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A Review of Bamboo: Characteristics, Components, and Its Applications

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ABSTRACT

The utilization of tropical lignocellulosic biomass is gaining momentum in renewable energy and sustainable material applications. This review focuses on bamboo, a fast-growing resource with high cellulose content and strong mechanical properties. A systematic analysis of Scopus-indexed publications (1990–2024) highlights bamboo's potential in bioenergy, biocomposites, and environmental remediation. Beyond its industrial value, bamboo holds cultural and economic significance for Indigenous and local communities, traditionally used in construction, tools, crafts, and music. These practices reflect deep ecological knowledge. Despite its promise, bamboo remains underrepresented in biomass research compared to temperate species, revealing a knowledge gap. Research is dominated by environmental science, aligning with global sustainability goals. However, challenges such as lignin removal efficiency and species-specific variability persist, hindering large-scale bioenergy applications. For instance, high hemicellulose content in species like *Gigantochloa apus* may offer advantages in fermentation efficiency. This review emphasizes the importance of selecting suitable biomass species and tailoring conversion technologies based on chemical composition. By integrating technical insight with socio-ecological context, this work supports the sustainable and culturally informed development of tropical biomass resources – especially bamboo – for future industrial and environmental applications.

摘要

热带木质纤维素生物质的利用在可再生能源和可持续材料应用方面正在取得进展. 本文重点介绍了竹子，这是一种纤维素含量高、机械性能强的快速增长资源. 对Scopus索引出版物（1990-2024）的系统分析突出了竹子在生物能源、生物复合材料和环境修复方面的潜力. 除了工业价值，竹子对土著和当地社区也具有文化和经济意义，传统上用于建筑、工具、手工艺和音乐. 这些做法反映了深厚的生态知识. 尽管竹子有希望，但与温带物种相比，竹子在生物质研究中的代表性仍然不足，这揭示了一个知识差距. 研究以环境科学为主导，与全球可持续发展目标保持一致. 然而，木质素去除效率和物种特异性变异等挑战仍然存在，阻碍了大规模的生物能源应

KEYWORDS
Bamboo; cellulose fiber; biomass; diversity; health; hydrogel

关键词
竹子; 纤维素纤维; 生物量; 多样性; 健康; 水凝胶

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用. 例如，Gigantochloa apus等物种的高半纤维素含量可能在发酵效率方面具有优势. 本文强调了选择合适的生物质物种和根据化学成分定制转化技术的重要性. 通过将技术见解与社会生态背景相结合，这项工作支持热带生物质资源（尤其是竹子）的可持续和文化知情发展，以用于未来的工业和环境应用.

Introduction

Bamboo is a versatile plant with rapid growth and many uses. It plays an important role in industry, employment, and environmental protection. Bamboo is a renewable resource with unique properties and applications. In addition, bamboo is also a sustainable biological resource that can have a short growth period with a high CO_2 fixation rate, so it can be a good choice to reduce global warming and climate change (Emamverdian et al. 2020). Sustainable bamboo production is in line with the United Nations (UN) Sustainable Development Goals (SDGs). Sustainable bamboo production and utilization are considered directly relevant to many of the UN-SDGs, which target important aspects of poverty alleviation, housing, urban development, sustainable energy use, combating climate change, and land degradation. Bamboo's properties make it ideal for paper, textiles, and bioenergy. Bamboo's high-water retention is beneficial for food industry applications. Bamboo belongs to the grass family and has diverse uses (Van Dam, Elbersen, and Daza Montaño 2018). With increasing demand, bamboo is now considered an important source for biofuel and biochemical production due to its faster growth, ease of propagation, and richness in polysaccharides. Compared to other natural resources, bamboo exhibits some specific environmental and structural benefits, such as rapid growth and climate adaptability (Verma et al. 2021).

Bamboo is a versatile and sustainable fiber with unique properties. Bamboo fibers are biodegradable, antibacterial, and used in many applications (Imadi, Mahmood, and Kazi 2014). Industrial applications of bamboo in food, biotechnology, and fiber extraction. Bamboo has global significance in the economy and distribution of resources. Bamboo has potential in the food industry, bioprocessing, and sustainable cultivation (Yasin and Priyanto 2019). As an alternative to wood, bamboo biomass can be utilized in various fields. Bamboo biomass may consist of culms containing fiber, fallen leaves, or roots that are no longer productive (Emamverdian et al. 2020). In addition, the utilization of lignin from bamboo biomass can be used as specialty chemicals. Bamboo is a promising non-wood resource for various applications. Lignocellulosic biomass can be categorized into agricultural residues (e.g., straw, husks, stover, shells, and bagasse), wood residues (e.g., softwood, hardwood, and sawdust), and energy crops (e.g., Timothy grass, switchgrass, and hybrid poplar, bamboo). These biomass sources provide an unlimited supply of chemical precursors that are now synthesized from fossil fuels. Bamboo is seen as one of the most promising non-wood resources (Kaur et al. 2022).

It focuses on the multifunctional applications of bamboo in India for energy and the environment. Discusses the bioenergy potential, land restoration, and economic aspects of bamboo. Highlights the role of bamboo in bioenergy production, CO_2 sequestration, and land restoration (Rathour et al. 2022). The potential of bamboo as a sustainable energy source is evaluated through a characterization analysis. Fossil fuels dominate global energy, leading to a search for alternatives. Indonesia is one of the countries with the largest abundance of bamboo in the world. Bamboo thrives in various regions in Indonesia due to climatic and soil conditions that support its growth. The abundance of bamboo in Indonesia provides many opportunities for economic development, environmental conservation, and cultural preservation. With proper management, bamboo can be a natural resource that continues to provide benefits to the people of Indonesia. For example, in the utilization of biomass energy from *Ampel* bamboo in Bali, the energy potential is assessed (Sucipta et al. 2017). Focus on innovative industrial uses of bamboo in various sectors globally. Bamboo properties and environmental impacts are highlighted for industrial applications (Borowski, Patuk, and Bandala 2022).

Bamboo has a role to play in climate change mitigation, as a biomass product, as well as in carbon credits. Focus on bamboo's carbon-saving benefits and global potential for carbon trading (Pan et al. 2023). Further research is needed on the potential of bamboo in various industrial sectors, lacking studies on lignin extraction in bamboo, bamboo bioprocessing, economic feasibility, and waste evaluation. There is also a lack of comparison of lignin with other biomass sources, as well as challenges in extracting bamboo fibers. According to recent statistic by Yadav et al., there are only 4.51% of annual global lignocellulose biomass production (approximately 181.5 billion tonnes) was converted into many applications. A highly abundant of lignocellulose biomass from bamboo tree was potentially could be valuable to be use for many applications such as bioenergy, polymer materials and biopharmaceuticals. Thus, further study of lignocellulosic biomass from bamboo plants is worth to be explored for many potential applications (Yadav et al. 2023).

The bamboo plant is considered a potential lignocellulose biomass due to its nature as one of the fastest-growing plants compared to all other plant species (Yadav and Mathur 2021). Bamboo plant shows high lignocellulose biomass production which is higher in cellulose and hemicellulose value. Due to its easy growth without using fertilizers and high biomass content productivity, biomass yield from bamboo is highly recommended to be a potential application in biotechnology, biorefinery, biomaterials, and biological activities (Ahmad, Farooq, and Zhang 2022). Recent studies have reported extracting and converting bamboo lignocellulosic biomass into promising applications such as nutraceuticals, bioenergy, carbon fibers, polymer materials, and functional foods (Silva et al. 2020).

Based on the background, this study aims to review how the utilization of bamboo in various fields especially from its components. In addition, this review will focus on the differences in bamboo species on the characteristics and amounts of chemical components that are considered important in influencing the application of its applications. By providing a comprehensive overview of the relationship between species, components, and applications, this review aims to provide guidance in the utilization of bamboo for the desired application. This review will be divided into several parts: 1. Introduction; 2. Bamboo; 3. Components of bamboo; 4. Application of bamboo; and 5. Conclusions.

