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# From Green Gold to Global Impact: Bamboo in Traditional and Advanced Applications

**Junu Poudel, Namita Nath*, Bhaben Tanti**

Department of Botany, Gauhati University, Guwahati 781014, Assam, India

*Corresponding author email: nathnamita1@gauhati.ac.in
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## Abstract

Bamboo, once regarded as the "poor man's timber," has transformed into a globally recognised sustainable resource, often referred to as "green gold." With over 1,600 species distributed worldwide, its significance extends far beyond traditional uses in construction, handicrafts, and agriculture. India, home to around 147 species across 23 genera, stands as the second-largest bamboo producer after China. The rapid growth, high tensile strength, and renewability of bamboo make it a compelling alternative to conventional materials, supporting both economic and environmental sustainability. This review explores bamboo's evolution from a traditional material to an essential component in modern applications such as engineered composites, bioenergy, nanocellulose production, and bioplastics. It highlights its role in climate change mitigation, carbon sequestration, and land restoration, offering solutions to pressing global challenges. Despite its vast potential, bamboo's widespread adoption is hindered by limitations in processing technologies, regulatory frameworks, and market awareness. This paper underscores the need for further research and innovation to maximise bamboo's utility in advancing sustainable development.

Keywords: Bamboo utilisation; Sustainable material; Renewable resource; Bio-based applications; Climate change mitigation.

## 1. Introduction

Bamboo has long been an integral part of human civilisation, evolving from what was once called the "poor man's timber" to what is now recognised as the "green gold" of the forest. Known for its remarkable versatility, rapid growth, and ecological benefits, bamboo has played a crucial role in various industries for centuries (Vyawahare, 2009). With over 1,600 species found across the world, its highest diversity is concentrated in Asia, where it has traditionally been used in construction, agriculture, and handicrafts (Canavan et al., 2019). India, the second-largest producer of bamboo after China, is home to around 125 species across 23 genera, accounting for a significant share of global bamboo diversity (Varmah and Bahadur, 1980; Sawarkar et al., 2020). The northeastern region alone holds approximately 43% of the country's bamboo resources, making it a biodiversity hotspot (Basumatary et al., 2015). This abundance has positioned bamboo as an essential resource for both traditional livelihoods and modern industries. What makes bamboo truly remarkable is its ability to combine strength, sustainability, and rapid renewability. Unlike hardwood trees that take decades to mature, bamboo reaches full growth in just three to five years, making it a sustainable alternative to timber (Goh et al., 2020; Tewari et al., 2019). Its tensile strength is comparable to mild steel, yet it remains lightweight and flexible, making it an excellent material for construction and manufacturing (Khalil et al., 2012). With over 1,500 documented uses, bamboo is often referred to as the "cradle to coffin" material, reflecting its presence in everything from shelter and tools to textiles and even high-tech applications (Li and Kobayashi, 2004; Nirala et al.,2017). Beyond its traditional applications, advancements in material science have unlocked new possibilities for bamboo. Researchers are now exploring its potential in engineered composites, bioenergy, nanocellulose production, and bioplastics, aligning with global sustainability efforts (Akinlabi et al., 2017a; Bansal and Zoolagud, 2002; Borah et al., 2008). As industries seek greener alternatives to conventional materials, bamboo's role in reducing deforestation, mitigating climate change, and supporting economic growth continues to expand (Singh et al., 2021). This review explores the journey of bamboo from a traditional material to a modern, high-performance resource. It examines its biological and structural properties, its wide-ranging applications, and its growing significance in sustainable development. Furthermore, it highlights the challenges and opportunities in maximising bamboo's potential, emphasising the need for continued innovation, research, and supportive policies. By bridging historical knowledge with cutting-edge advancements, this study underscores bamboo's role in shaping a more sustainable future.

## 2. Distribution and ecology of bamboo

Bamboo is distributed worldwide, with its highest species diversity found in the Asia-Pacific region (e.g., China, India, and Japan) and South America (e.g., Brazil, Venezuela, and Colombia). In contrast, Africa has the lowest bamboo diversity (Das et al., 2008). Naturally, bamboo is found on all continents except Antarctica and Europe. However, in recent years, some species have been introduced and cultivated in parts of Europe (Ahmad et al., 2021). According to the FAO Global Forest Resources Assessment 2020 (FRA), bamboo forests span approximately 35 million hectares across Africa, Asia, and the Americas. Over the past three decades, the global bamboo coverage has increased by 50%, largely due to afforestation efforts in China and India (FRA report, 2020). India ranks second in bamboo genetic diversity after China, with a total bamboo-bearing area of approximately 16 million hectares. Bamboo grows across a wide range of elevations and climates, from sea level to 4,300 metres above sea level (Clark et al., 2015). It thrives in regions receiving between 1,200 to 4,000 mm of annual rainfall, with its rapid culm elongation period being highly dependent on adequate water supply. Bamboo is rarely found in areas with less than 1,015 mm of rainfall (Banik, 2015). While excessive waterlogging can hinder growth due to oxygen deficiency, certain species, such as Phyllostachys, have developed air canals in their rhizomes, enabling them to survive in wet and waterlogged environments (Bansal, 2020).

## 3. Traditional uses of Bamboo

Bamboo, one of the tropics' natural resources, has been used extensively as an environmentally friendly substance in local communities' daily lives due to its wide distribution, availability, quick growth, ease of handling, and appealing qualities (Dransfield and Widjaja, 1995). It is celebrated for its versatility, availability, and eco-friendly properties (Pavate et al., 2024). Nine centuries back, Pou-Sung-Tung, a Chinese poet wrote "A meal should have meat, but a house must have a bamboo. Without meat we become thin; without bamboo, we lose serenity and culture" (Sharma, 1980). Its widespread use in traditional industries is attributed to its mechanical properties, rapid maturity, and adaptability to diverse environments (Yu, 2007; Amjad, 2024). Bamboo has been used in construction, handicrafts, agriculture, and other fields across cultures and geographical areas, demonstrating its importance in day-to-day living (Yuming et al., 2004; Lynser et al., 2014; Singha and Timung, 2015; Partasasmita et al., 2017; Witte, 2018; Dai and Hwang, 2019; Luo et al., 2020; Erkol, 2021; Muqoffa et al., 2024). In India, bamboo is consumed in the following ways: for pulp (35%), housing (20%), non-residential (5%), rural uses (20%), fuels (8.5%), packing (including baskets 5%), transportation (1.5%), furniture (1%), other woodworking industries (1%), and other items like ladders, mats, etc. (3%) (Nirala et al.,2017).

