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ECO-FRIENDLY ANTIBACTERIAL PACKAGING MATERIALS FROM BANANA FIBER: A REVIEW

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ABSTRACT: The global growth in plastic pollution has increased the demand for environmentally friendly and biodegradable packaging materials. Banana fiber, a natural fiber source, has garnered significant attention due to its biodegradability, high cellulose content, mechanical strength, and availability as agricultural waste. However, biodegradable materials often lack inherent antibacterial properties which is crucial for sensitive applications like food and medical packaging. The objective of this review is to evaluate the potential of banana fiber as a base material for eco-friendly antibacterial packaging with a focus on enhancing its functionality through modifications using tannic acid for food and medical applications. The review discusses the chemical composition, mechanical properties, and surface modification of banana fiber through alkali treatment. It further explores biofunctionalization techniques such as fiber immersion, surface coating, and blending with biopolymers to improve the antibacterial properties of the fiber. Additionally, the review outlines current approaches to manufacturing antibacterial packaging composites including pulping, sheet forming, hot pressing, and lamination. Potential applications in food, medicine, pharmaceutical, and agricultural industries are also highlighted. Although there is a growing interest in biodegradable packaging materials, limited research has explored the use of banana fiber in combination with plant-derived antibacterial agents such as tannic acid to develop multifunctional materials. Key findings include the fact that alkali treatment improves fiber bonding with tannic acid, tannic acid offers superior thermal stability compared to other natural antimicrobials, and banana fiber composites can extend food shelf life. These modifications support the development of sustainable, multifunctional packaging for various applications.

Keywords: antibacterial packaging, banana fiber, biodegradable material, tannic acid

1 INTRODUCTION

The problem of plastic waste has become one of the most critical environmental challenges of the 21st century. Single-use packaging accounts for nearly 40 per cent of global plastic waste. Unlike conventional plastics, which can persist in the environment for centuries, these materials leach microplastics and toxic additives into soil and waterways, posing long-term threats to ecosystems and human health. In response, many nations in the European Union have implemented stricter regulations, such as single-use plastic ban; however, the need for environmentally friendly alternatives has not been considered. Biodegradable and inherent antibacterial packaging materials are urgently required for the protection of the environment and food safety simultaneously. In addition to long-term environmental consequences, biodegradable materials for food packaging and pharmaceutical purposes often exhibit inferior antimicrobial properties (Zhong et al., 2020). The development of sustainable bio-composites that mix natural fibers with plant-derived antibacterial substances, such as tannic acid and chitosan, has recently gained significant attention (Zhang et al., 2023a). These materials not only represent an environmentally safe choice but also protect against bacteria, making them ideal for modern packaging solutions.

The creation of antibacterial and biodegradable packaging supports global advantages for circular economies, reduces waste, and ensures public health safety. This review selected tannic acid over other natural antibacterial agents because of its exceptional activity levels combined with plant origin and its compatibility with lignocellulosic fibers, including banana fiber. Tannic acid is a water-soluble polyphenol present in tea leaves alongside pomegranate peels and oak bark, among various agricultural waste materials. This potent antibacterial agent destabilizes bacterial cell membranes while binding to proteins and sequestering essential metal ions required for bacterial proliferation simultaneously (Farha et al., 2020). Tannic acid exhibits antibacterial properties alongside its antioxidant, anti-inflammatory, and UV-blocking abilities, which help enhance packaging material longevity and performance (Buzzini et al., 2008a; Lee et al., 2023). The material demonstrates biodegradability and non-toxicity while holding approval for food-contact use, which positions it as a suitable component for sustainable packaging systems (Zhang et al., 2023b). The process of extracting from local plant residues presents a straightforward method that provides economic advantages while adhering to circular economy standards. The study chose tannic acid as its focal antibacterial agent for these specified reasons.
In this context, the potential of banana fiber-based bio-composite materials employing natural antibacterial agents such as tannic acid, as a sustainable and multifunctional alternative to synthetic plastic packaging materials is assessed. The advantages of these materials such as abundance, biodegradability, and mechanical strength are discussed alongside their limitations and the process of biofunctionalization. The study also investigates the feasibility of applying tannic acid, a natural polyphenol derived from plants, with well-established antimicrobial and antioxidant properties, with a focus on enhancing the safety and shelf life of packaged food articles.