Literature review

Over the past 34 years (1990–2024), approximately 2,800 research papers and articles have been published with the keyword "bamboo" and "biomass" according to the advanced findings of Scopus. As shown in Figure 1, research on bamboo and its biomass components mainly focuses on the fields of environmental sciences (20.19%), agricultural and biological sciences (19.84%), energy (10.75%), chemical engineering (10.17%), engineering (8.14%), chemistry (7.14%), materials science (6.87%),

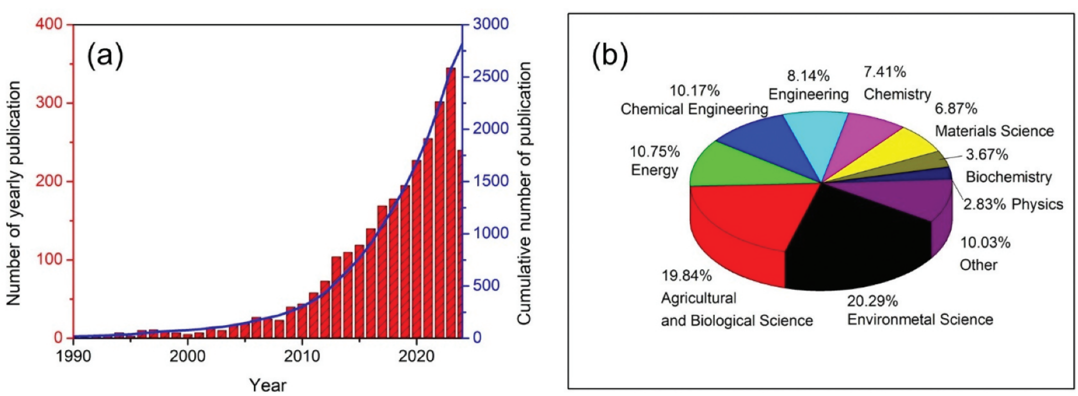

Figure 1. Environmental science leads bamboo research, reflecting sustainability priorities (a) Published findings trend and (b) Applications field.

biochemistry (3.67%), physics (2.83%), and others (10.03%). The environmental applications of bamboo use have dominated, likely reflecting the growing interest in bamboo as a sustainable and environmentally friendly resource, particularly in the context of climate change, carbon sequestration, and ecosystem restoration. Furthermore, bamboo's rapid growth, high biomass yield, and adaptability to diverse environments make it highly relevant for agricultural applications, land rehabilitation, and renewable resource studies, thus justifying a strong focus in these two disciplines.

Research trends and gaps

The process of finding literature on bamboo biomass research not only uses conventional search engine features but is also aided by VOSviewer software. VOSviewer uses innovative visualization techniques that allow researchers to transform bibliographic data into a visual form, enabling a more intuitive and comprehensive understanding of how studies relate to one another. The software supports various types of networks, including co-authorship, co-citation, and co-occurrence networks, and provides customizable visualizations with more complex layouts (Mondal et al. 2023).

By conducting bibliometric analyses on publications from 2014 to August 2024, valuable insights were gained into the scientific contributions, research networks, and research interests of researchers worldwide, particularly in bamboo and its biomass research. The keyword used in this analysis was "Bamboo biomass application" on the literature search engine platform Scopus. The results of this analysis provide information on the number of publications and topics attributed to the researchers, as well as the publication timeframe, which allows for the identification of topics that have been studied and research topics that have not been studied much in the past 10 years.

By examining research topics and characteristics, it was possible to identify collaboration and co-authorship patterns among researchers, as well as discover research gaps in bamboo biomass research topics (Figure 2). The bibliometric analysis also revealed the topics and research interests that received the most attention within the bamboo biomass research topic. The topics varied from data analysis methods, visualization, and applications of bamboo biomass in various fields such as health, food, environment, functional materials, and fiber composites.

The range of year scales shown can provide an overview of how to identify future research trends, thus allowing researchers to create collaborations with broader insights based on several existing topics. This review of bibliometric results also offers further insight into future research gaps, particularly in the research topic of bamboo biomass and its applications. In the depth of discussion analysis, the visuals that have the clearest and shallowest graphs show that the research topic has been studied by various researchers. Meanwhile, the visuals that are quite blurry and deep show that the topic has not been studied much and has the potential to be the latest study that can be collaborated with other topics.

Geographical distribution and species richness

Bamboo has a profound cultural significance in various regions, especially in East Asia and Northeast India. In East Asia, bamboo cultivation has a long and meaningful heritage, not only as a versatile material but also as a symbol of cultural identity and heritage for many peoples (Hong et al. 2011). Bamboo species play an important role in supporting wildlife and maintaining ecological balance. Bamboo forests provide essential habitat for a variety of wildlife, including birds, insects, and mammals. In addition, several species of bamboo are very important in Japan due to their ecological role and distribution patterns, especially in areas affected by human activities (Kobayashi et al. 2015). Bamboo is a sustainable resource that can be harvested sustainably, providing materials for construction, handicrafts, and more. Its sustainable use can reduce pressure on forests, provide benefits to wildlife habitats and improve ecological balance (Kobayashi et al. 2015). However, rapid climate change has a significant impact on global biodiversity, which has the potential to overshadow other environmental threats such as habitat destruction and biological invasion. The total area of bamboo

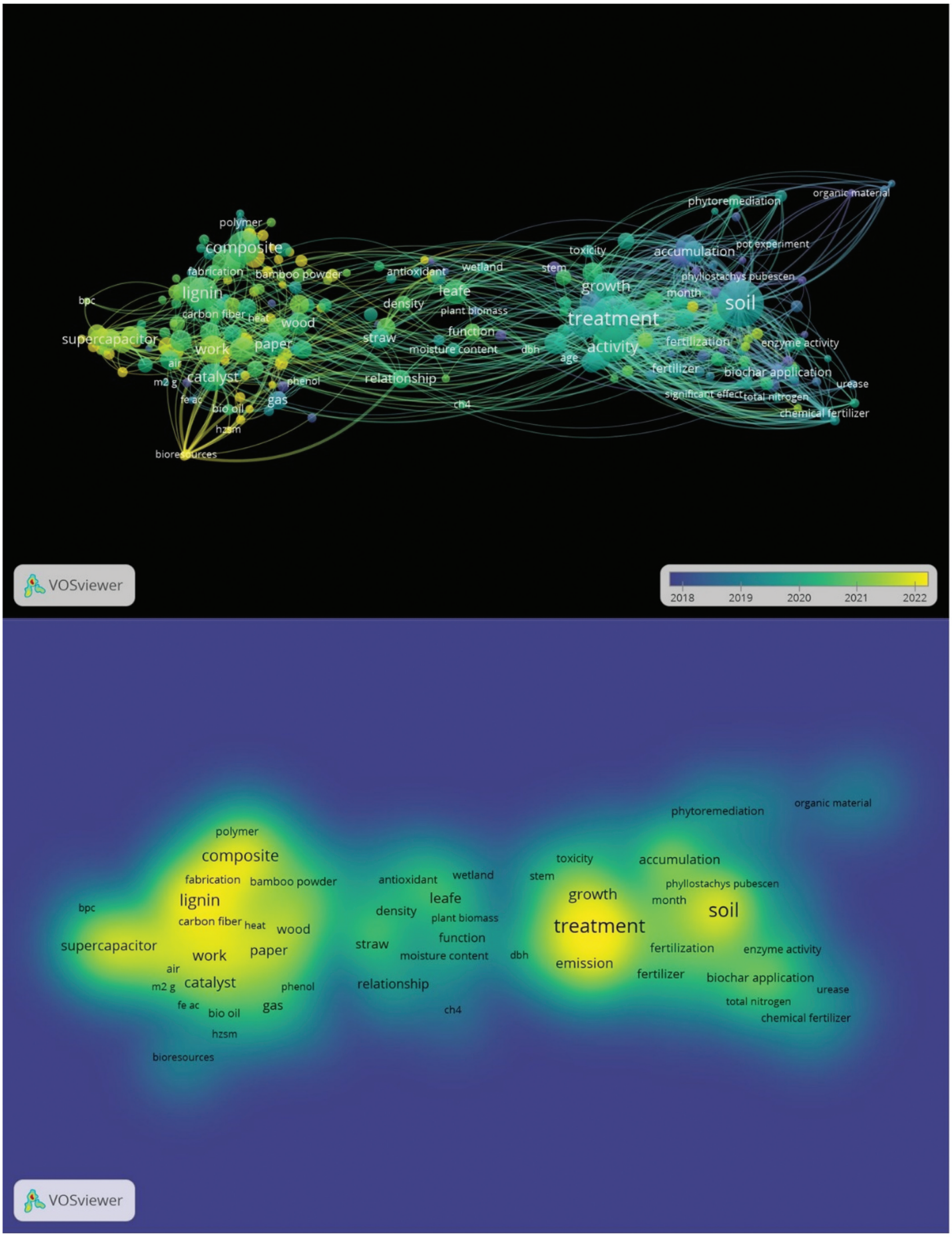

Figure 2. Scopus database analysis from 2014–2024 with a total of 586 articles. The latest research was conducted on keywords: bioresource, mechanical property, and specific surface area, while older research was conducted on keywords: Root, control, and moso bamboo. Some keywords that are still not widely studied include: bioresource, bamboo biomass, chemical fertilizers.

forests is expected to decrease by 9–22% by 2070, with significant losses occurring in certain mountain ranges. New climate-friendly areas for bamboo forests may emerge, covering 22–26% of the current bamboo forest area (Li et al. 2015).

