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Bamboo Fiber Composites: Characteristics, Manufacturing Processes, and Versatile Applications - A Review

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Abstract: Naturally occurring bamboo fibers, recognised for their environmentally sustainable characteristics, are gaining recognition as desirable natural fibers for composite materials. This review article provides an in-depth investigation of bamboo fibers, including their distinctive attributes, the diverse manufacturing techniques employed for fabricating of bamboo fiber-enhanced composites, the physical and mechanical properties of these composites, and their extensive array of applications. Bamboo fibers possess numerous advantages, including high strength, rigidity, resistance to corrosion, biodegradability, wide accessibility, affordability, and flexibility. The surface treatment of bamboo fiber is crucial for enhancing the adhesive strength, minimising water absorption, enhancing mechanical properties, ensuring uniform distribution of fibers, and enhancing resistance to deterioration. Consequently, bamboo fiber becomes an exceptional constituent for diverse industrial applications. Comprehending each manufacturing technique, together with its merits and drawbacks in relation to a particular application, can aid in selecting the suitable process for manufacturing composite materials with the needed performance. Bamboo fiber-enhanced composites provide outstanding attributes that make them highly promising for applications in the building, food packaging, transportation, and energy sectors.

Keywords: Bamboo fiber; composite; surface treatment; characteristic; applications

Introduction

Material engineering is categorised into four main groups: metal, polymer, ceramic, and composite. Several decades ago, metal played a major role in numerous applications. Metal is a versatile substance widely employed in several industries owing to its strength, stiffness, and excellent thermal and electrical conductivity. Metals possess several benefits, such as their inherent malleability and ductility, which allow for easy shaping and manipulation. Additionally, metals exhibit remarkable structural integrity and strength. Metals have extensive uses in diverse fields like electronic wave absorption (Ren et al., 2023), energy storage (Peng et al., 2022), biomedical devices (Li et al., 2021), and aircraft (Mao et al., 2020). However, its drawbacks include being heavy, corrosion-prone, and often difficult to recycle, thereby contributing to environmental damage (Briffa et al., 2020; Inaba et al., 2019; Singh et al., 2022). Hence, natural fiber serves as a viable substitute material to partially supplant the role of metal material. The many qualities of natural fibers make them an appealing substitute material for metals. Natural fibers consist of organic substances derived from plants and have several advantageous characteristics, including being lightweight, biodegradable, and possessing mechanical properties suitable for various applications (Jiang et al., 2020; Naveen et al., 2019). Bamboo is an exemplary natural fiber. Bamboo is renowned for its exceptional durability, fast regrowth, and many uses in construction, paper production, shoulder and elbow joint replacements, building materials, and as a primary ingredient in various goods (Adier et al., 2023; Chin et al., 2020; Sun et al., 2023; Zahedi et al., 2023).

Bamboo is a remarkably adaptable and environmentally friendly substance that has received much acclaim in diverse sectors. Due to its quick growth rate, strength, and flexibility, it is an excellent substitute for conventional materials like wood and plastic. Furthermore, bamboo's inherent ability to repel pests and fight illnesses diminishes the necessity for chemical intervention, rendering it an eco-conscious option for construction, furniture manufacturing, and even as a sustainable energy resource. Throughout history, bamboo has played a crucial role in numerous cultures worldwide, thanks to its adaptable and environmentally friendly characteristics. Bamboo has been utilised for various purposes throughout different cultures, spanning from ancient civilizations in Asia to indigenous tribes in South America. Its applications include construction, furniture production, handicrafts, and the creation of musical instruments (Chen et al., 2021; Quintero et al., 2022). Examining the extensive historical utilisation of bamboo underscores the significance of its durability and the inventive methods employed by diverse societies to exploit its capabilities.

Bamboo composite has become a viable substitute for conventional materials across multiple industries in recent times. The composite material possesses remarkable durability, low weight, and eco-conscious properties, making it highly promising for a wide range of uses, including supercapacitor electrode, automotive, and aerospace applications (Morales & Lopez, 2015; Tian et al., 2015). Nevertheless, it is crucial to delve into the significance of bamboo composite research in order to comprehensively grasp the revolutionary influence it can exert on our future. Although there is significant literature on bamboo fiber-enhanced composites, there is a limited number of reviews specifically focused on the manufacturing of bamboo-reinforced composites. Hence, this study primarily examines the attributes and efficacy of bamboo fibers, compares different production methods with the qualities of bamboo fiber-reinforced composites, and explores its many uses across numerous industries.

