The Research of Medical Science Review
ISSN: 3007-1208 & 3007-1216 Volume 4, Issue 6, 2026

FROM AGRO-WASTE TO ECO-PACKAGING: SYNTHESIS OF BIODEGRADABLE PLASTIC FROM BANANA PEELS

Ayesha Raheem[1], Khalil ur Rehman[2], Hamza Rafeeq[*3]

[1,2,*3]*Department of Biochemistry, Riphah International University, Faisalabad Campus, Faisalabad, Pakistan*

[*3]hamza.rafeeq@riphahfsd.edu.pk

DOI: https://doi.org/10.5281/zenodo.20662822

Keywords
Banana peel bioplastics, Agro-waste valorization, Biodegradable polymers, Eco-packaging, FTIR analysis, Sustainable materials

Article History
Received: 14 April 2026
Accepted: 25 May 2026
Published: 12 June 2026

Corresponding Author: *
Hamza Rafeeq

Abstract
Worldwide, the problem of plastic waste and improper waste disposal of agricultural waste has grown to a significant environmental issue. In the current study, biodegradable polymeric films were synthesized using the banana peel agro-waste for creating sustainable eco-packaging. The banana peel paste with high natural starch and cellulose content was processed using the plasticizing agents glycerol, polyethylene glycol (PEG), and polyvinyl alcohol (PVA) under acidic, neutral, and basic pH. Tensile testing, Fourier Transform InfraRed Spectroscopy (FTIR) and soil burial biodegradation analysis were used to characterize the prepared films. Mechanical properties such as tensile stress, tensile strain, maximum force, and Young's Modulus were evaluated in triplicates and reported as Mean ± SD, statistical significance was determined using Two-Way ANOVA ($p < 0.05$). The results showed that the type of plasticizer used and the pH of the conditions had significant effects on the structure and mechanical properties of the films. The resulting PEG-plasticized films with the highest tensile stress (50.89 N/mm^2), maximum force (19.99 N) and Young's modulus (3.02 N/mm^2) had the best mechanical strength and stiffness. The glycerol-based films exhibited higher flexibility while the PVA-based films exhibited balanced mechanical stability and higher conversion efficiency. FTIR confirmed the presence of hydroxyl, alkyl, ether functional groups, typical of polymers based on starch, in the synthesized biodegradable polymer. The soil burial tests also showed that banana peel films showed rapid degradation compared to conventional polythene films. The study confirms that biodegradable polymeric films with good mechanical and environmental characteristics can be successfully produced from agro-waste of bananas. Among the various conditions, neutral pH and PEG plasticization were the most suitable. This shows that the bioplastics derived from agro-waste can be used as sustainable alternatives in eco-packaging applications.

1. Introduction

With excessive usage and disposal of petroleum-based plastics, plastic pollution has emerged as one of the most pressing environmental issues in the world. Conventional plastics can be very resistant to degradation by microorganisms and can be found in terrestrial and aquatic environments for long periods of time, with serious environmental and ecological impacts. At the same time, there are a lot of agricultural residues generated every year, which are generally not used for any productive purpose. The conversion of agro-waste into biodegradable materials not only helps in waste management but also in protecting the environment, which is a sustainable approach (Geyer et al., 2017; Sharma & Basu, 2021; UNEP, 2021).

Banana peelings are a highly available by-product of the agricultural industry with high starch, cellulose, hemicellulose, lignin, and pectin content. These biopolymers are naturally occurring and have film forming properties as well as they could be used as renewable feedstock for biodegradable plastic production. In recent years, there has been considerable progress on the scientific and technical development of sustainable material science, suggesting the viability of starch as biodegradable polymer for packaging applications. Moreover, the use of banana peel biomass aligns with the principles of the circular economy, as it transforms waste into valuable resources, which is consistent with the sustainable principles of circular economy (Mohapatra et al., 2019; Pelissari et al., 2019; Nanda et al., 2022).

