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Review

Bamboo fibre: A sustainable solution for textile manufacturing

Akhtarul Islam Amjad

Department of Fashion Technology, National Institute of Fashion Technology, Panchkula, Haryana 134116, India

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ABSTRACT

This review paper provides insights into bamboo fibre, covering its extraction methods, properties and various applications. The initial focus is on the different techniques used to extract bamboo fibre, including mechanical and chemical processes, with an exploration of the advantages and challenges associated with each method. The paper then highlights the unique properties of bamboo fibres, such as their strength, flexibility and sustainability. A thorough analysis of the applications of bamboo fibre is presented, encompassing a wide range of sectors such as textiles, clothing, home furnishings and technical textiles. The review encompasses both traditional uses in clothing and emerging applications in technical and functional textiles. Additionally, the paper addresses the challenges that arise in the utilization of bamboo fibre, including concerns regarding labelling accuracy and environmental claims.

1. Introduction

Fibres are crucial in the textile industry as they determine the characteristics of fabrics and end products. Natural and man-made fibres undergoes various processes to form textiles, and their properties influence the durability, comfort and aesthetics of the final products. Sustainability considerations drive the adoption of eco-friendly options, such as natural and recycled fibres, in modern textile production, with bamboo being highlighted as an excellent choice due to its versatility and minimal environmental impact (Kozłowski and Mackiewicz-Talarczyk., 2020). Bamboo, known as the fastest-growing woody plant in the world, surpasses even the most rapid trees, with some species having an impressive growth rate of up to 1 m per day. (Janzen,1976). Major producers, such as India, China, and Brazil, dominate the annual market of over 40,000 tonnes of bamboo fibre. Apart from industrial applications, bamboo serves as a crucial resource in many regions for food, fodder and construction (Zuo et al., 2018). Bamboo fibres, often obtained from the tall *Phyllostachys edulis* (Carrière) J.Houz. commonly known as 'Moso bamboo', have become essential in textile applications. Regenerated bamboo viscose fibres, known for their high cellulose yield, have gained popularity in the market, positioning bamboo as a fashionable and durable eco-friendly building option (Prakash, 2020). In the current manufacturing landscape, bamboo culm fibres, known for their exceptional properties, are extensively used to create yarns and fabrics. This includes a wide range of products, such as clothing items such as underwear, sports gear, t-shirts and socks, as well as hygiene items such as sanitary napkins, masks and bandages. Bamboo's characteristics also make it suitable for UV-protective clothing, home furnishings and even food packaging. The growing interest in bamboo stems from its unique and beneficial qualities, leading to the production of bamboo fibre in abundance (Akinlabi et al., 2017).

The current literature on bamboo fibres within the textile industry lacks a comprehensive review that synthesizes and integrates processing technologies, environmental sustainability and consumer perspectives in a single source. Moreover, there is a pressing need for an exhaustive review that delves into the processing methods of bamboo fibres for textile applications, comparing and contrasting various techniques and assessing their impacts on the final product's quality and properties.

2. Chemical composition and structure of bamboo timber

Bamboo is composed primarily of cellulose, hemicellulose, and lignin, along with small quantities of other substances such as aqueous extract, pectin and inorganic substances. The specific chemical composition of bamboo is influenced by the species of bamboo chosen. When it comes to bamboo timbers, the main constituents are cellulose (60%-70%), pentosans (20%-25%), hemicelluloses (20%-30%) and lignin (20–30%) (Mousavi et al., 2022). Additionally, there are minor constituents present, including resins, tannins, waxes and inorganic salts. It is worth noting that the cellulose content in bamboo is lower compared to that of cotton. Hemicellulose, on the other hand, is an amorphous substance with a low degree of polymerization. It is distributed among the long fibres and micro fibre of bamboo and easily becomes wet and

E-mail address: akh.textile@gmail.com.

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swells when it absorbs moisture. Lignin, a complex macromolecular compound of the aromatic series, is distributed among the intercellular layers and tiny fibres of bamboo. The colour of bamboo fibre is determined by the presence of lignin. The chemical composition of bamboo is similar to that of hardwoods in terms of proximate chemical compositions, except for higher alkaline extract, ash, and silica contents. The carbohydrate content of bamboo plays a crucial role in its durability and service life [8]. The stability of bamboo against mould, fungal and borer attacks is strongly influenced by its chemical composition. Bamboo, being a natural nanocomposite, possesses multinodes and functional gradient structures at both macroscopic and microscopic levels. All the internodal cells of bamboo grow in a pale, end-to-end arrangement (Imadi et al. 2014; Akinlabi et al., 2017, Mousavi et al., 2022).

3. Bamboo fibre extraction

Bamboo fibre can be obtained through various methods, such as retting, mechanical extraction and chemical extraction. The characteristics exhibited by bamboo products largely depend on whether the bamboo fibre is derived from natural sources or is a regenerated type. The first two methods yield bundles of original or pure bamboo fibres in staple form, while the latter produces bamboo viscose filaments, also known as regenerated bamboo cellulose, which can be further transformed into staple fibres if necessary. In order to extract fibres from the bamboo culm, all three processes begin by splitting bamboo strips directly taken from the culm to eliminate the diaphragm and node. Subsequently, the remaining hollow sections of the stalks are subjected to either mechanical or chemical processing, depending on the intended applications (Tahir et al., 2011, Liu et al., 2012).

3.1. Retting or degumming

This process involves the careful removal of fibre bundles surrounding tissue while minimizing damage to the fibres themselves. The quality of the extracted fibres is dependent on the specific conditions used during the retting process (Singh and Dessalegn, 2021) Retting can be categorized into different types, including dew retting, enzymatic retting, water retting and chemical retting.