Bamboo is classified under the Poaceae grass family, specifically within the subfamily Bambusoideae, which includes herbaceous and woody types. Bamboo is a plant rich in lignocellulose and has high ecological, economic, and cultural value. Bamboo is part of the monophyletic BEP clade (*Bambusoideae, Ehrhartoideae, Pooideae*) in the grass family (Long et al. 2023). Bamboo thrives at various altitudes ranging from sea level to 4,000 meters, covering about 14 million hectares worldwide, especially in Asia. The highest species richness is found in the Asia-Pacific region, while Europe has no native bamboo species, and significant bamboo forests exist in South America, especially in Brazil, Peru, and Bolivia. In India, bamboo plantations cover 9.57 million hectares, about 12.8% of the country's total forest area, with distributions influenced by human activities and rainfall patterns. Different species of bamboo are associated with different agroclimatic zones, with specific genera thriving in mountainous, temperate, subtropical, and tropical areas (Yeasmin et al. 2015).

Due to its rapid and sustainable growth, bamboo serves as a substitute for wood and plays an important role in conservation efforts against climate change. Molecular data confirm that bamboo is a distinct lineage, with the classification encompassing about 546 species in *Arundinarieae*, 812 in *Bambuseae*, and 124 in *Olyreae*, with specific anatomical features distinguishing these groups. Bamboo thrives on all continents except Antarctica and Europe, occupying diverse habitats from temperate forests to tropical regions. They often dominate vegetation in certain areas, such as sub forests and mountainous ecosystems, demonstrating their ecological adaptability (Clark, Londoño, and Ruiz-Sanchez 2015). In the North American region, 44 species are recorded in Mexico, 28 in the Neotropics, 4 in the Nearctic. Half of the species live between 1000 and 2000 m altitude. Most species are concentrated in moist tropical mountain forests. The elevation of the place affects the richness of species and the pattern of endemism (Ruiz-Sanchez et al. 2019).

Global distribution shows significant diversity of bamboo, especially in China, Brazil, and India, with concerns about the potentially invasive introduction of introduced species in non-native habitats. *Bambusa rigida* is one of the most abundant bamboos spread in southwest China, its applications are such as in handicrafts and agricultural tools. This type of bamboo can be made into Bamboo scrimbers (BCs) with an optimal resin dosage of 11%. 4-year-old bamboo stalks are suitable for making BC because of their high performance of mechanical properties, acceptable water resistance of BC, and low cost of original green bamboo due to their relatively low moisture content (Huang et al. 2018).

Continuous monitoring is essential when introducing bamboo to new areas to reduce the risk of invasion and preserve the succession and diversity of local ecology (Buziquia et al. 2019). There is also a Neotropical woody bamboo (NWB) type with a genus native to the Western Hemisphere, classified into three sub-tribes: *Arthrostylidiinae, Chusqueinae*, and *Guaduinae*. The NWB is spread from northern Mexico and the West Indies to south-central Chile and Argentina, thriving at altitudes above sea level to more than 4,000 m. The diversity of the NWB currently includes 446 species from 23 genera, with a significant increase in species and genera richness since 2000. Brazil, Colombia, and Venezuela are highlighted as countries with the highest diversity of woody bamboo (Ruiz-Sanchez et al. 2021). Although bamboo is not typically grown in Europe, the number of bamboo plantations continues to increase in countries such as Spain, France, and Italy. Bamboo grown in temperate climates, however, is exposed to different environmental conditions during growth compared to bamboo from subtropical and tropical climates, such as those in China or Vietnam. Colder winters, snow, and lower rainfall in Italy can pose challenges for bamboo cultivation, although environmental conditions differ during growth, good compatibility in most geometric traits between Italian and Asian *Phyllostachys edulis* was found, demonstrating the potential for a unified global standard and international database for bamboo geometric internationally (Fritz and Kraus 2024).

In Indonesia, Bamboo is an important economic and environmental resource, including in soil conservation, water conservation, and greenhouse gas absorption. A total of 175 species and 25 bamboo genera are found in Indonesia or about 12% of the 1439 species and about 22% of the 116 bamboo genera in the world. Some of the new types of bamboo have been mentioned, but they still have the status of "sp." (Widjaja 2019). In addition, the addition of bamboo species also occurred because of a change in the status of bamboo species in Java. These types of bamboo grow spread throughout the islands of Indonesia and at first glance have a unique clan distribution pattern (Muzakki, Chikmawati, and Hartana 2020). Research conducted in Sulawesi has documented 39 species, 22 of which are endemic to Sulawesi, indicating the importance of this region as a center of *Dinochloa* diversity in Indonesia (Ervianti, Widjaja, and Sedayu 2018). Despite having significant economic value, the genetic diversity of commercially cultivated bamboo is still largely unexplored due to the challenges in assessing the phenotypic variability and extensive natural habitat of these plants. Recent advances in molecular marker techniques have facilitated research on the genetic diversity of bamboo species particularly in Asia (Li et al. 2019).

Bamboo usually has a straight stem, but some bamboo has a climbing habit which is the genus Dinochloa and is only spread in the western part of Indonesia. The Lesser Sunda Islands (LSI) and Sulawesi appear to be the easternmost region of the Dinochloa distribution in Indonesia, there are two recognized species of climbing bamboo from LSI: *Dinochloa kostermansiana* and *D. sepang*. There are two species of climbing bamboo from LSI, Indonesia recognized based on specimens, namely *Dinochloa kostermansiana* found on the islands of Flores and Sumba and *D. sepang* which is endemic to the island of Bali (Damayanto 2017). Also in Luzon island, Philippines there was 12 species of climbing bamboo and covers 32% of all bamboo in the Philippines and is distributed under three genera, namely *Dinochloa, Crytochloa*, and *Cephalostachyum*. The utilization of climbing bamboo can provide bamboo farmers with a wider range of options for plantation establishments and bamboo product manufacturers more choices for their raw materials (Bondad et al. 2023).

Another example in the West Java area has several variations of bamboo species in several studies. There are 8 types of bamboo found in Karangwangi Village with 1 species having 3 varieties (Setiawati et al. 2017), Karangwangi Village, Cianjur Regency recorded 13 species (Partasasmita et al. 2017), Naga Village in Tasikmalaya Regency has seven species (Irawan et al. 2019), Sukamenak Village in Sumedang Regency has 9 species of bamboo (Iskandar et al. 2022), and 5 species in Cijambu Village, Sumedang Regency (Ihsan, Irawan, and Iskandar 2024). Local communities make extensive use of bamboo for construction, household appliances and tools, relying on traditional knowledge passed down from generation to generation to differentiate between species. The classification of bamboo has traditionally been based on cultivation methods, morphology, and practical applications, which indicates people's deep understanding of the role of bamboo in their daily lives.

Traditional uses and socio-economic roles

The traditional use of bamboo in various countries forms a cultural heritage for many indigenous peoples around the world. Understanding the traditional knowledge (TK) of plant species is essential not only to preserve this knowledge, but also to direct management for sustainable use (Albuquerque, de Lucena, and Neto 2014). Currently, research on kindergarten is more interested in studying how demographic factors – including age, gender, ethnicity, and other attributes such as responsibilities at the household and community level, profession, and origin. Bamboo plays an important role in improving the livelihoods of rural communities (Honfo et al. 2015).

