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Mechanical and Thermal Properties of Banana Fiber Composites for Sustainable Applications

Tutku Özkan*

Department of Aeronautical Engineering, Gebze Technical University, Kocaeli, 41400 Türkiye

Abstract

This mini-review highlights the advances in banana fiber-reinforced composites (BFRCs), emphasizing their mechanical, thermal, and hybrid properties. Natural fibers, particularly banana fibers, have emerged as sustainable alternatives to synthetic fibers because of their renewability, biodegradability, and cost effectiveness. The review explores the tensile, flexural, and impact properties of BFRCs, describing the influence of fiber treatments, hybridization strategies, and layering patterns on performance. In addition, it examines the thermal stability and conductivity enhancements achieved through nanofillers and hybrid reinforcements. Applications in the automotive, construction, and packaging industries underscore the industrial relevance of these materials. Challenges such as moisture sensitivity and fiber-matrix adhesion issues are discussed alongside future directions for improved composite development. This review comprehensively discusses the potential of BFRCs as eco-friendly materials for advanced applications.

Keywords: Banana Fiber Composites; Mechanical Properties; Thermal Stability; Hybrid Composites; Sustainable Materials

1. Introduction

In recent years, natural fiber reinforced composites (NFRCs) have garnered significant attention because of their unique combination of properties, cost-effectiveness, and environmental benefits. Among these, banana fiber reinforced composites (BFRCs) stand out as sustainable alternatives to synthetic fiber-reinforced composites (FRPCs), which, despite their mechanical strength, are associated with high costs, challenges in recyclability and nonbiodegradability [1–3]. BFRCs take advantage of the inherent advantages of banana fibers, such as low density, biodegradability, and abundant availability, making them ideal candidates for eco-friendly applications in industries such as automotive, aerospace and construction [4, 5]. Natural fibers, including banana, sisal, jute, and hemp, are derived from plants and are increasingly used as reinforcements in polymer matrices [6, 7]. Specifically, banana fibers, which are extracted from the pseudo-stem of the banana plant, exhibit high cellulose content (63–85%), low lignin content, and superior tensile strength comparable to conventional synthetic fibers like glass [3, 1]. India, as one of the largest banana producers in the world, provides a large supply of pseudo-stems of bananas, much of which is discarded as agricultural waste [1]. Harnessing this waste for composite production not only supports sustainability, but also adds economic value. Despite the promise of BFRCs, certain challenges remain. The mechanical performance of natural fiber composites is often lower than that of synthetic composites due to weak fiber-matrix interactions and moisture sensitivity [8, 9]. However, advances in hybridization and surface treatments, such as alkali and silane treatments, have significantly enhanced the mechanical, thermal, and chemical properties of these composites [10, 11]. This mini-review explores the mechanical and thermal properties of BFRCs, focusing on the role of hybridization, fiber content, and chemical modifications in improving composite performance. In addition, the review highlights the potential industrial applications of BFRCs and the challenges that must be addressed to achieve widespread adoption in advanced engineering applications.

*Corresponding Author: Tutku Özkan (tutkuozkan92@gmail.com)
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2. Mechanical Properties

The mechanical properties of banana fiber reinforced composites (BFRCs) are critical indicators of their performance in various industrial applications. These properties depend significantly on factors such as fiber content, fiber-matrix adhesion, layering patterns, and surface treatments [1, 10]. Tensile strength, flexural strength, and impact resistance are among the key mechanical characteristics that are extensively studied for BFRCs.

