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Review Article

Weaving a Greener Tomorrow: A Mini Review of Bamboo Fiber, Textiles and Hand-woven Techniques for Sustainable Innovation

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ABSTRACT

Bamboo, known for its rapid growth and renewability, offers an eco-friendly alternative to traditional fibers, targeting the environmental effects of the textile and clothing industries. This review paper examines art-crafted weaving techniques, highlighting the incorporation of bamboo into traditional and modern designs to enhance the sustainability of bamboo-woven products. The paper thoroughly analyzes bamboo fiber extraction and hand-crafted techniques to produce sustainable, technical, and functional items such as sportswear and medical textiles. It also addresses the challenges linked to utilizing bamboo in textiles. Special emphasis is given to integrating bamboo into traditional weaving methods as a sustainable approach to enhance its uniqueness and preserve cultural heritage. By exploring sustainable practices and artistic innovation, this paper underscores the significance of connecting traditional craftsmanship with contemporary weaving design principles to fill research and practice gaps. In light of the ecological challenges posed by fast fashion, this study promotes sustainable practices by incorporating renewable materials and prioritizing brilliant material selection. Ultimately, this review emphasizes the vital role of design in fostering sustainability and provides a roadmap for preserving weaving traditions.

Keywords: Bamboo fiber, bamboo weaving, design for sustainability, eco-friendly materials, renewable fiber technologies, sustainable textiles, traditional weaving

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INTRODUCTION

The detrimental environmental impact of the textile and clothing industry underscores the urgent need to adopt sustainable practices.

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The fast fashion industry's reliance on non-renewable resources causes significant environmental harm, with millions of fabrics ending up in landfills daily. The global textile and clothing market, valued at USD 1,837 billion in 2023, is projected to grow by 7.4% from 2024 to 2030. Synthetic fibers, a cornerstone of modern textiles, significantly contribute to pollution due to their production processes and resistance to biodegradation. In this context, incorporating renewable materials like bamboo is beneficial and essential for fostering environmental sustainability.

Bamboo, recognized as the fastest-growing woody plant in the world, even surpasses the most rapidly growing trees, with some species capable of growing up to one meter per day. Its remarkable properties, including strength, flexibility, and UV protection, make bamboo culm fibers highly suitable for various applications, such as textile and yarn production. Products made from bamboo range from clothing to hygiene items (e.g., sanitary napkins, masks, bandages) and home furnishings. These unique qualities position bamboo as an intriguing and viable alternative to conventional fibers in the textile industry (Akinlabi et al., 2017; Kozłowski & Mackiewicz-Talarczyk, 2020).

In recent years, global trade and technological advancements have transformed industries, increasing awareness of the essential need to preserve and revitalize traditional crafts like weaving. Handloom and crafted woven products are a vital cultural bridge between heritage preservation and sustainable innovation. As timber from forests becomes scarce, industries seek cost-effective, fast-growing, and readily available alternatives such as bamboo, which has structural and physical properties comparable to wood. Beyond its functionality, bamboo textiles can be transformed into luxury items by incorporating design principles, resulting in intricate aesthetics and improved usability.

Government initiatives, such as expanding bamboo plantations and innovations in bamboo fiber processing, have spurred the growth of bamboo crafts and textiles. While bamboo has been studied for furniture, paper production, and the textile industry, its applications in handcrafted woven design and high-fashion products remain limited. To bridge this gap, integrating bamboo into either craft or handloom weaving practices in clothing and fashion design presents a promising opportunity to preserve the heritage of weaving techniques while allowing designers to create eco-friendly and innovative products. This paper aims to explore the prospects and existing practices in this field.

MATERIAL AND METHODS

This review examines bamboo’s role as a sustainable material, from its origin and extraction to handicraft design and handloom weaving, while emphasizing its minimal environmental impact. It synthesizes existing literature on bamboo’s unique properties, weaving techniques, and material applications to provide a comprehensive overview. A significant gap exists in extensive research that combines bamboo fiber processing with sustainable, art-crafted techniques. This gap in the literature highlights the need for further study. This paper investigates how bamboo catalyzes innovation in sustainable textiles while preserving traditional weaving heritage techniques. Bridging traditional craftsmanship with modern design principles offers designers a roadmap for integrating bamboo into future sustainable applications. A systematic literature review was conducted to achieve this, focusing on studies published over the past two decades. Keywords such as "bamboo textiles," "design innovation," "bamboo characteristics," "bamboo weaving," and "sustainable textile" guided the search across databases like Scopus, Google Scholar, and ScienceDirect. This review provides a detailed analysis of bamboo textiles from sustainability, material science, and design innovation perspectives, offering insights for future research and development.

RESULT AND DISCUSSION

Comparative Analysis of Bamboo Fiber and Other Natural Fibers

Bamboo is an exceptionally fast-growing plant, maturing in 3 to 5 years compared to 20 years for most types of wood. It can grow up to two inches per hour, reaching 60 feet within three months (Neha & Aravendan, 2023). According to Neha and Aravendan (2023), its primary components include cellulose (41%–73%), hemicellulose (61%–73%), and lignin (21%–28%), with its high lignin content providing bamboo with remarkable strength and mechanical properties. Cellulose, the dominant component in bamboo, is a sustainable biomaterial that is non-toxic, biodegradable, and renewable (Amjad, 2024). It imparts rigidity and tensile strength due to its composition of carbon, hydrogen, and oxygen (Neha & Aravendan, 2023). Furthermore, hemicellulose, the amorphous portion of bamboo fibers, contributes to their acidic nature, moisture retention, and bonding with lignin through ester bonds-variations in hemicellulose and lignin content influence bamboo's mechanical and chemical properties (Hu et al., 2019). For instance, nodes contain higher levels of moisture and hemicellulose but lower levels of lignin and cellulose, leading to reduced density and mechanical properties (Jalil, 2022). Bamboo's mechanical properties vary depending on species, growth conditions, and structural characteristics (Chen et al., 2017). Research has demonstrated that removing hemicellulose decreases bamboo's tensile modulus, while removing lignin has no significant effect (Chen et al., 2017). Fiber fineness impacts fiber length and density, with coarser fibers providing better durability and tensile strength (Rocky & Thompson, 2018). Additionally, bamboo's durability relies on its tensile strength, flexural strength, and moisture absorption. Smaller bamboo culms are less stable under humidity than larger, thicker-walled ones (Liese & Tang, 2015).