Characteristics of Bamboo

Bamboo, a member of the Poaceae family and a type of grass, possesses distinctive attributes that render it exceptional in multiple domains, particularly in construction, art, and as a raw material for numerous industries. Bamboo possesses a hierarchical arrangement consisting of interconnected segments referred to as nodal internodes. Every street is divided by a node, which contains a sturdy, unattached wall. The presence of bamboo in these areas provides the plant with remarkable pliancy and robustness. Bamboo exhibits a wide range of sizes and shapes, spanning from diminutive varieties measuring a few centimetres in height to towering forms surpassing 1200 cm in height. The leaves exhibit a lanceolate or orbicular shape and possess a characteristic green hue, facilitating proficient photosynthesis (Ramakrishnan et al., 2020).

The bamboo natural fiber, acknowledged as a secure and eco-friendly resource, encounters specific constraints in its range of utilization. Jiaxin et al. (2020) performed studies utilising ^{60}Co-γ beams to irradiate bamboo fibers with the intention of intentionally modifying their structure and boosting their physical and chemical characteristics. This was done to increase their utility and broaden their range of applications. The study employed infrared spectroscopy to examine alterations in the functional groups of Neosinocalamus affinis bamboo fibers that were subjected to different levels of irradiation. The experiment primarily examined alterations in hydration (mean water absorption, water adsorption capacity, water retention capacity), melting characteristics, and efficacy in absorbing heavy metal ions. The results demonstrated that irradiation treatment alters the peak type, position, and peak number in bamboo fibers, while only affecting the strength of absorption for specific characteristics. Nevertheless, the process of post-irradiation modification results in heightened hydration, expansion style, and the adsorption of heavy metal ions on bamboo fiber. The irradiation dose of 5 kGy yielded optimal results: the average water absorption reached 689%, the water retention capacity reached 7.49 (g·g−1), and the combined hydraulic style reached 6.84 (g•g−1); 4.03 (mL·g-1). Furthermore, the Ni2+ separation rate in water achieved a maximum of 41.0%, whilst the Cu2+ segregation rate reached an impressive 81.8%. The results indicate that exposure to 60Co-γ radiation can augment the distinctive physical and chemical characteristics of natural bamboo fibers. However, the progressive elevation of the irradiation dose to 10 kGy led to a reduction in hydration, expansion style, and the absorption of heavy metal ions.

Bamboo exhibits exceptional strength in proportion to its comparatively low weight, making it one of its primary distinguishing features. In certain specific instances, the traction strength of bamboo fiber composites is comparable to or even surpasses that of steel. Kaima et al., (2020) examined the impact of surface modification on the mechanical characteristics of bamboo. The bamboo was originally cut into little pieces of 60 mm in length, 5 mm in width, and 1 mm in thickness. The investigation incorporated the use of seven solutions, specifically filtered water (as a control), an ash solution, and NaOH (sodium hydroxide) in concentrations of 20%, 10%, and 5% by weight. Subsequently, bamboo segments are submerged in the solution for different durations, totaling 11 distinct immersions for all solutions except pure water, which entails five distinct immersion periods. Following the soaking process, the treated bamboo pieces undergo a thorough washing and are subsequently dried in the ambient air at room temperature for a duration of one week. The technique of hand separation is employed to extract processed bamboo fibers, with a penetration size ranging from 0.06 to 0.27 mm2. The testing procedure strictly adheres to the American Society for Testing and Materials, ASTM D3039 criteria, which require the examination of a minimum of five processed bamboo fiber samples. Specifically, higher concentrations of NaOH are associated with a reduction in traction strength, dropping below 100 MPa when using a 20% NaOH solution. Likewise, the traction force of the ash solution remains constant across various concentrations and immersion durations. When bamboo fibers are treated, their traction forces exhibit a range of 200–400 MPa during 48 hours of immersion. However, if the immersion duration exceeds 48 hours, the strengths of the fibers fall within the range of 275–300 MPa. In addition, when the fungus develops on the surface of bamboo fibers that have been immersed in purified water, the tensile strength of the bamboo fiber soaked in a 20% ashtray solution surpasses 100 MPa, in contrast to the bamboo fiber steeped in purified water for over 120 hours.

