The Use of Additive Manufacturing was Essential for Creating Customized Components, such as Locks, which Ensur Analysis of Banana Peel (*Musa* spp.) and Agar for Bioplastic Production Enriched with the Citronella (*Cymbopogon winterianus*) Extract with Repellent Action for Use in Waste Disposal

Xayala Brasil Xavier[1]*, Beatriz Neves do Espírito Santo[1], Raissa Sales Santos[1], Jéssica Conceição dos Santos[1], Kaiane Vitória Nascimento Santos[1], Tatiana Oliveira do Vale[1], Roseane Oliveira[1]
[1]SENAI CIMATEC University; Salvador, Bahia, Brazil

This study investigates the production of bioplastic from banana peel (*Musa* spp.) and agar enriched with citronella extract (*Cymbopogon winterianus*) for pest-repellent action in waste disposal. In light of the environmental problems caused by conventional plastics, the aim was to develop a biodegradable bioplastic using natural waste materials. The method employed was the casting method with a film-forming aqueous solution. The results demonstrated that the appropriate ratio of banana peel starch and glycerin provided both strength and flexibility to the bioplastic. The developed bioplastic exhibits the potential to protect the environment and reduce the spread of diseases, serving as a sustainable alternative for waste disposal.
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The discovery of the Bakelite polymer in 1907 marked the beginning of the plastic era. However, its extensive environmental impact—particularly its resistance to degradation, associated carbon emissions, health risks, and the proliferation of plastic waste—has become a global concern. Improperly discarded plastic contributes to urban pollution and serves as a breeding ground for insects, thereby increasing the spread of disease. In this context, alternatives such as bioplastics derived from starch and agar—sustainable, biodegradable raw materials that offer functional resistance—are essential for reducing dependence on conventional plastics and mitigating the environmental burden of polymeric waste.

The present study seeks to contribute to this effort by exploring viable solutions to reduce reliance on petroleum-based plastics, especially in waste management. One such solution is using citronella oil, derived from *Cymbopogon winterianus*, a plant of the Poaceae family native to Java, Indonesia. Extracted from fresh or partially dried leaves, citronella oil is renowned for its natural repellent properties due to volatile compounds such as citronellal, eugenol, and geraniol. Additionally, its antifungal and antibacterial characteristics enhance its potential for application in waste disposal, particularly in repellent garbage bags.

Agar, derived from red algae (agarophytes), is one of the most widely utilized gelling agents globally. Comprising agarose and agaropectin—responsible for approximately 70% of its gelling properties—agar plays a vital role in structuring biopolymers. Banana peels, meanwhile, represent a major source of organic waste. When properly utilized, they offer significant environmental and social benefits. Researchers have highlighted the potential of bioactive compounds in banana peels, such as phenolics and pectin, in developing biodegradable films, presenting an alternative to petroleum-based materials [1].

Accordingly, this research aims to analyze the viability of using banana peel (*Musa* spp.) and agar to produce bioplastic enriched with citronella extract (*Cymbopogon winterianus*) with repellent properties for waste disposal applications. The objective is to develop a biodegradable bioplastic derived from banana peel starch, agar, and citronella extract to combat insect infestation during waste disposal. The study involves extracting starch from banana peels, employing agar as a gelling [2] and

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Address for correspondence: Xayala Brasil Xavier. Av. Orlando Gomes, 1845, Piatã, Salvador, Bahia, Brazil. Zipcode: 41650-010. E-mail: xayala.xavier@ba.estudante.senai.br.

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film-forming agent, and incorporating citronella to provide repellent efficacy. The effectiveness of the insect-repellent properties is also evaluated, thereby contributing to environmental preservation by proposing a sustainable and functional alternative.