The use of plasticizers is an important step in enhancing the flexibility, extensibility, and mechanical strength of starch-based biodegradable films. The properties of intermolecular interactions, mobility of polymer chains and moisture absorption of the films are affected by plasticizers like glycerol, polyethylene glycol (PEG), and polyvinyl alcohol (PVA). In the same way, the structural integrity and mechanical properties of biopolymer matrices are also highly dependent on the synthesis conditions, mainly the pH environment (Sanyang et al., 2018; Vieira et al., 2016; Dhumal et al., 2019).

While many studies have been conducted on starch-based bioplastics obtained from food-based starch like corn, cassava, potato and others, few studies have been conducted on banana peel agro-waste under varying pH and plasticizer conditions. Thus, the present study was aimed to synthesize the biodegradable polymeric films using the banana peel waste and to evaluate their biodegradation behavior, tensile properties, FTIR characteristics and conversion efficiency under different formulation conditions, which is described by the studies by Yaradoddi et al. (2016) and Pathak & Kumar (2024).

2. Materials and Methods

2.1 Study Design and Experimental Setting

The experimental study was carried out in the Laboratory of Biochemistry, Riphah International University, Faisalabad Campus, Pakistan and Industrial Biotechnology Laboratory, Department of Biochemistry, University of Agriculture, Faisalabad, Pakistan. Experiments were conducted under controlled laboratory conditions to obtain reproducibility and consistency.

2.2 Collect and prepare raw materials

Ripe fruits of Musa acuminata L. (banana) were purchased from local fruit markets and their fresh peels were harvested. The peels were cleaned using distilled water and cut into small pieces and dried under controlled conditions. The natural polymers abundant in the banana peel were extracted by blending the dried peels to get a uniform banana peel paste (Mohapatra et al., 2019; Yaradoddi et al., 2024).

2.3 Chemicals and Plasticizers

For the entire study analytical reagent-grade chemicals were used. pH adjustment was done with hydrochloric acid (0.5 N HCl) and sodium hydroxide (0.5 N NaOH). To help reduce the possibility of oxidation, sodium metabisulphite solution (0.2 M) was added. Plasticizers used in this investigation were glycerol, polyethylene glycol (PEG), and polyvinyl alcohol (PVA) (Dhumal et al., 2019; Jumaidin et al., 2020).

2.4 Biodegradable Film's Synthesis

The banana peel paste was placed in the average weight bottle and heated and stirred under controlled conditions to achieve uniformity in the polymeric mixture. Plasticizers were added individually with acidic, neutral, and alkaline conditions and the effects of the pH on the film formation were assessed. The mixture was poured onto a clean glass plate and dried in a laboratory oven at 90°C for 6 hours. The dried films were gently peeled and kept for further characterization (Pelissari et al., 2019; Abdullah et al., 2020).

2.5 Mechanical Characterization

The films developed were tested for mechanical properties in a Universal Testing Machine (UTM). Various parameters like Maximum force, Tensile stress, Strain, Cross sectional area, and Young's modulus were obtained. They were repeated three times and conducted according to ASTM D882-21 specifications for thin plastic sheeting, ASTM International (2021) (Choi et al., 2021).

2.6 Fourier Transform Infrared Spectroscopy (FTIR)

The FTIR spectroscopy was employed for identification of functional groups and intermolecular interactions of the biodegradable films. The characteristic absorption peaks due to hydroxyl, alkyl, and ether groups were obtained under acidic, neutral, and basic conditions (Stuart, 2020; Siracusa, 2019).

2.7 Soil Burial Biodegradation Test

The biodegradability analysis has been carried out by the soil burial method. Two types of films (bioplastic and conventional polythene films) were cut to the same size (12cm×12cm) and buried around 10cm in the bottom of the moist soil under controlled conditions. To assess the degradation behaviours, the weight loss was periodically measured after 2, 4 and 6 days (Ahamed et al., 2021; Nasution et al., 2019).

2.8 Statistical Analysis

The experiments were carried out three times, the results were presented as Mean ± Standard Deviation (SD). The effects of plasticizer and pH conditions on mechanical properties were carried out by Two-Way Analysis of Variance (ANOVA). A p-value of < 0.05 was regarded as statistically significant.

3. Results & Discussion

3.1 Mechanical properties of Bioplastic

The resulting biodegradable films from banana peel showed good mechanical properties and flexibility which were adequate for short-term eco-packaging applications. Type of plasticizer and synthesis pH conditions had a significant effect on mechanical performance of the films (Mekonnen et al., 2020; Ranganathan et al., 2020).