Bamboo possesses a diverse array of applications across multiple disciplines. Bamboo is used not only for constructing materials and furniture but also for crafting traditional musical instruments, culinary utensils, writing implements, and as a source of raw materials in the textile and paper sectors. Bamboo has also been increasingly utilised in environmental applications, including reforestation, soil preservation, and erosion mitigation. In their study, Molari et al., (2020) investigated the potential of using bambo as an alternative to conventional construction materials across several applications. While several countries have a rich tradition of utilising bamboo in building for many years and consider it a very valued resource, there are other areas where knowledge about the structural characteristics of locally grown bamboo is still lacking. It is crucial to enhance understanding of the mechanical characteristics of indigenous bamboo species, together with the establishment of standardised testing protocols. In this way, they clearly explain the results of experiments that looked at the mechanical properties of five types of bamboo grown in Italy: Phyllostachys bambusoides, edulis, iridescens, violascens, and vivax. While the pressure testing technique adheres to the ISO Standard, the use of the ISO-recommended approach for pull testing presents a difficulty. Consequently, various arrangements have been suggested. Furthermore, the concluding section of this paper rigorously examines the International Standard Organization (ISO) approach and demonstrates its potential for enhancement. The findings of this study provide an understanding of current obstacles and propose potential future pathways for the broader implementation of natural materials in buildings.

In 2020, Martijanti et al., conducted an evaluation of the attributes of three varieties of bamboo, namely string bamboo, bamboo gombong, and haur hejo bamboo, to determine their suitability as amplifiers in composite buildings. The three types of bamboo fibers undergo a basic treatment with variations in NaOH content (4% and 6%) and immersion duration (1, 2, and 3 hours). The initial pre-treatment process entails subjecting the material to bamboo fiber under certain conditions: a temperature of 120°C and a pressure of 0.5 MPa, achieved by the utilisation of steam explosion technology. The bamboo fibers are subjected to characterisation using FTIR analysis, and the tensile strength is quantified. The traction test findings indicate that the bamboo rope, Gombong, and Haur Hejo possess traction strengths of 710 MPa, 418 MPa, and 457 MPa, respectively. In addition, the Fourier Transform Infrared Spectroscopy (FTIR) analysis revealed the presence of a consistent low-intensity peak of lignin, characterised by the aromatic C = C (alkyne) bond, within the wavelength range of 1500 to 2600 cm-1 across all species of bamboo. Furthermore, there was a noticeable augmentation in the maximum strength of cellulose, as shown by the presence of an aromatic group C = H (alkene), within the wavelength range of 1900-2400.

Several items establish certain criteria to ensure quality, such as heat stability. Hence, bamboo fiber plays a crucial role in enhancing the performance of bamboo-reinforced composite materials. Q. Zhang et al. (2022) improves the thermal stability and functioning of bamboo fibers with the application of non-electric coating techniques. Studies have shown that the quantity of metal deposits significantly influences the thermal stability of bamboo fiber (BF). By identifying critical thresholds, it is possible to determine the point at which the coating layer completely covers the entire BF surface, leading to a substantial enhancement in thermal stability. The thermogravimetric analysis exhibited a substantial 31°C rise in the first degradation temperature of BF. Additional understanding of the enhanced thermal resistance resulting from the application of a non-electric coating was acquired using X-ray diffraction (XRD) and thermogravimetric-Fourier transform infrared (TG-FTIR) spectroscopy. The findings indicate that the application of coatings efficiently functions as a barrier against the penetration of oxygen from the outside, consequently delaying the initiation of degradation and the pace of pyrolysis. Moreover, intriguing findings demonstrate that the non-electric coating procedure not only enhances thermal stability but also concurrently enhances the characteristics of hygroscopicity, electricity, and magnetism. This study presented a novel method for altering BF, highlighting the significance of broadening the range of BF implementation. The surface treatment of bamboo fiber is crucial for enhancing the adhesion with the matrix, enhancing mechanical capabilities, lowering water absorption, improving the uniformity of fiber distribution, and even enhancing resistance to corrosion or degradation.