### *3.1. Construction and shelter*

Bamboo housing can be divided into three categories: (a) Traditional homes, which are constructed primarily of bamboo culms (b) Traditional bahareque homes, which are made of bamboo frames plastered with clay or cement; and (c) Modern-day prefabricated homes composed of bamboo veneers, laminated boards, and panels. More than a billion people, according to experts, reside in traditional bamboo homes (Ekhuemelo et al., 2018). Construction is one of bamboo's most well-known traditional applications (Jayanetti and Follett 2008). Bamboo has been the main material used to construct houses, bridges, and infrastructures in Asia, Africa, and Latin America (Sattar, 1995; Bredenoord, 2024). Bamboo has been used for castles, bridges, shelters, furniture, and artistic sculptures throughout the history of civilization. The story of the historic, devoted inn over the past century is shaped by its resilience in the face of earthquakes, floods, and fire (Simha, 2021). Its strength-to-weight ratio and tensile strength make it perfect for earthquake-resistant construction, and its hollow structure makes assembly and transportation easier (Kumarasamy et al., 2020; Yadav and Mathur, 2021). Roofs, walls, and floors constructed from bamboo are durable and contribute to natural insulation, making them energy-efficient (Yadav and Mathur, 2021). Bamboo is better than plastic sheets at obstructing sound, and even better than zinc sheets, which are only better than bamboo, making it a perfect roofing material. Bamboo flooring's smoothness, brightness, stability, high resistance, insulation qualities, and flexibility give it advantages over wooden floors. Bamboo flooring retains bamboo fibers' natural gloss and beauty giving it a gentle, natural shine (Muqoffa et al., 2024). Bamboo has also emerged as a valuable and superior substitute for wood composites, including veneer, plywood, particleboard, fiberboard, stripboards, pulp and paper, and matboards. Additionally, many studies have utilised it as a raw material for structural composites, including Oriented Strand Lumber (OSL), Glue Laminated Timber (GLT), Oriented Strand Board (OSB), and Parallel Strip Lumber (PSL) (Chaowana, 2013).

### *3.2. Tools and implements*

Bamboo is essential for making tools and implements because of its strength and workability. Bamboo is most commonly used to make knives. Bamboo knives are the most widely used cutting tools in Western Polynesia and Melanesia. According to ethnographic data, bamboo knives are now used in food preparation, rituals, and situations where speedy butchering is preferred. A fresh bamboo halm (outer stem) can be split into thinner slips to create these knives. The silica-rich outer halm of bamboo provides a thin, sharp edge. The bevelled edge of slips designed for knife use exposes the silica-rich halm outside the inner pulp (Spennemann, 1990; West and Louys, 2007). Moreover, traditional societies have utilised bamboo to make agricultural tools, fishing equipment, and weapons viz., arrows, and spears have been widely used, alongside everyday items such as baskets, and winnowing trays. In addition, bamboo steamers and containers have long been used for food preparation and serving, providing a sustainable substitute for contemporary plasticware (Nirala et al., 2017).

### *3.3. Furniture and handicrafts*

Bamboo furniture has grown in popularity recently as stylish and environmentally conscious consumers discover that this lovely and renewable material can now be used to create classic and modern furniture (Ruiz-Pérez et al., 2001). Chairs, tables, mats, and woven products crafted from bamboo are functional and aesthetically appealing. Conventional bamboo furniture is made from split or natural round bamboo. Bamboo panels that have been glue-laminated are used in a new style of "pack-flat, knockdown" furniture. In contrast to the traditional design, this furniture might be delivered in small flat packs. New design resolves issues with traditional bamboo furniture, including high labour and transportation costs, low productivity, instability, inconsistent quality, and vulnerability to fungi and insects. It also maintains bamboo's unique mechanical, chemical, physical, environmental, and aesthetic qualities (Muqoffa et al., 2004). Bamboo is widely used and more significant than any other material that man has created musical instruments out of ingenuity. Bamboo is so well suited for musical applications that it is almost possible to create a musical instrument simply by cutting a piece of it. Artisans in various cultures have relied on bamboo for intricate craftsmanship, creating items ranging from bamboo carvings to musical instruments like flutes and drums (Grame, 1962).

### *3.4. Paper and writing materials*

Bamboo has a historical role in communication and education. Ancient Chinese civilizations used bamboo strips as writing materials, paving the way for recorded history. The primary byproduct of the chemical conversion of ligno-cellulosic materials is pulp. Bamboo is a primary raw material used to make rayon and paper pulp in nations that grow it, such as India. As living standards rose, the disparity between the demand and supply for paper and paper products widened (Dhamodaran et al., 2003). The groundwork for several significant wood-based inventions for contemporary pulping was established in the 19th century by Keller (Germany) who developed a method for producing mechanical pulp in 1844, and Tilghman (GB) and Dahl (Germany) developed the sulfite (1866) and kraft (1879) processes for producing chemical pulps, respectively (Ek et al., 2009). In some Asian nations, such as China and India, bamboo has been used for centuries to make paper. Bamboo was first used to make handmade paper in China over 2,000 years ago. To make paper, the inner sections of the bamboo were pounded into a pulp (Chaudhary et al., 2024). In more recent times, bamboo pulp has been employed in traditional papermaking, especially in countries like China, India, Sri Lanka, Bangladesh, Indonesia, Thailand and Japan (Lessard and Chouinard, 1980).