Dew retting involves cutting and distributing bamboo stems in a field, where they are exposed to pectinolytic microbes that break down the pectin and release the fibres (Asmarea et al., 2022). Enzymatic retting, on the other hand, utilizes pectin-degrading enzymes (pectinase) in a bioreactor to separate the fibres. Water retting relies on anaerobic bacteria to facilitate the separation of fibres. This process entails submerging bamboo culms or stems in open water, such as a pond, river or tank, for specific periods. The outermost region of the plant swells, leading to the growth of decay-causing microorganisms that aid in the removal of pectin and the extraction of the bamboo fibre from weakly bonded matrix and microfibril aggregations(Sisti et al., 2018).

Researchers have found that bio-retting of bamboo is a gentle and effective pre-treatment process, yielding more consistent fibre quality compared to mechanical retting techniques (Tahir et al., 2011;Liu et al., 2017; Sisti et al., 2018; Singh and Dessalegn, 2021). In mechanical retting, a high amount of fibre is extracted but control of the mechanical forces applied to the plant stems is difficult, and it often results in highly variable fibre lengths, containing high amounts of noncellulosic substances, resulting in low quality and being stiff to the touch. These fibres are only used for household and handicraft articles and as reinforcement for composite materials. However, mechanical retting is more efficient than biological retting alone (Liu et al., 2017). Chemical retting of bamboo culms can be accomplished using either acidic or alkaline treatments. Various solutions, such as sodium carbonate (Na_2CO_3) and hydrochloric acid (HCl), have been employed in these chemical treatments. Extensive research has been conducted to determine the most effective method of retting, including acid retting, alkali retting, and chemical-assisted natural (CAN) retting. Among these methods, CAN retting has been identified as the most efficient for the pre-treatment of bamboo cellulose in preparation for wet spinning. Additionally, several studies have documented the optimization of process parameters to produce bamboo fibres with desired characteristics (Kaur et al.,2013; Sugesty et al., 2015 Sadrmanesh and Chen, 2019).

3.2. Mechanical Route of Bamboo Fibre Production

The process of mechanical extraction, such as using a decorticator machine, relies on mechanical forces to break the bonds between the fibre and bonded matrix. Initially, the woody parts of the bamboo are cut and crushed, and then treated with natural enzymes to break the bamboo down into a soft, mushy and spongy mass. Fig. 1 shows the simplest way to obtain the bamboo fibre by mechanical extraction. The natural fibres can then be mechanically combed out to obtain individual fibres, which can be spun into yarn (Tahir et al., 2011). This process produces a fibre known as natural bamboo fibre. In addition to the decorticator machine, mechanical extraction methods can also involve procedures like steam explosion, heat steaming, high-pressure refinery, crushing and super grinding. These mechanical processes are classified based on the quality of the fibres obtained. Rough-textured fibres are obtained through a sequence of cutting, separation, boiling, and fermentation with enzymes, while fine fibres are obtained through a sequence of boiling, fermentation, washing, bleaching, oil-soaking and air-drying. Compared to chemical methods, mechanical methods of bamboo fibre extraction are considered environmentally friendly. However, they are less preferred by the clothing sector due to being more labour-intensive and expensive (Rocky and Thompson, 2018, Wu et al., 2021; Zhao et al., 2024).

3.3. Chemical route of bamboo fibre production

The production of regenerated bamboo viscose fibre involves a chemical process. First, bamboo leaves and the soft inner pith from a hard bamboo culm are extracted and crushed. The Moso bamboo culms used must be free from lignin and hemicellulose (Wu et al., 2021). Various techniques, such as acid or alkaline pre-treatment, wet oxidation, steam pretreatment and ammonia fibre explosion, have been explored by researchers to achieve this. The main idea behind the process is to cook the bamboo leaves and culms in strong chemical solvents and then perform alkaline hydrolysis combined with multi-phase bleaching. This process is similar to the conventional viscose manufacturing process, and the resulting product is comparable to rayon or modal (Xu et al., 2007; Majumdar and Pol, 2014; Periyasamy and Militky, 2020). The steps involved in the production of bamboo fibre are as follows (Imadi et al. 2014; Majumdar and Pol, 2014; Zuo et al., 2018)

As shown in Fig. 1(b), bamboo culms are extracted and crushed. In the steeping and pressing process, the crushed bamboo is soaked in a sodium hydroxide (NaOH) solution with a concentration of 15% – 20% at a temperature between 200°C and 250°C for one to three hours. This step forms alkali cellulose, which is then pressed to remove excess solution. Further shredding takes place to increase its surface area, facilitating further processing of the cellulose. The shredded cellulose is left to dry for 24 hours in the presence of ambient oxygen for the aging process. Carbon disulfide is added to the cellulose, causing it to gel. Excess carbon disulfide is then evaporated. This process is known as sulphurisation and xanthation. Further, a diluted solution of sodium hydroxide is added to the cellulose sodium xanthogenate, dissolving it and creating a viscose solution consisting of approximately 5% sodium hydroxide and 7% – 15% bamboo fibre cellulose. Afterward, it undergoes ripening, filtration and degassing, and ultimately, the bamboo viscose is wet-spun. This means that it is forced through spinneret nozzles into a diluted sulphuric acid solution, where the cellulose sodium xanthate is solidified and transformed back into bamboo viscose filaments. Essentially, sulphuric acid (H_2SO_4) acts as a quenching solution, allowing the strands to solidify into fibre and thus enabling them to

