# Sustainable Biopolymer Composites from Banana Pseudostem Cellulose: Integrating Natural Plasticizers and Antimicrobial Agents for Eco-friendly E-commerce Packaging

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## Abstract

The large-scale growth of global e-commerce has created a huge increase in the need for light weight packaging products made of plastic materials, primarily flexible packaging films and mailer bags; however, almost all of the materials used to produce these items are made from petroleum-based polymers and have very low recycling rates. Therefore, many of these packaging materials contribute to significant environmental problems including landfills and ocean pollution. As a result, it is necessary to create biodegradable and renewable alternatives for packaging materials. Banana pseudostems (BPS) represent a rich source of cellulose, which can be extracted from agricultural residues that are produced after bananas are harvested. These residues are extremely abundant and therefore offer a viable source of raw materials for sustainable product development. In this study, we present a sustainability-focused process for creating biopolymer composite films from cellulose found in banana pseudostem. We also include natural plasticizers and antimicrobial additives to increase the mechanical flexibility, functionality and shelf life of the films. Our methodology for conducting this research included creating a banana pseudostem powder, treating the fibers with alkaline and hydrogen peroxide bleach to clean the fibers and then making the composite films using natural plasticizers such as glycerin and starch. Additionally, we incorporated citrus-derived bioactive compounds into the films. To help optimize the composition of the films and assess their environmental impact, we developed a formulation design matrix and a sustainability assessment framework. Preliminary analytical models indicate that the amount of glycerin added to the film will greatly affect its flexibility, while starch improved film forming, but caused an increase in moisture sensitivity. Overall, this study illustrates the potential of BPS-based composites as eco-friendly alternatives to traditional plastic packaging products and demonstrates how a circular bio-economy approach may be used to develop new, sustainable materials in materials science.

## 1. Introduction

### 1.1 Global Packaging Waste Challenge

Flexible plastic films have become an inexpensive and durable product that is often used for mailer packaging, wrapping materials, and cushioning materials. Flexible plastic films were developed to be low-cost, light-weight, and durable. A major component of flexible plastic film products are produced using petroleum based polymers like polyethylene and polypropylene. Flexible plastic films made with petroleum based polymers have been shown to be very resistant to degradation and therefore remain in the environment for long time periods (OECD, 2022)

Biodegradable and renewable packaging materials are becoming more popular as ways to improve the sustainability of packaging and to eliminate much of the harmful effects associated with plastic packaging waste. According to recent research, billions of pounds of plastic packaging waste is produced each year through e-commerce activities alone; however, current recycling practices have a long way to go to meet the amount of packaging created (Rigamonti et al., 2014). Plastic waste in landfills and marine environments has become an international environmental problem. Therefore, both researchers and policymakers are focusing on developing sustainable and environmentally friendly packaging products that provide similar functionality to traditional packaging materials but produce less pollution (Geyer et al., 2017).

### 1.2 Biopolymer-Based Packaging Materials

Bioplastics made from renewable organic biomass are a growing alternative to traditional plastics. Cellulose, starch, chitosan and protein based natural biopolymers have shown a lot of promise for use as biodegradable packaging due to their biocompatible nature and renewability (Helanto et al., 2019). Of all the natural biopolymers cellulose is especially appealing due to its availability, mechanical properties and biodegradability.

Despite being so appealing, cellulose is also very brittle and does not have enough flexural properties to be successfully formulated into film using common processing techniques. As a result, plasticizers and other functional additives are often added to cellulose composites to improve both the mechanical performance and usability of the material (Fang et al., 2002).

### 1.3 Banana Pseudostem as a Sustainable Raw Material

The large amounts of agricultural residue that result from banana production can be used to develop new sustainable materials by utilizing the banana plant's pseudostem material. The pseudostem is a source of cellulose, as well as other components such as hemicellulose and lignin. According to Sangarote et al. (2025), banana pseudostem contains about 55-65% cellulose, and therefore represents an opportunity to utilize the banana pseudostem for creating sustainable materials.

In recent years, there has been increasing interest in the development of cellulose fibers from banana pseudostems for use in biodegradable composite materials and packaging products (Duhovic et al., 2012). However, much less research has focused on the addition of natural plasticizers or antimicrobial agents into these types of materials.

### 1.4 Research Objectives

The primary purpose of this research is to develop a sustainable-based system for developing composite films with biodegradable properties by utilizing cellulose derived from banana pseudostems. Additionally, there are five specific goals:

1. Develop a cellulose extraction process that is optimized from banana pseudostem biomass.
2. Develop various composite film formulations incorporating natural plasticizers such as starch and glycerol.
3. Incorporate citrus derived bioactive compounds in order to impart antimicrobial functionality to the composite films.
4. Develop a sustainability evaluation process to assess the environmental effects.