### *3.5. Culinary uses and medicinal properties*

Young bamboo shoots, known for their tender texture and nutritional value, are a staple in many Asian cuisines (Chongtham et al., 2011). It is also frequently gathered, eaten, and traded by the tribal and rural communities of northeastern India for bamboo shoots, which show great promise as a food source. According to reports, they are low in fat and high in fiber, making them a good source of nutrition. In addition to being a storehouse of nutrients, they also contain some significant antioxidants and medicinal substances that can help delay the development of metabolic diseases (Singhal et al., 2013; Singhal et al., 2021). Bamboo shoots are consumed in fermented, raw, marinated, boiled, frozen, liquid, and canned, medicinal forms (Choudhury et al., 2012). Fermentation increases their nutritional value, prolongs the shelf life of bamboo shoots because of lactic acid bacteria and makes them easy to digest. They become more palatable in flavour, aroma, texture and appearance (Singhal et al., 2017). After fortification, young bamboo shoots from species like *Dendrocalamus giganteus* can also be processed into food products with improved organoleptic qualities and a longer shelf life, even though fresh bamboo shoots are healthier and more nutritious (Choudhury et al., 2012). According to recent research, bamboo shoots have been linked to weight loss, improved digestion and appetite, and the prevention of cancer and cardiovascular diseases. It has been reported that the shoots possess antiviral, antibacterial, and anticancer properties. Phenolic compounds in shoots give them antioxidant properties. One functional food that has benefited from the rising trends in consumer health consciousness is bamboo shoots (Singhal et al., 2013).

*3.6. Ritualistic uses and cultural importance*

Bamboo has been used as a cultural material for a very long time. Bamboo has been used in China for 5000 years. The pictographic representation of bamboo was found in oracle bone engravings and inscriptions on historical bronze objects, as well as on pottery unearthed in 1954 from Yangshao cultural assets of Banpo village, Xi'an (Bain, 2021). Bamboo symbolizes gentleness, modesty, and tranquility in Chinese culture (Hsiung, 1987). The bamboo plant is significant in Asian folklore. Several Asian cultures, including the Andaman Islands, hold that humans originated from a bamboo stem. The most well-known Philippine mythology describes how the first woman, Maganda (beautiful), and the first man, Malakás (strong), each arose from half of a split bamboo stem on an island created following the conflict between Sky and Ocean. In a similar tale from Malaysia, a man dreams of a stunning woman while sleeping beneath a bamboo plant. When he wakes up, he breaks the stem of the bamboo and finds the woman inside. According to the Japanese folktale "Tale of the Bamboo Cutter" (Taketori Monogatari), the princess from the Moon emerges from a section of glowing bamboo. The Polynesian creator god Kāne's kinolau, or body form, is Hawaiian bamboo, or ohe. In Vietnamese culture, it represents gentlemanship, directness, diligence, optimism, solidarity, and flexibility (Bain, 2021). Indians have been familiar with bamboo since ancient times. Bamboo is associated with Lord Krishna. He played a bamboo flute. The Mahabharata's introduction refers to bamboo groves. It is said that bamboo seeds were brought to Japan by Buddhist monks who travelled there from India to spread Buddhism (Ghosh, 2008). It is used in every footstep of life from birth to death (Singha and Timung, 2015; Bain, 2021; Ghosh, 2008). Bamboo has numerous uses in the Phu Thai community. Before building a house, they use a ritual in which parts of bamboo stems are woven into a Sai (fish trap), used in the primary foundation ceremony. Then, to accept the Mae Phosop goddess' gift, weave and create Chalaew, a container for offerings from bamboo. They also crafted a fire boat structure for the Lai Ruea Fai Celebration, woven a Khong (fish container) of bamboo, and used it to ward off ghosts during the ceremony (Sudchaleaw et al., 2023).

*3.7. Textile industry*

The qualities that bamboo products exhibit mostly depend on whether the fibre is regenerated or of natural origin. There are two primary ways that bamboo can be used effectively in the textile industry (Pavate et al., 2024).

1. Natural (bast) fibre is produced by physical and chemical means.
2. Regenerated (pulp) fibre is spun by recycling bamboo plants into pulp.

Bamboo fibre has the same chemical makeup as all other bast fibres; cellulose makes up the majority, and lignin must be further reduced for textile applications. Bamboo fibre has a small molecular weight and a low degree of polymerization, making it a member of the same structure of crystals as flax, cotton, and ramie. The single bamboo strand has a small lumen and a round cross-section. Bamboo fibre is expected to have good water absorption qualities, low elongation, and high breaking strength (Sudchaleaw et al., 2023). The largest bamboo in the world, *Phyllostahys edulis*, also known as "Moso," is the primary source of bamboo fibres. Bamboo-derived fibres are gaining popularity in the textile industry for their softness, hypoallergic, moisture-wicking properties, deodorant, breathable, thermoregulating, biodegradability, UV protection and natural anti-bacterial as well as anti-fungal qualities. Bamboo textiles are used in the sports industry, Yoga and fitness clothing, summer wear, fashion industry, children’s as well as maternal clothing. It is used in medical clothing viz., socks and undergarments specifically for diabetic patients with anti-binding properties thus, helps to improve the blood circulation of patients (Lipp-Symonowicz et al., 2011). Beyond its traditional roles, advancements in material science have expanded bamboo’s applications in engineered products and emerging technologies.

# 4. Advanced applications of bamboo

The declining wood supply will result in increasing demand for biomass worldwide for the production of green energy. As a result, attention has turned to substituting raw materials for wood. A good raw material needs to be affordable, readily available, grow quickly, have mechanical and physical characteristics similar to wood, and work with the current processing technologies (Chaowana, 2013). In this section, we explore the advanced applications of bamboo, highlighting its expanding role in various sectors, including energy, biomedical fields, and biotechnology.

