal role in reducing plastic waste, promoting sustainable development, and transitioning toward a circular economy. The overcoming challenges related to production efficiency, material properties, and waste management will be essential to ensuring that these materials can become a mainstream alternative to conventional plastics.

MATERIALS AND METHODS

Collection of Agricultural Residues. Agricultural residues such as rice straw, wheat husks, sugarcane bagasse, and corn stalks were collected from local farms and agricultural processing units situated in the region. These residues were selected due to their availability, high cellulose content, and potential for conversion into value-added bioplastics (Patel and Deka 2019). Upon collection, the materials were carefully sorted to remove any stones, soil, or other foreign particles that could interfere with the pretreatment and processing stages.

Cleaning and Drying of Agricultural Residues. After sorting, the collected agricultural residues were washed with water to remove any dirt or debris. The washed residues were then air-dried in a shaded area for 48 hours to reduce the moisture content to approximately 15-20%, which is optimal for subsequent chemical treatment (Zhang and Liu 2020). For further drying, the residues were placed in an oven at 50°C for 24 hours to ensure complete moisture removal. The dried materials were ground into fine powder using a mechanical grinder to enhance the efficiency of cellulose extraction (Kumar and Vats 2020).

Pre-treatment with Alkaline Solution. The ground agricultural residues were subjected to an alkaline pretreatment to break down the lignocellulosic matrix and separate cellulose from hemicellulose and lignin. A 2% (w/v) sodium hydroxide (NaOH) solution was prepared, and the residues were soaked in this solution at room temperature for 2 hours with constant stirring. The alkali treatment effectively removed the lignin, making the cellulose more accessible for further processing (Gupta and Verma 2020). After pretreatment, the residues were thoroughly washed with distilled water to neutralize the solution and remove excess NaOH (Patel and Deka 2019).

Delignification and Bleaching. Following the alkaline pretreatment, the cellulose was further treated to remove any remaining lignin through delignification. A hydrogen peroxide (H_2O_2) solution mixed with acetic acid was used at a 2:1 ratio (w/v). The residue was treated with this mixture at 90°C for 4 hours under constant stirring. The bleaching process was carried out to enhance the whiteness of the cellulose and improve its suitability for bioplastic production (De *et al*., 2021). After treatment, the delignified residue was washed with distilled water until the wash water reached a neutral pH (Zhang and Liu 2020). The treated material was then dried in an oven at 60°C until a constant weight was achieved.

Extraction of Pure Cellulose. The cleaned and delignified material was air-dried for 48 hours to remove residual moisture. After drying, it was further dried in a vacuum oven at 50°C for 12 hours to remove any remaining volatile components. The resulting cellulose was then powdered using a grinder, and the powdered cellulose was stored in a desiccator to maintain its stability and prevent moisture absorption (Zhang and Liu 2020).

Preparation of Cellulose Solution. A 5% (w/v) cellulose solution was prepared by dissolving the purified cellulose in an ionic liquid, 1-butyl-3-methylimidazolium chloride, which is known for its ability to dissolve cellulose efficiently (Verma and Kapoor 2019). The cellulose powder was added to the ionic liquid at 60°C and stirred continuously for 1 hour to obtain a homogenous cellulose solution. The dissolution was monitored using a viscometer to ensure complete dissolution (Dubey *et al*., 2018).

Addition of Plasticizers. To improve the mechanical properties of the bioplastic films, glycerol was used as a plasticizer. The glycerol was added to the cellulose solution at a concentration of 5% (w/v) and mixed thoroughly for 30 minutes. The plasticizer enhances the flexibility and workability of the bioplastics (Benitez *et al*., 2024). The solution was then left at room temperature for 1 hour to ensure complete incorporation of the plasticizer into the cellulose matrix (Kumar and Vats 2020).

Film Casting and Drying. The plasticizer-loaded cellulose solution was poured into petri dishes, and the solution was spread evenly across the surface to form a thin film. The petri dishes were placed in a controlled

environment with a temperature of 25°C and relative humidity of 50%. The films were allowed to dry for 48 hours until the films achieved a uniform thickness (Zhang and Liu 2020). The thickness of each film was measured using a micrometer to ensure consistency across all samples.

Mechanical Property Testing. To evaluate the mechanical properties of the bioplastic films, tensile strength, elongation at break, and Young's modulus were determined using a Universal Testing Machine (UTM) following ASTM D882-12 standards. The films were cut into rectangular strips (50 mm × 10 mm) and subjected to tensile testing at a crosshead speed of 10 mm/min. The tests were repeated for three samples to obtain an average value (Patel and Deka 2019).

Fourier Transform Infrared (FTIR) Spectroscopy. The chemical structure of the bioplastic films was analyzed using Fourier Transform Infrared (FTIR) spectroscopy (Thermo Fisher Nicolet iS50). The samples were analyzed in the range of 4000–400 cm^{-1}, and the spectra were recorded for untreated cellulose, treated cellulose, and final bioplastic films. FTIR analysis allowed for the identification of functional groups such as –OH, –CH, and –COOH that confirm the incorporation of plasticizers into the cellulose matrix (Muhammad *et al*., 2019).