2 LITERATURE REVIEW

2.1 Properties of banana fiber

Banana fiber, derived from the pseudo stems of Musa species, has garnered significant attention as a sustainable raw material for eco-friendly packaging due to its renewable character, biodegradability, and excellent mechanical performance. The chemical makeup of banana fiber includes 55% to 65% cellulose, 12% to 25% hemicellulose, 5% to 15% lignin, along with small amounts of pectin, ash, and extractives (Badanayak et al., 2023). Cellulose, which is the main element of structure, is a hydrophilic polymer with a crystalline rod-like chain structure that adds to the fiber's tensile strength. Hemicellulose and lignin, which provide flexibility and rigidity to the structure, also play a crucial role in increasing water affinity, which in turn degrades durability. Banana fiber has high tensile strength exceeding 500 MPa and a density of around 1.28 g/cm^3, making it comparable to or superior to other natural fibers like jute and coir (Yahya et al., 2023). Its porous and rough morphology helps in interfacial bonding with hydrophilic agents and biopolymers. Treatment with sodium hydroxide (NaOH) further improves fiber performance by removing surface impurities, as well as lignin and hemicellulose, enhancing crystallinity and roughening the fiber surface. Optimized alkali conditions (e.g, 6.3% NaOH at 80°C for 60 minutes) have been shown to increase tensile strength by approximately 26% (from 615 to 775

MPa) and reduce water absorption by nearly 68% (from 209% to 69%) (Checol & Sendekie, 2025). Alkali treatment improves interfacial adhesion enhancing bonding of banana fiber with antimicrobial agents like tannic acid. These modifications not only improve the raw fiber but also contribute to the properties of the final developed packaging material. This ensures better mechanical strength, durability, and moisture resistance all of which are crucial for its practical use. Banana fiber has qualities similar to other natural fibers. It has a lower density while matching or surpassing the tensile performance of hemp or jute. It is low-cost, lightweight, and offers superior properties for lightweight eco-composites. The hydrophilicity of banana fibers improves biodegradability; however, its performance may degrade in wet environments due to stabilization challenges. The integration of banana fibers with tannic acid antimicrobial agents further enhances the packaging material's antibacterial activity while maintaining biodegradability. These improvements make banana fiber composites highly suitable for antibacterial packaging of food and medical products which require both mechanical strength and protection from microbial spoilage.

2.2 Biofunctionalization of banana fiber with natural antibacterial agents

The integration of natural antibacterial agents into lignocellulosic fibers, like banana fiber, has gained growing attention for enhancing the performance of biodegradable packaging in food and medical applications. Banana fiber offers mechanical strength and biodegradability, yet it lacks inherent antimicrobial properties, which limits its effectiveness in prevention microbial contamination in packaging. Recent Scientific investigation have examined the bio-functionalization of banana fiber using plant-derived antibacterial agents, including tannic acid, neem extract, chitosan, and essential oils (Zhang et al., 2023). Among these agents, tannic acid stands out as an exceptional candidate due to its broad-spectrum antibacterial properties combined with strong interaction with cellulose (Buzzini et al., 2008b; Farha et al., 2020). Derived from pomegranate peels, tea leaves, and oak bark tannic acid is safe for food applications. Through its intricate antibacterial mechanisms, tannic acid disrupts microbial cell membranes while simultaneously inhibiting essential enzymes and chelating metal ions needed for bacterial survival (Lee et al., 2023). Its polyphenolic structure enables strong bonding with banana fiber, especially after alkali treatment, which exposes more reactive hydroxyl groups on the fiber surface (Checol & Sendekie, 2025). Antibacterial treatment is typically performed by immersing banana fibers in a tannic acid solution prepared in a 70:30 ethanol-water mixture (Kim et al., 2024); however, this ratio can be adjusted to enhance solubility and achieve uniform surface modification. This modification enhances the fiber's antibacterial activity, UV resistance, and lower moisture uptake, which is important for keeping the integrity of the product (Xiao et al., 2024). While other agents like neem oil and chitosan have natural antibacterial characteristics, tannic acid is particularly promising for functionalizing banana fiber because it is more thermally stable, inexpensive, and adheres well to cellulose matrices. Tannic acid functionalization of banana fiber has a two-fold value: it improves food and pharmaceutical safety and reduces environmental concerns, making it a promising approach for creating biodegradable antibacterial packaging materials.

