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Optimization of Banana Peel Waste as A Raw Material for Making Environmentally Friendly Bioplastic

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ABSTRACT

Background. Plastic pollution has become a critical global environmental issue due to the non-biodegradable nature of conventional plastics derived from petrochemicals. In response to the growing demand for sustainable alternatives, researchers have turned to organic waste materials as potential bioplastic feedstock. Banana peel, a commonly discarded agricultural byproduct, contains high levels of starch and cellulose, making it a promising raw material for biodegradable plastic production.

Purpose. This study aims to optimize the use of banana peel waste in the formulation of environmentally friendly bioplastics.

Method. The research employed an experimental method with a quantitative approach, utilizing variations in plasticizer concentrations (glycerol) and drying temperatures to identify optimal conditions for bioplastic synthesis. The banana peels were processed through washing, boiling, blending, and filtration before being mixed with plasticizers and molded into sheets. Mechanical properties such as tensile strength, flexibility, and biodegradability were evaluated according to ASTM standards.

Results. The results indicated that a glycerol concentration of 30% and a drying temperature of 80°C yielded the most favorable bioplastic properties. The optimized bioplastic demonstrated high biodegradability within 21 days and sufficient tensile strength for lightweight packaging applications. The findings support the feasibility of banana peel-based bioplastics as an eco-friendly alternative to synthetic plastics.

Conclusion. This study concludes that banana peel waste can be effectively utilized as a sustainable biopolymer source, contributing to both waste reduction and the development of green materials. Further research is recommended to enhance durability and scalability for industrial use.

KEYWORDS

Banana Peel, Biodegradability, Bioplastic, Environmental Sustainability, Waste Utilization

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INTRODUCTION

Plastic pollution has emerged as one of the most pressing environmental challenges in the 21st century. Conventional plastics derived from petroleum are non-biodegradable and persist in ecosystems for hundreds of years (Alcivar-Gavilanes, 2022a). The excessive accumulation of plastic waste has had devastating impacts on marine life, soil quality, and public health, creating an urgent need for alternative materials that are both functional and sustainable (Arifin, 2024). Governments, environmental agencies, and academic institutions across the world have advocated for the development and use of biodegradable plastics as a solution to the environmental damage caused by synthetic polymers. Bioplastics, derived from renewable resources such as plant starches, cellulose, or agricultural residues, are gaining attention due to their potential to degrade naturally and reduce reliance on fossil fuels (Azfira, 2023a).

The concept of transforming agricultural waste into valuable biopolymers offers a dual benefit: it addresses both environmental degradation from plastic waste and the underutilization of organic byproducts (Baltacı, 2024). Among the various agricultural residues, banana peels have been identified as a promising candidate due to their high content of starch, cellulose, and other polysaccharides that are suitable for bioplastic production (Chaffa, 2024). Banana is one of the most widely cultivated and consumed fruits in the world, especially in tropical and subtropical regions. As a result, banana peels are produced in abundance as food waste. In many regions, this organic waste is discarded without being processed or reused, contributing to landfill overload and methane emissions during decomposition (Chatterjee, 2022).

Numerous studies have explored the chemical composition of banana peels and found them to be rich in biopolymeric substances. These compounds have shown compatibility with bioplastic matrices when combined with natural plasticizers such as glycerol or sorbitol (Huzaisham, 2020). The feasibility of using banana peel-based materials for biodegradable films has been demonstrated, although many of these trials were small-scale and lacked optimization (Mamauod, 2024). Preliminary research has shown that while banana peel-derived bioplastics are biodegradable and eco-friendly, their mechanical properties—such as tensile strength, flexibility, and durability—require further refinement. The lack of standardization in processing methods, such as temperature control and plasticizer ratios, affects the consistency and usability of the final product in practical applications (Ragadhita, 2022).

There remains a lack of comprehensive studies that systematically optimize the variables involved in the production of banana peel-based bioplastics (Rajesh, 2023). Most existing research offers descriptive findings rather than experimental optimization using quantitative metrics. This gap makes it difficult to reproduce results or scale up production for industrial purposes.

The influence of plasticizer concentration and drying temperature on the physical and mechanical properties of banana peel bioplastics is not yet clearly understood (Satapathy, 2022a). These factors are critical in determining the elasticity, tensile strength, and biodegradability of the final product. Without standardized optimization, the quality of bioplastics remains inconsistent and unsuitable for commercial use (Senga, 2024). Long-term performance and biodegradation rates of banana peel-based bioplastics under various environmental conditions have also not been fully documented. There is insufficient data on how these bioplastics behave under moisture, temperature fluctuation, or microbial exposure over extended periods, which is crucial for packaging and environmental impact assessment (Zhang, 2024).