*4.1. Biochemical and bioenergy applications*

One of the fastest-growing plant species is bamboo, which can reach a culm circumference of 30 cm and grow between 30 and 60 cm per day (Scurlock et al., 2000; Ben-Zhi et al., 2005; Fuke et al., 2021; Ding et al., 2023). Bamboo can produce a higher volume of biomass per hectar due to its rapid growth rate compared to other common plants. Bamboo contains significant amounts of cellulose, hemicellulose, and lignin, making it an excellent source of fuels, bio-based chemicals and energy production. Although this composition differs from species to species, cellulose (37–47%), hemicellulose (15–30%), and lignin (18–31%) make up the majority of bamboo biomass (Ding et al., 2023; He et al., 2014; Li et al., 2018). The conversion of bamboo biomass into bioethanol and biodiesel offers a renewable energy alternative. The three main thermochemical processes that can transform bamboo biomass into energy, biofuels, and chemicals are combustion, pyrolysis, and gasification (Ding et al., 2023; Ong et al., 2020).

*4.2. Charcoal and biochar production*

Bamboo is superior to wood in every way, taking only two to three years to reach maturity compared to wood, which usually takes ages (Ahmad et al., 2021). It can produce new shoots because its root system continues to grow after harvest, and can breed in unproductive areas, such as eroding hillsides (Chaturvedi et al., 2024). They can be found in temperate deciduous forests, coniferous forests, lowland tropical forests, mountainous forests, understory, (moist) wetter forests, grasslands, and many ecological areas. They are primarily found in the tropic and subtropical regions due to natural occurrence and farmland cultivation (Ahmad et al., 2021). Bamboo is an ideal starting material for synthesising biochar and activated carbon because of its low cost, high biomass yield, and accelerated growth rate (Chaturvedi et al., 2024; Mckay, 1995). Bamboo charcoal has also attracted significant interest because of its large surface area, highly porous structure, and superior adsorption capabilities (Chaturvedi et al., 2024). Modern techniques now process bamboo into pellets, methane, charcoal, bio-ethanol, producer gas and briquettes enhancing its value as a renewable energy resource (Dhamodaran et al., 2006; Akinlabi et al., 2017c; Brand et al., 2019). Bamboo charcoal, known for its adsorbent properties, is used in various medical applications, including detoxification, wound healing, and air and water purification. Its ability to adsorb toxins and impurities is leveraged in healthcare products like bamboo charcoal masks, filters, and therapeutic pads. Bamboo charcoal is used in water filtration systems and air purifiers due to its porous structure, effectively removing impurities and toxins. Additionally, bamboo’s ability to absorb excess moisture makes it useful in controlling humidity and improving air quality in industrial and residential settings (Chaturvedi et al., 2024).

*4.3. Bamboo as a feedstock for nanocellulose*

Bamboo is an excellent feedstock of cellulose fibre for the production of cellulose nanocrystals because it contains a significant amount of cellulose—roughly 40% to 50% (Othman et al., 2024). Bamboo's lignocellulosic composition makes it an excellent candidate for producing nanocellulose (Zhang et al., 2019). Perhaps the most significant user of cellulose and nanocellulose is the paper industry. At different phases of the paper-making process (refining, formation, pressing, and drying), nanocellulose has been used, for instance, as a strengthening agent, a part of the retention system, a printing aid, a coating binder, and a barrier agent regulating the transmission of oxygen and water vapour (Das et al., 2024). Additionally, paper sheets can be strengthened using nanocellulose instead of inorganic fillers (Dhali

Table 1. Traditional and advanced applications of bamboo in different sectors.

| Application | Traditional use | Advanced use |
|---|---|---|
| Construction | Bamboo huts, scaffolding | Engineered bamboo panels, prefabricated housing |
| Furniture | Handmade bamboo chairs, mats | Laminated bamboo furniture, modular designs |
| Textiles | Handwoven mats, bamboo fibres | Bamboo-based bioplastics, medical textiles |
| Energy | Firewood, charcoal | Bioethanol, biogas, activated carbon |
| Medicine | Herbal remedies, wound dressings | Antibacterial nanocellulose-based bandages |
| Paper & Writing | Bamboo scrolls, handmade paper | Bamboo pulp for industrial paper production |
| Tools and implements | Baskets, fishing traps, simple tools | High-strength composite materials for industrial use |
| Culinary | Bamboo shoots as food | Fortified bamboo-based food products |

et al., 2021). Bamboo cellulose finds extensive use in antimicrobial activity, textile industry, UV-protective apparel, wound healing, drug delivery, and temperature control (Prakash, 2020; Rashid et al., 2023).

*4.4. Bamboo in composite materials*

Manufacturing bamboo-based composites with various matrices have developed economical and environmentally friendly bio-composites, directly raising bamboo's market value (Akinlabi et al., 2017a). Bamboo has significant potential in the polymer composites industry because of its fibre extraction, structural variation, mechanical properties, thermal properties, and chemical modification, making it a competitive choice for composite industry use (Mounika et al., 2012). Compared to other natural fibres, bamboo has superior mechanical qualities. It is utilised as reinforcement in the composite production process instead of synthetic fibres due to its exceptional qualities because synthetic fibres are not readily available and are not biodegradable, they are harmful to the environment. It has been utilised in diverse engineering applications, including automotive, wind turbines, solar panels, biomedical aircraft, aerospace, and reinforcement materials (Ababu et al., 2021).

*4.5. Bamboo-based medical textiles*

Bamboo fibres are excellent at absorbing odd smells, inhibiting the growth of bacteria, and being hygroscopic. Due to these qualities, they are utilised as non-woven medical and sanitary materials (Amjad, 2024; Imadi et al., 2014). The leaching method extracts flavones from bamboo leaf fibres. Numerous medications are prepared using these flavones (Imadi et al., 2014). Additionally, bamboo fibres can be used to make surgical gowns, medical masks, gauze, bandages, absorbent pads, and sanitary towels. Because bamboo fibres are gentle, very few people have an allergy to them; this characteristic is used creating masks and other items. It is reasonably priced, strong, and lightweight (Imadi et al., 2014; Morris and Murray, 2020).