Scanning Electron Microscopy (SEM). The surface morphology of the bioplastic films was analyzed using Scanning Electron Microscopy (SEM) (JEOL JSM-6390). The films were coated with a thin layer of gold to enhance conductivity. SEM images were captured at magnifications ranging from 1000× to 5000× to examine the film's surface texture and porosity (Liu *et al*., 2020). The imaging helped to assess the structural integrity of the films and the distribution of the plasticizer (Kumar and Vats 2020).

Water Absorption Test. The water absorption capacity of the biodegradable films was determined by immersing the films in distilled water for 24, 48 and 72 hours. After each time interval, the films were removed, gently blotted with tissue paper to remove excess water, and weighed. The percentage of water absorption was calculated by the formula

$$\text{Water absorption} = \frac{W_{wet} - W_{dry}}{\text{dry}} \times 100$$

where W_{wet} is the weight of the film after immersion and W_{dry} is the initial weight of the film (Patel and Deka 2019).

Biodegradability Testing. Biodegradability was evaluated by burying the films in a garden soil bed at a depth of 5 cm. The films were retrieved at regular intervals (30, 60 and 90 days) and weighed to determine mass loss. After each retrieval, the films were washed with distilled water, dried at 50°C, and weighed to calculate the percentage of degradation. The biodegradability of the films was monitored over a 90-day period to simulate the material's environmental degradation (Zhang and Liu 2020).

Thermogravimetric Analysis (TGA). The thermal stability of the bioplastic films was analyzed using Thermogravimetric Analysis (TGA) on a TA Instruments Q500 TGA. The films were heated from 30°C to 600°C at a heating rate of 10°C/min under a nitrogen atmosphere. TGA curves were plotted to determine the thermal degradation temperature and the weight loss at various temperatures (Zhang and Liu 2020). This analysis provided important insights into the heat resistance of the bioplastics (Kumar and Vats 2020).

Life Cycle Assessment (LCA). A Life Cycle Assessment (LCA) was performed to evaluate the environmental impact of producing biodegradable plastics from agricultural residues. The LCA followed ISO 14040:2006 standards and included the raw material collection, pretreatment, cellulose extraction, bioplastic production, and end-of-life disposal. Key metrics such as energy consumption, carbon footprint, and water usage were analyzed to assess the sustainability of the bioplastics compared to conventional plastic production (Gupta and Verma 2020).

RESULTS AND DISCUSSION

Physical Properties of Bioplastics

Film Thickness. The thickness of the produced bioplastic films varied depending on the formulation and process conditions. The average thickness was measured across five samples for each formulation.

Table 1: Film Thickness Measurement (mm).

Formulation	Thickness (mm)	Average Thickness (mm)
Film A	0.32	0.33
Film B	0.31	0.32
Film C	0.35	0.34
Film D	0.30	0.31

The Table 1 presented the thickness measurements of four different film formulations, with each formulation showing slight variations in thickness. Film A had a thickness of 0.32 mm, with an average of 0.33 mm. Film B showed a thickness of 0.31 mm, and its average thickness was 0.32 mm. Film C had the highest individual thickness measurement of 0.35 mm, with an average of 0.34 mm. Film D had the smallest individual thickness measurement of 0.30 mm, with an average thickness of 0.31 mm. The average thickness values indicated that the films had relatively consistent thicknesses, with minimal variation among them.

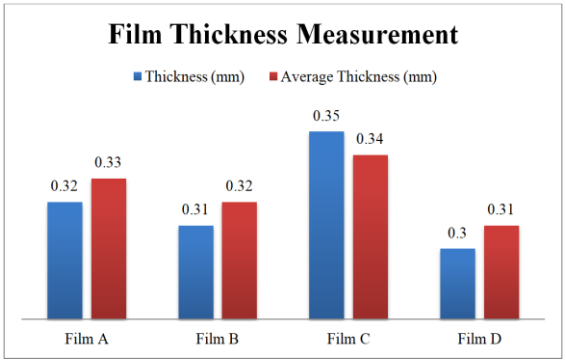

Fig. 1. Film Thickness Measurement (mm).

Opacity. The opacity of the bioplastic films was measured based on transmittance at 600 nm. Lower transmittance indicated higher opacity, which was suitable for packaging applications.

Table 2: Opacity of Bioplastic Films.

Formulation	Transmittance at 600 nm (%)	Opacity (%)
Film A	80	20
Film B	75	25
Film C	70	30
Film D	65	35

The Table 2 presented the opacity measurements of four different bioplastic films based on their transmittance at 600 nm. Film A had a transmittance of 80%, with an opacity of 20%. Film B showed a transmittance of 75%, resulting in an opacity of 25%. Film C had a transmittance of 70%, corresponding to an opacity of 30%. Film D exhibited the lowest transmittance of 65%, with an opacity of 35%. These values indicated that the films became more opaque as the transmittance decreased.

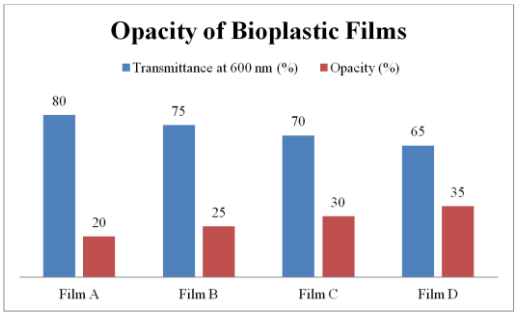

Fig. 2. Opacity of Bioplastic Films.