Bamboo has a multifunctional socio-economic, cultural, and ecological role in rural communities (Nath, Lal, and Das 2015). From a socio-cultural perspective, bamboo also offers many benefits, such as being used as a material for traditional musical instruments, clothing fibers, and traditional rituals (Iskandar et al. 2022; Partasasmita et al. 2017). In addition, bamboo litter biomass contributes significantly to soil organic matter and supplies bamboo with nutrients in natural stands and cultivated plants. Bamboo leaf litter occurs year-round but has two annual peaks – in spring (April-May) and late autumn (November). The amount of annual waste is greatly influenced by the biological properties of bamboo and environmental conditions (Nirala 2017). More than 100 species of bamboo are used commercially and have the potential to provide an excellent means of income in primary and secondary processing with little capital investment. They are essential for biomass production and play an increasing role in local and world economies (Nirala 2017).

Bamboo can be used for energy generation through traditional burning methods, but this is inefficient and contributes to health problems; Industrial applications offer a more efficient alternative. Research on bamboo torrefaction in Malaysia shows that the time and energy required to grind heated bamboo charcoal is significantly reduced compared to grinding raw bamboo charcoal, proving the importance of the torrefaction process. The physicochemical properties of charcoal show that the energy content increases significantly with the degree of torrefaction (Saha et al. 2022). Bamboo is widely cultivated one of which is in Indonesia, found in forests and community gardens, and culturally significant, used for a variety of purposes including food and construction. The well-established existence of bamboo in local farms can facilitate its integration into bioenergy production systems. Bamboo's abundance, rapid growth, and various uses position it as a valuable resource for bioenergy production in Indonesia. Integrating bamboo into the energy system can help meet sustainable energy targets while supporting land restoration efforts. More research is needed to assess the feasibility of bamboo for bioenergy, including its economic viability and potential environmental impact (Sharma, Wahono, and Baral 2018).

Bamboo has great potential to contribute to the growth of rural economies around the world and is therefore known as the "green gold of the poor." Due to the high rate of clonal propagation, bamboo can be a good and sustainable biological source to meet various demands to meet human lifestyles. Bamboo ethnobotanical utility suitable for the daily life of indigenous peoples such as in the manufacture of handicrafts, artifacts, jewelry, baskets, furniture, and construction (Banerjee et al. 2021). Forest products, including bamboo, provide additional cash income, but their contribution is limited compared to other sources such as honey and forest wood. Traditional forest tenure systems practiced by local communities play an important role in managing forest resources sustainably. Bamboo is commonly used for traditional construction, with significant economic value associated with its wide range of applications. Connecting traditional knowledge with scientific research can support the development of bamboo-based industries and improve local livelihoods (Bahru, Kidane, and Mulatu 2021).

While bamboo forests provide ecological benefits, their expansion can threaten biodiversity; As such, sustainable harvesting practices are essential for balancing energy production and ecosystem health. Bamboo species exhibit significant diversity in morphological properties and biochemical composition, with woody bamboo containing more than 70% lignocellulose, which is essential for energy processing. The nature of photosynthesis varies between species, with Sympodial Bamboo showing the highest levels, suggesting potential differences in biomass productivity. Effective utilization of bamboo biomass can contribute significantly to sustainable energy generation. The Energy Bamboo Species Evaluation System (EBSES) uses an analytical hierarchical process to assess bamboo species based on growth characteristics, chemical composition, and energy conversion potential. Future EBSES improvements can improve its objectivity and applicability in selecting bamboo species suitable for bioenergy production. Bamboo's rapid growth and high cellulose content position it as a promising source of biomass energy, with biochar and bioethanol identified as key products for development. Emphasizing efficient pretreatment and conversion methods, along with selecting high-cellulose bamboo species, can optimize the environmental and economic benefits of bamboo biomass utilization (Liang et al. 2023).

Anatomical, chemical, mechanical properties

Bamboo among other plants has great benefits and unique varieties. The traits of bamboo species vary between species and along their culms. About half of the world's population uses bamboo products, such as houses, panels, mats, chopsticks, stickers, bamboo charcoal or activated carbon, papermaking, and bamboo shoots (Zakikhani et al. 2017). The manufacturing process of this product is influenced by the characteristics of bamboo, The anatomical properties of bamboo are important because of its effect on mechanical properties, preservative absorption, and final product properties, especially on pulp and paper (Siam et al. 2019). An example of a type of bamboo that is suitable for use as paper based on its unique characteristics is *Bambusa pervariabilis*, based on measurements of its fibers and durability (Xiang et al. 2020).

The morphological development of bamboo culms takes place mainly in two typical stages. The first stage is the growth of the main thickening of the shoots of the shoots underground, which is mainly driven by the shoot apical meristem (SAM). The second stage is the rapid growth of young bamboo, which is driven by the intercalative meristem (Wang et al. 2022). Bamboo can usually reach optimal material properties at the age of 4, and bamboo wood has special properties namely better splitting, easy preparation, high strength, medium rigidity, and good toughness, which is much higher than that of ordinary wood (Fei et al. 2016). The main differences in the characteristics of bamboo with ordinary trees are shown in Table 1.

Bamboo has many similarities and differences with woody plants. The formation of cell walls in bamboo takes place in a different way than in woody plants. Thickening growth of the culm does not occur. The epidermis is the outer layer of the trunk, including elongated cells, short cork and silica cells, and stomata. In addition, bamboo has a natural two-phase reinforced composite, with fibers as the structural reinforcement phase and parenchyma tissue as the matrix. Thus, culm tissue composition governs mechanical properties and pulp quality (Fei et al. 2016; Xiang et al. 2020).

The outer cell wall of bamboo is usually covered by small protrusions, a quilt layer, and a wax layer. The thickness of the cell wall varies with its location. The cortex is located between the hypodermis and soil tissues, including several layers of parenchymal cells. Soil tissue is also made up of parenchymal cells and a vascular system. The macrostructure of a bamboo culm is composed of the epidermis, cortex, soil tissue, and lacuna, as shown in the Figure 3 (Fei et al. 2016).

The length of the fibers of all species is higher on the outside than on the inside of the culm. There is a significant difference in fiber percentage between bamboo species. Significant differences were also found in the diameter of blood vessels and the dimensions of parenchymal cells among bamboo

Table 1. Comparison of growth characteristics between bamboo and trees in general (reproduced with permission (Fei et al. 2016), copyright 2016, Elsevier).

Growth	Bamboo	Tree
Height growth	Bamboo reaches the final height for 2–4 months, which is relatively short; height growth mainly depends on the intercalary meristem kept during the whole height growth phase.	Trees keep growing higher in their whole lifetime; Height growth of trees mainly depends on the primordial meristem on the tip of the trees.
Diameter growth	During the stage of sprouting and height growth, the culm diameter and wall thickness increases a little, and both will stop growing absolutely after reaching the final height.	Diameter growth of trees is a result from the activity of the cambium and occurs during the whole lifetime.

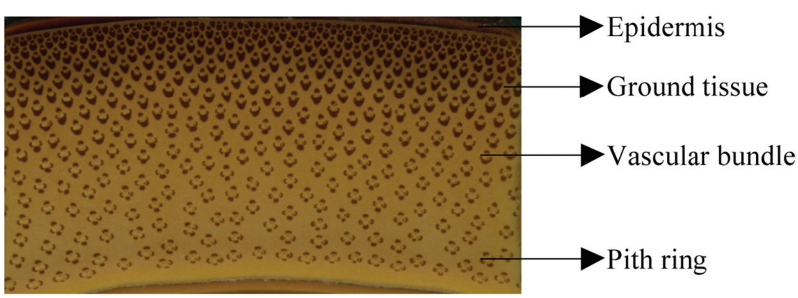

Figure 3. Cross-sectional cuts on the wall of the bamboo culm of the vessel (reproduced with permission (Fei et al. 2016), copyright 2016, Elsevier).

species. There is little difference in crystalline properties between the outside and inside of the culms and between bamboo species (Maulana et al. 2021). Significant differences were also found in the diameter of blood vessels and the dimensions of parenchyma cells among bamboo species, vascular bundle density, vascular diameter, and parenchymal cell length. For example, in the three species of Gigantochloa bamboo in the Figures 4 and 5.