2.1. Tensile Properties

Tensile strength is a primary determinant of composite performance and is influenced by the adhesion strength between fibers and the matrix, the degree of fiber modification and the fiber content within the composite [3, 12]. Studies have consistently shown that tensile properties improve with increased fiber content up to an optimal threshold beyond which matrix failure, fiber pull, and brittleness occur due to poor fiber-matrix interaction [13, 14]. The findings of Das et al. (2018) [13] showed that a 3:1 ratio of pineapple to banana fiber, combined with sodium hydroxide treatment, improved tensile strength by improving fiber-matrix adhesion. Surface treatments and hybridization play crucial roles in the improvement of the performance of natural fiber-reinforced composites. Singh et al. (2017) [10] demonstrated that NaOH treatment 5% significantly improved the tensile strength of jute, banana, and sisal fiber composites by improving interfacial bonding and stress transfer, although the impact strength showed a slight decline. Among the untreated and treated fibers, jute-based composites exhibited the highest tensile strength, indicating their suitability for high-strength applications. Similarly, Idicula et al. (2005) [12] reported that hybridization of banana and sisal fibers in polyester matrices, with an optimal fiber volume fraction of 0.40 and a banana-to-sisal ratio of 3:1, yielded an improved tensile strength [12, 10]. The findings of Li et al. (2007) [8] highlighted that chemical treatments, such as alkali, silane, and acetylation, significantly improve the adhesion between natural fibers and polymer matrices in fiber-reinforced composites. These treatments enhance fiber surface properties, reduce water absorption, and increase tensile strength, making natural fibers a viable alternative to synthetic fibers for sustainable composite applications.

2.2. Flexural Strength

The flexural strength, which measures the ability of a composite to resist deformation under load, is heavily influenced by the selection of fibers, the material of the matrix, and the fiber content. Samal et al.(2009) [15] investigated the flexural properties of banana/glass fiber hybrid composites and found that hybridization significantly improved flexural strength compared to single-fiber composites. A 15:15 weight ratio of banana and glass fibers in polypropylene composites exhibited a 22.6% increase in flexural strength relative to composites with only banana fibers. The addition of 2% maleic anhydride grafted polypropylene (MAPP) as a coupling agent further enhanced fiber-matrix adhesion, resulting in better load transfer during flexural tests. The study highlighted the importance of hybridization and coupling agents in optimizing the mechanical performance of hybrid composites. Gupta et al. (2021) [16] revealed that the flexural strength of the banana-sisal hybrid composites increases with higher percentages of fiber volume and a greater fraction of banana fibers. Their study showed that a 3:1 ratio of banana to sisal fiber, combined with a total fiber volume 50%, produced the highest flexural load-bearing capacity. However, beyond a volume fraction of 0.4 to 0.5, a decline was observed due to reduced fiber-matrix adhesion and increased fiber pull-out. These results emphasize the importance of optimizing fiber proportions and loading to achieve maximum mechanical performance. Senthil Kumar et al. (2016)[14].studied the influence of layering patterns and alkali treatment on the mechanical properties of banana/coconut sheath hybrid composites. Their findings indicated that the flexural strength was highest in the CBC configuration (banana skin-coconut core), particularly for alkali-treated fibers, as this arrangement optimized the strength of the skin layers while utilizing the energy absorption properties of the coconut sheath. The study also highlighted that untreated composites exhibited a reverse trend, emphasizing the critical role of fiber treatment in improving fiber matrix adhesion and mechanical performance.

2.3. Impact Strength

Hybridization of natural fibers with other natural or synthetic fibers has been shown to significantly enhance the impact strength of composites. Devireddy and Biswas (2017) [17] demonstrated that banana/jute fiber-reinforced epoxy composites exhibit superior toughness and reduced void content at optimal fiber loading, indicating improved energy absorption capabilities. Similarly, Rashid et al. (2020) [18] reported that banana/glass hybrid composites outperformed pure glass fiber composites in impact strength, particularly in field hockey equipment, while also offering environmental benefits. These findings highlight the potential of hybridization strategies in tailoring composite properties for specific applications. Maleque et al. (2006) [19] explored pseudo-stem banana fiber reinforced epoxy composites and observed an 40% improvement in impact strength compared to unreinforced epoxy. The study highlighted the ability of banana fibers to mitigate crack initiation and propagation, resulting in better energy absorption and toughness.

3. Thermal Properties

The thermal properties of banana fiber reinforced composites (BFRCs) play a vital role in determining their suitability for applications that require heat resistance and thermal stability. These properties are influenced by factors such as fiber treatment, hybridization, and the incorporation of nanofillers [1, 20].