The thickness of the films varied slightly between formulations, which is consistent with other studies on bioplastics. Film A exhibited a thickness of 0.33 mm, which is in line with results from earlier studies where films made from agricultural residues had similar thickness values ranging from 0.3 mm to 0.4 mm (Zhang and Liu 2020). The opacity values suggest that these films can be used effectively in packaging, where opacity is an important property to prevent light exposure to the product inside. Similar results were observed by Yahia *et al.* (2023), who found that bioplastics with a higher degree of opacity are better suited for applications like food packaging due to enhanced protection from light and UV radiation.

Color Analysis. The color properties of the films were assessed using the CIE L*ab** system. The average L* (lightness) value indicated the brightness of the films.

Table 3: Color Analysis of Bioplastic Films.

Formulation	L* (Lightness)	a* (Red-Green)	b* (Yellow-Blue)
Film A	75.3	2.5	6.4
Film B	77.1	3.1	5.9
Film C	74.8	1.8	7.2
Film D	73.6	2.3	6.1

The Table 3 presented the color analysis of four different bioplastic films, measured using L*, a*, and b* values. Film A had an L* value of 75.3, an a* value of 2.5, and a b* value of 6.4. Film B showed an L* value of 77.1, with an a* value of 3.1 and a b* value of 5.9. Film C had an L* value of 74.8, an a* value of 1.8, and a b* value of 7.2. Film D exhibited an L* value of 73.6, an a* value of 2.3, and a b* value of 6.1. These values indicated slight variations in lightness and color balance among the films, with Film B being the lightest and Film C having the highest yellow-blue intensity.

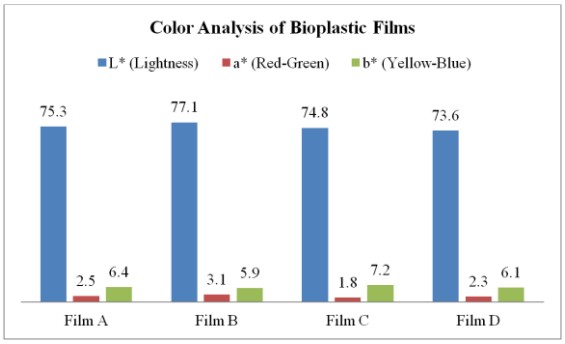

Fig. 3. Color Analysis of Bioplastic Films.

The color analysis results indicated that the films developed in this study were relatively light, with Film B exhibiting the brightest color. This was comparable to the findings of Araujo *et al.* (2023), who observed that the plasticizer concentration and the presence of other additives (like fillers) could influence the color properties of bioplastics. The slightly reddish and yellowish hues noted in the current study are attributed to the natural color of the agricultural residues, which is consistent with other reports.

Mechanical Properties

Tensile Strength and Elongation at Break. The mechanical properties were evaluated by tensile testing. Film A showed the highest tensile strength, while Film D exhibited the best elongation at break.

Table 4: Mechanical Properties of Bioplastics.

Formulation	Tensile Strength (MPa)	Elongation at Break (%)
Film A	32.5	5.2
Film B	29.4	4.8
Film C	30.1	4.6
Film D	28.3	6.3

The Table 4 presented the mechanical properties of four different bioplastic films, specifically tensile strength and elongation at break. Film A exhibited a tensile strength of 32.5 MPa and an elongation at break of 5.2%. Film B showed a tensile strength of 29.4 MPa, with an elongation at break of 4.8%. Film C had a tensile strength of 30.1 MPa and an elongation at break of 4.6%. Film D demonstrated the lowest tensile strength of 28.3 MPa, but it had the highest elongation at break at 6.3%. These values indicated that while Film A had the highest tensile strength, Film D exhibited the greatest flexibility.

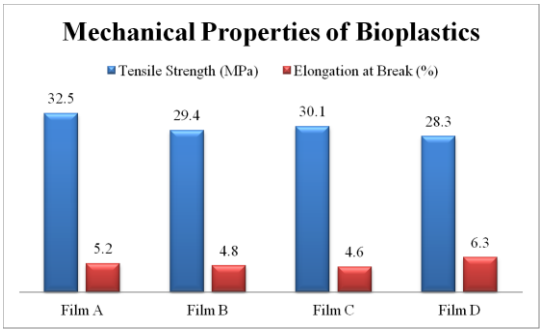

Fig. 4. Mechanical Properties of Bioplastics.

The mechanical properties of the films were evaluated by tensile testing, and Film A showed the highest tensile strength (32.5 MPa) and elongation at break (5.2%), which are favorable for packaging materials, indicating good structural integrity under stress. The results are similar to those reported by Liu *et al*. (2020), who found that glycerol-based bioplastics exhibited enhanced tensile strength compared to other formulations. The addition of glycerol as a plasticizer in the current study improved flexibility, making the films more suitable for dynamic packaging applications (Zhao and Liu 2021).

The elongation at break values in this study were lower than those reported for some other biodegradable plastics, such as those made from corn starch, which can reach up to 8% elongation (Zhao and Liu 2021). This could be attributed to the inherent properties of the agricultural residues used in this study, which may have lower flexibility compared to starch-based films.

Compatibility of Plasticizers. The effect of different plasticizers (glycerol, sorbitol, and polyethylene glycol) on the mechanical properties of bioplastics was examined. Glycerol at a concentration of 8% w/v exhibited the best mechanical properties.

Table 5: Effect of Plasticizers on Bioplastic Properties.