As a natural resource, bamboo requires significantly less water for cultivation compared to water-intensive crops like cotton (Gericke & Van der Pol, 2010). Restrepo et al. (2016) highlighted bamboo's potential to reduce environmental harm in manufacturing processes. Many bamboo species thrive without pesticides or fertilizers, which minimizes the environmental impacts of chemical use in agriculture. This underscores bamboo's potential as an eco-friendly alternative to conventional materials like wood-polymer composites, offering a significantly lower carbon footprint (Rocky & Thompson, 2018). Shinohara et al. (2019) also underscored bamboo's capability to prevent erosion and improve soil quality, emphasizing its long-term conservation value. Despite its numerous benefits, many current extraction techniques are not environmentally sustainable. The extraction processes impact the removal of lignin, which affects fiber stiffness and discoloration, as well as non-cellulosic components that influence properties like strength, density, moisture absorption, and flexibility (Kozłowski & Mackiewicz-Talarczyk, 2020). Additionally, chemical treatments lighten the yellowish-brown fibers caused by lignin and enhance bamboo's UV absorption and antibacterial properties, making it suitable for textiles (Neha & Aravendan, 2023). The following section will address strategies for improving the sustainability of bamboo fiber processing.

Previous research compared bamboo viscose fibers with other textiles, highlighting their superior tensile extensibility and comfort. For instance, Mishra et al. (2012) showed that bamboo viscose fabrics exhibited greater tensile extensibility than cotton and blends of cotton and bamboo viscose. Compared to cotton, bamboo viscose's reduced shear rigidity and bending stiffness contribute to its enhanced comfort and hand feel (Mishra et al., 2012). Additional studies indicate that natural bamboo yarns possess improved tearing strength, excellent dye absorption, and better wrinkle resistance than cotton, making bamboo an appealing choice for sustainable textile applications (Kushwaha et al., 2023; Singh & Dessalegn, 2021). Bamboo's minimal water requirements make it a sustainable option, especially in water-scarce regions, as it uses significantly less water than cotton, sometimes as little as 500 liters per kilogram of biomass without additional irrigation (Nayak & Mishra, 2016). Nassar et al. (2020) examined the thermal comfort properties of single jersey fabrics made from 100% bamboo, cotton-bamboo-polyester microfiber, bamboo-polyester microfiber, and cotton-polyester microfiber blends. The 100% bamboo fabric exhibited the highest thermal conductivity of the tested fabrics, while the cotton-polyester fabric had the lowest (Nassar et al., 2020).

Additionally, bamboo fabric demonstrated better thermal conductivity than bamboo-polyester microfiber fabric (Tausif et al., 2015). Tausif et al. (2015) found that the yarn arrangement within the fabric also plays a crucial role in determining fabric thickness, and the low weight of bamboo samples suggests that bamboo fibers could serve as a competitive alternative to cotton and microfiber polyester, particularly in sportswear applications such as sports headscarves. Figure 1 outlines the key properties of bamboo as a material resource. The methods used for fiber extraction have a significant impact on the characteristics of the final product, with viscose-like chemical processes providing predictability in fiber structure and properties thanks to cost-effective equipment, low energy requirements, and

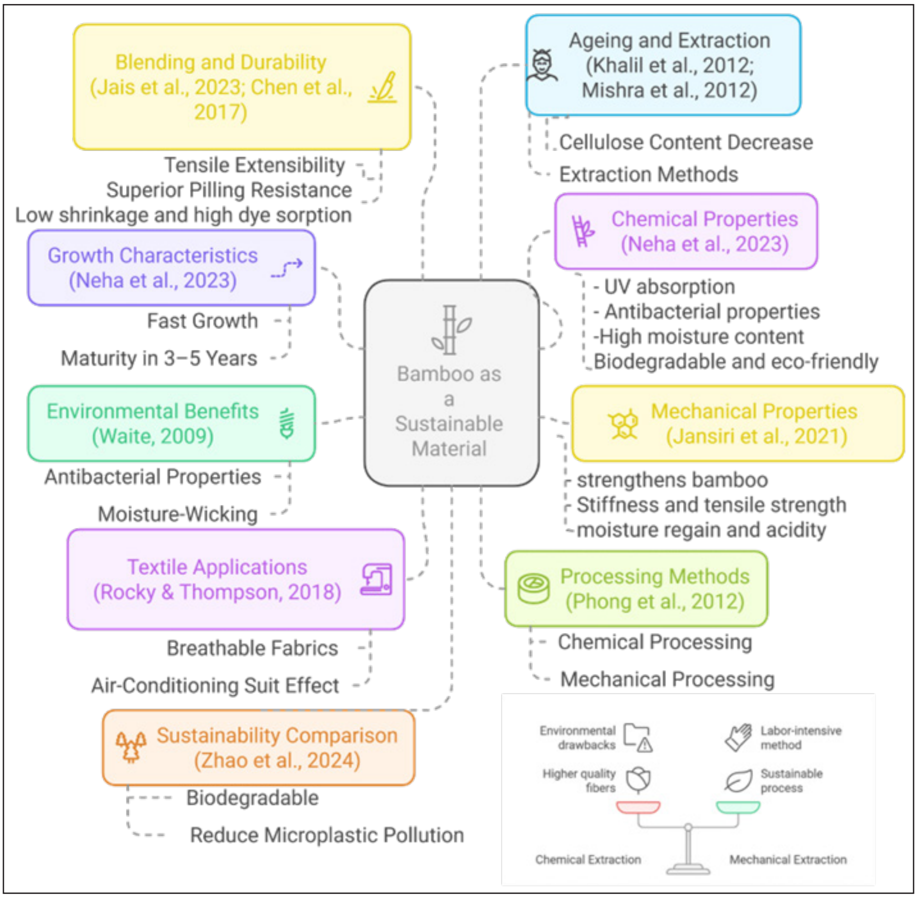

Figure 1. Key characteristics and properties of bamboo as a renewable and sustainable material resource

control over fiber attributes compared to mechanical or steam-explosion methods (Phong et al., 2012).