By applying appropriate surface treatment, the incorporation of bamboo fibers into composites can greatly enhance their quality, strength, and durability, while also enhancing their overall performance in various applications (Yamashiro & Nishida, 2015). An in-depth comprehension of the physical and mechanical characteristics of bamboo fibers is crucial for their utilisation in industry. This data serves as the foundation for designing materials that are optimised, devising manufacturing processes that are efficient, anticipating the performance of materials under different conditions, and enhancing materials while also generating new innovations. By acquiring the appropriate expertise, it is possible to enhance and expand the utilisation of bamboo fibers across several industrial domains.

Manufacturing and Properties of Bamboo Composite Materials

The process of bamboo extraction commences with the careful selection of suitable bamboo culms, followed by the precise cutting and elimination of moisture and other non-cellulosic substances. Subsequently, bamboo fibers are removed by mechanical or chemical means in order to procure pristine and robust fibers (Liew et al., 2015). Bamboo fibers undergo treatment through several methods, including alkaline treatment using a NaOH solution (X. Zhang et al., 2015). This treatment serves to enhance the fiber's durability and eliminate undesirable lignin and resin. Treatment may additionally encompass processes such as desiccation, refining, or other interventions with the objective of enhancing the mechanical characteristics and overall excellence of bamboo fibers. Following the extraction and treatment procedure, bamboo fibers can be utilised as primary resources for composite production. During the manufacturing process, bamboo fibers are combined with matrices such as resins or other polymers. Subsequently, these combinations are created and manipulated as necessary, perhaps utilising techniques such as moulding, lamination, or other fabrication processes, in order to produce robust, lightweight, and appropriate bamboo composites for specific purposes, such as construction materials, furniture, or other items.

Pacaphol et al. in 2023 have investigated the process and method of extracting natural fibers from bamboo plants. The pulp purification process entails pulverising desiccated bamboo leaves and subjecting them to a solution of 6% b/v sodium hydroxide (NaOH with a density ratio of 1:12) at a temperature of 80°C for a duration of 3 hours, which is repeated three times prior to proceeding to the bleaching phase. To bleach the pulp, it is subjected to boiling using a 1.8% b/v (density ratio: liquid 1:12) $NaClO_2$ solution (sodium chlorite) at a temperature of 85°C for a duration of 3 hours. Acid acetate is added to adjust the pH to 3.5–4, ensuring successful bleaching. The bleaching procedure is iterated three times to achieve a significant level of pulp bleaching. Regarding the production of bamboo leaf nanofiber, the pulp that has never been dried is diluted with water to achieve a concentration of 0.5% by volume. Subsequently, the mixture was blended in a high-speed blender (BUO −121280, Buono, Taiwan) at a speed of 38,000 rpm for a duration of 8 minutes. A high-pressure homogenizer (LM20 Microfluidizer, Microfluidics, Westwood, MA) with a Z-type interaction chamber (87 μm channel) was used to defibrillate the suspension. The defibrillation process is conducted with a constant circulation of 200 mL of cellulose powder at an operating pressure of 1.380 bar and a cooling temperature of 20°C. The defibrillation time is set at 60 minutes. In addition, a homogeneous liquid suspension comprises 0.5% by volume bamboo leaf nanofiber that is stored in a refrigerator at a temperature range of 8–10°C for later usage.

The application of surface modification of bamboo fiber can be extended to many materials. Wang et al. (2020) conducted a study on the surface treatment of bamboo fiber (BF) employing three distinct silane refractors, resulting in the formation of diverse functional groups: amino (KH550), epoxy (HH560), and methyl (KH570). The objective is to enhance the flexibility of the BF/polypropylene composite by improving the interaction between the fiber and the matrix. An investigation is conducted to analyse the impact of silane treatment on the mechanical characteristics and thermal behaviour of composites. The mechanical test evaluation demonstrated that the KH570 treatment exhibited the most efficient alteration, surpassing both KH550 and KH560 in enhancing mechanical qualities. The BF composite, treated with KH570 to enhance its traction strength and flexibility, achieved values of 36.1 and 54.7 MPa, respectively. This represents an increase of 15.4% and 23.6% compared to the Untrerated BF/PP composite when treated with a 5 wt% concentration of KH570. Furthermore, there was a rise in thermal stability from 467.0°C (untreated bamboo fiber) to 470.6°C. Incorporating 5% bamboo fiber treated with KH570 silane led to a rise in the crystallisation temperature by 1.7°C and a reduction in crystallinity by 5.8%.