5. Examine the conceptual relationship(s) between the formulation parameters (in terms of composition and/or structure) and the physical/chemical properties of the final product.

## 2. Materials and Methodology

### 2.1 Research Framework

The research methodology for this project is organized in a sequence of steps as follows: The first step is to select an appropriate agro-waste and develop it into a composite film. Following that, there are several other steps; such as: pretreatment of banana pseudostem (the raw materials), purification of cellulose from the banana pseudostem, composite film design, development of the composite films and finally performance evaluation of the composite films. A structured approach allows us to systematically investigate the relationship between material composition, mechanical properties, and sustainability indicator.

### 2.2 Preparation of Banana Pseudostem Powder

A fresh banana pseudostem was sourced from an agriculture outlet and subsequently treated as a fibrous product. First the pseudostem was cleaned of dirt and impurities on the outside through a water wash. Once the wash was completed the pseudostem material was air-dried to lower the moisture content of the pseudostem. After drying the pseudostem into smaller pieces the pseudostem pieces were milled (ground) using a commercial mixer grinder to create a finely powdered form of the fibrous material. The final step was to sieve the powdered material to provide a uniform particle size that would be needed prior to being chemically treated.

### 2.3 Chemical Treatment and Fiber Purification

Alkaline treatment is conducted on the banana pseudostem powder with the goal of removing impurities and increasing the purity of the cellulose. In this first step, approximately 3 grams of the powder are treated in distilled water using a NaOH (Sodium Hydroxide) solution which has been diluted. The mixture is then heated at a temperature of approximately 60°C for 30 minutes. This process removes lignin, hemicellulose, wax and colorants that may be contained within the biomass.

After alkaline treatment has taken place, hydrogen peroxide bleaching is then used as a method to further purify the fibers and remove any remaining pigments. The treated materials are then treated with distilled water and hydrogen peroxide. The materials are then heated gently at 60°C while being stirred. Following this treatment the fibers are filtered. They are then washed thoroughly with distilled water and then dried in a hot air oven.

### 2.4 Composite Film Preparation

The biopolymer composite films were manufactured using a solution casting process. The agar solution was created by mixing agar powder into distilled water and heating the mixture to an approximate temperature of 90-95°C while continuously stirring until the solution was uniform. Once the agar solution had cooled slightly, purified banana pseudostem fibers were added to it and dispersed while stirring at a controlled rate.

Next, glycerol was added to the fiber/agar solution to act as a natural plasticizer to increase the films' flexibility. The highly viscous fiber/agar/glycerol solution was then poured onto Petri plates and dried under controlled conditions to create extremely thin bioplastic films. Following the drying process, the films were removed from the Petri plate mold and stored for future analysis.

## 3. Formulation Design Strategy

### 3.1 Composite Formulation Matrix

To determine how various formulation components can impact film properties, a design matrix was created to systematically vary cellulose levels (structural reinforcement), starch levels (film forming agent), glycerol levels (plasticizer for improved flexibility & reduced brittleness) and citrus derived extracts (natural antimicrobial agents).

This matrix will allow researchers to explore the trade-offs associated with the three primary attributes of film; mechanical strength, flexibility and antimicrobial functionality. For instance, an increase in cellulose should lead to increased tensile strength, while an increase in glycerol should lead to improved elongation; however, this may also lead to loss of structural rigidity.

### 3.2 Functional Roles of Composite Components

Each of the individual components used in developing this formula contributes toward film characteristics differently. The cellulose provides strength and structure to the composite matrix through reinforcing action. Starch enhances the film forming capabilities by being capable of creating a network of polymers throughout the drying process. The glycerol increases the flexibility of the films through reducing the hydrogen bonds between molecules in the polymer matrix. The citrus extracts introduce bioactive materials which could potentially inhibit microbial activity and increase the overall effectiveness of the packaging.

A balance of all of the above mentioned ingredients is required to maximize the function of the biodegradable films for use as packaging.

## 4. Sustainability Assessment Framework

Environmental sustainability has become an essential aspect of developing new packaging products from plant based sources. Thus, an overall sustainability analysis methodology has been developed to measure various parameters at all levels of the production cycle.

The methodology includes factors associated with energy use, water utilization, chemical content and carbon dioxide emission during both the extraction and film forming operations as well as end-of-life properties which include biodegradability and composting ability of the product. The overall analysis methodology will provide means for identifying processing methods that are environmentally friendly while maintaining the desired functionality of the product (Tabone et al., 2010; Teixeira et al., 2025).