Bamboo Fiber Extraction Methods and Their Impact on Textile Properties

Bamboo fiber can be obtained through three primary methods: mechanical, chemical, and hybrid extraction techniques (Hu et al., 2019). Mechanical and chemical methods yield bundles of natural bamboo fibers, while chemical processes, such as the viscose method, produce regenerated bamboo cellulose, commonly known as bamboo viscose (Hu et al., 2019). The fiber extraction process begins by splitting bamboo culms into strips, followed by either mechanical or chemical processing based on the intended use (Phong et al., 2012). Mechanical processing produces coarse and rigid fabrics, whereas viscose-extracted fibers create soft, drape-friendly textiles (Singh & Dessalegn, 2021). Mechanical extraction involves soaking bamboo strips in water or boiling them, beating, scraping, and combing to produce spinnable fibers (Hu et al., 2019). These fibers undergo further treatment with alkali solutions to improve their properties (Nayak & Mishra, 2016). The variations in strength and durability between these methods arise from molecular changes introduced during chemical treatments, which modify the fiber's structural alignment and level of polymerization. Chemical extraction entails treating bamboo slices with caustic chemicals like sodium hydroxide or sodium silicate to produce fine fibers suitable for textiles (Hu et al., 2019). Enzymatic and microbial treatments have also been investigated for degumming; however, these methods are time-consuming and may not suffice for industrial needs (Zhao et al., 2024). Asmarea et al. (2022) noted that the combined extraction methods, which included alkali and a newly developed composite enzyme in both concentrated and solution forms, produced finer bamboo fibers from three different bamboo species by breaking down and removing non-cellulosic components of the bamboo strips.

Sustainable manufacturing practices aim to reduce environmental harm, minimize waste generation, and lessen reliance on non-renewable resources, enhancing overall environmental performance (Jalil, 2022). Mechanical extraction is more sustainable because it avoids chemicals and preserves bamboo's natural properties (Hu et al., 2019). However, this method is labor-intensive, water-intensive, and costly, resulting in coarser fibers. In contrast, less sustainable chemical methods produce finer fibers with superior softness and drape. These distinctions significantly affect the behavior of yarns and fabrics derived from each method (Gericke & Van der Pol, 2010; Khalil et al., 2012). However, chemical bamboo extraction is more cost-effective and generates fine, soft fiber since it eliminates lignin. Despite this advantage, it is less sustainable and requires closed-loop systems to manage environmental damage. Given that the complex structure of bamboo contains high levels of lignin, which obstructs prompt fiber extraction (Phong et al., 2012), it is challenging to achieve absolute benefits from extracting fibers using any one technology (Singh & Dessalegn, 2021).

Previous researchers combining pretreatment or post-treatment of bamboo strips with some alkali solutions, such as softeners and mechanical processes, achieved highly effective and improved thermal properties (Rocky & Thompson, 2018; Singh & Dessalegn, 2021). Some researchers have utilized a combined extraction method that employs low alkali consumption and multiple enzymes to transform spinnable fibers while maintaining their antibacterial properties and minimizing environmental impact (Jalil, 2022). The type of extraction influences fiber characteristics, spinning qualities, and ecological sustainability, benefiting sustainable textile applications. Although enzymatic treatment is the most sustainable, the microbial culture is not economically viable (Rocky & Thompson, 2018). Both extraction methods begin with splitting the strips, followed by either mechanical, chemical, or enzymatic treatment (Zhao et al., 2024). Mechanical treatments demonstrate the highest tensile strength, making them ideal for the construction sector due to their compatibility with high-strength materials (Rocky & Thompson, 2018). In contrast, chemical or combined treatments result in lower tensile strength as the fiber becomes weaker, finer, and suitable for yarn processing (Neha & Aravendan, 2023).

Several wash cycles are necessary to eliminate the residual chemicals in wastewater, which are not deemed fully sustainable, as Hu et al. (2019) noted, to prevent issues with bamboo crystallinity. However, the primary focus of sustainability in textile products pertains to the use of harsh chemicals and process efficiency. Mechanically extracted bamboo fibers outperform flax and jute in their resistance to pilling and abrasion. Furthermore, they exhibit lower shrinkage, improved color clarity, and a soft luster without mercerization. As illustrated in Figure 2, combined treatments are more sustainable, offer faster processing times, consume less energy, and yield better results. This process produces fine, soft fibers that are beneficial for textile applications. Tausif et al. (2015) discovered that bamboo fibers possess properties comparable to viscose rayon, cotton, and modal fibers but with slightly more extraordinary wet tenacity. Bamboo's versatility allows it to blend well with other fibers, such as cotton, hemp, and lyocell, resulting in fabrics with varied characteristics (Jais et al., 2023). As shown in Figure 1, maintaining a balance between fiber quality and sustainability is crucial in bamboo fiber production.