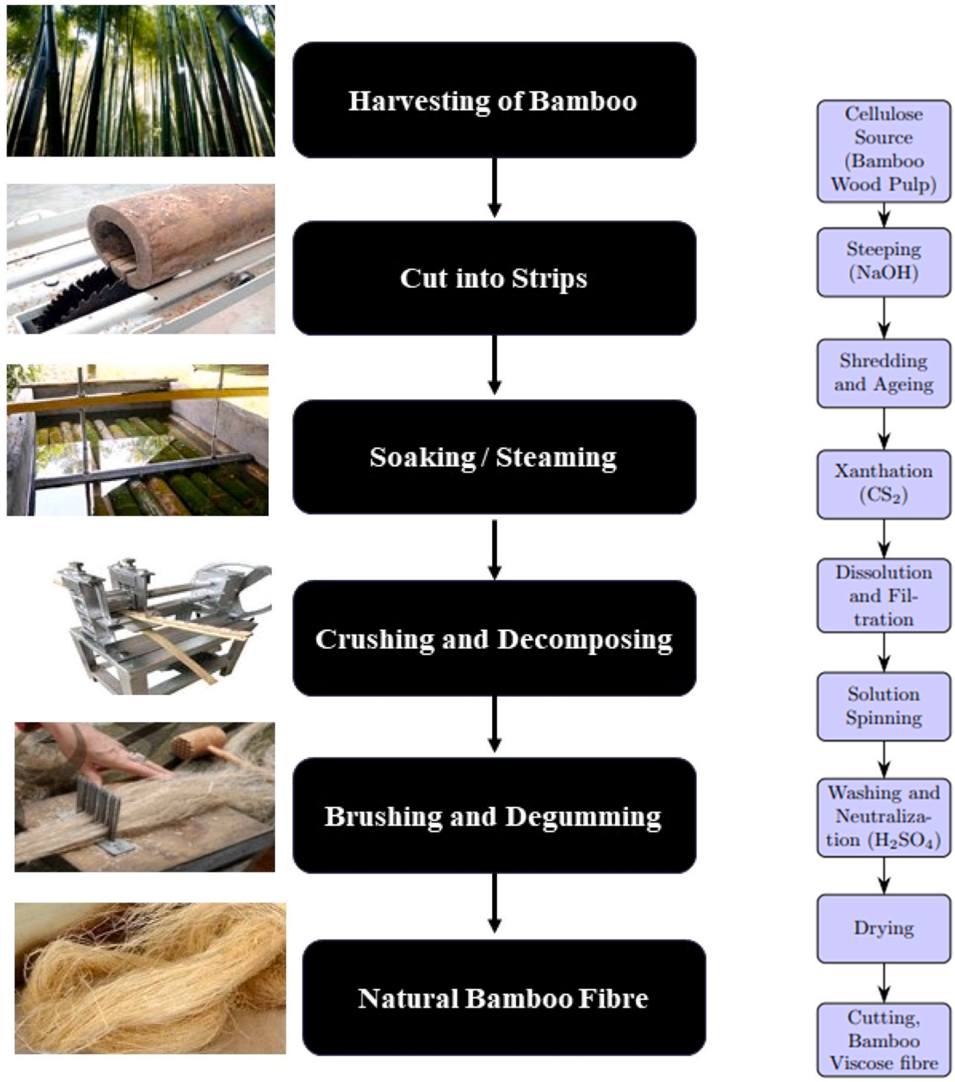

Fig. 1. Bamboo fibre extraction by a. mechanical process and b. chemical process (Imadi et al. 2014; Majumdar and Pol, 2014; Zuo et al., 2018).

be spun into yarn (Majumdar and Pol, 2014; Singh et al., 2017; Amjad and Kumar, 2023).

Concerns have arisen frequently over the environmental friendliness of the chemical process involved in bamboo viscose fibre production. Carbon disulfide is known to be toxic, posing a potential threat to factory workers and causing pollution through air emissions and wastewater (Periyasamy and Militky, 2020). Moreover, the recovery rate of carbon disulfide in most industries is only around 50%. Additionally, sodium hydroxide and sulphuric acid also fall into the category of potentially hazardous chemicals. One solution is to consider a process similar to the lyocell process used in the production of bamboo fibre. In this case, N-methylmorpholine-N-oxide (NMMO) is used as a solvent, and the hardening bath typically consists of a water-methanol solution, both of which are non-toxic. Furthermore, this process operates in a closed-loop system, with 99.5% of the chemicals used being recycled for reuse, resulting in only minimal traces being emitted into the environment (Singh et al., 2017; Wu et al., 2021).

3.4. Combination of mechanical and chemical routes

The utilization of this method is more prevalent within the pulp and paper sector as opposed to the textile industry. The bamboo strips undergo a chemical treatment process, which is subsequently followed by either compression moulding or roller milling. The combination of both mechanical and chemical treatments results in better separation of fibres. In this method, bamboo is pretreated with chemical substances to dissolve the lignin, glia, and hemicellulose and to weaken the binding force between fibres. The fibres are then formed by a mechanical external force. The extracted bamboo fibre can be used for processing isotropic composite material. This method of production of bamboo fibre can be used to make a variety of composite materials. The products can be further developed, but the bamboo fibre produced by these methods cannot be used for weaving (Maiti et al. 2022; Zhao et al., 2024)

4. Ecological reasons for using bamboo for textiles and clothing

Utilizing bamboo for textiles and clothing is underpinned by several compelling ecological reasons, making it a sustainable alternative in the fashion industry (Liese and Köhl, 2015).

4.1. Renewability

Bamboo plant as a renewable resource is available in plenty almost every region of the globe and plays a great role in socio-economic development (Wang et al., 2008). Bamboo is considered a renewable source primarily due to its rapid growth rate and ability to regenerate quickly after harvesting. Bamboo cultivation requires fewer resources compared to traditional timber forestry. Apart from these, antibacterial characteristic, ecofriendly extraction of the fibre from bamboo, and diverse textile application make it renewable resource for the textile industry (Kozłowski and Mackiewicz-Talarczyk., 2020).