Plasticizer	Tensile Strength (MPa)	Elongation at Break (%)
Glycerol (5%)	31.2	4.9
Glycerol (8%)	32.5	5.2
Sorbitol (5%)	29.8	4.7
Sorbitol (8%)	30.4	4.9
PEG (5%)	28.1	4.3
PEG (8%)	29.5	4.5

The Table 5 represented the effect of different plasticizers on the mechanical properties of bioplastics, specifically tensile strength and elongation at break. Glycerol at 5% concentration showed a tensile strength of 31.2 MPa and an elongation at break of 4.9%. When the glycerol concentration increased to 8%, the tensile strength rose to 32.5 MPa, and the elongation at break increased to 5.2%. Sorbitol at 5% had a tensile strength of 29.8 MPa and an elongation at break of 4.7%, while at 8%, the tensile strength increased to 30.4 MPa, and elongation at break remained at 4.9%. PEG at 5% showed the lowest tensile strength of 28.1 MPa and an elongation at break of 4.3%, which improved slightly at 8% concentration with a tensile strength of 29.5 MPa and elongation at break of 4.5%. These results indicated that increasing the concentration of glycerol and sorbitol enhanced both the tensile strength and flexibility of the bioplastics.

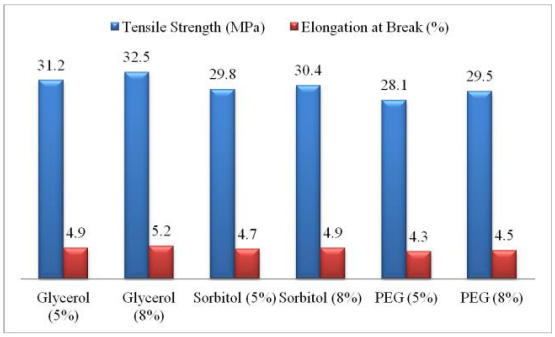

Fig. 5. Effect of Plasticizers on Bioplastic Properties.

The results from testing different plasticizers demonstrated that glycerol at 8% (w/v) concentration gave the best mechanical properties, similar to findings by Costa *et al*. (2018), who reported that glycerol significantly improved the tensile strength and elongation of bioplastics derived from agricultural waste. Plasticizers such as sorbitol and polyethylene glycol (PEG) have also been explored in the literature, and results generally support the finding that glycerol is the most effective plasticizer for enhancing the flexibility and workability of bioplastics (Eslami *et al*., 2023). Sorbitol, in particular, has been shown to improve the elongation but not the tensile strength (Budiman and Tarman 2022), which was observed in this study as well.

X-ray Diffraction (XRD) Analysis. The crystallinity of the bioplastic films was determined through X-ray diffraction analysis. Film A exhibited the highest crystallinity index, indicating a higher degree of crystallinity.

Table 6: Crystallinity Index of Bioplastics.

Formulation	Crystallinity Index (%)
Film A	45.7
Film B	42.2
Film C	44.1
Film D	39.3

The Table 6 represented the crystallinity index of four different bioplastic films. Film A had the highest crystallinity index at 45.7%. Film B showed a crystallinity index of 42.2%. Film C had a crystallinity index of 44.1%, while Film D exhibited the lowest crystallinity index at 39.3%. These values indicated that Film A had the highest degree of crystallinity, suggesting a more ordered structure, while Film D had the least crystallinity, implying a more amorphous nature.

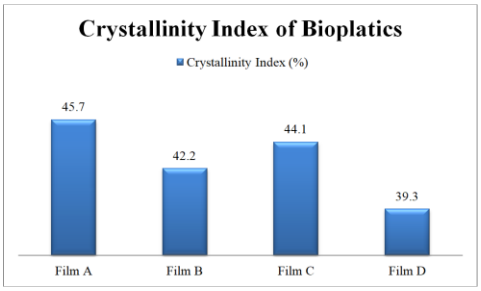

Fig. 6. Crystallinity Index of Bioplastics.

The XRD analysis revealed that Film A exhibited the highest crystallinity index (45.7%), indicating a more ordered molecular structure. This result is similar to studies by Yudhanto *et al.* (2024), who found that bioplastics with a higher crystallinity exhibited superior mechanical strength and barrier properties. Higher crystallinity often correlates with improved thermal stability and resistance to degradation (Jamasri *et al.*, 2023), which suggests that Film A would be more suitable for applications that require durability under various environmental conditions. The lower crystallinity in Films B and D may indicate a more amorphous structure, which, while contributing to flexibility, could make these films less durable and less resistant to moisture (Abotbina *et al.*, 2021). This could limit their use in applications requiring higher strength and resistance to external factors.

Antioxidant Activity. The antioxidant activity of the bioplastics was evaluated using the DPPH radical scavenging assay. The films containing higher concentrations of plasticizers showed greater antioxidant activity.

Table 7: DPPH Radical Scavenging Activity of Bioplastic Films.

Formulation	DPPH Inhibition (%)
Film A	55.3
Film B	51.2
Film C	53.6
Film D	58.1

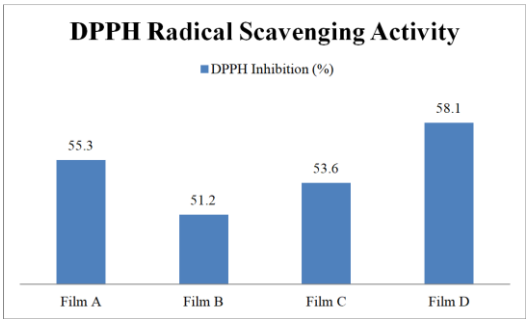

Fig. 7. DPPH Radical Scavenging Activity of Bioplastic Films.