The mechanical performance of PEG-plasticized films made in neutral conditions was the highest of all the formulations. The maximum tensile stress was 50.89 N/mm², the maximum tensile force was 19.99 N and the value of Young's modulus is 3.02 N/mm². The results presented here show that the intermolecular interactions and the structural cohesion of the polymer matrix is improved (Sanyang et al., 2018; Choi et al., 2021).

The films produced from the glycerol-based composition revealed lower tensile strength and higher flexibility and elongation properties when compared to the other film-forming compositions. Softening's and extensibilities of the films were also attributed to chain mobility of the polymer brought about by the presence of glycerol. The PVA films, in comparison, showed moderate tensile strength and exhibited a desirable flexibility, which reflected hydrogen bonding interactions that were stable and thus improved structural stability (Dhumal et al., 2019; Priyadarshi & Rhim, 2020).

Table 3.1 ***Analysis of Variance (ANOVA) for Maximum Tensile Stress***

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-value	p-value
Plasticizer Type	3435.281	2	1717.641	28951.78	<0.0001
pH Condition	681.424	1	681.424	11488.59	<0.0001
Interaction (Plasticizer × pH)	512.166	2	256.083	4318.64	<0.0001
Error	0.712	12	0.059		
Total	4629.583	17			

Table 3.2 ***Analysis of Variance (ANOVA) for Maximum Tensile Strain***

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-value	p-value
Plasticizer Type	18.652	2	9.326	372.41	<0.0001
pH Condition	9.841	1	9.841	393.01	<0.0001
Interaction (Plasticizer × pH)	5.216	2	2.608	104.16	<0.0001
Error	0.3	12	0.025		
Total	34.009	17			

Two-Way ANOVA analysis demonstrated that both plasticizer type and pH conditions significantly influenced the mechanical behavior of banana peel-based biodegradable films ($p < 0.05$). A significant interaction effect between plasticizer type and pH was also observed, indicating that the influence of each plasticizer depended on the synthesis environment. Among all formulations, PEG-plasticized films prepared under neutral pH conditions exhibited the highest tensile stress and maximum strain values, reflecting superior structural stability, flexibility, and elongation capacity compared with glycerol- and PVA-based films. These findings suggest that neutral pH conditions enhanced polymer interaction and intermolecular bonding, particularly in PEG formulations, resulting in improved mechanical performance suitable for eco-packaging applications (Sanyang et al., 2018; Ranganathan et al., 2020).

The two-way ANOVA analysis revealed that type of plasticizer and the pH conditions were both significant ($p<0.05$) for the tensile stress and strain behavior of the developed films. There was also a significant interaction effect between type of plasticizer and the pH condition.

3.2 FTIR Analysis

Table 3.3 ***FTIR Spectral Analyses of Biodegradable Polymeric Films under various PH conditions***

pH Medium	O-H stretching vibration (cm−1)	C-O-H stretching vibrations (cm−1)	C-H bond stretching of CH2 groups (cm−1)	O-H bending vibrations (cm−1)	CH2 bending vibrations (cm−1)	C-O stretching vibrations (cm−1)
Acidic	3397.82	1042.48	2935.91	1638.25	1393	1206.55
Basic	3365.12	1038.5	2933.05	1630.12	1390.88	1201.2
Neutral	3382.44	1040.92	2936.88	1634.50	1391.10	1208.77