4.2. Minimal environmental impact

Major species of bamboo requires minimal water for cultivation compared to water-intensive crops like cotton. Additionally, bamboo often thrives without the need for pesticides and fertilizers, reducing the environmental impact associated with chemical use in agriculture. Bamboo can be cut and grown again without hurting the environment around it. it grows back without needing to be planted again (Gupta, and Kumar, 2008). The studies by Bahari and Krause (2016) and Restrepo et al. (2016) highlight the potential of utilizing bamboo in manufacturing processes to reduce environmental impact. The research demonstrates that bamboo can serve as a sustainable alternative to traditional materials, such as wood-polymer composites, and significantly decrease carbon footprint. Additionally, Agyekum et al. (2017) found that bamboo bicycle frames have a lower environmental impact compared to aluminum and steel frames, showcasing the benefits of incorporating bamboo into various industries for greener and cleaner products.

4.3. Carbon sequestration and reducing global warming

Bamboo grows super-fast and has a notable capacity to absorb carbon dioxide, acting as a carbon sink and contributing to climate change mitigation year-round unlike other forests that become carbon sources during non-growing periods. Numerous global studies have evaluated various bamboo species' carbon fixation abilities using specific metrics. For example, Tang et al. (2016), found that the carbon sequestration rate (CSR) for certain bamboo species could reach up to 70.11 tCO2/ha/yr (Dendrocalamus giganteus). In another study, a Moso bamboo forest managed for 60 years was projected to sequester 18.69 tCO2/ha/yr, while a younger Moso bamboo forest could sequester 1.86 tCO2/ha/yr within the first five years of planting (Zhang et al., 2020). In Assam, India, bamboo forests were estimated to accumulate carbon at rates ranging from 4.77 to 8.43 tCO2/ha/yr. (Chaowana et al., 2021; Pan et al., 2023).

4.4. Reduced water usage

Bamboo's lower water requirement for growth makes it a water-conscious choice, particularly in regions facing water scarcity. Growing cotton needs a lot of water, but bamboo does not. In few cases it only needs 500 litres of water to make 1 kg of biomass, and does not need extra watering (Nayak and Mishra,2016)

4.5. Eco-friendly and biodiversity conservation

Bamboo fibre comes from plants, so it is natural and breaks down in the soil with the help of microorganisms and sunlight. Clothes made from bamboo can be composted and disposed of in an environmentally friendly way. Bamboo forests support biodiversity by providing habitats for various species. Sustainable bamboo cultivation practices help maintain diverse ecosystems. Connected rhizome bamboos are often regarded as a viable option for enhancing soil properties in a relatively brief timeframe, owing to their extensive root system. It is worth noting, however, that the majority of these assertions are based on anecdotal evidence. However, a few researchers have made efforts to validate these assertions by conducting data analysis. Tardio et al. (2018), and Hairiah et al. (2020) highlights how bamboo's deep roots help anchor soil, preventing erosion and promoting stability. Shinohara et al. (2019) underscore bamboo's effectiveness in reducing soil erosion and enhancing soil health, making it a crucial ally in long-term soil conservation.

5. Properties of bamboo fibres

The essential properties of textile fibres play a pivotal role in determining the success of the spinning process and the quality of the final textile product. The length-to-diameter ratio, strength, cohesiveness, and torsional rigidity are fundamental characteristics that directly impact efficiency and spinnability. Achieving a harmonious balance among these properties is crucial for producing high-quality yarns suitable for diverse textile applications. Additionally, desirable properties such as fineness, resiliency, uniformity, porosity, lustre, durability and commercial availability further contribute to the overall performance and aesthetic appeal of textile materials. These properties are not only essential for the conversion of fibres into yarns but also influence the end product's texture, appearance, breathability and longevity (David and Pailthorpe., 2002; Harwood and Smith, 2020).

Bamboo fibre possesses all the necessary and desirable properties to be utilized as a textile fibre. However, the characteristics of bamboo fibres tend to vary over time due to the decrease in cellulose concentration as they age. Additionally, the method used to extract the fibre significantly impacts the quality of the final product. Bamboo pulp fibre, similar to viscose rayon, is produced through solution spinning, resulting in comparable structure and properties (Sfiligoj Smole et al., 2013). Moreover, chemical procedures, in comparison to steam explosion and mechanical processing methods, require less expensive equipment, consume less energy and offer greater control over fibre qualities. Furthermore, different extraction methods have varying degrees of success in removing lignin, which contributes to the stiffness and yellowing of bamboo fibres. Non-cellulosic components also influence fibre properties such as strength, density, moisture absorbency and flexibility (Majumdar and Pol, 2014; Singh et al., 2017; Kozłowski and Mackiewicz-Talarczyk., 2020). Fabrics woven from mechanically extracted fibres tend to be rough and stiff, while those woven from viscose-type chemical processes have a soft feeling and good drape. Additionally, mechanically processed fibres exhibit higher strength and durability. These differences can be attributed to changes in the physical form of the fibre during chemical processing, resulting in alterations in molecular orientation and polymerization degree. Consequently, yarns and fabrics produced from each manufacturing process behave differently (Gericke and Van der Pol., 2010; Khalil et al., 2012; Prakash et al., 2013).