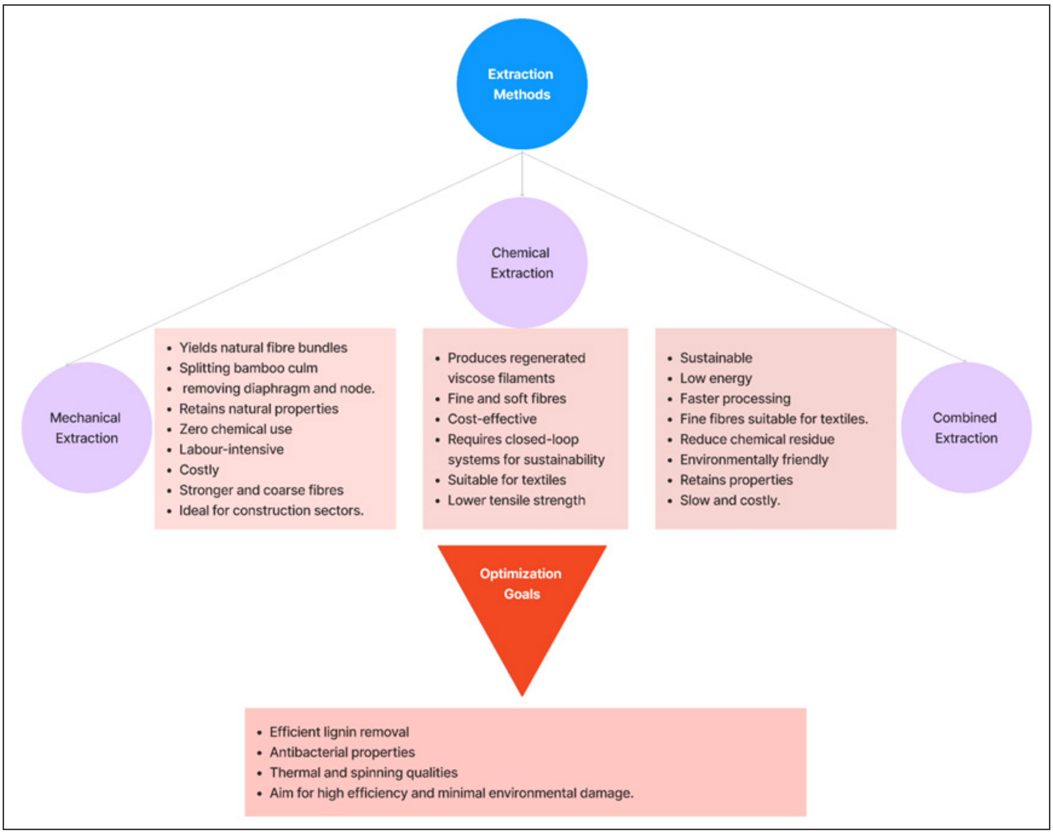

Figure 2. Extraction of bamboo methods and their characteristics

Bamboo Textile Properties

Bamboo fiber is widely used in the textile industry because of its unique properties, with applications in yarns, woven, knitted, and nonwoven fabrics. Bamboo yarn, made from continuous filaments, is the foundation for textile construction (Waite, 2009). Knitted bamboo fabric, created by interlocking loops, is flexible and breathable, making it ideal for comfortable garments (Mishra et al., 2012). In contrast, woven bamboo fabric, produced by interlacing two sets of yarn at right angles, offers durability suitable for garments and upholstery, although its production is not environmentally sustainable (Mishra et al., 2012). Nonwoven bamboo fabric, made directly from fibers without weaving or knitting, is used in items such as filters, wipes, and medical textiles, showcasing bamboo's versatility (Gericke & Van der Pol, 2010; Prakash et al., 2021; Zhao et al., 2024). Integrating bamboo into sustainable textiles and crafts addresses global demands for eco-friendly solutions (Jalil, 2022).

Khalil et al. (2012) noted that its use in functional clothing, sanitary products, biocomposites, and geotextiles illustrates its potential across various industries. Gao et al. (2024) pointed out that innovation in weaving techniques and material combinations can help overcome challenges, ensuring bamboo remains relevant in contemporary design. Products derived from bamboo are often marketed as "green" or "biodegradable," regardless of their production methods (Hardin et al., 2009). Structurally, bamboo is an anisotropic natural composite material primarily made of vascular bundles embedded in a parenchymatous matrix (Liese & Tang, 2015). Research by Ozkan (2021) examined the engineering potential of bamboo for sustainable textile development, focusing on its unique properties, benefits, and limitations. Previous research highlights the tensile strength of bamboo and its blended fabrics, which enhances the tensile performance of textiles (Chen et al., 2017). Bamboo viscose offers superior hand value to cotton due to its smoother texture and lower bending rigidity (Kaur et al., 2016). These properties position it as a critical resource for sustainable textiles combined with bamboo's rapid renewability and environmental benefits (Waite, 2009). In contrast to modern textiles, which predominantly use non-renewable materials, bamboo fibers are sustainable and have multiple advantages (Hu et al., 2019). Bamboo textiles are lightweight, breathable, moisture-wicking, and anti-static, with antibacterial properties that make them highly marketable (Tausif et al., 2015).

A study conducted by the China Textile Industrial Testing Centre and the Japan Textile Inspection Association found that 100% bamboo fabric achieved a 99.8% antibacterial kill rate (Waite, 2009). Bamboo textiles have inherent antimicrobial properties (Chaowana et al., 2021). Waite (2009) noted that bamboo fibers are soft, lightweight, and low-density, with a loose structure that enhances air permeability and comfort, especially in hot climates. Chonsakorn et al. (2024) indicated that a 70:30 bamboo-to-polyester fiber ratio is optimal for fabric production, providing enhanced strength, antibacterial activity, and suitability for medical and hygiene applications. This innovation aligns with sustainable textile practices by utilizing waste materials and reducing environmental impact (Chonsakorn et al., 2024). By leveraging these properties, bamboo textiles offer a promising path toward sustainable fashion and ecological responsibility.

Chonsakorn et al. (2024) developed a method for producing nonwoven fabrics by integrating bamboo and polyester fibers, utilizing mechanical bonding techniques such as needle punching. The resulting fabrics exhibited durability, a lightweight structure, and antibacterial efficacy, making them suitable for medical lifestyle products (Chonsakorn et al., 2024). Chonsakorn et al. (2024) emphasized the potential of bamboo waste as a renewable resource for sustainable textile applications, providing significant advantages in tackling environmental and public health challenges (Chonsakorn et al., 2024; Santos et al., 2021). This approach facilitates the creation of antibacterial nonwoven fabric, positioning it as a practical solution for elderly care in community settings (Chonsakorn et al., 2024). Nassar et al. (2020) demonstrated that the arrangement of yarns within the fabric influenced fabric thickness.

Furthermore, most functional bamboo textiles and fabrics feature moisture-wicking properties and UV protection, making them ideal for activewear, intimate apparel, and summer clothing (Amjad, 2024). Their natural antibacterial, hypoallergenic, and UV-blocking qualities further enhance their suitability for baby clothing, pregnant women, undergarments, and socks. Additionally, their smooth texture and draping qualities make them popular choices for home decor and accessories, including scarves, hats, and gloves (Kaur et al., 2016; Rocky & Thompson, 2018). Bamboo fibers and nonwoven bamboo fabrics are also used in sanitary products, such as bandages, masks, and surgical attire, due to their sterilizing and bacteriostatic characteristics (Rocky & Thompson, 2018). Products like hygienic towels and absorbent pads benefit from bamboo's natural antimicrobial attributes, eliminating artificial agents and reducing allergy risks (Lipp-Symonowicz et al., 2011; Tausif et al., 2015).