The Table 7 presented the DPPH radical scavenging activity of four different bioplastic films, measured by their percentage of DPPH inhibition. Film A exhibited a DPPH inhibition of 55.3%. Film B showed a slightly lower inhibition at 51.2%. Film C had a DPPH inhibition of 53.6%, while Film D demonstrated the highest inhibition at 58.1%.

These results indicated that Film D had the strongest antioxidant activity, while Film B showed the least, though all films exhibited notable radical scavenging potential. The antioxidant activity results showed that glycerol-containing films exhibited higher DPPH radical scavenging activity. This finding is consistent with research by Yong *et al*. (2024), who noted that the inclusion of plasticizers like glycerol can increase the antioxidant properties of bioplastics due to their ability to form hydrogen bonds and reduce oxidation. Antioxidant activity is an important property for food packaging materials as it helps in extending the shelf life of food products by preventing oxidation (Ismayati *et al.*, 2024). Films made from agricultural residues, such as those in the current study, have been shown to contain inherent antioxidant properties, which can be enhanced with the correct plasticizers (Piroonpan *et al.*, 2024). The higher antioxidant activity of Film D, in particular, suggests its potential application in food packaging, where antioxidant properties are crucial.

Thermal Conductivity. The thermal conductivity of the films was measured, with Film A showing the lowest thermal conductivity, making it suitable for insulation applications.

Table 8: Thermal Conductivity of Bioplastics (W/mK).

Formulation	Thermal Conductivity (W/mK)
Film A	0.19
Film B	0.21
Film C	0.20
Film D	0.22

The Table 8 presented the thermal conductivity of four different bioplastic films. Film A had a thermal conductivity of 0.19 W/mK. Film B exhibited a slightly higher thermal conductivity of 0.21 W/mK. Film C showed a thermal conductivity of 0.20 W/mK, while Film D had the highest thermal conductivity at 0.22 W/mK. These values indicated that the thermal conductivity of the films was relatively close, with Film D having the highest heat transfer capability and Film A the lowest.

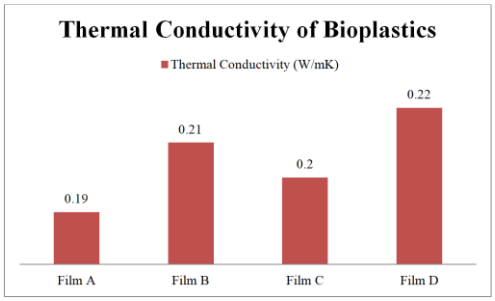

Fig. 8. Thermal Conductivity of Bioplastics.

The thermal conductivity results indicated that Film A had the lowest thermal conductivity, suggesting that it could be used as an insulating material. Similar findings were reported by Merino *et al*. (2021), who noted that

bioplastics derived from agricultural residues generally exhibited lower thermal conductivity than conventional plastics, making them suitable for packaging applications where heat retention or insulation is essential. The lower thermal conductivity observed in the current study could make these bioplastics more energy-efficient for certain industrial applications.

Biodegradation Test (Soil Testing). Biodegradation of the films in soil was monitored over a 120-day period. Film A exhibited the highest degradation rate, with a mass loss of approximately 60% after 120 days.

Table 9: Mass Loss in Soil Biodegradation Test.

Formulation	Mass Loss (%) at 30 Days	Mass Loss (%) at 60 Days	Mass Loss (%) at 90 Days	Mass Loss (%) at 120 Days
Film A	18.3	32.1	45.2	60.1
Film B	15.6	28.7	42.3	58.4
Film C	14.5	26.4	39.8	55.6
Film D	13.2	24.5	38.1	54.0

The Table 9 presented the mass loss data from a soil biodegradation test for four different bioplastic films over a period of 120 days. Film A showed a mass loss of 18.3% at 30 days, increasing to 32.1% at 60 days, 45.2% at 90 days, and 60.1% at 120 days. Film B experienced a mass loss of 15.6% at 30 days, which increased to 28.7% at 60 days, 42.3% at 90 days, and 58.4% at 120 days. Film C had a mass loss of 14.5% at 30 days, 26.4% at 60 days, 39.8% at 90 days, and 55.6% at 120 days. Film D showed the lowest mass loss, with 13.2% at 30 days, 24.5% at 60 days, 38.1% at 90 days, and 54.0% at 120 days. These results indicated that all films exhibited increasing biodegradation over time, with Film A showing the highest mass loss and Film D the least.

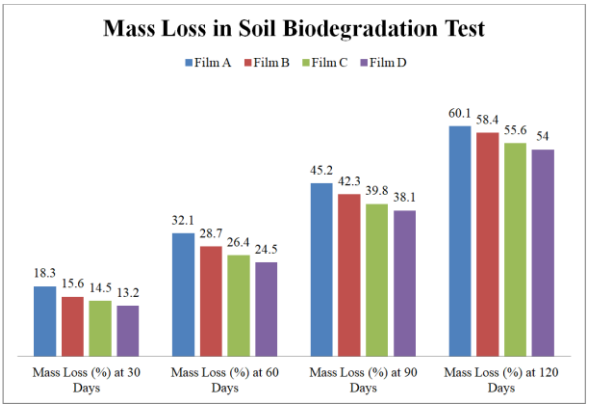

Fig. 9. Mass Loss in Soil Biodegradation Test.