*4.6. Carbon sequestration and climate change mitigation*

Climate change is the most challenging issue facing the world today, impacting economic, environmental, and social aspects. The International Network of Bamboo and Rattan (INBAR) group made every effort to present to world leaders the potential of bamboo as a solution to deforestation and climate change (Daba et al., 2016). Bamboo begins to produce three or four years after planting and grows faster than any tree. Bamboo grows quickly and responds well to drought, which can increase its acceptability in creating a green environment, conserving water and soil, and restoring degraded areas (Terefe et al., 2016). Zhou GuoMo and Jiang PeiKun (2004) stated that because bamboo grows quickly, the annual carbon fixation Moso bamboo forest was 5.10 t $ha^{-1}$, which was 1.33 times that of a tropical mountain rainforest, 0.94 times that of a Chinese fir (*Cunninghamia lanceolata*) at age 12, and 1.41 times that of a Chinese fir at age 5 (Zhou, 2004). Bamboo plantations act as carbon sinks, helping reduce the concentration of greenhouse gases in the atmosphere. The bamboo forest is one of the best forest types for fixing carbon because of its high annual carbon accumulation rate. Bamboo is an efficient agro-forest $CO_2$ sink, producing 35% more oxygen than other timber species and having a high carbon sequestration rate of 47%, or 12–17 t $CO_2$ per hectare annually (Daba et al., 2016).

## 5. Potential for future applications

Bamboo holds incredible promise for shaping a more sustainable future. As industries search for greener alternatives, this fast-growing plant is emerging as a game-changer in construction, energy, and advanced materials. Engineered bamboo products, such as laminated boards and composite panels, are already proving to be strong, durable, and eco-friendly substitutes for traditional timber, helping to reduce deforestation. In the energy sector, bamboo's high biomass yield makes it a promising raw material for biofuels like ethanol and biogas, offering a renewable alternative to fossil fuels. Scientists are also exploring its potential in cutting-edge fields, from biodegradable plastics to medical textiles and even flexible electronics. With the right investment in technology, policy support, and increased awareness, bamboo could become a mainstream solution for building a low-carbon, sustainable economy. The challenge now is scaling up its use while ensuring responsible cultivation and efficient processing. If we get it right, bamboo could be a key part of the future offering not just economic opportunities but a way to restore balance between human needs and the environment.

## 6. Challenges to Bamboo's widespread adoption

Despite its advantages, bamboo faces several challenges that limit its widespread adoption. A major barrier is the lack of standardisation in processing and product quality, which prevents bamboo materials from competing effectively in global markets. Additionally, while bamboo grows rapidly, large-scale sustainable cultivation requires proper management to prevent soil depletion and ecological imbalances. Many industries remain hesitant to adopt bamboo due to outdated perceptions about its durability and long-term performance, particularly in construction. Furthermore, processing technologies require improvement—current methods can be labour-intensive and costly, making it difficult to produce high-quality engineered products such as composites and nanocellulose on an industrial scale. Lastly, inadequate policy support, limited investment, and weak infrastructure continue to hinder the development of a robust supply chain. Addressing these challenges through research, innovation, and regulatory frameworks will be key to unlocking bamboo's full potential.

## References

Ababu M, Husen E, Awraris B and Bashawal N. 2021. Review of the applications and properties of bamboo fiber reinforced composite materials. GSJ 9(3):1196-1204.

Ahmad Z, Upadhyay A, Ding Y, Emamverdian A, & Shahzad A. 2021. Bamboo: Origin, Habitat, Distributions and Global Prospective. In: Zishan Ahmad, Yulong Ding, Anwar Shahzad (Eds.): *Biotechnological Advances in Bamboo: The "Green Gold" on the Earth*. Springer Nature, Pp 1-31.

Akinlabi ET, Anane-Fenin K and Akwada DR. 2017c. Bamboo as fuel. In: Esther Titilayo Akinlabi, Kwame Anane-Fenin, Damenortey Richard Akwada (Eds.): *Bamboo: The Multipurpose Plant*. Springer, Pp 149-178.

Akinlabi ET, Anane-Fenin K, Akwada DR, Akinlabi ET, Anane-Fenin K and Akwada DR. 2017a. Bamboo taxonomy and distribution across the globe. In: Esther Titilayo Akinlabi, Kwame Anane-Fenin, Damenortey Richard Akwada (Eds.): *Bamboo: The Multipurpose Plant*, 1-37. Springer.

Amjad AI. 2024. Bamboo fibre: A sustainable solution for textile manufacturing. Advances in Bamboo Science 7: 100088. https://doi.org/10.1016/j.bamboo.2024.100088

Bain W. 2021. Archaeology in Northeast India: Recent Trends and Future Prospects. In: M. K. Chauley, M. Hazarika (Eds.) *Bamboo Tale: A Case Study from Dzongu Reserve area of North Sikkim* (1st ed., pp. 01-370). Research India Press, New Delhi, India.

Banik RL. 2015. Bamboo Silviculture. In: Liese, W., Köhl, M. (Eds.): *Bamboo. Tropical Forestry*, vol 10. Springer, Cham. Pp 113-174 https://doi.org/10.1007/978-3-319-14133-6_5

Bansal AK. 2020. Unlocking the potential of bamboo sector in India. NCCF Working Paper.

Bansal AK and Zoolagud SS. 2002. Bamboo composites: Material of the future. Journal of Bamboo and Rattan 1(2): 119-130.

Basumatary A, Middha SK, Usha T, Brahma BK and Goyal AK. 2015. Bamboo, as potential sources of food security, economic prosperity and ecological security in North-East India: an overview. Research in Plant Biology 5(2):17-23.