5.1. Dimensional and morphological properties of bamboo fibre

Bamboo fibre, obtained from the mechanical extraction process, differs from other bast fibres like ramie and jute in terms of its fineness and shorter length. The dimensional parameter depends on the extraction method. Mechanically extracted bamboo fibre ranges in length from 5 mm to 5 cm, with an average length and diameter of 22.8 mm and 150 μm, respectively. Lengths less than 12.5 mm do not contribute to the yarn manufacturing. These fibres are typically found in bundles consisting of 10–20 individual fibres. Due to their short length, it is challenging to process them into yarn and fabric. Consequently, they are commonly utilized as technical fibres in the production of nonwovens. Regenerated bamboo (chemically processed) fibre can be obtained with long length and pre-decided diameter. Bamboo fibres have a rough surface and a circular cross-section with a small round lumen. The composition of bamboo fibres includes 36–41% cellulose, 22–26% lignin, and 16–21% pectin (Sadrmanesh and Chen, 2019; Malekzadeh et al., 2021). On the other hand, bamboo viscose is derived from the chemical extraction process and possesses distinct properties. It is classified as cellulose II, characterized by low crystallinity and high-water retention and release ability. Bamboo viscose is found in the form of filaments, which are continuous and long strands of material that can be converted into the desired staple length (Xu et al. 2007). The cross-sectional shape of bamboo viscose fibres can vary, influencing the packing density of the yarn and subsequently affecting the mechanical behaviour of fabrics under low stress. The cross-section of bamboo viscose fibre has been observed to be irregular and toothed, indicating similarities in longitudinal and cross-sectional morphology with regular viscose rayon fibre. Additionally, bamboo viscose fibres exhibit striated cracks along their length and numerous voids in their cross-section, both of which indicate a good water retention capacity (Li et al., 2019; Prakash, 2020; Prakash et al., 2013).

5.2. Mechanical properties

The durability of bamboo fibre is determined by various factors such as tensile strength, flexural strength, tensile load, elasticity and moulding capability. When compared to flax and jute, fabric made from mechanically extracted bamboo fibre exhibits superior resistance to pilling and abrasion under both dry and wet conditions (Chen et al., 2017; Li et al., 2019). Natural bamboo fibres show lower shrinkage, higher dye sorption, better colour clarity, increased wrinkle resistance and improved lustre without mercerization when compared to cotton fabrics. Xu et al. (2007) compared the properties of bamboo viscose fibres to those of viscose rayon, cotton and modal fibres. Their findings revealed that bamboo viscose and viscose rayon have similar dry tenacity, elongation at break and moisture absorption properties. However, the wet tenacity of bamboo viscose was slightly higher than that of viscose rayon. Bamboo viscose also had lower tenacity than cotton and modal fibres, both in dry and wet states. Bamboo fibre is used for versatile applications with other textile fibres such as cotton, hemp, modal, lyocell and others. This has resulted in a wide range of fabric properties. Among these blends, bamboo viscose fabric stands out in terms of tensile extensibility when compared to both cotton and the cotton/bamboo viscose blend fabrics (Prakash et al., 2013; Jais et al., 2023). On the other hand, researchers have explored the inherent strength properties of bamboo fibres and cotton bamboo blends, revealing remarkable tensile strength. This finding confirms the potential of bamboo fibres to enhance the overall tensile performance of fabric blends. This suggests reduced comfort and lower hand values in fabrics containing cotton, highlighting the importance of considering material interactions in fabric blends. Furthermore, the overall bending rigidity of cotton fabric was higher due to its inherent stiffness and larger diameter of constituent yarn compared to bamboo viscose and viscose rayon yarns. The total hand value, which indicates the overall feel and texture of the fabric, was found to be higher for viscose rayon and bamboo viscose fabrics compared to cotton fabric (Wang et al., 2014; Kaur et al., 2016; Jais et al., 2023).

5.3. Moisture and heat management properties

Fabrics made from natural bamboo fibre possess hollow cross-sections, allowing them to breathe and providing a cool and comfortable wearing experience. However, the variability in length of such fibres leads to difficulty in yarn and fabric manufacturing. So chemically extracted fibre is dominantly used to make the fabrics. Such fabrics also possess moderate moisture management capabilities. The presence of micro-gaps and micro-holes in the fibre contributes to its excellent wicking ability, effectively drawing moisture away from the skin and facilitating quick evaporation, resulting in a cooling sensation (Basit et al., 2018). Moreover, the large number of micro-cracks and grooves on the fibre surface enhances the breathability and moisture regulating properties of the fabrics, surpassing those of cotton and hemp. These fabrics also have high hygroscopicity, enabling the fibres to absorb water up to three times their weight, making them easy to dye and finish (Ramamoorthy et al., 2015; Oner, 2019; Kushwaha et al., 2023). The fibre derived from the mechanical extraction process of bamboo retains many of the plant's original properties. However, it should be noted that the washing fastness of these fabrics is unsatisfactory, even under normal washing conditions. Despite this drawback, bamboo fibre offers desirable characteristics such as comfort, aesthetics and processing advantages, including moisture absorption, permeability, softness, pleasant tactile sensation and excellent dye-ability (Nayak and Mishra, 2016; Malekzadeh et al., 2021). Additionally, the thermal properties of bamboo fibre have been explored, revealing fabrics with enhanced thermal conductivity and potential benefits for heat dissipation. As a result, bamboo fibre has gained significant popularity in the textile industry and is widely used in yarn and fabric production due to its unique properties (Majumdar et al., 2010; Oner, 2019).