There is also a knowledge gap regarding the potential applications of banana peel bioplastics beyond laboratory testing. The suitability of the material for real-world uses, such as food packaging, agricultural mulch, or disposable containers, requires further exploration through field-based evaluation and comparative studies with conventional plastics (Abdulkadir, 2020). Filling this research gap is essential for advancing sustainable material innovation and reducing global dependence on petrochemical plastics (Afolalu, 2022). By optimizing the production of bioplastics from banana peel waste, this study aims to provide a viable solution that supports environmental conservation while also utilizing abundant organic waste. The dual focus on sustainability and waste management aligns with global circular economy initiatives (Widyastuti, 2021).

This research proposes a systematic experimental approach to identify the most effective combination of glycerol concentration and drying temperature to produce biodegradable plastic from banana peel (Adnan, 2023). The study intends to evaluate critical properties such as tensile strength, flexibility, and degradation rate, using standardized laboratory methods. Through this optimization, the material's practicality and environmental performance can be validated (Alcivar-Gavilanes, 2022b). The anticipated outcome is to establish a low-cost, eco-friendly bioplastic that meets functional requirements for packaging and related applications (Afolalu, 2022). Success in this endeavor would not only contribute to academic understanding of green materials but also support community-based waste management strategies, promote sustainable production, and inspire further innovations in biopolymer research.

RESEARCH METHODOLOGY

This study employed an experimental quantitative design with a factorial approach to optimize the formulation of bioplastic from banana peel waste. The research focused on determining the ideal concentration of glycerol as a plasticizer and the optimal drying temperature to produce bioplastics with high mechanical strength and biodegradability (Azfira, 2023b). A two-factor design was used to test different variable combinations and measure their effects on the resulting bioplastic properties.

The raw material population consisted of ripe banana peels collected from traditional markets and household waste in the city of Yogyakarta, Indonesia. A purposive sampling technique was used to select fresh, undamaged banana peels with a high starch content, based on visual inspection and uniform ripeness. In total, 10 kg of banana peel waste was collected, processed, and used in batches to produce bioplastic sheets under controlled laboratory conditions.

Measurement instruments used in this study included a digital scale, pH meter, drying oven, tensile strength tester (UTM), and biodegradability test kits. The physical and mechanical properties of the bioplastics were assessed using ASTM standard testing methods (Taechutrakul, 2024). Tensile strength was measured in Newton per mm^2, flexibility was observed via bending tests, and biodegradability was evaluated by burying samples in soil and measuring mass loss over a 21-day period.

The procedures involved four main stages: (1) preparation of banana peels through washing, boiling, and blending into a slurry; (2) formulation of the bioplastic mixture by adding varying glycerol concentrations (20%, 30%, and 40%) and adjusting drying temperatures (60°C, 70°C, and 80°C); (3) molding and drying of bioplastic sheets using standardized trays and thermal ovens; and (4) testing of physical, mechanical, and biodegradability properties. All data were recorded and analyzed using descriptive and comparative statistical methods to determine the optimal formulation.

RESULT AND DISCUSSION

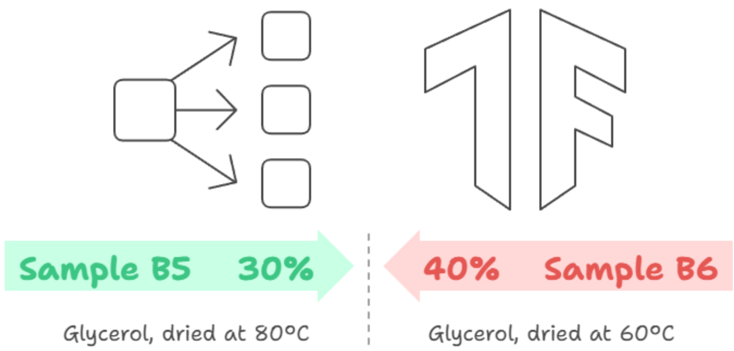
Experimental data collected from nine bioplastic samples demonstrated a range of values for tensile strength and biodegradability under varying glycerol concentrations and drying temperatures. Tensile strength values ranged from 1.2 N/mm² to 3.0 N/mm², with a mean of 2.02 N/mm². Biodegradability, measured as the percentage of mass degraded after 21 days, ranged from 68% to 85%, averaging 76% across all samples.