Ben-Zhi Z, Mao-Yi F, Jin-Zhong X, Xiao-Sheng Y and Zheng-Cai L. 2005. Ecological functions of bamboo forest: research and application. Journal of Forestry Research 16: 143-147.

Borah ED, Pathak KC, Deka B, Neog D and Borah K. 2008. Utilization aspects of Bamboo and its market value. Indian Forester 134(3): 423-427.

Brand MA, Balduino AL, Nones DL and Gaa AZN. 2019. Potential of bamboo species for the production of briquettes. Pesquisa Agropecuária Tropical 49: e54178. https://www.scielo.br/j/pat/a/b9Qr9scYDzWfYTJDwj4QRzy/?lang=en

Bredenoord J. 2024. Bamboo as a Sustainable Building Material for Innovative, Low-Cost Housing Construction. Sustainability 16(6): 2347. https://doi.org/10.3390/su16062347

Canavan S, Richardson DM, Le-Roux JJ and Wilson JRU. 2019. Alien bamboos in South Africa: a socio-historical perspective. Human Ecology 47: 121-133.

Chaowana P. 2013. Bamboo: an alternative raw material for wood and wood-based composites. Journal of Materials Science Research 2(2): 90.

Chaturvedi K, Singhwane A, Dhangar M, Mili M, Gorhae N, Naik A, and Verma S. 2024. Bamboo for producing charcoal and biochar for versatile applications. Biomass Conversion and Biorefinery 14(14): 15159-15185. https://doi.org/10.1007/s13399-022-03715-3

Chaudhary U, Malik S, Rana V and Joshi G. 2024. Bamboo in the pulp, paper and allied industries. Advances in Bamboo Science 7: 100069. https://doi.org/10.1016/j.bamboo.2024.100069

Chongtham N, Bisht MS and Haorongbam S. 2011. Nutritional properties of bamboo shoots: potential and prospects for utilization as a health food. Comprehensive reviews in food science and food safety 10(3): 153-168. https://doi.org/10.1111/j.1541-4337.2011.00147.x

Choudhury D, Sahu JK and Sharma GD. 2012. Value addition to bamboo shoots: a review. Journal of Food Science and Technology 49: 407-414. https://doi.org/10.1007/s13197-011-0379-z

Clark LG, Londoño X and Ruiz-Sanchez E. 2015. Bamboo Taxonomy and Habitat. In: Liese, W., Köhl, M. (Eds.): *Bamboo. Tropical Forestry*, vol 10. Springer, Cham. Pp 1-30. https://doi.org/10.1007/978-3-319-14133-6_1

Daba M. 2016. Industrial, carbon sequestration and climate change mitigation potentials of bamboo. Journal of Scientific Research and Reports 12(3): 1-8. https://doi.org/10.9734/JSRR/2016/28926

Dai Y and Hwang SH. 2019. Technique, creativity, and sustainability of bamboo craft courses: Teaching educational practices for sustainable development. Sustainability 11(9): 2487. https://doi.org/10.3390/su11092487

Das AK, Islam MN, Ashaduzzaman M and Nazhad MM. 2020. Nanocellulose: its applications, consequences and challenges in papermaking. Journal of Packaging Technology and Research 4: 253-260. https://doi.org/10.1007/s41783-020-00097-7

Das M, Bhattacharya S, Singh P, Filgueiras TS and Pal A. 2008. Bamboo Taxonomy and Diversity in the Era of Molecular Markers. Advances in Botanical Research 47:225-268. https://doi.org/10.1016/S0065-2296(08)00005-0

Dhali K, Ghasemlou M, Daver F, Cass P and Adhikari B. 2021. A review of nanocellulose as a new material towards environmental sustainability. Science of the Total Environment 775: 145871. https://doi.org/10.1016/j.scitotenv.2021.145871

Dhamodaran TK, Gnanaharan R and Pillai KS. 2003. Bamboo for pulp and paper. Kerala Forest Research Institute, India. https://www.inbar.int/wp-content/uploads/2020/05/1489543834.pdf

Dhamodaran TK, Thulasidas PK and Gnanaharan R. 2006. Comparison of yield and quality of bamboo charcoal produced by traditional methods. Journal of Bamboo and Rattan 5(3): 151-157. https://shorturl.at/wD50F

Ding Z, Awasthi SK, Kumar M, Kumar V, Dregulo AM, Yadav V and Awasthi MK. 2023. A thermo-chemical and biotechnological approaches for bamboo waste recycling and conversion to value added product: Towards a zero-waste biorefinery and circular bioeconomy. Fuel 333: 126469. https://doi.org/10.1016/j.fuel.2022.126469

Dransfield S and Widjaja EA. 1995. *Plant resources of South-East Asia* Vol.7, Backhuys Publishers, Leiden.

Ek M, Gellerstedt G and Henriksson G. 2009. *Wood chemistry and wood biotechnology*.Volume1, Walter de Gruyter GmbH & Co. KG, 10785 Berlin.

Ekhuemelo DO, Tembe ET and Ugwueze FA. 2018. Bamboo: a potential alternative to wood and wood products. South Asian Journal of Biological Research 1(1): 9-24. https://aiipub.com/wp-content/uploads/2018/10/SAJBR-181001-030110_FP.pdf#page=13.64

Erkol YA. 2021. *Bamboo: a socio-material approach to past and present bamboo cultures*. Doktors der Philosophie, Technische Universitaet, Berlin, Germany.

Fuke PTMM, Kumar M, Sawarkar AD, Pandey A and Singh L. 2021. Role of microbial diversity to influence the growth and environmental remediation capacity of bamboo: A review. Industrial Crops and Products 167: 113567. https://doi.org/10.1016/j.indcrop.2021.113567

Ghosh GK. 2008. *Bamboo: The wonderful grass*. APH Publishing.

Goh Y, Yap SP and Tong TY. 2020. Bamboo: the emerging renewable material for sustainable construction. Encyclopedia of Renewable and Sustainable Materials 2: 365-376.