Previous researchers have extensively looked into the relationship between surface treatment and the mechanical properties of composites. In 2022, Nelson & Riddle conducted a study in which they examined the correlation between the media treatment and the tensile strength and tensile modulus of a composite material made of bamboo-reinforced polypropylene. The results of this study are presented in Figure 1. Surface treatment has the ability to modify the surface characteristics of the fiber, hence impacting the adhesion between the fiber and the matrix in a composite material. Varying treatment techniques can lead to varying degrees of adhesions, impacting the transmission of load between the fiber and matrix.

Consequently, this has an effect on the tensile strength and the resulting composite modules.

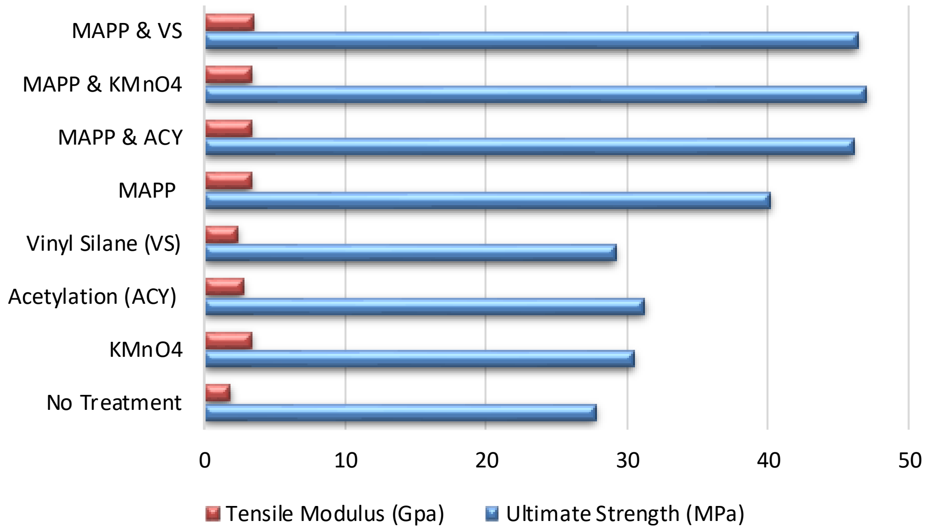

Figure 1. Mechanical properties of bamboo fiber-reinfroced polypropylene composite

Venkatesha & Saravanan, (2020) assess the impact of including fillers in a composite material reinforced with bamboo. As a particle filler, cenosphere fusion is looked at in this study to see how it affects the mechanical properties of hybrid materials made from bamboo and crab species. This hybrid composite has bamboo and E-glass fibers as reinforcements, combined with an epoxy matrix. The hybrid composite is infused with varying weight percentages of cenospheres, ranging from 0.5% to 2%. The ASTM standard provides guidelines for conducting mechanical property tests on samples to evaluate the impact of filler material content. When up to 2% of cenosphere ceramic waste is added as a filler, the results show that the mechanical properties, such as tensile strength, flexibility, and inter-laminar shear strength, are much better than when the composites are not filled. Moreover, Elements Analysis entails a comparison between the simulation results and the experimental findings. The study shows that the experimental values from the pull and slope tests and the values from element analysis are very similar. This means that the two datasets are very closely related.

In their study, Y. Zhang et al. (2023) assessed the variation in compression ratio during the manufacturing process of bamboo-reinforced composite materials. The absorption characteristics of the Neosinocalamus affinis bamboo fiber composite (BFC) were examined at compression ratios of 1.50, 1.83, and 2.17. The objective was to enhance the production of BFCs and reduce product absorption. The results indicate that, at different levels of relative humidity (RH), the BFC sample exhibits lower hygroscopicity compared to raw bamboo across all three compression ratios. More precisely, BFC generated with a compression ratio of 1.50 exhibited the lowest water balance (EMC) content. The BFC absorption capacity has a noticeable trend as the compression ratio increases, particularly at relative humidity values exceeding 60%. A refinement in the suggested BFC water-absorption model establishes a connection between variations in moisture, porous structure, and chemical reactions. Adding formaldehyde phenolic resin (PF) and pressing materials together reduces the number of water-moving channels, like bamboo cell lumens, holes, and fractures, and also the amount of water that can be absorbed by cell walls. Simultaneously, increased BFC compression ratios present a difficulty in water absorption. The enhanced ability of BFC to absorb moisture in a high relative humidity (RH) environment is due to an elevated compression ratio, which leads to a higher proportion of mesopores. Consequently, this results in a greater amount of water being retained on the poly layer. Hence, it is crucial to ascertain the ideal BFC compression ratio by considering the many performance criteria and the required application environment relative humidity (RH) in practical scenarios.