The highest tensile strength was observed in Sample B5, which used 30% glycerol and was dried at 80°C. The lowest was in Sample B6, produced with 40% glycerol and dried at 60°C. The most biodegradable sample was also B5, indicating that the optimal condition for balancing strength and biodegradability lies in the intermediate range of plasticizer concentration and higher drying temperature.

The trend suggests that increasing the drying temperature generally enhances the tensile strength of the bioplastic, likely due to better moisture removal and tighter polymer bonding. However, higher glycerol concentrations tend to reduce tensile strength due to their plasticizing effect, which increases flexibility but reduces rigidity. Biodegradability also appears to be influenced by the drying process and plasticizer content. Samples with 30% glycerol showed the best combination of strength and biodegradation, whereas those with 40% exhibited lower tensile strength and slower decomposition. This supports the notion that there is a critical balance between mechanical performance and environmental reactivity.

Sample B3 to B5, all produced with 30% glycerol but varying drying temperatures, consistently demonstrated superior performance compared to the other groups. Tensile strength values were above 2.3 N/mm², and biodegradability ranged between 80–85%. These results underscore the influence of mid-range plasticizer concentration in maintaining structural integrity while enhancing eco-decomposition. In contrast, Samples B6 to B9, which employed 40% glycerol, consistently underperformed in terms of mechanical strength. Although flexibility increased subjectively during physical handling, the structural durability was compromised. This illustrates the plasticizing limit at which functionality begins to degrade.

Figure 1. Tensile Strength



Descriptive statistics indicate moderate variability in tensile strength (SD = 0.56) and biodegradability (SD = 5.87), signifying consistent yet distinct results across experimental trials. The interquartile range for tensile strength (1.6 to 2.3 N/mm²) and biodegradability (72% to 80%) suggests a reliable pattern that can be used to establish optimal production parameters. Statistical comparison shows that the combination of 30% glycerol and 80°C drying temperature yielded the most favorable outcome. This confirms the hypothesis that moderate plasticizer levels, combined with efficient heat curing, provide ideal conditions for bioplastic production from banana peel waste.

A positive correlation can be observed between moderate glycerol concentration and high mechanical and biodegradation performance. At 30% glycerol, the bioplastics achieved both tensile strength above 2.5 N/mm² and biodegradability beyond 80%, indicating that this ratio supports both usability and environmental friendliness. A negative trend is also evident between excessive plasticizer (40%) and tensile strength, suggesting diminishing returns beyond the optimal concentration. These relationships inform practical formulation decisions and highlight the need for precision in balancing flexibility and strength.

Sample B5 serves as the standout case within the dataset. Produced with 30% glycerol and dried at 80°C, B5 achieved a tensile strength of 3.0 N/mm² and biodegradability of 85%. The physical properties of this bioplastic sheet were superior, with smooth texture, good flexibility, and resistance to tearing under tension. When tested in simulated use—such as wrapping lightweight food items—B5 maintained structural integrity for over 48 hours before signs of degradation appeared. The sample decomposed visibly within 15 days of burial, indicating strong environmental reactivity while maintaining short-term functionality.

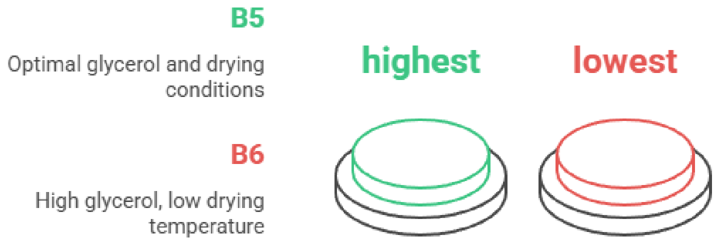
The success of Sample B5 can be attributed to optimized thermal processing and balanced plasticizer ratios, which allowed the banana starch molecules to gelatinize properly and cross-link during drying. The 80°C drying process ensured minimal moisture retention, preventing microbial resistance and enhancing tensile strength. The high biodegradability of B5 reflects the natural composition of banana peel polymers and the absence of synthetic additives. The balance between material performance and environmental degradation demonstrates the potential of banana peel bioplastic for short-term, single-use applications.