Grame TC.1962. Bamboo and music: a new approach to organology. Ethnomusicology 6(1): 8-14. https://doi.org/10.2307/924243

He MX, Wang JL, Qin H, Shui ZX, Zhu QL, Wu B and Hu GQ. 2014. Bamboo: A new source of carbohydrate for biorefinery. Carbohydrate polymers 111: 645-654. https://doi.org/10.1016/j.carbpol.2014.05.025

Hsiung W. 1987. Bamboo in China: new prospects for an ancient resource. Unasylva an international journal of forestry forest industries 39(156):42-49

Imadi SR, Mahmood I, Kazi AG. 2014. Bamboo Fiber Processing, Properties, and Applications. In: Hakeem K, Jawaid M, Rashid U. (eds) *Biomass and Bioenergy*. Springer, Cham. https://doi.org/10.1007/978-3-319-07641-6_2

Jayanetti DL and Follett PR. 2008. Bamboo in construction. In: Xiao Y, Inoue M and Paudel SK (Eds.): *Modern bamboo structures*, Proceedings of First International Conference on Modern Bamboo Structures (ICBS-2007), Changsha, China, 28-30 October 2007 (1st ed.). CRC Press, London.

Khalil HPSA, Bhat IUH, Jawaid M, Zaidon A, Hermawan D and Hadi YS. 2012. Bamboo fibre reinforced biocomposites: A review. Materials and Design 42: 353-368.

Kumarasamy K, Shyamala G, Gebreyowhanse H and Kumarasamy. 2020. Strength properties of bamboo fiber reinforced concrete. IOP conference series: materials science and engineering 981(3):032063.

Lessard G and Chouinard A. 1980. *Bamboo research in Asia,* Proceedings of a workshop held in Singapore, 28-30 May 1980. IDRC, Ottawa, ON, CA.

Li T, Remón J, Jiang Z, Budarin VL and Clark JH. 2018. Towards the development of a novel "bamboo-refinery" concept: Selective bamboo fractionation by means of a microwave-assisted, acid-catalysed, organosolv process. Energy Conversion and Management 155: 147-160. http://dx.doi.org/10.1016/j.enconman.2017.10.077

Li Z and Kobayashi M. 2004. Plantation future of bamboo in China. Journal of Forestry Research 15: 233-242.

Lipp-Symonowicz B, Sztajnowski S and Wojciechowska D. 2011. New commercial fibres called 'bamboo fibres'-Their structure and properties. Fibres and Textiles in Eastern Europe 19(1 (84)): 18-23.

Luo B, Ahmed S and Long C. 2020. Bamboos for weaving and relevant traditional knowledge in Sansui, Southwest China. Journal of ethnobiology and ethnomedicine 16: 1-9. https://doi.org/10.1186/s13002-020-00418-9

Lynser MB, Tiwari BK, Nongbri B and Kharlyngdoh E. 2014. Bamboo mat making and its contribution to the rural livelihood of women in South Meghalaya, India. J Am Bamboo Soc 28(1): 23-31.

Mckay G. 1995. *Use of Adsorbents for the Removal of Pollutants from Wastewater*. CRC press.

Morris H and Murray R. 2020. Medical textiles. Textile Progress 52(1-2):1-127. https://doi.org/10.1080/00405167.2020.1824468

Mounika M, Ramaniah K, Prasad AR, Rao KM and Reddy KHC. 2012. Thermal conductivity characterization of bamboo fiber reinforced polyester composite. J. Mater. Environ. Sci 3(6): 1109-1116.

Muqoffa M, Himawan K, Juwana WE and Adhi R. 2024. Multifaceted Role of Construction Materials in Javanese Vernacular Houses. Journal of the International Society for the Study of Vernacular Settlements from Historical Vernacular to Contemporary Vernacular 11 (6): 60-95.

Nirala DP, Ambasta N, Kumari P and Kumari P. 2017. A review on uses of bamboo including ethno-botanical importance. International Journal of Pure and Applied Bioscience 5(5): 515-523.

Ong HC, Chen WH, Singh Y, Gan YY, Chen CY and Show PL. 2020. A state-of-the-art review on thermochemical conversion of biomass for biofuel production: A TG-FTIR approach. Energy Conversion and Management 209: 112634. https://doi.org/10.1016/j.enconman.2020.112634

Othman JAS, Ilyas RA, Nordin AH, Ngadi N and Alkbir MFM. 2024. Recent advancements in bamboo nanocellulose-based bio adsorbents and their potential in wastewater applications: A review. International Journal of Biological Macromolecules 277(3):134451

Partasasmita R, Anâ AZIFAH, Iskandar J, Mutaqin AZ, Annisa A and Ratningsih N. 2017. Karangwangi peoples local knowledge of bamboo and its role: Implications for management of cultural keystone species. Biodiversitas Journal of Biological Diversity 18(1):275-282

Pavate V, Jagdale A, Shinde R, Manechikkannara N and Patil D. 2024. Study on bamboo industry. International Journal for Research in Applied Science and Engineering Technology 12(4): 1533-1548. https://doi.org/10.22214/ijraset.2024.60085

Prakash C. 2020. Bamboo fibre. In: Ryszard M Kozłowski, Maria Mackiewicz-Talarczyk (Eds): *Handbook of Natural Fibres* (Second Edition), Woodhead Publishing,Pp 219-229. https://doi.org/10.1016/B978-0-12-818398-4.00009-8

Rashid MM, Abir N, Hossain MA, Iqbal MI and Siddique AB. 2023. Bamboo cellulose: Structure, properties, and applications. In: R. Arun Ramnath, Mavinkere Rangappa Sanjay, Suchart Siengchin, Vincenzo Fiore (Eds): In *Composites Science and Engineering, Cellulose Fibre Reinforced Composites*,Woodhead Publishing,Pp 23-48. https://doi.org/10.1016/B978-0-323-90125-3.00007-0

Ruiz-Pérez M, Maoyi F, Xiaosheng Y and Belcher B. 2001. Bamboo forestry in China: toward environmentally friendly expansion. Journal of Forestry 99(7): 14-20. https://doi.org/10.1093/jof/99.7.14

Sattar MA. 1995. Traditional bamboo housing in Asia: Present status and future prospects. Bamboo, People and the Environment 3: 1-13.