In contrast to other plants, the water retention capacity in bamboo species is correlated with a number of parenchymal cells. This suggests that the number of parenchymal cells from the bottom to the top in the bamboo wood zone decreases as the height of the bamboo culm increases and the vascular bundles become denser (Zakikhani et al. 2017). The invisible part of bamboo is generally rhizome. Rhizomes are bamboo biomass underground, and their function is to support, colonize the land, and transfer nutrients from the soil to plant tissues. The rhizome forms a compact and stable underground network, which develops in monopodial or sympodial structures. Monopodial structures grow horizontally and often with surprising speed and force; Its segments can develop new horizontal rhizomes or new vertical stems (Marchi et al. 2023).

Based on the physical characteristics of the bamboo species such as the thickness of the culm wall, segments, and culm length, it can also be used to determine the appropriate utilization. For example, in three types of bamboo species; two species *B. Vulgaris* and *G. Apus*, and *G. Weberbaueri*. It is shown that the three species of bamboo have differences in their anatomical structure, the main difference between them is the bundle of culm blood vessels. Regarding physical traits, significant differences can be found between the three species (Portal-Cahuana, Velarde, and de Moura Palermo 2023). Other example is form species *Phyllostachys edulis* (commonly known as Moso) that grows in temperate regions of Italy can produce a varying number of shoots depending on its age, which will develop on mature stems. *Phyllostachys edulis* annually absorbs 30 times more carbon dioxide from the atmosphere than mixed forests that grow in temperate climates. Bamboo plantations can act as carbon sinks and are used as climate change mitigation measures thanks to the rapid growth of biomass and carbon sequestration (Marchi et al. 2023).

Bamboo *Phyllostachys edulis* shows a positive correlation of thickness with the diameter of the internode; thus, both the diameter and the thickness of the internode play an important role in determining the height of the stem and its mechanical properties. However, monthly rainfall in December and January negatively affects the diameter and thickness of the internodes, which suggests that precipitation can negatively impact the growth of primary thickening during these months, which affects the diameter and thickness of the internodes (Zhang et al. 2024). Research shows that segment length and functional properties can be affected by ambient temperature. The reduction in stem diameter, the shortness of the internode length, and the reduction in the number of internodes

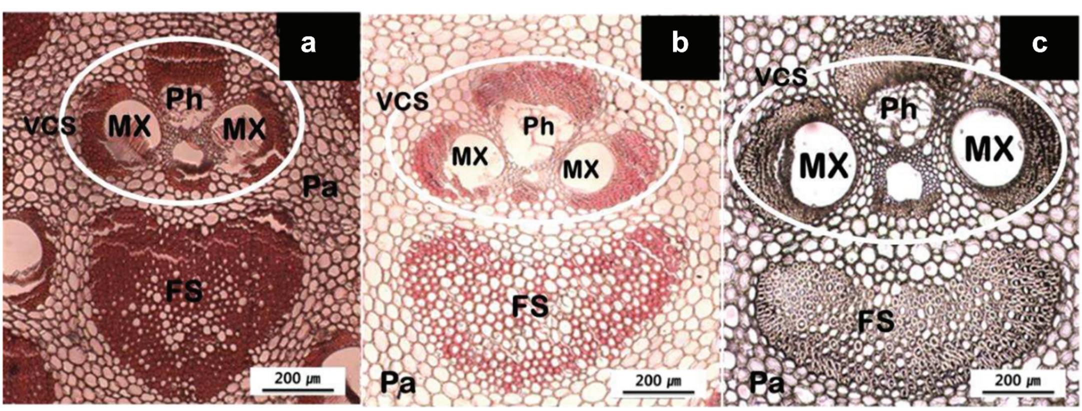

Figure 4. Vascular bundles in the cross-sections of *G. pseudoarundinacea* (a), *G. apus* (b), and *G. atroviolacea* (c); VCS: vascular central strand, Pa: parenchyma cells, FS: fiber strand, MX: metaxylem vessels, Ph: phloem vessels (reproduced under terms of the CC-BY license (Maulana et al. 2021), copyright 2021, BioResources).

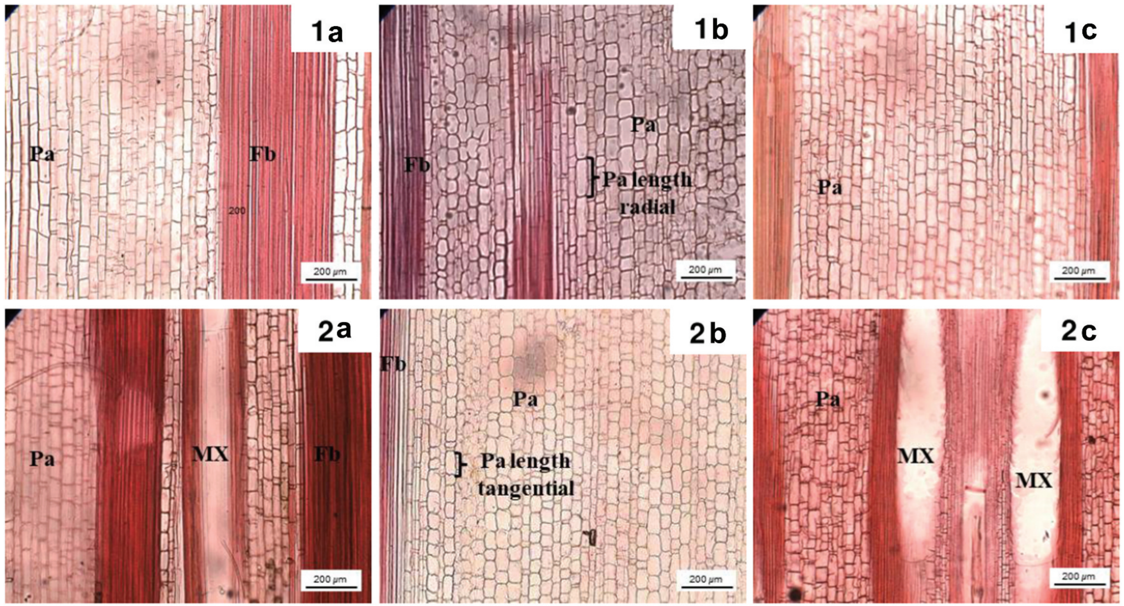

Figure 5. Optical micrographs of radial (1A, 1B, and 1C) and tangential (2A, 2B, and 2C) sections of *G. pseudoarundinacea* (a), *G. apus* (b), and *G. atroviolacea* (c); Pa: parenchyma cells, MX: metaxylem vessels, fb: fiber bundles (reproduced under terms of the CC-BY license (Maulana et al. 2021), copyright 2021, BioResources).

significantly reduce the fresh weight, thus contributing to the reduction of biomass and the morphological development of bamboo stalks (Yu et al. 2017; Zha et al. 2023).

Chemically, bamboo stalks are composed of approximately 52% parenchyma, 40% fibers, and 8% conductive tissue. Similar to wood and agricultural residues, bamboo primarily consists of cellulose, hemicellulose, and lignin, although the content of these compositions differs as shown in Table 2. In particular, bamboo has a relatively higher cellulose content, which is advantageous for fiber-based applications. This high cellulose concentration contributes to improved mechanical strength, thermal stability, and compatibility in the formation of biodegradable composites, paper, textiles, and plastics (Rani et al. 2021). In addition, the fine microstructure and high aspect ratio of bamboo cellulose fibers enhance their reinforcing ability in polymer matrices, making bamboo an excellent raw material for advanced materials and green manufacturing (Iroegbu and Ray 2021).

Given its long-term history of use as a building material and furniture manufacturing in Southeast Asian countries, bamboo species from *Thyrsostachys oliveri* is considered to have great utilization potential. The results of morphological analysis showed that the moisture content and base density of the stem wall were 73.01% and 0.64 g/cm_3, respectively. Lignin accounts for a high proportion of the chemical composition of the stem wall, which can give its bamboo stem excellent physical and mechanical properties (Zhang, Rao, and Wang 2022). The base density and carbon content are higher in bamboo species than in biomass from some agricultural residues. Compared to wood, the average values of the biomass studied were similar for fixed carbon content and volatile content, on the other hand, higher for base density (only for bamboo species), moisture content and ash content. The biomass analyzed here is considered suitable for energy purposes, with key property values that are close to those of energy biomass found in the literature (Rusch et al. 2021).