Injection moulding is a commonly used technique in the production of bamboo-reinforced, eco-friendly composites. Govinda & Widiastuti (2023) have conducted research on optimising injection mould parameters for producing polypropylene composite (r-PP) or recycled cotton using the Taguchi method. This study used the L9 orthogonal Taguchi matrix, which has undergone three replications. (considered as noise). The primary process parameters consist of 1) barrel temperature, 2) print temperature, and 3) cooling time, each having three distinct levels. The traction properties of specimens are being looked at in this study using an orthogonal arrangement, signal-to-noise ratio (S/N), and variance analysis (ANOVA). The results indicate that while the processing parameters have a negligible effect on the traction force, they predominantly influence the modules. The barrel and stamp's temperatures were the main determinants of the pull module. The parameter that yielded the most favourable results, with minimal deviation from the desired value of the pull modulus, was determined to be a barrel temperature of 165 °C, a printing temperature of 75 °C, and a cooling period of 18 seconds. The purpose of this outcome is to determine the optimal parameter value for the printing process of recycled polypropylene composite injection reinforced with bamboo fiber.

The thermo-mechanical characteristics of bamboo fiber-reinforced epoxy polymer compounds can be assessed and manufactured using compression printing techniques and hand layouts. The laboratory-scale compression printing equipment is constructed using recycled components sourced from the Tezpur University Centre workshop in India. In order to achieve the desired concentration of NaOH for treating bamboo fiber pieces, samples were subjected to solutions with NaOH concentrations of 5, 8, 12, and 15 wt.% for a duration of 12 hours per sample. By conducting a single fiber pull test, a single fiber withdrawal test, electron microscope scanning (SEM), and Fourier transformation infrared spectroscopy (FTIR), it was shown that bamboo pieces treated with a 12 wt.% NaOH solution yielded the best results for composite manufacture. The alkaline treatment especially enhances the bond strength between the interface and the epoxy resin. The research findings indicate that bamboo fiber slices treated with sodium hydroxide (NaOH) concentrations of 8, 12, and 15 wt.% exhibited enhanced compatibility with resin. Furthermore, the study examined the impact of mechanical and thermal properties on composites fabricated using two distinct production methods. Thermogravimetry analysis (TGA) was employed to investigate the thermal properties of composites. Comparative analysis demonstrated that composites fabricated with a compression printing machine exhibited higher mechanical properties in comparison to the composites created using hand-lay-up techniques. The citation is from (Barman et al., 2023).

Shi et al. conducted a study in 2021 to assess the impact of the moulding process on the bamboo-reinforced epoxy polymer composite. Filament folding is an advanced method used to create high-performance composites. It allows for the production of intricate non-planar composites without the need for pressure. This approach involves employing curved fibers that are soaked in resin. The work employed filament fusion processing (FWP) to fabricate bent bamboo fiber composites (TBF) using short bamboo fibers (SBF) and long bamboo filaments (LBFs) by heat pressing (HP) and resin transfer printing (RTM). The findings revealed a direct association between the dimensions of bamboo and epoxy resin composites, indicating a positive relationship. The bamboo/epoxy fiber composites manufactured by FWP exhibited exceptional sliding performance, but the composites generated by RTM demonstrated superior sliding characteristics. The use of dynamic thermo-mechanical analysis allows for the identification of optimised interfaces in composites manufactured using FWP. FWPs encompass the process of immersing resin and aligning TBFs with folding equipment once they have been coated with resin. Bubble pores are evenly distributed on both sides of the TBF after post-heating solidification, and they remain in fixed locations. The implementation of filament folding processing enhances the efficacy of bamboo fiber composites, indicating broader potential applications in this domain.