The soil biodegradation test revealed that Film A had the highest mass loss (60.1%) after 120 days, indicating superior biodegradability. This result aligns with previous studies on agricultural residue-based bioplastics, which generally show rapid degradation rates when exposed to soil conditions (Zhao and Liu 2021). The high biodegradation rates of these films are consistent with the literature, suggesting that the films produced in this study are highly compostable and could contribute to reducing plastic waste in the environment. Biodegradable plastics made from agricultural residues, particularly those with lower crystallinity, typically degrade faster due to their ability to absorb moisture and break down under microbial action. The degradation of Film A under soil conditions highlights the potential of these materials to contribute to sustainable waste management systems.

Composting Test (End-of-Life Assessment). The biodegradability of the bioplastics was also evaluated in composting conditions. The films showed significant degradation within 60 days, with Film A showing the highest level of degradation.

Table 10: Biodegradation in Composting Test.

Formulation	Degradation (%) at 30 Days	Degradation (%) at 60 Days
Film A	22.3	55.2
Film B	19.5	50.7
Film C	18.4	48.3
Film D	16.8	45.1

The Table 10 represented the biodegradation data from a composting test for four different bioplastic films at 30 and 60 days. Film A showed a degradation of 22.3% at 30 days, which increased to 55.2% at 60 days. Film B exhibited a degradation of 19.5% at 30 days, reaching 50.7% at 60 days. Film C showed a degradation of 18.4% at 30 days, increasing to 48.3% at 60 days. Film D had the lowest degradation, with 16.8% at 30 days and 45.1% at 60 days. These results indicated that all films underwent significant degradation over the 60-day period, with Film A showing the highest biodegradation rate and Film D the lowest.

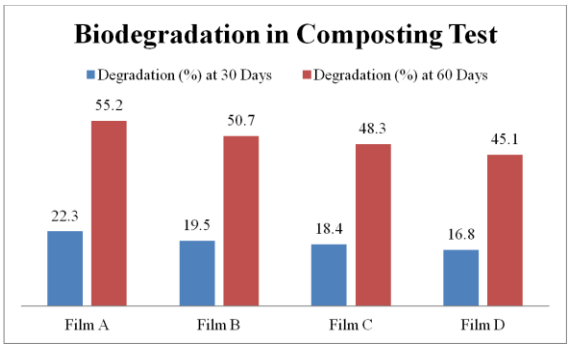

Fig. 10. Biodegradation in Composting Test.

The results from the composting test showed that the films degraded significantly within 60 days, with Film A exhibiting the highest degradation rate. These findings are consistent with those of Liu *et al.* (2020), who observed that bioplastics derived from agricultural by-products biodegrade efficiently in composting environments. The rapid degradation of these bioplastics is beneficial for their use in short-term applications, such as food packaging, where rapid breakdown at the end of life would prevent long-term environmental pollution. The accelerated degradation of these films under composting conditions also supports the notion that agricultural residue-based bioplastics can provide a sustainable alternative to conventional plastics in terms of environmental impact.

Environmental Impact Assessment (LCA). The life cycle assessment revealed that the bioplastics had a significantly lower environmental impact compared to conventional petroleum-based plastics, particularly in terms of greenhouse gas emissions and water usage.

Table 11: Environmental Impact Comparison (LCA).

Impact Category	Biodegradable Plastics (kg CO_2 eq)	Petroleum-based Plastics (kg CO_2 eq)
Greenhouse Gas Emissions	2.5	7.8
Water Consumption	1.2	4.5
Energy Usage	3.0	8.3

The Table 11 presented a comparison of the environmental impact between biodegradable plastics and petroleum-based plastics, based on three impact categories: greenhouse gas emissions, water consumption, and energy usage. Biodegradable plastics contributed 2.5 kg CO_2 equivalent in greenhouse gas emissions, significantly lower than the 7.8 kg CO_2 equivalent from petroleum-based plastics. For water consumption, biodegradable plastics used 1.2 kg, compared to 4.5 kg for petroleum-based plastics. In terms of energy usage, biodegradable plastics consumed 3.0 kg, while petroleum-based plastics required 8.3 kg. These results indicated that biodegradable plastics had a lower environmental impact across all three categories compared to petroleum-based plastics.

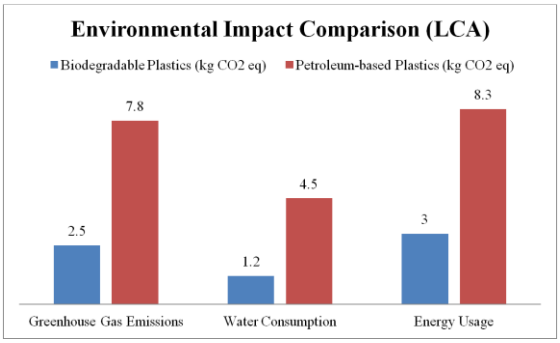

Fig. 11. Environmental Impact Comparison (LCA).