Bamboo and carbon biomass are characterized by physico-chemical analysis to investigate the main changes caused by the pyrolysis process in carbon properties. The surface morphology of bamboo and carbon biomass was determined using scanning electron microscopy (SEM). In addition, a discussion on the advantages and disadvantages of carbon production by slow pyrolysis is presented, considering the conventional methods applied in the process. The results reveal the advantages of the pyrolysis process due to the simultaneous production of carbon and bio-oil. Bamboo carbon presents properties suitable for its use as an energy source and for agricultural applications (Hernandez-Mena, Pecora, and Beraldo 2014). The application of bamboo carbon product is shown in research conducted by Xia et al. (2023) that developed an innovative method to process bamboo parenchyma cells into multi-layered, highly porous micro-capsule-shaped biomass carbon. This carbon product is designed as an energy storage electrode and adsorbent for removing cationic dyes from wastewater. This method utilizes the natural structure of bamboo parenchyma cells to produce highly porous biomass carbon, efficient in energy storage and absorption of water pollutants. This approach offers a sustainable solution: using bamboo waste for energy and water treatment applications simultaneously. The process can be applied on an industrial scale, combining energy storage and waste management in one sustainable system using bamboo, an abundant and fast-growing renewable resource (Xia et al. 2023).

In Indonesia, bamboo has been cultivated alongside trees and food crops in several residential gardens called *Pekarangan*. and widespread in Java, Bali, and Sulawesi. Bamboo is one of the BBC groups (Bamboo, Banana, Coconut) which has a very important role in daily life in Indonesia. The

Table 2. Comparison of the chemical composition of bamboo, wood, and agricultural residues (reproduced with permission (Fei et al. 2016), copyright 2016, Elsevier).

Biomass type	Species	Cellulose (%)	Hemicelluloses (%)	Lignin (%)
Wood	Pine	40–45	25–30	26–34
	Maple	45–50	21–36	22–30
Bamboo	Moso bamboo	42–50	24–28	24–26
Agriculture residues	Rice straw	41–57	33	8–19
	Rice husk	35–45	19–25	20
	Bagasse	40–46	25–29	12.5–20
	Cotton stalk	43–44	27	27

volume and weight of carbonized bamboo decreased as the carbonization temperature increased and showed the greatest change between 200 and 400°C. Yellow Bamboo (*B. vulgaris* var. *striata* (Lodd. Ex Lindl)) and *Ampel* (*B. vulgaris* Scharad. ex-Wendland) showed the highest weight loss and weight reduction. The density of carbonized bamboo decreases to 600°C and then increases slightly to 1,000°C. The highest density is found in *Ampel* bamboo and the lowest is in *Betung* bamboo (*D. asper*) (Park et al. 2018).

Components of bamboo

Cellulose and hemicellulose

Among the biomass components, cellulose is the main material responsible for fiber stability and mechanical strength. Cellulose consists of long linear chains neatly composed of anhydro-D-glucose $(C_6H_{10}O_5)_n$ units with β-1,4 glycosidic bonds (Figure 6a). The glucose ring shows a high degree of polymerization, and the compound is insoluble in aqueous media. Due to its high crystallinity and degree of polymerization, cellulose has higher thermal stability and resistance to mechanical stress compared to other non-cellulosic plant fiber components (Rusch et al. 2023). The cellulose content in bamboo culms varies from 40 to 60% and, together with the hemicellulose and lignin content, represents more than 90% of the total weight (Yan, Kasal, and Huang 2016).

Hemicellulose consists of a heterogeneous group of alkali-soluble polysaccharides that do not form a well-organized fibrous network. Compared with cellulose, it has an amorphous structure and a low degree of polymerization but is responsible for many of the important properties obtained from processing lignocellulosic materials (Wan, Wang, and Xiao 2010). Hemicellulose can easily absorb

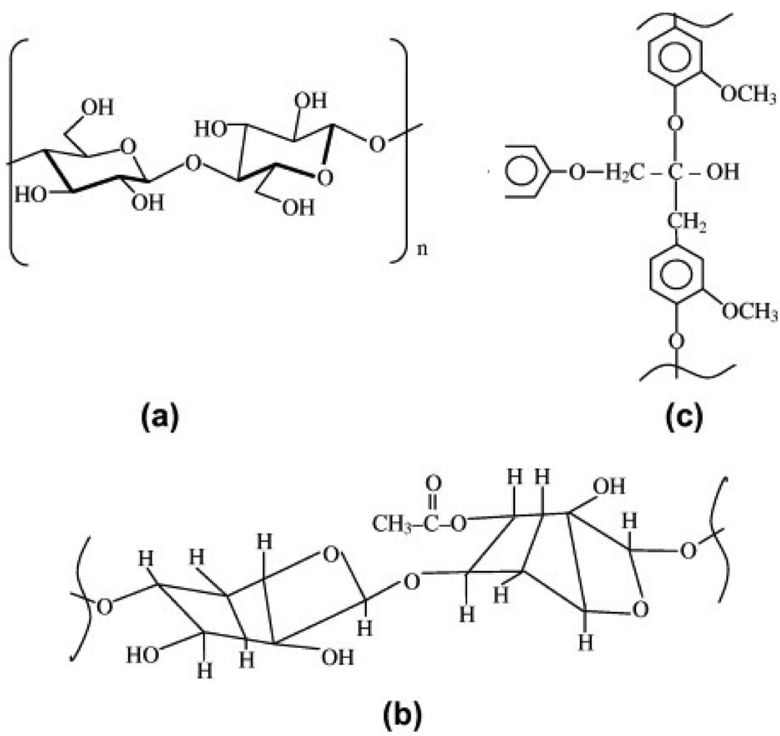

Figure 6. Chemical structure of (a) cellulose (b) hemicellulose, and (c) lignin (reproduced with permission (Kabir et al. 2012), copyright 2012, Elsevier).

water due to its low molecular weight and irregular configuration. Figure 6b shows the partial chemical structure of hemicellulose (Vinod et al. 2020).

Holocellulose is a total polysaccharide fraction consisting of alpha-cellulose and hemicellulose. Maulana et al have studied the holocellulose, alpha-cellulose, and hemicellulose content of seven types of bamboo in Indonesia (Figure 7). Andong bamboo (*Gigantochloa pseudoarundinacea*) has the lowest holocellulose content while Ampel bamboo (*Bambusa vulgaris*) showed the highest. These results suggest that bamboo species significantly influence the composition of holocellulose, alpha-cellulose, and hemicellulose content (Maulana et al. 2020). For comparison, *Phyllostachys pubescens* grown in Louisiana, USA, has a holocellulose content of around 69.94% and alpha-cellulose of around 46.08% (Li et al. 2007), while, *Gigantochloa scortechinii* from Kedah, Malaysia has a holocellulose content of around 81.4% and alpha-cellulose of around 55.2% (Salim, Wahab, and Ashaari 2009). Bamboos with high hemicellulose content, such as *Gigantochloa apus*, are generally more susceptible to microbial degradation (Maulana et al. 2020). However, this characteristic can be advantageous in specific applications. For example, the elevated hemicellulose levels contribute to faster hydrolysis and enhanced fermentation rates, making such bamboo types highly suitable for bioethanol and biogas production (Sun and Cheng 2002). Conversely, species with higher alpha-cellulose content are more favorable for high-strength fibers, paper production, or polymer-reinforced composites due to their structural integrity and resistance to biological decay (Alonso, García, and Del Río 2014).

Liew et al.'s research has made bamboo cellulose through chemical processes including dewaxing, delignification, and mercerization. Four samples namely green bamboo fiber (GBF), dewaxed bamboo fiber (DBF), delignification of bamboo fiber (DLBF), and cellulose fiber (CF) have been analyzed. Figure 8a shows the Fourier transform infrared (FTIR spectra), the peak intensity at 1514 cm^{-1} of GBF is caused by the C=C stretching vibration of the aromatic ring of lignin. However, CF does not show C=C tension which indicates that lignin has been removed well through the chemical process (Liew et al. 2015). The peak at 1724 cm^{-1} in DLBF represents the ester bond of the carboxylate group in hemicellulose (Figure 8b). The absence of this CF peak is due to the removal of hemicellulose during the alkaline treatment (Chen, Yu, and Liu 2011). Comparison between commercial cellulose (CC) and cellulose fiber (CF) shows that both celluloses have identical peaks.