Materials and Methods

The research was designed with quantitative, exploratory, bibliographic, and experimental characteristics. The bioplastic synthesis process was conducted in the Biotechnology Laboratory of the Integrated Campus of Manufacturing and Technology—SENAI CIMATEC. The primary raw material used was banana peel fiber (*Musa* spp.), complemented with agar and enriched with citronella oil to provide insect-repellent properties.

Extraction of Starch from Banana Peel

The bananas used in the experiment were purchased from local vendors in Salvador, Bahia. The banana peels were collected and placed in a 500 mL beaker containing 2 mL of sodium hypochlorite diluted in 250 mL water for 5 minutes to ensure proper disinfection. After disinfection, the peels were thoroughly rinsed with distilled water.

Next, 75 g of banana peel were weighed using an analytical balance and then blended with 225 mL of distilled water until the mixture was homogenized entirely. The resulting pulp was filtered through a fine sieve into a 500 mL beaker using a spatula to facilitate the separation of solids. The filtered material was allowed to rest undisturbed for 1 hour to enable sedimentation. After decantation, the supernatant was carefully transferred to another beaker, leaving the sedimented starch behind. A vacuum pump was employed to remove the remaining supernatant, isolating the decanted starch for bioplastic synthesis to enhance the separation efficiency.

Production of Bioplastic – Casting Method

The bioplastic was produced following the casting method described by Morais and colleagues (2019) [1]. The formulation consisted of 30 mL of distilled water, 10% citronella oil, 2 g of agar, and 10 mL of glycerin. All materials were combined in a 250 mL container. The mixture was heated to 90 °C and maintained at that temperature for 10 minutes under constant stirring.

After boiling, the solution was poured into Petri dishes and dried under two conditions: (1) in a bacteriological incubator with air circulation at 35 °C for 48 hours and (2) via bench drying at room temperature for performance comparison. After drying, the bioplastic films were weighed using a precision balance, and their thickness was measured with a micrometer.

Incorporation of Citronella for Repellent Action

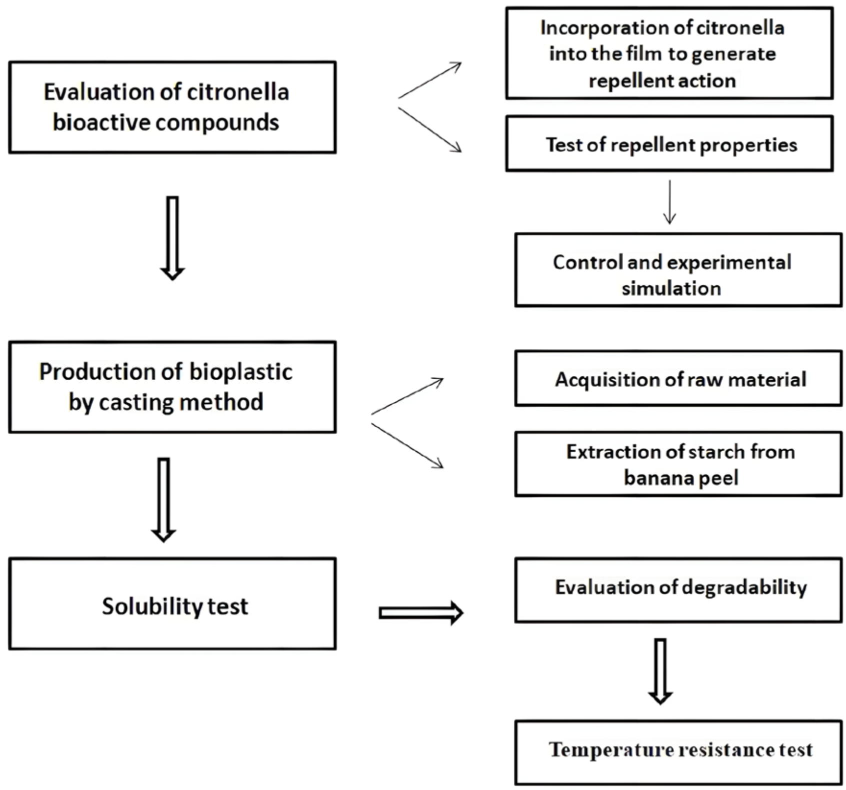
Citronella essential oil (*Cymbopogon winterianus*) with 100% purity (brand: Viaroma) imparted repellent properties to the bioplastic. A 10% citronella oil concentration was incorporated into the bioplastic mixture during the heating process. This concentration was selected to maximize repellent efficacy against insects while ensuring the aroma remained mild enough not to cause discomfort to humans or animals. The selected concentration was also evaluated for its potential antifungal action in the bioplastic matrix derived from banana peel starch. This dual function—repellent and antifungal—was crucial in enhancing the material's practical applications in waste disposal.