Different techniques used in the production of bamboo fiber-enhanced composites have a notable influence on the performance of the composites (Xie et al., 2016). These factors can be observed through their impact on the arrangement and spread of fibers, the level of interaction between fibers and the matrix, the compactness of the material, the presence of empty spaces, and the overall structure of the composite at both microscopic and macroscopic levels. Different manufacturing techniques also have an impact on the composite's thermal characteristics and stability. Hence, it is crucial to carefully choose the appropriate manufacturing technique to guarantee that the composite possesses qualities that align with the application's requirements and achieve optimal performance.

Applications of Bamboo Composite Materials

Bamboo, a highly adaptable and environmentally friendly material, has gained significant popularity in recent times due to its wide range of applications. Bamboo's composite material is highly promising, as it harnesses the inherent strength of bamboo fibers and blends them with various bonding agents to produce a diverse array of creative goods. Bamboo fibers have achieved notable advancements in the transportation business, particularly in the production of vehicles such as automobiles, trains, aircraft, and even spacecraft. Polylactic acid (PLA) can be used as a constituent in a composite hybrid material, together with pine, bamboo, and coir fiber, to create a substance that functions as a sound absorber and vibration suppressant in automobiles (Yusoff et al., 2023). The fabrication of automotive coating materials involves the amalgamation of titanium dioxide (TiO2) within a bamboo fiber/polypropylene composite. The citation is from the work of K. Zhang et al. published in 2023. In a study conducted by Murali et al. (2023), epoxy-resin hybrid composites were created to strengthen kevlar, aloe vera in mat form, and bamboo. These composites were intended for use in automobile applications, specifically for engine protectors, damper covers, roof panels, door panels, and wipers. The strength, stiffness, lightweight, corrosion resistance, environmental friendliness, vibration and noise insulation, and design flexibility of bamboo fibers make them valuable in the transportation industry.

Bamboo fibers are extensively utilised for various applications owing to their plentiful natural availability, commendable performance, environmentally friendly nature, and sustainable characteristics. Bamboo fibers can be easily combined with different types of fibers and fillers to create products for use in the construction, food, packaging, drinks, and energy industries (Borowski, 2021). The use of fibers and bamboo slices as additives in the manufacturing process of loose concrete beams is justified by their superior pressure strength values, surpassing the standards set for commercial products (Torres et al., 2023). Bamboo fiber can be used in conjunction with clay soil and corn starch for the production of food storage containers and packaging due to its superior heat conductivity in comparison to pure polystyrene material (Balakrishnan & Hashim, 2022). Jia et al. (2022) employed waste paper cups combined with cellulose-based film derived from bamboo as a beneficial inclusion in the packaging and transportation industry because of its affordability and impressive mechanical and hydrophobic characteristics. Previous studies have indicated that composites made of bamboo microcrystalline cellulose-reinforced poly (lactic acid) (PLA) and poly (butylene succinate) (PBS) exhibit favourable characteristics for packaging purposes. These composites possess high tensile strength, thermal stability, and the ability to transform brittle materials into flexible ones (Rasheed et al., 2021). H. Zhang et al., (2023) found that bamboo fiber composites containing CaO have significant promise for solar energy storage in the energy field. These materials are also well-suited for large-scale industrial applications. Figure 2 illustrates many applications of bamboo fiber-reinforced composites.