5.4. Anti-bacterial properties

The antibacterial activity of bamboo is its most advantageous property when it transitions from plant to fibre form. This is due to the presence of a bacteriostasis bio-agent called 'bamboo-kun,' specifically 2.6-bimethoxy-p-benzoquinone, which provides natural resistance to microbes on the plant. Additionally, the protein dendrocin found in bamboo exhibits highly distinctive fungal resistance (Afrin et al., 2012). These beneficial substances are tightly bound to the bamboo cellulose molecule, allowing them to persist even after mechanical processing. As a result, bamboo fabric made from such bamboo fibres effectively eliminates bacteria and mildew, unlike other cellulosic fabrics that promote their growth, leading to unpleasant odours and potential fibre degradation. The medicinal (anti oxidant) use of bamboo in ancient Chinese medicine can be attributed to this property (Wróblewska et al., 2018; Prakash et al., 2021).

A study conducted by the National Textile Inspection Association of China (NTIA), Shanghai, Microorganism Research Institute, and Japan Textile Inspection Association revealed that bamboo fabric retains significant antibacterial properties even after undergoing 50 washes. Another factor contributing to bamboo's inherent bacterial resistance is the presence of chlorophyll and sodium copper chlorophyllin, which act as antibiotics and deodorizers. Softness and good moisture retention property of bamboo fabric leads the comfort to the wearer when it is used near to skin (Hardin et al., 2009; Feng et al., 2023). Moreover, the absence of free electrons in bamboo fibres makes the resulting fabric antistatic, allowing it to fit comfortably against the skin and drape lightly over the body without clinging (Chen, and Guo, 2007). Despite the fact that mechanically processed bamboo fibres have been recognized for their ability to resist pest and fungi infestation due to the antimicrobial properties of bamboo, disagreement exists amongst researchers about the anti-bacterial properties of regenerated cellulose-based bamboo fibres. However, some argue that bamboo viscose fibres do exhibit antibacterial, antifungal and UV protection properties (Teli and Sheikh., 2013; Mishra et al., 2012)

5.5. UV protection

Bamboo fibre is renowned for its inherent ability to provide natural protection against UV rays, making it an ideal material in the textile industry, particularly for sun-exposed clothing. Extensive research has shown that natural bamboo fibre boasts an impressive Ultraviolet Protection Factor (UPF), signifying a substantial increase when compared to ramie and viscose, (Mishra et al., 2012; Hatua et al., 2013). Moreover, studies have indicated that bamboo fabric exhibits lower reflectivity than other materials like flax and cotton, indicating its efficacy as a UV radiation absorber. The presence of sodium copper chlorophyllin in bamboo fibre is noteworthy, as it possesses a UV absorption capacity that is twenty times higher than that of cotton fibre. Furthermore, the density of bamboo fibres plays a crucial role in blocking UV rays. The tightly packed structure of bamboo fibres creates a formidable barrier that minimizes the penetration of harmful UV radiation (Teli and Sheikh., 2013; Mishra et al., 2012).

5.6. Eco values of organic bamboo

Organic bamboo fabric, also known as virgin bamboo, possesses the remarkable quality of being fully biodegradable in soil without releasing harmful pollutants such as methane. This natural fibre, derived from bamboo, is celebrated as a sustainable and environmentally friendly textile material for the modern era. Consequently, garments crafted from pure bamboo have an insignificant impact on the environment. Unlike synthetic fibres, which persist in landfills for extended periods, bamboo clothing can be composted organically (Saha and Mandal, 2020; Plakantonaki et al., 2023).

6. Bamboo fibre in the form of various textile products and applications

Bamboo fibre is extensively utilized in the textile industry due to its distinctive characteristics, finding versatile applications in textile forms, including yarns, and woven and knitted fabrics. Fig. 2 illustrates the use of bamboo fibre in various textile forms. Bamboo yarn is a continuous filament composed of fibres. Knitted bamboo fabric is created by interlocking loops of bamboo yarn, resulting in a flexible and stretchable material that is commonly used in the production of comfortable and breathable clothing. On the other hand, bamboo woven fabric is formed by the interlacing of two sets of yarn at right angles, producing structured and durable textiles that are suitable for garments and upholstery. In contrast, nonwoven bamboo fabric is manufactured directly from fibres without the need for weaving or knitting. This type of fabric finds applications in a wide range of products, such as filters, wipes and medical textiles. Bamboo fibre is also used for functional clothing and incorporates specialized features, such as moisture-wicking or UV protection, which enhance performance and comfort (Gericke and Van der Pol., 2010; Prakash et al., 2021; Zhao et al., 2024).

Bamboo fibre is particularly favoured for creating soft and breathable garments such as T-shirts, underwear, socks and sportswear. Fabrics made from bamboo yarns possess a smooth texture and exceptional draping qualities, which contribute to their widespread popularity. In the realm of intimate clothing, bamboo fibres are employed to manufacture a diverse range of products, including sweaters, bathing suits, lingerie, and blankets. Notably, the natural anti-bacterial properties of bamboo make it an ideal choice for undergarments, snug t-shirts and socks, providing a natural defence against microbial intruders. Moreover, bamboo's ability to block ultraviolet radiation makes it a highly sought-after material for summer clothing, particularly for safeguarding pregnant women and children. Furthermore, its hypoallergenic and soft nature renders it perfect for baby clothing and accessories (Kaur et al., 2016; Rocky and Thompson, 2020).