In addition to textiles, biotechnology has proven effective as a leading approach for advancing a sustainable and environmentally friendly wet-processing sector in textiles and producing eco-friendly value-added products. Therefore, bamboo fibers enhance biocomposites, providing eco-friendly, cost-effective, and biodegradable alternatives to traditional materials (Saha & Mandal, 2020; Santos et al., 2021). Ensuring wearing comfort is crucial since textiles remain in contact with the human body day and night. Ozkan (2021) noted that bamboo fibers have a naturally channeled structure with micro-holes that enable rapid moisture absorption and evaporation. This porous quality contributes to the fiber's capacity to absorb significant water, offering strength and low elasticity. Ozkan (2021) concluded that textiles made from natural bamboo fibers deliver superior wearing comfort due to their breathable structure.

Bamboo Craft Techniques

Gao et al. (2024) noted that the bamboo weaving craft in China, which achieved sophistication during the Song Dynasty (960–1279 AD), has been a hallmark of artistic and technological evolution. This traditional craft, using bamboo silk or splints in intricate weaving techniques, remains culturally significant and sustainable. Moreover, Yu (2023) noted that hand spinning, a unique and ancient technique for producing yarn and weaving, aligns with sustainable goals, as it does not require electric machinery and entails minimal energy consumption. Gao et al. (2024) found that modern and internationalized features in bamboo weaving patterns arise through specific coding styles. Geometric elements like circles, squares, and hexagons symbolize modernity. In contrast, patterns that incorporate traditional characters and motifs or plant-inspired designs evoke ethnic and traditional aesthetics, as noted by Luo et al. (2020). Additionally, central symmetry in patterns is generally linked with conventional designs, whereas asymmetry signifies modern aesthetics (Gao et al., 2024).

According to Kumalasari et al. (2021), the techniques for bamboo craft weaving are generally consistent. The weaving of bamboo products is based on various techniques, with their uniqueness and applications illustrated in Figure 3. Bamboo weaving includes diverse methods, each possessing distinct characteristics and applications. Standard techniques include twilling, coiling, plaiting, and checking, along with herringbone and hexagonal methods, which are widely used for modern three-dimensional designs (Gao et al., 2024; Kumalasari et al., 2021) to create items such as baskets, vases, and straw shoes (Yu, 2023; Kumalasari et al., 2021). Twilling involves the diagonal weaving of bamboo strips to form patterns with adjustable angles, making it very popular in basketry. Historical evidence from the Jomon era shows that bamboo twilling in basket-making is particularly strong and sustainable compared to other types (Gao et al., 2024; Yu, 2023). Kumalasari et al. (2021) noted that coiled and twined baskets employ spiral structures formed by warps and wefts while plaiting and checking techniques enable the creation of diagonal-patterned products. These methods demonstrate the versatility of bamboo weaving in crafting intricate designs (Gao et al., 2024; Kumalasari et al., 2021).

Specific techniques such as parallel weaving, which involves laying thin bamboo strips over molds, allow for greater control over product shapes (Gao & Gu, 2020). Dai bamboo weaving methods-picking, folding, pressing, curving, and coiling-are the foundation for innovative techniques like broken warp weaving, flora weaving, and float carving weaving in conjunction with traditional methods (Zheng & Zhu, 2021). These handcrafted designs incorporate cultural and artistic elements, including geometric and floral patterns, reflecting creativity and cultural expression in bamboo craftsmanship, as Zhang (2019) and Gao and Gu (2020) noted. Modern bamboo weaving combines flat and curved techniques. Flat weaving, categorized into horizontal, vertical, and oblique patterns, presents a consistent