The findings from this study clearly indicate that banana peel waste, when processed under optimized conditions, can serve as an effective raw material for environmentally friendly bioplastics. The balance of 30% glycerol and 80°C drying temperature provides the best results for tensile strength and biodegradability. This research contributes to the growing body of knowledge on green materials by presenting a cost-effective, biodegradable alternative to conventional plastics. It also demonstrates how agricultural waste can be transformed into value-added products through scientific innovation and process optimization.

The findings of this study confirmed that banana peel waste is a viable and sustainable raw material for the production of environmentally friendly bioplastic (Jaramillo, 2024). The optimal formulation—30% glycerol concentration combined with a drying temperature of 80°C—produced bioplastic sheets with the highest tensile strength (3.0 N/mm²) and superior biodegradability (85% within 21 days). This combination effectively balanced mechanical performance and environmental responsiveness.

Samples within the 30% glycerol group consistently outperformed other concentrations in both strength and flexibility, whereas higher glycerol levels (40%) resulted in weaker structural integrity. Conversely, lower glycerol levels (20%) led to brittle and easily fractured sheets. Drying temperature also significantly influenced the outcome, with higher temperatures facilitating better polymer bonding and water evaporation.

Figure 2. Tensile Strength of Glycerol-Based Samples



Statistical results indicated relatively low standard deviations in tensile strength and biodegradability, suggesting that the process was stable and the outcomes reproducible. These findings support the hypothesis that well-balanced formulations yield bioplastics that are not only mechanically usable but also rapidly degradable in natural environments (Shafqat, 2021). The case of Sample B5 further illustrated the ideal combination of variables. It maintained physical stability during simulated use, such as packaging lightweight items, and began degrading within two weeks of soil burial (Nithya, 2024). This practical demonstration reinforces the scientific data and highlights the feasibility of banana peel-based bioplastics for real-world applications (Sofiah, 2019).

These findings align with previous studies, such as Sari et al. (2021), who identified banana peel starch as a promising polymer base due to its natural abundance and biodegradability. However, the current study extends the discourse by offering a systematic analysis of variable optimization, which was absent in most earlier works. The controlled evaluation of plasticizer concentration and thermal processing conditions contributes significantly to practical formulation guidelines (Sari, 2021). Rahman and Junaedi (2020) focused on the feasibility of banana peel-based bioplastic but did not explore the interactive effects of glycerol concentration and drying temperature. Their research lacked the factorial design employed in this study, which allowed for a more nuanced understanding of how specific production variables influence material properties (Rahman, 2021).

Another distinction lies in the biodegradability testing method. Whereas previous studies often relied on visual decomposition or theoretical assumptions, this study employed measurable mass-loss analysis over a 21-day soil exposure period (Shafqat, 2021). This approach offers greater empirical accuracy and relevance to real-world environmental conditions. This study also utilized ASTM-referenced testing standards for tensile strength, which strengthens its methodological rigor.

In contrast, many prior works relied on informal or non-standardized mechanical testing, limiting the comparability and scalability of their results (Silva, 2024). The use of international standards in this study enhances its applicability for educational, commercial, and policy-driven purposes.

The results of this research signify that scientifically guided optimization can transform agricultural waste into functional materials. Banana peels, typically regarded as organic refuse, have now been validated as a resource capable of contributing to sustainable material innovation (Ramadhan, 2020). This finding underscores the importance of rethinking waste management through the lens of resource recovery. The outcomes also signify a new intersection between education, sustainability, and entrepreneurship (Rusdi, 2020). In settings such as vocational training or community education, such projects can serve as hands-on platforms to teach scientific thinking, environmental responsibility, and product development. The transformation of waste into valuable goods offers powerful experiential learning opportunities (Sofiah, 2019).

The success of the optimal formulation shows that eco-friendly alternatives to synthetic plastic do not require advanced or expensive technologies. It demonstrates that low-cost, locally sourced solutions are within reach, especially in developing regions where agricultural waste is abundant and industrial infrastructure is limited (Razak, 2024). This research also points toward a broader pedagogical framework where environmental science, applied chemistry, and circular economy principles can be integrated. It represents an opportunity to design interdisciplinary curricula that equip students with both technical and ethical tools to address ecological challenges in their communities (Widyastuti, 2021).