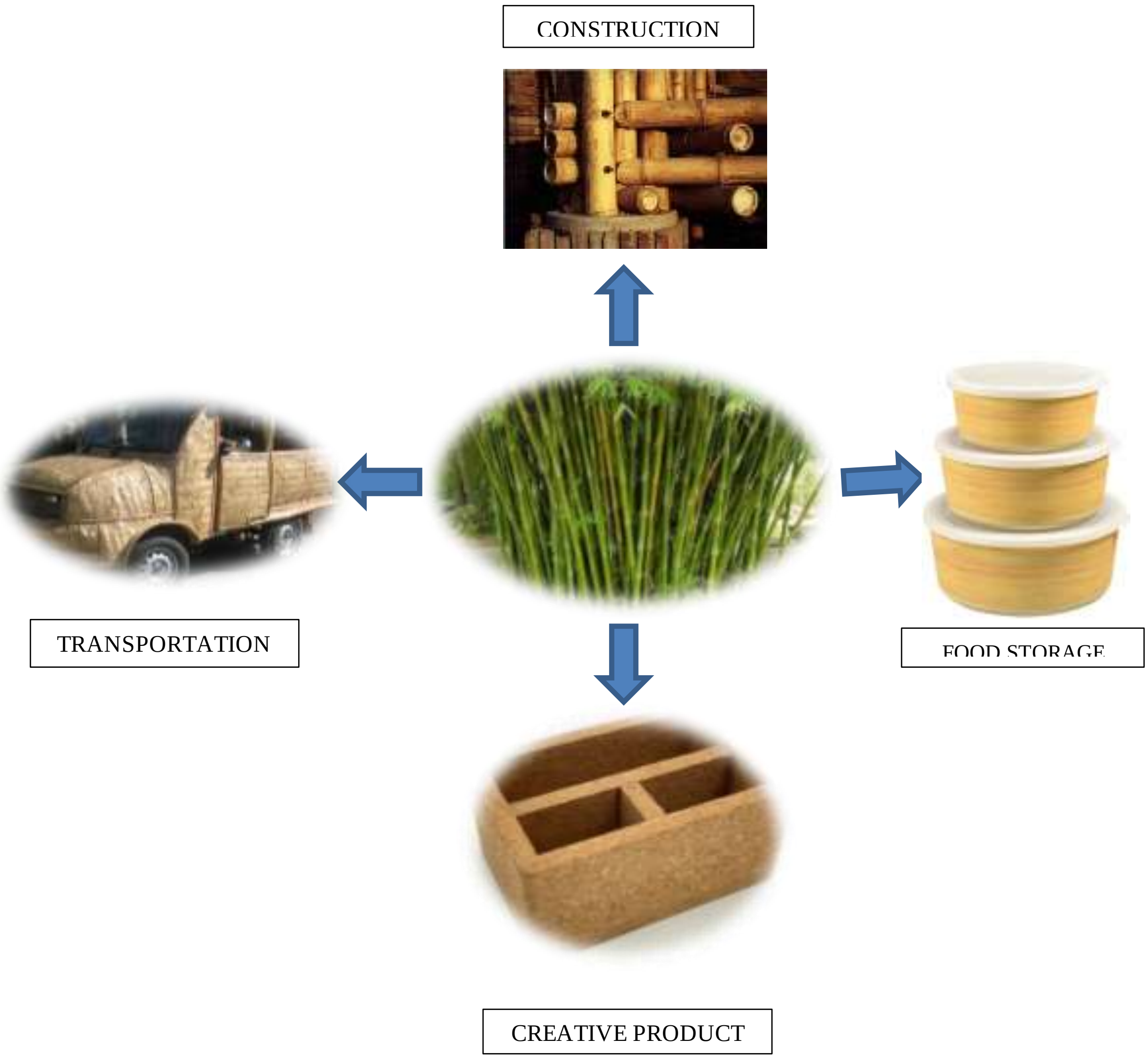

Figure 2. Application of bamboo fiber-reinforced composite

Conclusion

This review article provides an in-depth overview of the properties of bamboo fibers, the several manufacturing techniques used to produce bamboo fiber-reinforced composites, the physical and mechanical attributes of these composites, and the diverse range of applications they can be used for. Bamboo fiber possesses several valuable characteristics that render it an appealing option as a natural fiber for composites, such as its strength and stiffness, lightweight nature, resistance to corrosion, biodegradability, and ecologically beneficial properties. Additionally, it is widely accessible and cost-effective, while also offering flexibility and adaptability. The surface treatment of bamboo fibers is crucial for enhancing binding strength, minimising water absorption, enhancing mechanical properties, ensuring uniform distribution of fibers, improving resistance to degradation, and making it a superior component for various industrial applications. Understanding the attributes, benefits, and limitations of each manufacturing technique in the given application context can aid in selecting the suitable process to fabricate composite materials with the necessary performance. Bamboo fiber-enhanced composites possess exceptional attributes such as strength, light weight, and eco-friendly features, making them highly potential for use across numerous industries such as construction, food packaging, transportation, and energy.

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