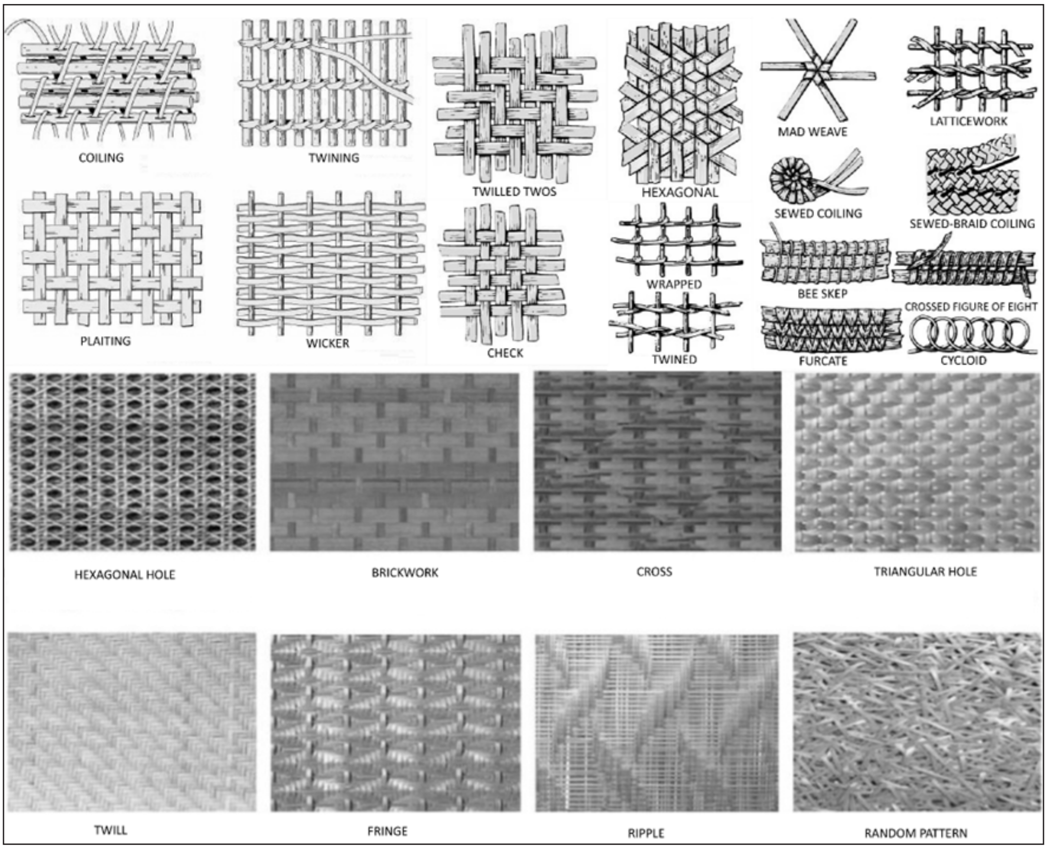

Figure 3. Bamboo art-crafted patterns in craft and woven products

and organized appearance (Gao et al., 2024). Curved weaving offers dynamic and intimate aesthetics and is frequently used in furniture design for elements such as chair backs and cabinet doors (Gao et al., 2024; Kumalasari et al., 2021) 3. Geometrical rules underlying the traditional patterns can be analyzed using digital tools to establish a systematic design framework (Gao et al., 2024; Kumalasari et al., 2021).

Bamboo Handloom Weaving Techniques

Some bamboo products come in different textures and pattern surfaces, crosses, hexagonal holes, firings, and twill map weaving, as shown in Figure 3. Gao et al. (2024) stated that bamboo handloom weaving products, an essential craft in textile decoration, create textures, patterns, and structural modeling. Handloom weaving involves warp and weft yarns, with fabric strength influenced by geometry, thread density, fiber type, and weave design (Yu, 2023). Bamboo yarn is used in warp and weft directions, producing durable fabrics, although the weft's higher density results in stiffer textures (Gao et al., 2024; Kumalasari et al., 2021). Kumalasari et al. (2021) stated that handcrafted bamboo textiles are traditionally made using handlooms, a sustainable alternative to industrial weaving, which often involves chemically processed bamboo fibers. Promoting handloom techniques can enhance sustainability by incorporating fibers from various extraction methods (Gao et al., 2024; Kumalasari et al., 2021). Modular textile weaving techniques further expand design possibilities, enabling the assembly of multiple pieces into diverse forms (Yu & Pashkevych, 2023; Yu, 2023).

Additionally, Zhang et al. (2020) stated that combining bamboo with materials like leather or fabric enhances the designs' tactile and visual appeal and can help make products look luxurious and more sustainable. As shown in Figures 4(a), KanaLili 2025 and Figure 4(b), Central Saint Martin's Spring/Summer 2018 Ready-To-Wear, the handcrafted dress showcases the delicate art of bamboo weaving. Central Saint Martin's designers experimented with bamboo strips of varying widths and colors, pressing and weaving them to create a dynamic textile with structural power for the spring-summer 2018 Ready-To-Wear (RTW) collection. The intricate patterning is enhanced with subtle lighting, creating a soft, shimmering effect that captures the eye. Moreover, Balmain applied various weaving techniques to achieve a three-dimensional effect, emphasizing structural lines and layering in the style [Figure 4(c)]. Balmain's square-conjoint pattern of cross-woven leather with bamboo strips also introduced rhythmic, organic designs that adapt to human movement.

Moreover, Dolce & Gabbana explored bamboo weaving's rigidity and flexibility, shaping garments extending freely from the body or contouring to enhance form in the RTW collection of Spring 2013, as shown in Figure 4(d). These innovative approaches highlight combining traditional craftsmanship with contemporary fashion (Yu et al., 2023). Handloom bamboo products exemplify low-carbon, green, and eco-sustainable design, adhering to

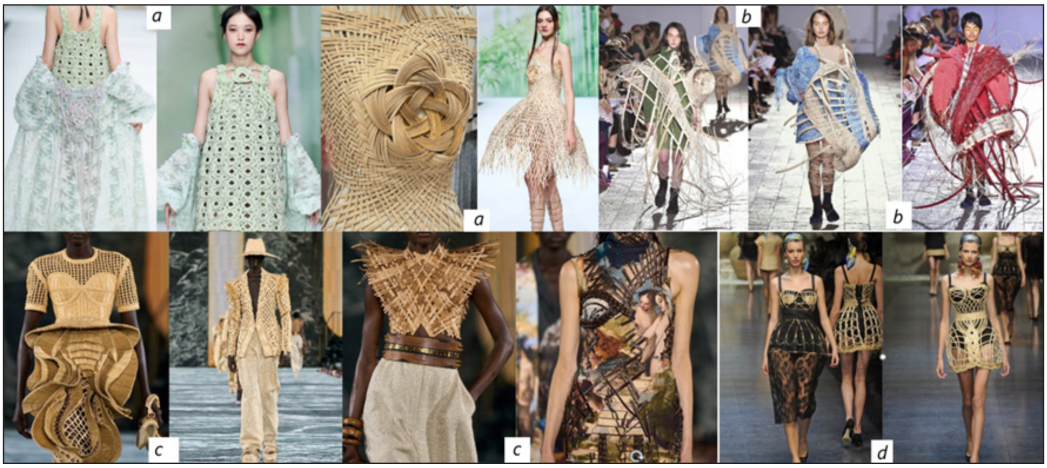

Figure 4. (a) KanaLili 2025, (b) Central Saint Martin's RTW Spring/Summer 2018, (c) Balmain RTW Spring 2023 Collection, (d) Dolce & Gabbana RTW Spring 2013

material efficiency, reduced consumption, and recycling, achieving zero pollution since it is produced based on customization purposes. This aligns with the United Nations Sustainable Development Goal (SDG) 12 (Responsible Consumption and Production) (Gao et al., 2024). Moreover, handloom weaving, a sustainable manual process that avoids reliance on electric machinery and fossil fuels, supports SDG 13 (Climate Action). Despite being labor-intensive, it minimizes textile waste and produces durable, long-lasting fabrics (Yu et al., 2023). Yu et al. (2023) stated that initiatives like the Dirty Fashion Campaign 2017 proposed a closed-loop system for viscose production, illustrating the growing demand for sustainable bamboo-based textiles, which could lead to innovations in fabric technology and broader adoption within the fashion industry. This approach is highly recommended for bamboo textiles and crafted products.