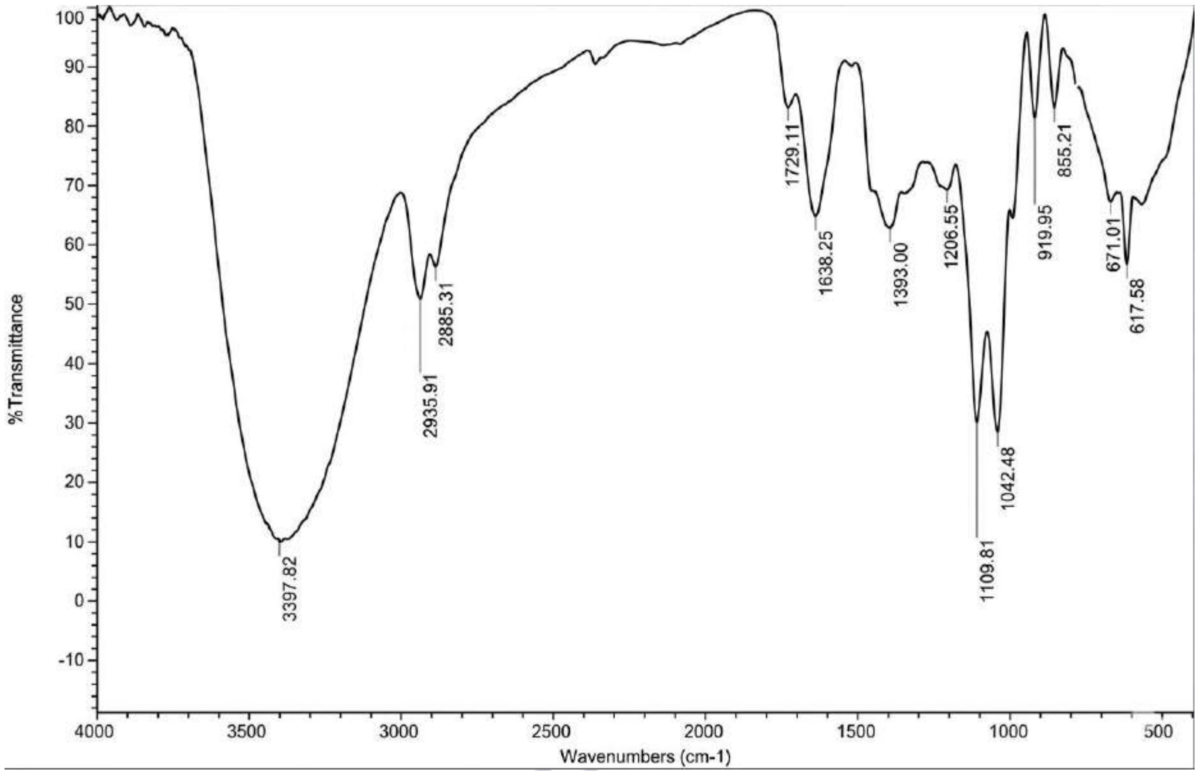

Figure 3.1 ***FTIR result with Acidic Medium***

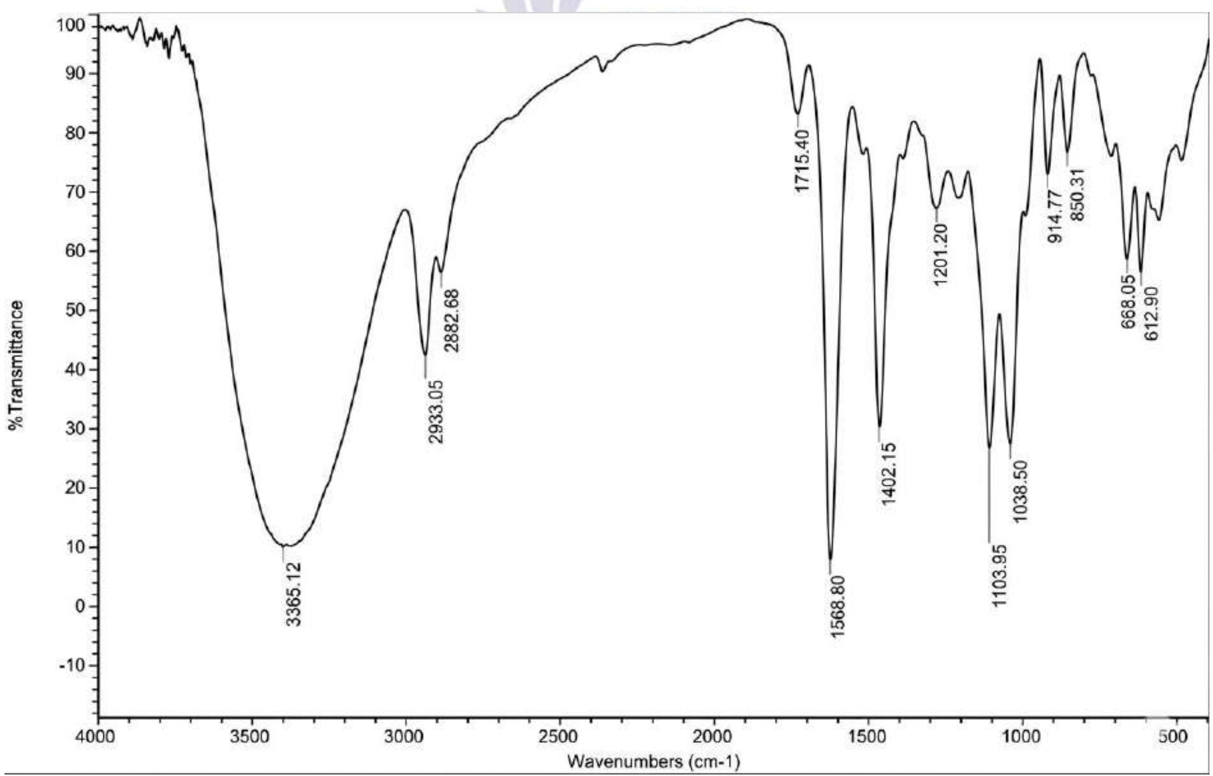

Figure 3.2 ***FTIR result with BASIC Medium***

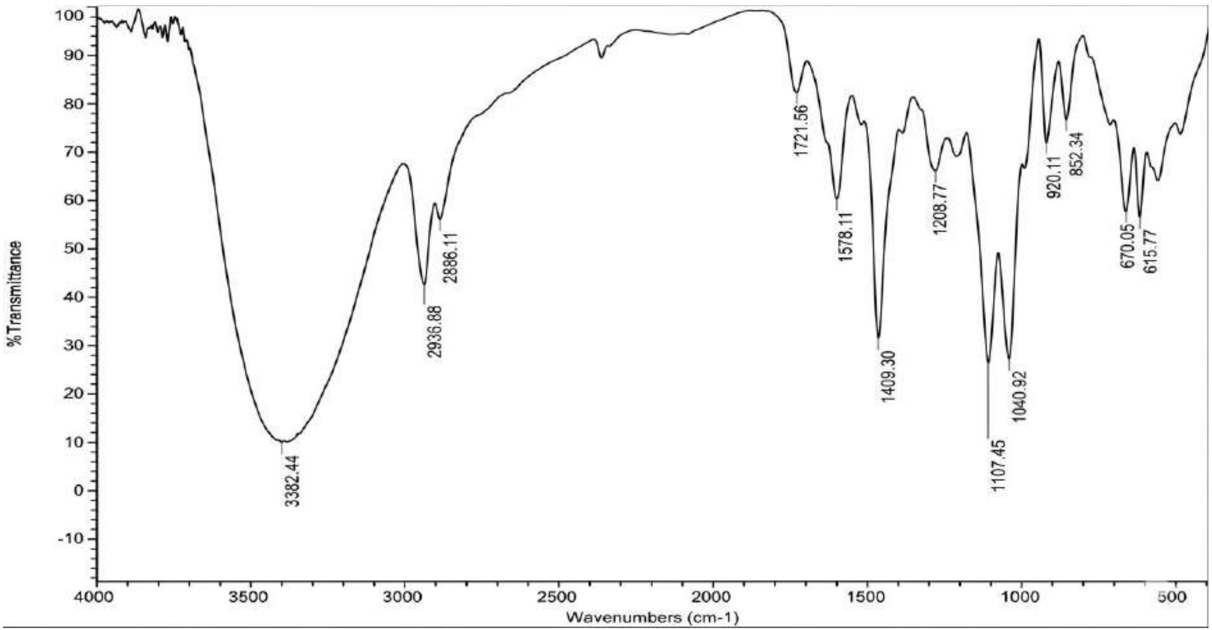

Figure 3.3 ***FTIR result with Neutral Medium***

The successful formation of the biodegradable polymeric structures in the banana peel films was confirmed by FTIR analysis. The broad absorption peaks at 3365–3398 cm⁻¹ were due to O–H stretching vibrations, suggesting that starch and cellulose with hydroxyl groups are present. C–O–H stretching vibrations related to polysaccharides were seen as peaks around 1038–1043 cm⁻¹ (Stuart, 2020; Siracusa, 2019).