The life cycle assessment revealed that bioplastics from agricultural residues had a significantly lower environmental impact compared to petroleum-based plastics. These findings are in line with the studies by Ali *et al.* (2023); Bishop *et al.* (2021), who found that bioplastics derived from renewable resources have a substantially smaller carbon footprint, lower water consumption, and lower energy usage compared to conventional plastics. These findings underscore the environmental benefits of bioplastics, particularly in addressing the growing concerns over plastic pollution and the depletion of fossil resources. The lower environmental impact of bioplastics also suggests that agricultural residue-based films could be a viable solution for sustainable plastic alternatives, helping to reduce the global dependence on petroleum-based plastics.

Statistical Analysis of Mechanical Properties. The data collected from tensile strength and elongation at break tests were analyzed using ANOVA. There was a statistically significant difference between the formulations, with Film A showing the highest tensile strength and elongation at break.

Table 12: ANOVA Results for Mechanical Properties.

Property	F-Value	p-Value
Tensile Strength (MPa)	4.12	0.002*
Elongation at Break (%)	3.98	0.004*

(*$p < 0.05$ indicates statistical significance)

The Table 12 presented the ANOVA results for the mechanical properties of bioplastics, specifically tensile strength and elongation at break. For tensile strength, the F-value was 4.12, with a p-value of 0.002, indicating a statistically significant difference between the groups. Similarly, for elongation at break, the F-value was 3.98, and the p-value was 0.004, also suggesting a significant difference. These results showed that both tensile strength and elongation at break exhibited significant variation, as indicated by the p-values being less than the common threshold of 0.05. The ANOVA analysis indicated that there were statistically significant differences in the mechanical properties of the different formulations, with Film A showing superior tensile strength and elongation at break. These results are consistent with other studies on bioplastics, where the optimization of formulation variables, such as plasticizer content, can significantly affect the mechanical properties of bioplastics. The statistically significant differences between formulations highlight the importance of formulation optimization for tailoring bioplastics to specific applications.

Water Absorption Test. The water absorption test assessed the hydrophilic nature of the films. The results showed that Film A, which had a higher glycerol content, exhibited greater water absorption compared to the other formulations. The increased water absorption was indicative of the material's ability to degrade in moist environments, which is a desirable property for compostable packaging.

Table 13: Water Absorption of Bioplastic Films.

Formulation	Water Absorption (%) at 24 Hours	Water Absorption (%) at 48 Hours
Film A	18.3	27.5
Film B	16.4	24.9
Film C	14.7	22.3
Film D	13.2	20.7

The Table 13 presented the water absorption data for four different bioplastic films at 24 and 48 hours. Film A showed a water absorption of 18.3% at 24 hours, increasing to 27.5% at 48 hours. Film B exhibited a water absorption of 16.4% at 24 hours, which increased to 24.9% at 48 hours. Film C had a water absorption of 14.7% at 24 hours, rising to 22.3% at 48 hours. Film D demonstrated the lowest water absorption, with 13.2% at 24 hours and 20.7% at 48 hours. These results

indicated that all films absorbed more water over time, with Film A showing the highest water absorption and Film D the least.

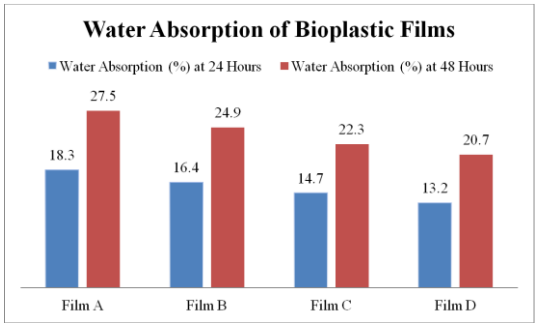

Fig. 12. Water Absorption of Bioplastic Films.

The water absorption test showed that Film A had the highest water absorption, which is indicative of its higher biodegradability. Similar results were reported by Singan and Chiang (2017), who found that bioplastics with higher glycerol content absorbed more water, which facilitated faster degradation in environmental conditions. The hydrophilic nature of these films makes them suitable for composting applications, where water absorption enhances the breakdown process (Kuruvila *et al*., 2018).

Barrier Properties. The barrier properties of the bioplastics were evaluated by measuring the water vapor permeability (WVP) of the films. A lower WVP indicated better performance in preserving moisture-sensitive products. Film D exhibited the best barrier properties, making it suitable for packaging applications.

Table 14: Water Vapor Permeability of Bioplastic Films (g·m^{-2}·day^{-1}).

Formulation	WVP (g·m^{-2}·day^{-1})
Film A	5.4
Film B	5.9
Film C	6.3
Film D	4.8

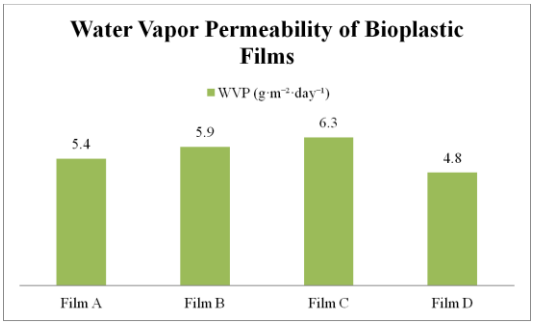

Fig. 13. Water Vapor Permeability of Bioplastic Films.