Innovative Techniques and Sustainability Solutions to Weaving a Greener Tomorrow

Traditional art-crafted techniques are employed to craft the textile's base structure, especially the weaving techniques, while bamboo strips are cut, smoothed, and prepared for integration (Luo et al., 2020). Gao and Gu (2020) stated that the innovative approaches expand creative possibilities for artisans, enriching the cultural heritage of traditional weaving while promoting sustainability. The study underscores the crucial need for collaboration between designers and artisans to regenerate sustainable traditional bamboo crafts and integrate them into contemporary design. Due to quality and innovation, Yu (2023) introduced supplemental weft, inlay, and lattice or overlay techniques to make bamboo products more sustainable. In the supplemental weft technique, bamboo strips complement the primary threads, enhancing the fabric's texture and visual appeal. However, inlay involves inserting bamboo strips directly into the fabric structure to create intricate embellishments and designs (Yu, 2023). The lattice or overlay technique weaves bamboo strips over the fabric surface, adding texture and depth through weaving and knotting techniques. Yu (2023) stated that the evolving relationship between bamboo craft and design exemplifies a promising strategy for product development, blending tradition with innovation to create timeless artistry.

Other studies have explored integrating traditional decorative patterns with bamboo weaving for innovative product designs, particularly in textiles and clothing (Yu & Pashkevych, 2023; Yu, 2023). Techniques include combining bamboo weaving with other materials and applying cutting-edge technology to enhance efficiency and precision (Yu & Pashkevych, 2023; Yu, 2023). For instance, attaching bamboo weaving to fabric surfaces using modern production technology and weaving bamboo segments into three-dimensional forms represents innovative approaches (Yu & Pashkevych, 2023). This integration has yielded vibrant patterns and luxurious forms, showcasing bamboo's versatility in crafting modern, sustainable living items. Gao and Gu (2020) stated that bamboo weaving techniques offer diverse applications, with traditional methods excelling in sustainability and traditional preservation, while modern approaches enhance efficiency and aesthetic versatility. Geometric elements, vibrant colors, and innovative techniques like hexagonal weaves reflect contemporary preferences while maintaining traditional craftsmanship (Yu & Pashkevych, 2023).

Traditional techniques like handloom weaving minimize waste but can be time-consuming and less adaptable to contemporary trends, as Gao and Gu (2020) noted. Techniques such as modular textile weaving and three-dimensional bamboo weaving enable intricate, innovative designs, as Yu (2023) and Yu and Pashkevych (2023) pointed out. Moreover, integrating advanced manufacturing technologies, such as 3D printing, can support personalized designs, standardized production, and mass customization, aligning the bamboo weaving industry with the principles of Industry 4.0 for greater sustainability (Zhang, 2019). Kumalasari et al. (2021) also indicated that artisan cooperatives producing bamboo-woven fabrics could target high-end fashion designers, sustainable clothing brands, and eco-conscious consumers, expanding beyond local markets into international fair trade as part of one of the successful projects in the real world. Despite challenges like production scalability and material rigidity, merging traditional and modern weaving techniques and technology presents opportunities for sustainable and innovative design solutions. The dual benefit of cultural preservation and environmental sustainability highlights the importance of bamboo weaving in contemporary design and production (Yu, 2023).

Additionally, Gao et al. (2024) emphasized the appeal of dynamic arrangements and vibrant patterns in attracting younger generations who appreciate the integration of tradition and modernity. However, production scalability and material rigidity warrant further exploration to maximize bamboo's potential in sustainable fashion and textiles (Zhang, 2019). Zhang (2019) stated that ongoing innovation in weaving methods, such as integrating bamboo with other materials and developing new weaving technologies, is vital for addressing these challenges. Furthermore, Gericke and Van der Pol (2010) mentioned that raising consumer awareness about bamboo products' environmental and cultural value can enhance their marketability and promote sustainable practices. The future of bamboo weaving lies in its ability to adapt to evolving consumer preferences and environmental needs.

It is credible that bamboo is a sustainable material; therefore, addressing concerns about false claims, labeling accuracy, and certifications for bamboo products is becoming increasingly significant. Labeling bamboo clothing presents major challenges that could impact consumer confidence and the broader sustainability goal in the textile industry. Research emphasizes that trust in sustainable fashion (Jalil, 2020) relies on garments' biodegradability and antimicrobial properties at the time of purchase. Standardized certification shapes consumer preferences in distinguishing between greenwashed alternatives and genuinely sustainable bamboo textiles (Ajmad, 2024). Amjad (2024) noted that several certifications ensure environmental and ethical integrity for bamboo products. The OEKO-TEX Standard 100 guarantees that bamboo textiles are free from harmful substances, while the Global Organic Textile Standard (GOTS) adheres to strict environmental and social criteria. When evaluated through the triple bottom line of sustainability, the textile industry has a poor record of addressing social and ecological issues (Waite, 2009).

Okafor et al. (2021) highlighted the scarcity of textile recycling facilities in many countries, emphasizing the necessity for sustainable fabric waste management through innovative design and production to support a circular economy. Jalil (2020) stressed that achieving sustainability necessitates substantial product design and changes in consumer behavior. While recycling efforts aim to minimize virgin material usage, they often result in "downcycling." A free-market approach might be more effective in managing post-consumer textiles (Okafor et al., 2021). Jalil (2020) also pointed out that waste separation at the source and efficient collection systems cannot transform waste into a valuable resource. Programs such as the Blue Box Recycling Initiative (Okafor et al., 2021), which rewards participants with redeemable points, offer a viable textile recovery, reuse, and reprocessing model. Sustainable textile design, which aims to reduce energy consumption, minimize waste, and create efficient products, has found a promising partner in bamboo (Jalil, 2022).