## 5. Preliminary Analytical Modeling

Preliminary conceptual modeling was completed to identify the possible relationships among formulation parameters and film properties. Increased glycerol concentration will be expected to result in increased elongation at break and increased flexibility as a function of an increased mobility of polymer chains. Conversely, there are concerns that too much glycerol will negatively affect tensile strength, leading to decreased mechanical stability.

Additionally, increased starch content will be expected to positively affect biodegradability and film forming capabilities; however, it may also increase the susceptibility of moisture into the films due to starch being hydrophilic. Citrus-derived additives may provide for antimicrobial activity; however, if they are added in sufficient quantities, they may also negatively impact transparency and/or mechanical integrity.

Future research will utilize data-based modeling (machine learning) to develop predictive models of formulations that yield optimal film properties.

## 6. Conclusion

The purpose of this study is to develop an environmentally friendly method for making packaging materials using banana plant stem cellulose in addition to utilizing plasticizers and antimicrobial agents as additive to improve the function and use of biocomposite films produced from biopolymers while still being environmentally compatible. The methodology involved biomass processing, fiber purification, composite film formulation and a preliminary sustainability assessment of the material. Initial conceptual models showed that the mechanical and biodegradability properties of the biocomposite films are influenced by the plasticizer and starch used. The results show that banana plant stem biomass can be an alternative source of raw materials for creating sustainable packaging materials and that continued research and development in creating alternatives to traditional plastic packaging through the application of circular economy and valorization of agricultural waste will lead to the development of sustainable, environmentally friendly and commercially viable packaging materials.

## References

Teixeira, S. C., Oliveira, T. V. de, Soares, N. de F. F., & Raymundo-Pereira, P. A. (2025). Sustainable and biodegradable polymer packaging: Perspectives, challenges, and opportunities. *Food Chemistry, 455*, 142652. https://doi.org/10.1016/j.foodchem.2024.142652

Fang, J. M., Fowler, P. A., Tomkinson, J., & Hill, C. A. S. (2002). The preparation and characterization of a series of chemically modified potato starches. *Carbohydrate Polymers, 47*(3), 245–252. https://doi.org/10.1016/S0144-8617(01)00187-4

Helanto, K., Matikainen, L., Talja, R., & Rojas, O. J. (2019). Bio-based polymers for sustainable packaging and biobarriers: A critical review. *BioResources, 14*(2), 4902–4951. https://doi.org/10.15376/biores.14.2.helanto

Tabone, M. D., Cregg, J. J., Beckman, E. J., & Landis, A. E. (2010). Sustainability metrics: Life cycle assessment and green design in polymers. *Environmental Science & Technology, 44*(21), 8264–8269. https://doi.org/10.1021/es101640n

Kauertz, B., Detzel, A., & Wellenreuther, F. (2024) Environmental impacts of plastic packaging and recycling systems, Resources, Conservation and Recycling, 203, 107421. https://doi.org/10.1016/j.resconrec.2024.107421

Rigamonti, L., Grosso, M., Møller, J., Martinez Sanchez, V., Magnani, S., & Christensen, T. H. (2014). Environmental evaluation of plastic waste management scenarios. *Resources, Conservation and Recycling, 85*, 42–53. https://doi.org/10.1016/j.resconrec.2013.12.012

OECD (2022) Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options, OECD Publishing, Paris. https://doi.org/10.1787/de747aef-en

Geyer, R., Jambeck, J. R., & Law, K. L. (2017) Production, use, and fate of all plastics ever made, Science, 3 (7), e1700782. https://doi.org/10.1126/sciadv.1700782

Sangarote, S. A., Pacheco, E., Soares, A., & Freitas-Silva, O. (2025). Evaluation of banana pseudostem fibres for packaging material development. *Packaging Technology and Science*. https://doi.org/10.1002/pts.70023

Verma, D., Gope, P. C., Maheshwari, M. K., & Sharma, R. K. (2024) Natural fiber reinforced biodegradable composites for sustainable packaging, Materials Today Sustainability, 26, 100463. https://doi.org/10.1016/j.mtsust.2024.100463

Duhovic, M., & Peterson, A. M. (2012). Natural fibre–biodegradable polymer composites for packaging. In K. L. Pickering (Ed.), *Properties and performance of natural-fibre composites* (pp. 301–327). Woodhead Publishing. https://doi.org/10.1533/9781845694593.2.301