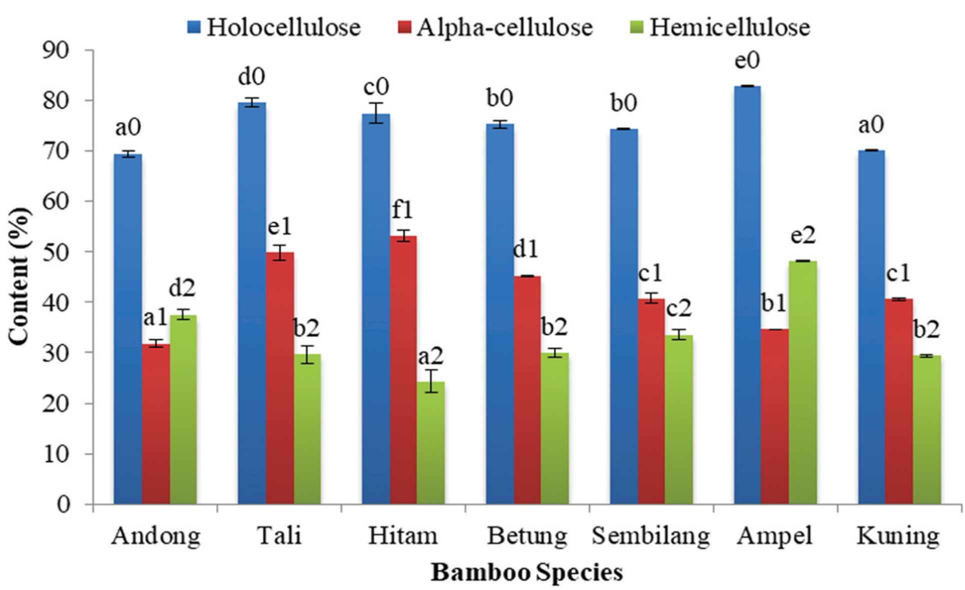

Figure 7. Holocellulose, alpha-cellulose, and hemicellulose content of seven Indonesian bamboo species (reproduced under terms of the CC-BY license (Maulana et al. 2020), copyright 2020, IOP publishing).

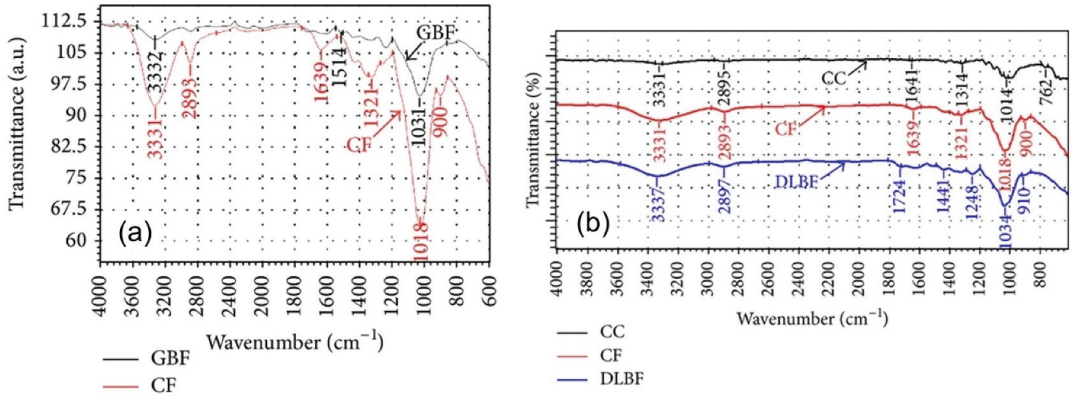

Figure 8. (a) FTIR spectra of green bamboo fiber (GBF) and cellulose fiber (CF), (b) FTIR spectra of commercial cellulose (CC), cellulose fiber (CF), and delignified bamboo fiber (DLBF) (reproduced under terms of the CC-BY license (Liew et al. 2015), copyright 2015, Wiley).

Research conducted by Brito et al. has prepared bamboo cellulose nanocrystals (CNCs) from sulfuric acid hydrolysis of bleached bamboo fibers. In addition to bamboo, CNCs are produced from three other Brazilian plants: eucalyptus, sisal, and curauá. In all cases, negatively charged ribbon-like nanoparticles composed of several laterally associated elementary crystallites were observed. Morphological and structural characterization of CNCs showed that all are composed of several laterally associated elementary crystallites (Brito et al. 2012).

Lignin

Lignin is an amorphous and phenolic macromolecule, consisting of phenyl propane units (C6-C3) and has no crystalline structure. Lignin has high resistance and is incorporated into the cell wall matrix of cellulose and hemicellulose. Lignin provides strength and stiffness to plant tissues and prevents the degradation of cellulose and hemicellulose in plant biomass. Lignin is also considered an energy store responsible for transferring stress between fibers (Ibrahim et al. 2011). The structure of lignin is shown in Figure 6c. Lignin has a high molecular weight and is the second most abundant component in bamboo, which appears from several stages of lignification related to the age of the plant. However, bamboo reaches its final height between 3 and 6 months during its growth process. The proportion of lignin and carbohydrates varies during the maturation process and tends to be stable when the plant is about 1 year old (Rusch et al. 2023).

Understanding the differences in the chemical structure of the main components at different heights of bamboo increases knowledge of its biological properties and adaptive mechanisms. Study conducted by Wang et al. (2025) that extracted lignin and lignin-carbohydrate complexes (LCCs) from the base, middle, and upper parts of the bamboo stem of *Schizostachyum funghomii* McClure explain the differences in chemical composition and structural characteristics at various altitudes. The results showed that the content of lignin and hemicellulose followed the upper order of the base > middle > along the bamboo stem. The size and number of fibrous cells decreased from the base upwards, with the highest lignin content in the upper cell tissue.

In a study conducted by Maulana et al. (2020), the lignin content of bamboo in Indonesia was calculated, expressed as Klason lignin and acid-soluble lignin. Klason lignin is a residue resulting from the hydrolysis and condensation reaction with sulfuric acid, while acid-soluble lignin is the fraction of lignin dissolved during the reaction. Klason lignin and acid-soluble lignin from seven bamboo species are shown in Figure 9. These results indicate that bamboo species have a significant effect on lignin content.

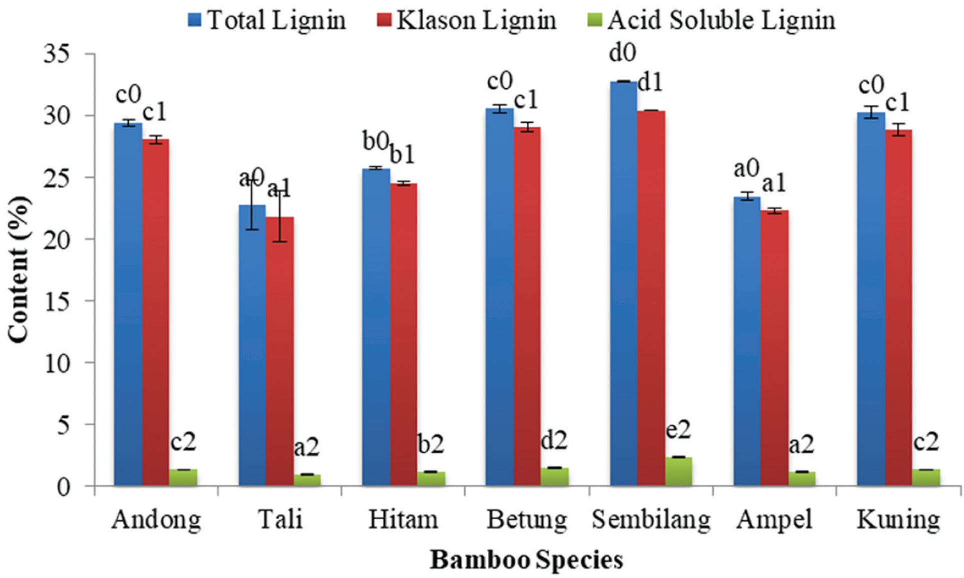

Figure 9. Lignin content of seven Indonesian bamboo species (reproduced under terms of the CC-BY license (Maulana et al. 2020), copyright 2020, IOP publishing).