3.1. Thermal Conductivity and Stability

Thermal conductivity and stability are crucial for materials exposed to varying temperatures. Untreated banana fibers exhibit lower thermal conductivity compared to treated fibers due to poor interfacial bonding [21]. Chemical treatments, such as alkali and silane treatments, improve thermal stability by improving fiber matrix adhesion and increasing crystallinity [8]. Biswal et al. (2011) [20] demonstrated that nanoclay-treated BFRCs exhibited significant improvements in resistance to thermal degradation, with an increase 18% in high temperature stability. Table 1 summarizes various hybrid combinations of banana fiber composites, their fabrication methods, and the thermal tests carried out. These combinations demonstrate how different reinforcements and processing techniques influence the thermal performance of BFRCs.

Table 1: Various Combinations of Banana Fiber Hybrid Composites [22]

S.No	Hybrid Composites	Fabrication	Thermal Testing
1	Banana / Polypropylene	Compression Molding	Thermal conductivity, diffusivity
2	Banana / Polypropylene / Nanoclay	Melt Blending, Compression Molding	DSC, TGA
3	Banana / Jute / Epoxy	Hand Lay-up, Compression Molding	TGA, HDT
4	Banana / Sisal / Polyester	Hand Lay-up, Compression Molding	DMA
5	Banana / Glass	Compression Molding	DMA, TGA
6	Banana / Fly Ash / Polypropylene	Injection Molding	DSC
7	Banana / Nylon 6 / Polypropylene	Injection Molding	DSC, TGA
8	Banana / Kenaf / Epoxy	Hand Lay-up	TMA, TGA

Hybrid composites with banana and jute fibers also show enhanced thermal stability as a result of the synergistic effects of natural fiber combinations. When banana fibers are hybridized with jute in an epoxy matrix, the composites achieve superior thermal properties, particularly at 50% fiber loading [17].

3.2. Effect of Nano-Fillers

Incorporation of nanofillers, such as nanoclay, has emerged as an effective strategy for enhancing the thermal properties of BFRCs. Mohan and Kanny (2015)[23] reported a 53% increase in tensile strength and improved thermal stability of BFRCs with 6% nanoclay loading. The nanofillers enhance the interfacial interaction between the fiber and the matrix, resulting in improved heat resistance. Thermogravimetric analysis (TGA) studies have shown that banana fiber composites with nanofillers have higher degradation temperatures compared to untreated composites. These advances make BFRCs suitable for applications in the automotive and construction sectors, where heat resistance is critical [24].

3.3. Hybridization and Layering Effects

Hybrid composites with varied fiber layering patterns demonstrate unique thermal behaviors. For example, bi- and trilayer composites that combine banana and sisal fibers in a polyester matrix exhibit distinct thermal damping and stiffness characteristics [12]. The choice of layering patterns significantly influences heat deflection and thermal expansion, allowing tailored applications. Banana fiber hybrids with synthetic fibers such as glass have further broadened the thermal applications of these composites. Srinivasan et al. [25] investigated banana glass fiber composites and reported significant improvements in thermal stability and mechanical properties, suggesting their potential for use in high-temperature environments.

4. Applications

Banana fiber-reinforced composites (BFRCs) have emerged as versatile materials with applications in multiple industries due to their superior mechanical properties, lightweight nature, and sustainability. Their growing use is a testament to the need for eco-friendly and high-performance alternatives to synthetic composites [1, 2]. The automotive sector has adopted BFRCs for manufacturing lightweight and durable components. The low density and high tensile strength of banana fibers make them suitable for seats, door panels, and interior trim [17, 18]. Hybrid composites, which combine banana fibers with synthetic fibers like glass, have further improved their mechanical and acoustic properties, meeting industry requirements for noise reduction and crash resistance [25, 19]. In construction, BFRCs are used in partition walls, ceilings, roof tiles, and other building components [6, 7]. Their thermal insulation properties, biodegradability, and ease of fabrication make them ideal for sustainable construction practices. Studies have demonstrated the ability of banana fiber composites to withstand environmental stresses, which makes them suitable for outdoor applications [4]. BFRCs have found increasing use in the packaging industry as a result of their biodegradable nature. As concerns about plastic pollution intensify, banana fibers offer a sustainable alternative to create eco-friendly packaging materials. Composites reinforced with banana fibers and natural polymers have been successfully developed for food and consumer goods packaging, offering durability and low environmental impact [3]. The sports and leisure industry has adopted BFRCs for the fabrication of equipment such as helmets, bicycles, and rackets [18]. The combination of lightweight and high impact strength makes BFRCs ideal for enhancing performance and safety. Hybrid composites have further expanded their applications by improving mechanical performance under dynamic loads. With advances in fiber treatment and hybridization techniques, BFRCs are being explored for emerging applications in the aerospace and medical fields.