2.3 Manufacturing of antibacterial packaging material

The development of antibacterial packaging from banana fiber is a multi-stage process, illustrating the economic integration of mechanical, chemical, and functional treatments to create value-added biodegradable products from agricultural waste. The first stage involves mechanical extraction of fibers from banana pseudo-stems which are available in abundant quantities after harvest. Mechanical decortication is preferred because it is cheap and it physically removes fibers while preserving their structure. After extraction, the fibers undergo an alkali treatment using NaOH. This treatment is important because it removes non-cellulosic content (lignin, hemicellulose, and surface waxes) and modifies the fibers by improving fiber crystallinity, increasing fiber surface roughness, and exposing more hydroxyl groups. These improvements allow for better compatibility with hydrophilic antibacterial agents and improve interfacial bonding in composite materials. After cleaning and activation, fibers are prepared for antibacterial functionalization with tannic acid. Tannic acid is a natural polyphenol that has been reported to exhibit broad-spectrum antimicrobial activity. The fibers are treated by depositing them in a 50:50 mixture of ethanol and water in a solution of tannic acid. This method allows for effective diffusion into and interaction with the fiber surface. Tannic acid adheres to cellulose through hydrogen bonds and possibly hydrophobic sites to create a permanent antibacterial layer on the fiber surface. Next, the fibers undergo via a pulping process during which they become a slurry and are combined with biodegradable binders (rice starch) to create a pulp. This pulp is made into sheets using sheet-forming equipment and then air-dried to remove moisture. The sheets are further processed using a hot press to improve mechanical properties, surface finish, and consistency of structure. Cutting may also be applied to form the packaging into dimensional forms.

2.4 Potential applications of banana fiber packing material

The antibacterial packaging material from banana fiber treated with tannic acid offers numerous applications in sectors that value sustainability, hygiene, and biodegradability. In the food sector, the packaging material can be used effectively to wrap fresh produce such as fruits, vegetables, and herbs, where the antibacterial properties will help reduce spoilage rates and extend shelf life. In the food service industry, the biodegradable packaging material can be formed into disposable trays, wraps, or containers for takeaway meals providing a more sustainable alternative to plastic while also ensuring food against microbial contamination (Barretto et al., 2024). The material is also suitable for sensitive applications in medical and pharmaceutical secondary packaging, such as the encasement of herbal soaps, wound dressings, or hygiene products, where surface protection against contact contamination during handling and distribution is paramount (Umapathi et al., 2025). In addition, fiber composite sheets could be formed into biodegradable nursery pots or seedling and cutting trays in agriculture. The antimicrobial surface would protect young plants from fungal and bacterial infections during early development, thereby supporting healthy growth without reliance on chemical fungicides. Other applications include eco-friendly gift wraps, garment packaging, and customized shopping bags for sustainable brands that committed to ecologically eliminating plastics from their value chains. With further development and process optimization, banana fiber-based antibacterial packaging could serve as a cost-effective and environmentally responsible alternative for a wide range of commercial applications.

2.5 Knowledge gap

While there is extensive research on the application of natural fibers in biodegradable packaging, the potential of banana fiber integrated with plant-derived antibacterial agents such as tannic acid remains underexplored in the context of food packaging. Most existing studies focus either on improving the mechanical properties of banana fibers or on investigating the antibacterial effects of tannic acid in isolation. However, there are a few studies which had attempted to integrate both aspects into a marketable product. Current methods have not sufficiently addressed the need for multifunctional antibacterial packaging. This review study aims at exploring the possibility of combining banana fiber and tannic acid for packaging applications. Moreover, the green extraction of tannic acid from agricultural waste is still unexplored in the context of food packaging. Future research should focus on optimizing processing methods while case studies and pilot projects could further demonstrate the practical relevance and feasibility of this novel packaging solution.

3 CONCLUSION

The demand for sustainable and biodegradable food packaging to replace plastic is increasing. Banana fiber, a renewable and biodegradable agricultural byproduct possesses significant potential as a packaging substrate due to its fibrous structure which enables the use of plant-based antibacterial agents such as tannic acid to reduce plastic waste and improve product safety in microbial terms. Research highlights that alkali treatment improves the compatibility of banana fiber with tannic acid, thereby enhancing antibacterial properties and mechanical strength. However, there are still some challenges in achieving antibacterial effectiveness and improving the manufacturing process. Future studies should focus on the optimization of functionalization processes and performance validation through standardized techniques. Case studies and pilot projects would be valuable in facilitating the transition of such products from the laboratory research to industrial application which is an integral part of sustainable development.

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