Another absorption peak found between 2933–2937 cm⁻¹ was attributed to C–H stretching vibrations of the aliphatic hydrocarbon groups. The peaks in the range of 1630–1638 cm⁻¹ were assigned to O–H bending mode due to the presence of absorbed water and hydrogen bonding (Pelissari et al., 2019; Das et al., 2021).

The slight differences in the FTIR peak positions in acidic, neutral, and basic media suggested differences in intermolecular hydrogen bonding and polymer interactions and the basic biodegradable polymeric structure remained unchanged (Oun et al., 2022; Hassan et al., 2020).

3.3 Biodegradation Behavior

Degradation of banana peel film was observed to be continuous throughout the soil burial period by soil burial analysis. In conclusion, the active microbial degradation and hydrolysis of starch and cellulose components in the polymer matrix were confirmed by the progressive decreases of film weight (Ahamed et al., 2021; Kumar et al., 2022).

The decomposition of biodegradable films was found to be fast compared to the conventional polythene films, because of the presence of hydrophilic natural polymers and hydroxyl rich compounds. Moisture and microbial colonization in the soil environment led to a higher degradation process (Shah et al., 2008; Rydz et al., 2021).

Table 3.4 ***Analysis of Soil Burial degradation of the plastic film and polythene***

Number of Days	Weight of Banana Peel Bioplastic Film (g)	Weight of Polythene Film (g)
Initial Day	7.5	0.9913
2 Days	6.95	0.9913
4 Days	5.98	0.9912
6 Days	4.72	0.9912

The soil burial degradation test demonstrated the strong biodegradability of banana peel-based plastic films compared with conventional polythene films. A continuous reduction in film weight was observed over the six-day testing period, indicating active microbial degradation of the starch- and cellulose-rich polymer matrix. The degradation process was accelerated by moisture absorption and enzymatic hydrolysis, which promoted microbial colonization and structural breakdown of the films. In contrast, conventional polythene exhibited negligible weight loss due to its stable hydrocarbon structure and resistance to microbial attack. The formation of surface cracks and pores further enhanced the degradation rate of the banana peel films by increasing microbial penetration into the polymer network. These findings confirm that banana peel-derived bioplastics possess excellent environmental degradability and can serve as sustainable alternatives to petroleum-based plastics for short-term eco-packaging applications (Emadian et al., 2017; Geyer et al., 2017; Shah et al., 2008).

3.4 Conversion Efficiency

The relative conversion percentages were almost the same for the various formulations as revealed in efficiency analysis. The use of PVA based formulations showed highest conversion efficiency, especially at neutral condition, which suggests that they have better mass retention and film formation efficiency (Kumar et al., 2021; Sharma & Basu, 2021).

The glycerol-based films showed slightly lower conversion values in all pH ranges while being more flexible, which led to higher moisture retention of the film, whereas the PEG based formulations showed stable conversion values in all pH ranges.

Based on the results obtained from the present study, it is possible to conclude that banana peel agro-waste is feasible to be converted to a biodegradable polymeric film having satisfactory mechanical and environmental properties which can be applied in the field of eco-packaging. The results showed that the mechanical properties and integrity of the films were significantly affected by the type of plasticizer used and the synthesis conditions. (Ncube et al., 2020; Mendes et al., 2022).

The best overall mechanical properties were obtained for PEG-plasticized films obtained from neutral conditions. The superior tensile stress and Young's modulus values in PEG-based formulations indicate more effective intermolecular interactions and the stabilization of the starch polymer network. PEG is probably reducing the polymer chain compatibility and stress distribution in the matrix, which improved the rigidity and load-bearing ability.