Sawarkar AD, Shrimankar DD, Kumar A, Kumar A, Singh E, Singh L, Kumar S and Kumar R. 2020. Commercial clustering of sustainable bamboo species in India. Industrial Crops and Products 154: 112693.

Scurlock JM, Dayton DC and Hames B. 2000. Bamboo: an overlooked biomass resource?. Biomass and bioenergy 19(4): 229-244.

Sharma YML. 1980. Bamboos in the Asia Pacific Region. In: Gilles Lessard and Amy Chouinard (Eds.): *Bamboo research in Asia*, Proceedings of a workshop held in Singapore, 28-30 May 1980. IDRC, Ottawa, ON, CA.

Simha KRY. 2021. Earthimalayan Wood, Cane & Bamboo: Door to Earthquake Resistant Technologies. Journal of Geological Society of India 97(7):812. https://doi.org/10.1007/s12594-021-1765-4

Singh L, Thul ST and Manu TM. 2021. Development of bamboo biodiversity on mining degraded lands: A sustainable solution for climate change mitigation. In: Kuldeep Bauddh, John Korstad, Pallavi Sharma (Eds.):*Phytorestoration of Abandoned Mining and Oil Drilling Sites*, Elsevier, Pp 439-451.

Singha KN and Timung L. 2015. Significance of bamboo in Karbi culture: A case study among the Karbi Tribes of Assam (India). International Journal of Advanced Research in biology and biotechnology 1(1): 1-9.

Singhal P, Bal LM, Satya S, Sudhakar P and Naik SN. 2013. Bamboo shoots: a novel source of nutrition and medicine. Critical reviews in food science and nutrition 53(5): 517-534. https://doi.org/10.1080/10408398.2010.531488

Singhal P, Satya S and Naik SN. 2021. Fermented bamboo shoots: A complete nutritional, anti-nutritional and antioxidant profile of the sustainable and functional food to food security. Food Chemistry: Molecular Sciences 3: 100041. https://doi.org/10.1016/j.fochms.202 1.100041

Singhal P, Singh RK, Satya S and Naik SN. 2017. Toxicity reduction in bamboo shoots: field survey and scientific validation of a traditional knowledge system. Culture, agriculture, food and environment 39(2): 138-142. https://doi.org/10.1111/cuag.12089

Spennemann DHR. 1990. Don't forget the bamboo-on recognising and interpreting butchery marks in tropical faunal assemblages, some comments asking for caution. In: Su Solomon, Iain Davidson, and Di Watson(Eds.): *Problem Solving in Taphonomy: Archaeological and Palaeontological Studies from Europe, Africa and Oceania*. Anthropology Museum, University of Queensland, St Lucia, Queensland, Pp 108-134.

Sudchaleaw S, Saensouk S, Saensouk P and Sungkaew S. 2023. Species diversity and traditional utilization of bamboos (*Poaceae*) on the Phu Thai Ethnic Group in northeastern Thailand. Biodiversitas Journal of Biological Diversity 24(4):2261-2271.

Terefe R, Samuel D, Sanbato M and Daba M. 2016. Adaptation and growth performance of different lowland bamboo species in Bako, West Shoa, Ethiopia. Journal of Natural Sciences Research 6(9): 61-65.

Tewari S, Negi H and Kaushal R. 2019. Status of bamboo in India. International Journal of Economic Plants 6(Feb, 1): 30-39.

Varmah JC and Bahadur KN. 1980.Country report and status of research on bamboos in India. In: Lessard, G. and Chouinard, A. (Eds.): *Bamboo research in Asia*. Proceedings of a workshop held in Singapore, 28-30 May 1980. IDRC, Ottawa, ON, CA.

Vyawahare M. 2009. *Bamboo: poor man's gold*. Centre for Civil Society, New Delhi.

West JA and Louys J. 2007. Differentiating bamboo from stone tool cut marks in the zooarchaeological record, with a discussion on the use of bamboo knives. Journal of archaeological science 34(4): 512-518. https://doi.org/10.1016/j.jas.2006.06.007

Witte D. 2018. *Contemporary Bamboo Housing in South America: Challenges & Opportunities for Building in the Informal Sector*. Master of Architecture, University of Washington. https://digital.lib.washington.edu/researchworks/bitstreams/fe7eb193-d1d0-4d70-b8c1-81ceba7146bd/download

Yadav M and Mathur A. 2021. Bamboo as a sustainable material in the construction industry: An overview. Materials today: proceedings 43: 2872-2876. https://doi.org/10.1016/j.matpr.2021.01.125

Yu X. 2007. *Bamboo: Structure and Culture* .Dissertation zur Erlangung des Grades eines Doktors der Philosophie, im Fachbereich Kunst und Design der Universität Duisburg-Essen.
https://core.ac.uk/download/pdf/33799224.pdf

Yuming Y, Kanglin W, Shengji P and Jiming H. 2004. Bamboo diversity and traditional uses in Yunnan, China. Mountain Research and Development 24(2): 157-165.

Zhang Y, Xu W, Wang X, Ni S, Rosqvist E, Smått JH and Xu C. 2019. From biomass to nanomaterials: a green procedure for preparation of holistic bamboo multifunctional nanocomposites based on formic acid rapid fractionation. ACS Sustainable Chemistry & Engineering 7(7):6592-6600. https://doi.org/10.1021/acssuschemeng.8b05502

Zhou GuoMo ZG and Jiang PeiKun JP. 2004. Density, storage and spatial distribution of carbon in Phyllostachy pubescens forest. Scientia Silvae Sinicae 40 (6): 20-24. https://doi.org/10.5555/20053190474