The use of bamboo fibre in decorating and home textiles is continuously expanding, thanks to its antibacterial and ultraviolet-resistant properties. Wallpaper and curtains made from bamboo fibre effectively absorb ultraviolet radiation across various wavelengths (Akinlabi et al., 2017). Additionally, bed linens, towels and curtains crafted from bamboo fibre offer natural antimicrobial benefits. Bamboo towels and bathrobes provide a soft and comfortable feel, along with excellent moisture absorption. The antibacterial properties of bamboo fibre prevent the growth of bacteria and eliminate unpleasant odours. The popularity of indoor bamboo fibre in textiles and home decor is on the rise, making it more easily accessible than ever before. Bamboo fabric has proven to be highly beneficial in the realm of activewear, as it effectively wicks away moisture and allows for breathability, ensuring optimal comfort during physical activities. Furthermore, bamboo fabric is also utilized in the creation of lightweight accessories such as scarves, hats and gloves, providing both comfort and style (Karthikeyan et al., 2016). In the field of sanitary materials, bamboo fibres are widely employed in various items including bandages, masks, surgical attire and nurses' uniforms. The inherent sterilizing and bacteriostatic properties of bamboo fibres make them highly advantageous for sanitary applications such as sanitary towels, gauze masks, absorbent pads and food packaging. Importantly, the natural antibacterial function of bamboo fibres eliminates the need for artificial antimicrobial agents, ensuring that these products do not cause skin allergies. Moreover, the competitive pricing of bamboo sanitary materials makes them accessible and appealing in the market (Lipp-Symonowicz et al., 2011, Tausif et al., 2015). Bamboo non-woven fabric, derived from pure bamboo pulp, shares similar characteristics with viscose fibres. However, bamboo exhibits remarkable potential in various hygiene products such as sanitary napkins, masks, mattresses and food-packaging bags, owing to its inherent ability to resist bacteria (Min et al., 2019). Furthermore, bamboo textiles have found application in the reinforcement and utilization of biocomposites. The inclusion of bamboo fibres enhances the performance of composite products. Bamboo, as a natural fibre composite, has emerged as a superior alternative to previously used materials. Its advantageous properties include being eco-friendly, cost-effective, lightweight, non-toxic and biodegradable. Additionally, bamboo textiles are utilized in geotextile applications. Geotextiles are specialized fabrics that enhance the engineering performance of soil. The unique antibacterial and bacteriostatic bio-agent properties of

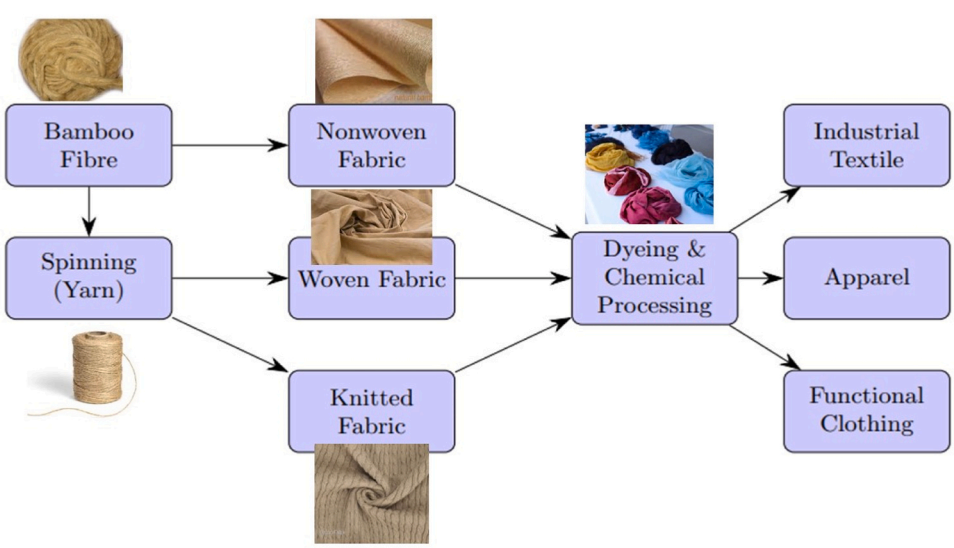

Fig. 2. : Various textile forms of bamboo fibre (Gericke and Van der Pol., 2010; Amjad and Kumar., 2020; Prakash et al., 2021; Zhao et al., 2024).

bamboo fibres make them highly resistant to pathogens and play a crucial role in reducing soil loss (Saha and Mandal, 2020; Santos et al., 2021).

7. Concern related to bamboo and labelling of bamboo fibre

Bamboo fibres have been surrounded by numerous uncertainties, leading to confusion among users. In the late 2000s, textile manufacturers, especially those operating online, extensively promoted bamboo fabrics, claiming that they possessed a luxuriously soft texture, deeper colours than cotton, exceptional UV protection and natural antimicrobial properties. These claims were supported by the assertion that bamboo was grown in an eco-friendly manner. However, to verify the accuracy of these assertions, government authorities and researchers worldwide embarked on an investigation to uncover the true nature of the bamboo used in these unique garments (Gericke and Van der Pol., 2010; Nayak and Mishra, 2016). To address these concerns, Hardin et al. (2009) conducted a thorough examination by obtaining samples of these fabrics. Their analysis focused on identifying the fibres and evaluating their antimicrobial activity. The findings revealed that the fibres closely resembled conventional viscose rayon fibre, indicating that they were not genuine bamboo fibres derived from the bast variety. Instead, they were spun from regenerated cellulose sourced from bamboo. Furthermore, the samples did not exhibit any antimicrobial activity, confirming that the fibre was, in fact, a type of rayon and not authentic bamboo. Consequently, the Federal Trade Commission (FTC) took legal action against deceptive sellers for engaging in fraudulent labelling and misleading advertising practices. Collaborative endeavours involving the industry, regulatory bodies, and consumer advocacy groups are imperative in order to tackle these concerns effectively. Several certifications and standards have been formulated and utilized for bamboo textiles to ensure environmental sustainability, ethical sourcing and quality. Fig. 3 shows the various labels that likely indicate genuine textile products.