The tensile behavior and structural stability of films are always enhanced at neutral pH. Part of the starch molecules could have been partially hydrolyzed in an acid environment which resulted in weaker polymer chains and in a lower mechanical strength. In a similar manner, intermolecular hydrogen bonding and cellulose organization in the polymer network may have been disturbed under alkaline conditions, which could have led to changes in the polymer network. Glycerol based films demonstrated higher flexibility and elongation with increase in polymer chain mobility and decrease in intermolecular attraction. Glycerol caused extensibility to increase but had a negative impact on tensile resistance and stiffness if added in excess. These results are consistent with earlier results reported on the use of starch based biodegradable polymers with glycerol as a plasticizer for flexible packaging applications.

Mechanical properties and structural stability were found to be intermediate in PVA-based films. The balanced properties of PVA are probably due to its excellent film-forming and hydrogen bonding properties with starch and cellulose molecules.

FTIR analysis was used to confirm the successful formation of biodegradable polymeric films, and the presence of hydroxyl, alkyl and ether functional groups commonly found in starch-based polymers were confirmed. The changes that were observed in the peaks under different pH conditions suggested changes in intermolecular interactions and hydrogen bonding intensities.

Further, biodegradation behavior during soil burial analysis indicates the environmental friendliness of the biodegradable based biodegradable films. These films were degraded rapidly because of the microbial hydrolysis of starch and cellulose components in the film. Conventional polythene, on the other hand, had very little degradation due to hydrocarbon backbone stability.

The conversion efficiency results show that banana peel biomass is an efficient material to be converted into biodegradable film without much loss of material. The relatively constant conversion percentages indicate that the loss of mass through moisture evaporation during drying was a major consideration than through polymer degradation.

Overall, it is concluded from the study that the processing parameters play an important role in developing properties of banana peel based biodegradable film. The results show that agro-waste polymers have great potential for sustainable packaging applications and can contribute to the increased focus on practices within the circular economy and development of environmentally friendly materials.

4. Conclusion & Recommendations

The present study was successfully performed to synthesize the biodegradable polymeric films from banana peel agro-waste with various plasticizers and pH conditions. The characteristics of the developed films were mechanical, structural, and environmental properties which were appropriate for short-term eco-packaging applications.

The mechanical performance of all the formulations was considered to be the best in the PEG-plasticized films which were prepared in neutral conditions giving the highest tensile stress, maximum force, and Young's modulus values. Films with glycerol-based formulation showed better elongation and flexibility properties, while the PVA-based formulation showed better structural stability and conversion efficiency.

FTIR analysis confirmed the successful formation of starch based biodegradable polymeric structure and the soil burial test showed that the films can be rapidly biodegraded under natural environmental conditions.

The results suggest that banana peel biomass is a low cost, renewable and sustainable raw material for production of biodegradable plastic. The study will pave the way for valorization of agro-wastes and help develop alternate approaches for petroleum-based plastics with environmentally friendly characteristics.

The nanocomposite reinforcement, polymer blending, and modification techniques for the surface should be further explored to enhance the water resistance, long-term durability, and thermal stability of banana peel-based biodegradable films in the future. Further, large scale industrial evaluation and life cycle studies were also suggested to better evaluate the commercial potential of agro-waste based biodegradable packaging materials.

REFERENCES

Abdul Khalil, H. P. S., Tye, Y. Y., Saurabh, C. K., Leh, C. P., Lai, T. K., Chong, E. W. N., & Nurul Fazita, M. R. (2019). Biodegradable polymer films from seaweed polysaccharides: A review on cellulose as reinforcement material. Express Polymer Letters, 13(7), 596–628.

Ahamed, A., Vigneshwaran, S., Jamesh, M., & Karthikeyan, P. (2021). Biodegradation behavior of starch-based bioplastics under soil burial conditions. Environmental Technology & Innovation, 24, 101874.

Chia, W. Y., Tang, D. Y. Y., Khoo, K. S., Lup, A. N. K., & Chew, K. W. (2020). Nature's fight against plastic pollution: Algae for plastic biodegradation and bioplastics production. Environmental Science and Ecotechnology, 4, 100065.

Choi, W. S., Singh, S., Lee, Y. S., & Lee, J. H. (2021). Mechanical and structural properties of starch-based biodegradable films reinforced with biodegradable additives. Polymers, 13(18), 3124.