Testing and Evaluation Methods

A series of tests were conducted to evaluate the functional properties of the bioplastic—Repellent Activity (repellent efficacy) [3]:

Simulation Test: It was performed using two containers—one containing organic waste covered with the bioplastic and another (control) with only waste. The presence and behavior of insects were observed and compared to evaluate the bioplastic's performance in repelling pests.

Figure 1. Flowchart of the experimental procedure.



Solubility Test: The water solubility of the bioplastic films was determined using the method proposed by Almeida and colleagues (2019) [4]. The films were first dried at 70 °C for 24 hours, then immersed in distilled water and dried again, and their solubility was calculated based on the difference in dry mass before and after immersion.

Biodegradability Test: The degradation rate of bioplastic fragments was assessed following the procedure outlined by Silva and colleagues (2020) [5]. Fragments were incubated in soil for 18 days, after which the remaining dry weight was measured to calculate the biodegradation percentage.

Thermal Resistance Test: This test involved exposing bioplastic samples to a range of temperatures in a greenhouse for 30 minutes. Physical alterations such as cracks and deformations were recorded, with 80 °C being the maximum temperature tested to assess heat tolerance.

Results and Discussion

Evaluation of Bioplastic Formulation

This study investigated the formulation of bioplastics derived from banana peel starch and essential oil, focusing on optimizing the concentrations of citronella and plasticizer to improve the material's physicochemical and functional properties. Initial tests using 50 g of banana peel, 2 g of agar, and 1% citronella oil resulted in thick, brittle bioplastic films with minimal citronella aroma, primarily attributed to excessive glycerin, which interfered with film integrity. Subsequent modifications included increasing the amounts of agar and glycerin and incorporating banana pulp—an ingredient richer in starch—which improved film flexibility. While citronella oil did not significantly alter the material's texture, lower concentrations (below 10%) failed to demonstrate antifungal effectiveness.

Optimizing the composition by increasing the proportion of banana peel and reducing water content led to bioplastics with enhanced malleability, an ideal thickness of 0.7 microns, and a perceptible and pleasant citronella aroma. The optimal citronella oil concentration for both insect-repellent activity and fungal inhibition was determined to be 10%. This concentration also enhanced the overall sensory profile of the film, providing a characteristic fragrance and consistent repellent action.

Improvements in the drying process—particularly through a bacteriological incubator—helped mitigate contamination risks, especially in samples that initially contained banana pulp. Reducing pulp content and fine-tuning component concentrations ultimately resulted in a bioplastic with improved structural integrity, durability, and bioactive properties.

Antifungal Activity of Citronella

Microbiological analyses conducted 48 hours after fabrication revealed fungal and bacterial growth in nearly all bioplastic formulations, necessitating the removal and isolation of contaminated samples. Contributing factors included residue buildup and cross-contamination within the laboratory environment.

Notably, bioplastics embedded with citronella oil exhibited significantly reduced microbial activity compared to control samples, highlighting the antifungal potential of citronella's active compounds, such as citronellal, geraniol, and eugenol. Although a protective paper mask was used to limit exposure to airborne contaminants, it was ineffective against biofilm-forming bacteria. Introducing a bacteriological incubator proved crucial for safeguarding sample integrity and accelerating experimental results by limiting environmental contamination [1,6,7].