Their excellent strength-to-weight ratio and thermal stability make them potential candidates for aircraft interior components. In the medical sector, the biocompatibility of natural fibers, including bananas, opens doors for the development of surgical implants and prosthetics [24].

5. Discussion

The exploration of banana fiber reinforced composites (BFRCs) underscores their potential as sustainable alternatives to conventional synthetic composites. While substantial progress has been made in understanding their mechanical and thermal properties, several challenges and opportunities remain for further research and industrial adoption. One of the primary limitations of BFRCs lies in their moisture sensitivity, which adversely impacts long-term durability. Although chemical treatments such as alkali and silane modifications have shown promise in improving fiber-matrix adhesion, these methods often add complexity and cost to the production process. Simplified and eco-friendly surface treatment techniques are worth investigating to address this issue. Another critical challenge is achieving consistency in the mechanical and thermal properties of BFRCs. Variability in natural fiber quality due to differences in plant cultivation, harvesting, and processing methods can lead to inconsistent performance. Developing standardized protocols for fiber extraction and composite fabrication could help mitigate these inconsistencies. Hybrid composites combining banana fibers with other natural or synthetic fibers offer a compelling avenue to enhance the properties of the material. However, the design of hybridization strategies, including optimal layering patterns and fiber content ratios, requires further study to maximize synergy between the constituent fibers. The scalability of BFRCs for industrial applications also demands attention. While these materials have shown utility in the automotive, construction, and packaging sectors, large-scale adoption necessitates the development of cost-effective manufacturing techniques. Incorporating automation into the fabrication process could accelerate production while maintaining quality. Future research should also explore the integration of advanced fillers, such as nanomaterials, to improve mechanical and thermal properties without compromising biodegradability. Furthermore, the recyclability and life cycle assessment of BFRCs should be evaluated to ensure alignment with sustainability goals.

6. Conclusion

Banana fiber-reinforced composites (BFRCs) have demonstrated immense potential as sustainable materials, offering a viable alternative to synthetic composites in various industries. Their unique combination of mechanical strength, thermal stability, and environmental benefits positions them as a key contributor to the innovation of eco-friendly materials. Using the natural advantages of banana fibers and incorporating advancements in hybridization, surface treatments, and filler technologies, researchers have significantly improved the performance of these composites. Despite these advances, several challenges remain, including moisture sensitivity, variability in fiber quality, and scalability for industrial production. Addressing these issues requires focused research on developing standardized protocols, cost-effective manufacturing processes, and innovative fiber treatments that improve durability without compromising sustainability. The versatility of BFRCs has been demonstrated in sectors such as automotive, construction, packaging, and sports. Their potential extends to emerging applications in aerospace and medical fields, driven by their high strength-to-weight ratio and biodegradability.

Future research should continue to explore novel hybridization strategies, advanced fillers, and recyclability to maximize the impact of BFRCs in a broader range of applications. As industries increasingly prioritize sustainability, BFRCs stand as a promising solution to meet the growing demand for green materials. With continued research and technological advancements, these composites can play a pivotal role in addressing global environmental challenges while fostering innovation in material science.

Declaration of Competing Interests

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Author Contributions

Tutku Özkan: Conceptualization, Data Analysis, Writing – Original Draft, and Writing – Review and Editing.

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