The OEKO-TEX Standard 100 provides assurance that textiles, including bamboo, are devoid of any harmful substances. On the other hand, the Global Organic Textile Standard (GOTS) specifically applies to organic textiles, ensuring that bamboo production adheres to strict environmental and social criteria. The Forest Stewardship Council (FSC) certifies bamboo that is sourced from responsibly managed forests. USDA Organic certification verifies that bamboo is grown organically, while the Rainforest Alliance Certification promotes sustainability. Assessments such as Cradle to Cradle (C2C) and ISO 14001 evaluate the overall sustainability and environmental management of bamboo products. Fair Trade Certification focuses on ensuring fair labour practices. These various certifications provide consumers and businesses with the confidence to choose bamboo products that align with environmental and ethical standards, thereby promoting responsible sourcing and manufacturing practices. It is important to consider regional variations in certification requirements to ensure compliance with specific standards (Hardin et al. 2009; Nayak and Mishra, 2016; Plakantonaki et al., 2023).

8. Challenges and ambiguities of bamboo and bamboo fibres

As a fast-growing natural renewable material, bamboo could offer excellent sustainable solutions to reducing the carbon footprint, especially in highly populated regions in the world where bamboo is available in abundance. However, the rapid growth of bamboo, although beneficial in some contexts, can pose challenges in terms of plantation management. Clumping bamboos, like Bambusa vulgaris, have rhizomes that grow vertically and remain close to the original plant, resulting in dense and compact growth within the planted area. On the other hand, running bamboo species produce rhizomes that extend far from the parent plant, allowing them to spread over larger distances. These rhizomes can grow several feet away, Uncontrolled spreading can lead to ecological imbalances, disrupting native vegetation and reducing biodiversity. Bamboo leaves containing phenolic acid that inhibits the growth of other plants, enhancing the competitive advantage of bamboo. Beyond the positive aspects, this expansion can lead to invasive tendencies, reducing biodiversity and altering soil properties. Moso bamboo forests not only invade original forest spaces, leading to a reduction in biodiversity but also induce changes in the soil properties of affected areas. In China, Ying et al. (2016) observed that an evergreen broadleaf forest was more vulnerable to Moso bamboo invasion than deciduous broadleaf and coniferous forests. They found that Moso bamboo had certain edaphic preferences and thrived in warm, moist and sunny areas, with over 70% of the biomass and expansion occurring on slopes of 15°–30° with southerly, southeasterly and easterly aspects. Based on remote-sensing cover maps, Moso bamboo also commonly colonizes riverbank areas (Xu et al., 2020).

Bamboo has attracted worldwide attention because of its distinctive life history. It is a perennial flowering plant, but many bamboo species remain in a vegetative phase for decades, or even a century, followed by mass synchronous flowering and subsequent death (Janzen, 1976). Mass flowering in certain bamboo species, "known as "gregarious flowering," disrupts the plant's life cycle, triggering ecological events with extensive impacts. The aftermath includes bamboo plant deaths, leading to soil vulnerability and environmental damage. Communities relying on bamboo for material and food face disruption, causing an ecological imbalance. The phenomenon attracts rats, particularly Rattus, accelerating their population growth due to the estrogen in bamboo seeds. This surge leads to issues like the depletion of bamboo resources, rat invasion and subsequent famine. Thus, bamboo flowering has a negative effect on the livelihoods of people who depend on bamboo resources and could lead to famine among self-sufficient farmers (Sertse et al., 2011). For example, Bambusa balcooa Roxb., B. tulda Roxb., Dendrocalamus hamiltonii Nees & Arn. ex Munro, and Stapletonia arunachalensis (H.B. Naithani) P.Singh, S.S.Dash & P.Kumari all flowered in 2009 in Arunachal Pradesh, India. Subsequently, rodent outbreaks were reported in the flowering area, which caused severe damage to many crops (Kumawat et al., 2014). It is therefore essential to acknowledge both the positive aspects and potential ecological drawbacks to provide a balanced and informed perspective on the overall environmental implications of bamboo cultivation and utilization.

When thinking about buying bamboo faIric, it is essential to know that it usually costs more than cotton, especially for sustainable bamboo

Fig. 3. : Various labels and certifications for the authenticity of the textile products.

rather than bamboo rayon. Even though growing and harvesting bamboo is done sustainably, most bamboo clothes are made using a chemically intensive process called viscose to create bamboo rayon. The solvent employed in this procedure is carbon disulfide, a hazardous chemical known to pose risks to human reproduction. Its use in manufacturing can potentially jeopardize the health of factory workers and contribute to environmental pollution through both air emissions and wastewater discharge. Although mechanically extracted bamboo fibres are used for composite and technical textiles, much research is still needed on the mechanical extraction of bamboo fibre (Hardin et al. 2009; Nayak and Mishra, 2016).

9. Conclusion

The market for bamboo clothing is growing due to its sustainability and unique attributes. Mechanical extraction of bamboo fibre is emerging as more environmentally friendly process in comparison to chemically regenerated bamboo fibre. Due to the false claims, concerns regarding labelling accuracy and certifications are becoming important for bamboo fibre. Bamboo fibre possesses antibacterial properties and provide UV protection, making them highly promising for a wide range of textile applications. Although there are a lot of environmental benefits of bamboo and its fibres, it is crucial to recognize the ecological concerns associated with its rapid and aggressive growth.

CRediT authorship contribution statement

Akhtarul Islam Amjad: Writing – review & editing, Writing – original draft, Resources, Data curation, Conceptualization.

Declaration of Competing Interest

The author does not have a potential conflict of interest. To the best of my knowledge, no financial or personal relationships with individuals or organizations could have influenced the objectivity, integrity, or validity of the presented work. If applicable, we disclose any affiliations, financial involvements, or other situations that might be perceived as potential conflicts of interest.

Data availability

Data will be made available on request.

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