Repellent Potential of Citronella

Samples were placed in containers with organic waste to attract insects to assess the repellent properties of citronella-infused bioplastic. Formulations containing 10% citronella oil demonstrated complete repellent activity, with 100% effectiveness observed during exposure. In addition to deterring insects, this concentration inhibited surface-level microbial growth, suggesting synergistic antimicrobial and insect-repellent effects [7].

Lower concentrations of citronella oil were less effective, displaying a rapid decline in fragrance intensity and bioactivity. The 10% citronella bioplastic retained its characteristic aroma and antimicrobial action for approximately 18 days. However, insect activity and microbial colonization resurgence were noted after this period, indicating the gradual loss of volatile compounds responsible for bioactive effects.

Solubility Analysis of Bioplastics

The solubility assessment of bioplastics derived from banana peel revealed a solubility rate of approximately 75%. Despite this significant solubility, the bioplastic did not fully dissolve in water, indicating a structural integrity that resists complete disintegration. This partial solubility can be attributed to the intermolecular interactions among biopolymer constituents—particularly starch—which forms hydrogen bonds that limit water penetration. With its inherent capacity for water absorption and gelatinization,

Banana peel starch contributes to gel-like consistency while retaining mechanical strength. Such findings are critical in evaluating the material's resilience under humid or aqueous conditions, highlighting its potential for applications requiring moderate water resistance. Moreover, incorporating citronella essential oil demonstrated antifungal effects, as evidenced by minimal microbial activity on the film surface. This supports the multifunctionality of the bioplastic for sustainable waste containment.

Biodegradation Analysis

Biodegradability tests used formulations containing 50 g, 30 g, and 20 g of starch to explore the influence of starch concentration on decomposition rates. While the materials exhibited considerable degradation within 15 days, none of the samples fully decomposed. The observed rates are considered promising since bioplastics typically decompose over 3 to 6 months under natural conditions [8].

Notably, thinner films with lower starch content degraded more rapidly, suggesting a direct correlation between material thickness and decomposition time. In contrast, denser films exhibited slower but more consistent degradation, balancing structural durability and environmental degradation. These results support the feasibility of tailoring bioplastic formulations to suit varying degradation timelines, depending on the intended application [9,10].

Thermal Resistance Assessment

The optimized bioplastic's thermal resistance was evaluated across a temperature range of 30°C to 70°C. At ambient conditions (30°C–40°C), the material maintained its integrity and functional properties. However, significant structural alterations were observed at elevated temperatures (60°C and 70°C), with the material becoming viscous and sticky. Although no visible surface cracks were noted, deformation and loss of mechanical strength occurred at higher temperatures, indicating the onset of thermal breakdown. Despite these limitations, the bioplastic's stability at room temperature is sufficient for its proposed use in waste disposal, where exposure to extreme heat is unlikely. This thermal profile confirms its applicability in typical environmental settings.

Conclusion

This study evaluated the feasibility of producing biodegradable and insect-repellent bioplastic from banana peel (*Musa* spp.) and agar enriched with citronella essential oil (*Cymbopogon winterianus*) for waste containment. The experimental results confirmed the achievement of the proposed objectives: the bioplastic exhibited satisfactory physicochemical properties, effective insect-repellent action, and resistance to microbial contamination.

Nonetheless, limitations such as moisture sensitivity and variability in raw material composition were identified, underscoring the need for further optimization. Future research should focus on refining the drying and storage processes, exploring alternative natural additives, and expanding the range of biodegradable sources to enhance product performance and scalability. By offering an eco-friendly solution grounded in circular economy principles, this study contributes to developing sustainable alternatives to conventional plastics. It also reinforces the relevance of biopolymer research in addressing global environmental challenges associated with plastic pollution and public health risks.

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