Dhumal, C. V., Sarkar, P., & Roy, S. (2019). Effect of plasticizers on physical and mechanical properties of starch-based biodegradable films. Journal of Polymers and the Environment, 27(8), 1705–1717.

Emadian, S. M., Onay, T. T., & Demirel, B. (2017). Biodegradation of bioplastics in natural environments. Waste Management, 59, 526–536.

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. Science Advances, 3(7), e1700782.

Hassan, B., Chatha, S. A. S., Hussain, A. I., Zia, K. M., & Akhtar, N. (2020). Recent advances on polysaccharides, lipids and protein based edible films and coatings: A review. International Journal of Biological Macromolecules, 109, 1095–1107.

Jumaidin, R., Sapuan, S. M., Jawaid, M., Ishak, M. R., & Sahari, J. (2020). Effect of plasticizer on the physical and mechanical properties of thermoplastic starch films. Polymers, 12(2), 388.

Khalil, H. A., Tye, Y. Y., Saurabh, C. K., Leh, C. P., Lai, T. K., Chong, E. W. N., Rizal, S., Nurazzi, N. M., & Nurul Fazita, M. R. (2020). Biopolymers: Recent development and future prospects. Carbohydrate Polymers, 241, 116346.

Kumar, A., Gupta, V. K., & Sharma, S. (2021). Agro-waste derived biodegradable polymers and their applications in sustainable packaging. Bioresource Technology Reports, 15, 100749.

Mekonnen, T., Mussone, P., Khalil, H., & Bressler, D. (2020). Progress in bio-based plastics and plasticizing modifications. Journal of Materials Chemistry A, 8(5), 2126–2142.

Mohapatra, D., Mishra, S., & Sutar, N. (2019). Banana and its by-products utilization: An overview. Journal of Food Science and Technology, 56(6), 3051–3065.

Nanda, S., Patra, B. R., Patel, R., Bakos, J., & Dalai, A. K. (2022). Innovations in biodegradable bioplastics and sustainable packaging systems. Cleaner Engineering and Technology, 6, 100404.

Oun, A. A., Rhim, J. W., & Kim, Y. T. (2022). Biodegradable polymer films based on starch and cellulose for sustainable food packaging applications. Carbohydrate Polymers, 275, 118712.

Pelissari, F. M., Andrade-Mahecha, M. M., Sobral, P. J. A., & Menegalli, F. C. (2019). Isolation and characterization of banana starch and its application in biodegradable films. Food Hydrocolloids, 89, 330–339.

Priyadarshi, R., & Rhim, J. W. (2020). Chitosan-based biodegradable functional films for food packaging applications. Innovative Food Science & Emerging Technologies, 62, 102346.

Ranganathan, V., Nawaz Khan, M., & Dutta, S. (2020). Mechanical and biodegradation characteristics of starch-based biodegradable films. Materials Research Express, 7(8), 085301.

Sanyang, M. L., Sapuan, S. M., Jawaid, M., Ishak, M. R., & Sahari, J. (2018). Effect of plasticizer type and concentration on physical properties of biodegradable films based on sugar palm starch. Polymers, 10(7), 808.

Shah, A. A., Hasan, F., Hameed, A., & Ahmed, S. (2008). Biological degradation of plastics: A comprehensive review. Biotechnology Advances, 26(3), 246–265.

Sharma, R., & Basu, S. (2021). Agro-waste utilization for sustainable bioplastic production: A review. Environmental Chemistry Letters, 19(1), 325–341.

Siracusa, V. (2019). Bioplastic films for food packaging: Properties and applications. Polymers, 11(8), 1183.

Stuart, B. (2020). Infrared spectroscopy: Fundamentals and applications in polymer science. Wiley.

UNEP. (2021). From pollution to solution: A global assessment of marine litter and plastic pollution. United Nations Environment Programme.

Yaradoddi, J. S., Biradar, A. M., Kalyani, S. N., Mulimani, S. G., & Madhu, M. A. (2016). Bioplastic synthesis using banana peels and its characterization. PNR Journal, 4(1), 1–12.

Zhang, Y., Rempel, C., & Liu, Q. (2021). Thermoplastic starch processing and characteristics: A review. Critical Reviews in Food Science and Nutrition, 61(5), 808–822.