Integrating bamboo into sustainable textile practices offers a unique opportunity to blend sustainability with textile heritage (Yu & Pashkevych, 2023), providing ecological and economic advantages. This review takes the opportunity to include the circular economy of bamboo, from cultivation to production, usage, and disposal. Bamboo clothes made from organic bamboo, not mixed products, can all be composted (Jalil, 2022). It includes investigating closed-loop technologies that allow for the recycling and reusing of bamboo fibers, reducing waste, and lowering environmental effects (Jalil, 2020). Furthermore, customer behavior is important in boosting demand for genuinely sustainable bamboo goods since conscious purchase decisions can encourage firms to adopt more ethical and transparent methods (Gao et al., 2024). Moreover, artisans can leverage bamboo’s renewable properties in textile production to create high-demand sustainable products, opening new markets and enhancing livelihoods while preserving traditional craftsmanship (Gao, 2024). This biodegradable material, with unique properties such as antibacterial capabilities, UV protection, breathability, and moisture absorption, provides a compelling alternative for sustainable textile applications (Tausif et al., 2015).

Chen et al. (2017) investigated the possibility of combining mechanical pretreatment with low-alkaline chemical treatments to produce high-quality bamboo fibers. Further modifications, such as combing and carding, enhance the fibers’ usability for textile production, as suggested by Hu et al., 2019. Producing bamboo fabric using hand-spinning and handloom techniques supports sustainability by reducing energy consumption, waste, and water usage (Gao et al., 2024; Luo et al., 2021). Twill weave is identified as the optimal method for bamboo textile weaving, providing a uniform structure that balances flexibility and durability for various applications (Yu & Pashkevych, 2023). By starting with basic twill patterns, it is possible to develop aesthetically pleasing and advanced designs comparable to those created using other techniques (Hu et al., 2019). Innovations enable businesses to retain a proper competitive position in the market (Zheng & Zhu, 2021). Zheng and Zhu (2021) stated that using bamboo as an ecological material allows for implementing eco-innovations and participation in the closed-loop economy. In many sectors of the economy, the innovative use of bamboo provides a competitive edge while benefiting the environment. Chen et al. (2017) stated that a perfect bamboo product for the circular economy should be durable, replace abiotic materials, and be 100% bio-based, reusable, biodegradable, or energy-efficient when discarded.

Yu et al. (2023) stated innovative approaches to lightweight, portable, and multifunctional bamboo ideas through modular design, composite material innovations, and optimized joint structures. Bamboo weaving patterns, known for their symmetry and rhythmic structure, can be creatively reinterpreted through scattered compositions and free weaving techniques (Yu & Pashkevych, 2023). These innovations break away from traditional rigid designs, offering new possibilities for artistic expression and design flexibility, as demonstrated in various scholarly studies (Yu et al., 2023). De Vos (2010) explored laminated bamboo as a composite material. Luo et al. (2020) examined the evolution of bamboo weaving, emphasizing the integration of modern elements for sustainable development. Despite these studies, limited research exists on applying Interactive Genetic Algorithm (IGA) technology to bamboo weaving design. Pathways to sustainable bamboo textiles are represented in Figure 5.

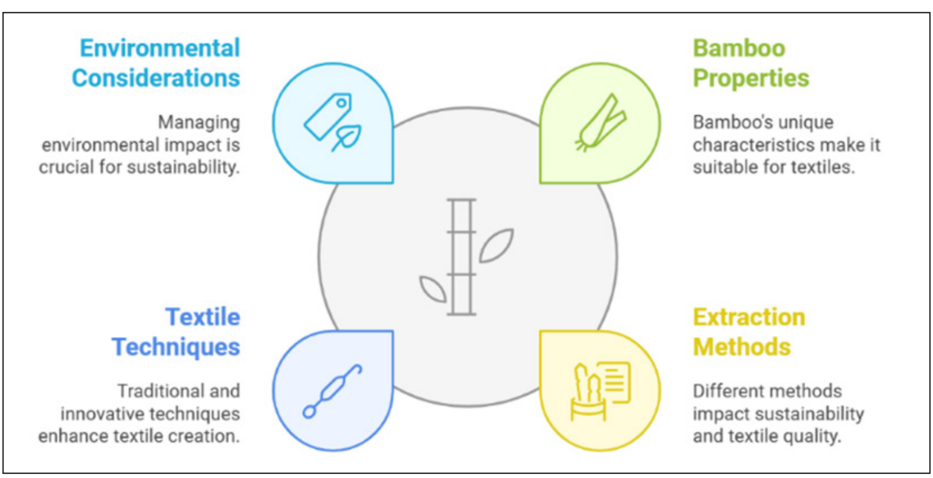

Figure 5. Pathways to sustainable bamboo textiles

CONCLUSION

Bamboo, known for its antibacterial properties and UV protection, offers significant potential for various textile and clothing applications. Despite the environmental benefits of bamboo, some ecological concerns need to be addressed to ensure its sustainable use. This paper reviewed bamboo's potential for sustainable handloom and craft weaving development. However, it acknowledges limitations, particularly regarding the environmental implications of alkaline treatments that reduce lignin content. While these treatments are cost-effective and energy-efficient, they produce chemical-laden wastewater, necessitating proper management through neutralization or closed-loop production systems. Public demand for organic textiles may encourage the adoption of less chemically intensive bamboo farming and production methods. Several areas could be explored to enhance the conclusion with actionable recommendations and future research directions. Further investigation into natural bamboo fiber production, yarn processing, handloom production, and wastewater treatment is vital for establishing fully sustainable bamboo products. Improving mechanical extraction techniques for bamboo fibers is crucial to enhancing efficiency while maintaining eco-friendly processing. Addressing these challenges through innovative solutions could establish bamboo as a cornerstone of sustainable fashion and clothing design. Research could focus on developing scalable, cost-effective, and energy-efficient mechanical methods to lessen reliance on chemical treatments. Incorporating bamboo materials into traditional patterns and weaving techniques represents a blend of tradition and innovation, contributing to cultural preservation and creative expression. Therefore, collaboration between designers and artisans is essential for revitalizing sustainable traditional bamboo crafts and integrating them into contemporary design. The evolving relationship between bamboo craft and design presents a promising strategy for product development, seamlessly combining tradition with innovation to create timeless artistry. Finally, future studies could evaluate the life cycle impact of bamboo textiles, addressing concerns about their long-term environmental benefits and potential ecological drawbacks.

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