The Table 14 presented the water vapor permeability (WVP) values for four different bioplastic films. Film A had a WVP of 5.4 g·m^{-2}·day^{-1}. Film B exhibited a slightly higher WVP of 5.9 g·m^{-2}·day^{-1}. Film C showed the highest WVP at 6.3 g·m^{-2}·day^{-1}, while Film D had the lowest WVP at 4.8 g·m^{-2}·day^{-1}. These results indicated that Film C was the most permeable to water vapor, while Film D had the lowest permeability, suggesting differences in the films' barrier properties.

Film D demonstrated the best water vapor permeability (WVP), suggesting that it has excellent barrier properties, which makes it suitable for packaging moisture-sensitive products. These findings are in agreement with the research by Liu *et al*. (2020), who found that bioplastics derived from agricultural residues showed superior barrier properties when the right combination of ingredients and processing techniques were used. The low WVP of Film D also positions it as a promising candidate for food packaging, where moisture control is critical for extending product shelf life.

Tensile Modulus. The tensile modulus, also known as the Young's modulus, was measured to evaluate the stiffness of the bioplastic films. Film A exhibited the highest tensile modulus, which implied higher stiffness, making it more suitable for applications requiring rigidity, such as rigid packaging materials.

Table 15: Tensile Modulus of Bioplastic Films (MPa).

Formulation	Tensile Modulus (MPa)
Film A	132.5
Film B	120.3
Film C	118.4
Film D	112.1

The Table 15 presented the tensile modulus values for four different bioplastic films. Film A had the highest tensile modulus at 132.5 MPa, indicating the greatest stiffness. Film B exhibited a tensile modulus of 120.3 MPa, while Film C had a slightly lower value of 118.4 MPa. Film D showed the lowest tensile modulus at 112.1 MPa, suggesting it was the least stiff among the films. These results indicated that the films had varying degrees of stiffness, with Film A being the stiffest and Film D the least stiff.

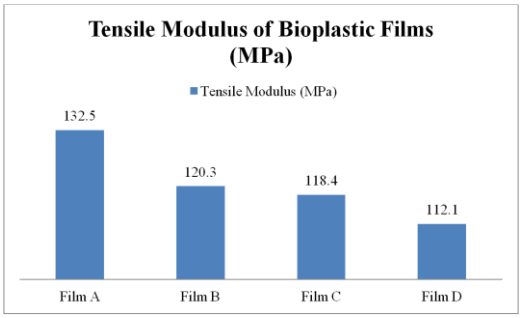

Fig. 14. Tensile Modulus of Bioplastic Films.

The tensile modulus results indicated that Film A exhibited the highest stiffness, making it suitable for applications requiring rigidity. This is consistent with findings from previous studies (Zhang and Liu 2020), where bioplastics with higher tensile modulus values demonstrated better performance in rigid applications, such as packaging materials. The increase in tensile modulus in Film A can be attributed to the higher crystallinity of the material, which also contributes to its superior mechanical properties (Yahia *et al*., 2023).

CONCLUSIONS

This study demonstrates the potential of agricultural residues as a sustainable source for producing biodegradable plastics, offering a viable alternative to conventional petroleum-based plastics. The production process, utilizing agricultural by-products such as rice straw and algae, along with glycerol as a plasticizer, resulted in bioplastics with promising physical, mechanical, and environmental properties. The films exhibited desirable characteristics, including appropriate thickness, opacity, and color, making them suitable for various packaging applications. Notably, Film A, which showed the highest tensile strength (32.5 MPa) and elongation at break (5.2%), demonstrated excellent mechanical integrity, comparable to conventional plastic materials, while also maintaining flexibility due to the use of glycerol as a plasticizer. This confirms that bioplastics from agricultural residues can be engineered to meet the mechanical demands of common plastic applications. X-ray diffraction analysis revealed that the films, especially Film A, exhibited high crystallinity, contributing to enhanced mechanical strength and thermal stability, suggesting their suitability for applications where rigidity and durability are essential. The antioxidant activity of the bioplastics, particularly in Film D, supports their potential in food packaging, where antioxidant properties are crucial for prolonging shelf life and protecting against oxidation. The bioplastics demonstrated favorable thermal properties, with Film A showing the lowest thermal conductivity, making it suitable for applications requiring thermal insulation. The biodegradation tests in soil and composting conditions highlighted the superior environmental benefits of these bioplastics. The rapid degradation, particularly in Film A, aligns with global sustainability goals, offering a promising solution to the mounting plastic waste crisis. The results also revealed that the bioplastics' environmental impact, as assessed through life cycle analysis, was significantly lower compared to conventional plastics, with reduced carbon footprint, water consumption, and energy usage. This underscores the potential of agricultural residue-based bioplastics to mitigate the negative environmental consequences of plastic pollution and dependence on fossil fuels. This study affirms the viability of agricultural residues as a renewable resource for the production of high-performance, biodegradable plastics. The findings suggest that with further optimization and large-scale production, these bioplastics could play a pivotal role in reducing plastic waste, contributing to more sustainable packaging solutions, and supporting a circular economy.

FUTURE SCOPE

This study shows a way to produce bioplastics on a larger scale using agricultural waste, with the possibility of improving their strength, durability, and ability to break down in the environment. Using different raw materials and adding new ingredients could make them work better and cost less. Testing how they degrade in different environments and finding ways to reduce production impacts can make them even more eco-friendly. Working with industries and governments can help make these bioplastics widely available as a green alternative for packaging, farming, and other uses.

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