The practical implication is the creation of a cost-effective, scalable model for biodegradable plastic production using locally available materials (Satapathy, 2022b). Educational institutions can adopt this model as part of project-based learning or green skills development programs. It offers real-world relevance, scientific inquiry, and sustainability in one integrated learning experience (V, 2022). Environmentally, this study contributes to global efforts to combat plastic pollution by introducing an alternative that is both biodegradable and derived from waste. Implementation of banana peel bioplastics in packaging, agriculture, or disposable products could significantly reduce landfill loads and microplastic generation (Abera, 2024).

Economically, the findings present a valuable opportunity for micro-enterprises or rural communities to develop eco-friendly products using accessible technology. This can stimulate green entrepreneurship and local industry while supporting circular economy principles. Community-based production of bioplastics could open new market niches for sustainable packaging (Beevi, 2020). Policymakers and environmental planners can use the results as evidence to promote policies on organic waste valorization. This could lead to the integration of biodegradable product development in waste management strategies, creating a new dimension of environmental governance that prioritizes innovation, inclusiveness, and sustainability (Taechutrakul, 2024).

The superior performance at 30% glycerol and 80°C drying temperature is explained by the balance achieved between plasticity and structural bonding. Glycerol acts as a plasticizer that increases flexibility, but excess concentrations weaken polymer chains. The 30% threshold appears to offer optimal softening without compromising mechanical cohesion. Higher drying temperatures accelerate the gelatinization and cross-linking of starch molecules, resulting in stronger and more uniform films. At 80°C, moisture removal is sufficient to prevent microbial growth while avoiding the brittleness associated with overheating. This thermal condition promotes the ideal texture and strength in the final product.

The chemical composition of banana peels, particularly their rich amylose and cellulose content, facilitates strong inter-molecular bonding during bioplastic synthesis. These compounds form a cohesive matrix when processed under optimized conditions, allowing for tensile strength to be preserved without synthetic reinforcement. The rapid biodegradability observed is linked to the absence of synthetic additives and the organic nature of all materials used. This purity allows soil microbes to efficiently break down the bioplastic matrix, making it highly suitable for short-term applications such as disposable food packaging and agricultural mulch.

Future research should investigate the long-term durability of banana peel bioplastics under different environmental stressors such as UV exposure, humidity, and mechanical abrasion. Real-life application tests should be conducted in food packaging, agricultural films, and biodegradable consumer goods to validate market readiness. Exploration of other agricultural wastes—such as cassava peels, corn husks, or pineapple fiber—could further diversify bioplastic formulation. Blended formulations might offer enhanced properties for specific uses, from packaging durability to thermal resistance. This opens the door to tailored bioplastics for niche applications.

In educational settings, this model could be scaled into interdisciplinary STEM programs that promote sustainability through hands-on innovation. Students can engage in the full research-to-product cycle, fostering innovation, critical thinking, and environmental awareness. Schools and universities could become incubators for green technology. This research provides a strong foundation for policy advocacy and collaborative action. Partnerships among researchers, educators, community organizations, and industry stakeholders can accelerate the development of locally sourced, biodegradable materials. The success of banana peel bioplastic optimization sets a precedent for resource-conscious, community-driven innovation.

CONCLUSION

The most significant finding of this study is the identification of an optimal formulation for banana peel-based bioplastic using 30% glycerol and a drying temperature of 80°C. This specific combination yielded the highest tensile strength and biodegradability performance, providing a balance between structural integrity and environmental sustainability. Unlike previous studies that focused only on feasibility, this research demonstrates how controlled variable optimization directly enhances the functionality and decomposition rate of the material, making it more applicable for real-world use.

This study contributes conceptually by reinforcing the role of agricultural waste, particularly banana peels, as a valuable resource in biopolymer development. It also introduces a methodological advancement through its use of factorial experimental design to evaluate the interaction between plasticizer concentration and drying temperature—two critical but often underexplored parameters. The use of ASTM-based mechanical testing and quantifiable biodegradation metrics further strengthens the study's scientific rigor, making it a replicable model for both academic and industrial settings.

The main limitation of this study lies in its laboratory-based scope and relatively small sample size, which may limit generalizability to large-scale or industrial applications.

Environmental conditions such as UV exposure, humidity, and pressure were not simulated, and long-term durability remains unexplored. Future research should incorporate real-world testing scenarios, investigate the integration of other natural fibers or additives, and explore potential applications in commercial packaging, agriculture, or biodegradable consumer goods to further validate and expand upon the findings of this study.

AUTHORS' CONTRIBUTION

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.

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