Extractives and ashes

Extractives are aromatic organic compounds such as fatty acids, terpenes, flavonoids, steroids, etc. distributed in leaves, shells, culms, and other parts of plants but are not cell walls. Variations in bamboo extracts and ash content are related to plant type, age, and season (Wan, Wang, and Xiao 2010). In addition, weather factors also affect the chemical composition of plants (Vinod et al. 2020). Ash content, especially the amount of silica in bamboo, is also influenced by its species. *Bambusa vulgaris* has a low ash content, while the genus Schizostachyum shows a higher ash content (Rusch et al. 2023).

There is a secondary element in the chemical composition of bamboo; (1) the wax content in the epidermis is influenced by the plant species; (2) the ash content and especially the amount of silica varied according to the species and was influenced by age and location, and *Bambusa vulgaris* showed a low content, while the genus Schizostachyum showed a higher value. In addition, the starch content varies according to the season but is also related to the species, whereas *Bambusa vulgaris* and *Dendrocalamus asper* show high content. While *Gigantochloa atter* has a low starch content Rusch et al. (2023).

Several studies have reported that phenolic compounds from bamboo leaves have shown antioxidant and anticancer activities (Shang, Kim, and Um 2014). Bamboo leaves extracted using the supercritical carbon dioxide extraction method showed a high amount of polyphenols (7.31 ± 0.06 mg/g bamboo leaves). Soxhlet extraction method produced higher phenolic compounds (10.85 ± 0.52 mg/g bamboo leaves). The main antioxidant compounds identified from bamboo were dl-alanine, gluconic acid, phosphoric acid, ß-siosterol, -amyrene, -amyrin acetate, and friedelin (Figure 10) (Zulkafli et al. 2014).

Then in the bamboo shoot shell, ultrasonic-assisted extraction (UAE) produced total phenolic content (TPC) up to 85.3 mg GAE/g. Fifteen phenolic acids, seven flavonoids, nineteen organic acids, two iridoid glucosides, and one neoglycan were identified. Among them, p-coumaric acid (119 µg/g DW), chlorogenic acid (87 µg/g DW), rutin (39 µg/g DW), and ferulic acid (17 µg/g DW) were found to be the most abundant phenolic compounds (Jiang et al. 2019).

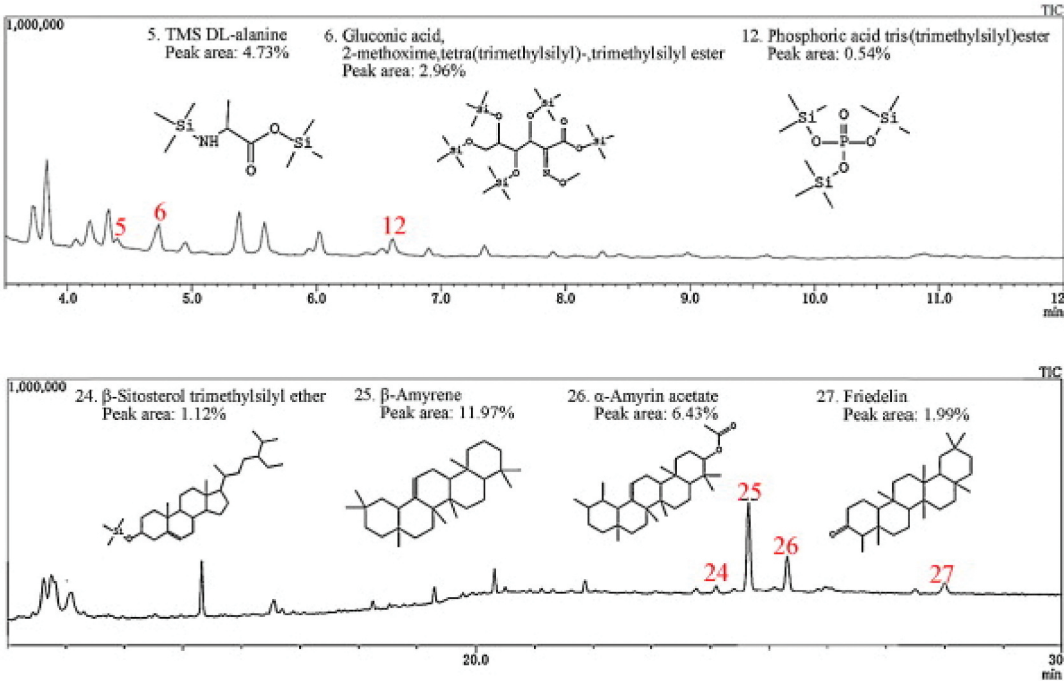

Figure 10. Gas chromatography – mass spectrometry (GC – MS) of supercritical CO_2 extraction sample. The components identified and their relative amount of individual composition, which are expressed as a percentage of peak area relative to total peak area (reproduced under terms of the CC-BY license (Zulkafli et al. 2014), copyright 2014, MDPI).

In biomass, low ash content is a good determinant of raw material quality. The ash content of bamboo varies (0.8–5% on a dry basis) (Darabant et al. 2014). XRF results show that the main components of bamboo ash are K_2O, SiO_2, and SO_3. The chemical composition of mineral materials in biomass and coal ash of ten are in the form of oxides. The chemical composition of all ashes is shown in Table 3. It was found that bamboo ash had higher K and Na contents, indicating that bamboo ash is more easily slagged than pine and coal. The high alkali metal content in bamboo ash has important implications for its use in cementitious materials. These components can affect the hydration process, setting time, and long-term durability of cement-based composites (Liu et al. 2018). In particular, high levels of K_2O and Na_2O can increase initial reactivity but also pose challenges related to alkali-silica reaction (ASR) when reactive aggregates are present. In addition, the presence of SiO_2 contributes to the potential for pozzolanic activity, which can improve mechanical properties and reduce the permeability of hardened cement pastes (Ou, Fernando, and Gattas 2019). Therefore,

Table 3. Chemical composition of bamboo. The high SiO_2 content in bamboo ash enhances pozzolanic activity, justifying its use as a cement substitute (Liu et al. 2018).

Oxide content of bamboo	Compositions (%)
SiO_2	24.32 ± 0.34
Al_2O_3	2.80 ± 0.02
Fe_2O_3	2.38 ± 0.08
TiO_2	0.20 ± 0.01
CaO	3.99 ± 0.02
MgO	6.69 ± 0.02
K_2O	34.23 ± 0.94
Na_2O	1.14 ± 0.02
MnO_2	1.03 ± 0.02
SO_3	14.05 ± 0.43
P_2O_5	2.51 ± 0.01

although bamboo ash shows promise as an adjunct cementitious material (SCM), careful control of its composition and interactions with other constituents is essential to optimize performance and mitigate durability issues.

Applications of bamboo

Structural application

Laminated bamboo lumber (LBL)

Bamboo is a suitable choice for conventional building materials because it is environmentally friendly. Laminated bamboo materials have been widely used in building molding, deck flooring, furniture, and, most recently, building structures. For example, *Bambusa balcooa* Roxb. is a bamboo native to central Vietnam and is widely used in the daily life of the local people. Experimental tests on columns and beams made of laminated bamboo show that the load-bearing capacity of laminated bamboo is controlled by stiffness rather than by strength. These results are consistent with the relatively warm and humid climate that bamboo prefers (Ding and Xian 2024).

Laminated bamboo lumber (LBL) has been studied for the past decade as a connection in buildings. LBL has been used in LBL sheathing-to-framing connections, LBL dowel-type connections, and glued-in rods (GIROD) in LBL connections (Dauletbek, Li, and Lorenzo 2023). LBL is formed from natural bamboo tubes made into thin flat laminae which are then laminated. LBL is divided into parallel laminated bamboo wood and cross-laminated bamboo wood types (Figure 11) (Su et al. 2021). Moso bamboo is widely used in LBL due to its fast growth and strength that can be comparable to other construction materials. The mechanical properties of LBL from moso bamboo are known to have properties comparable to or exceeding those of wood-based products and achieve the same good performance as other engineered bamboo products (Chen et al. 2020).

LBL as a connection has a strong correlation with material properties, fastener geometry, end and edge distances, fastener spacing and number, and load configuration. However, LBL connections are

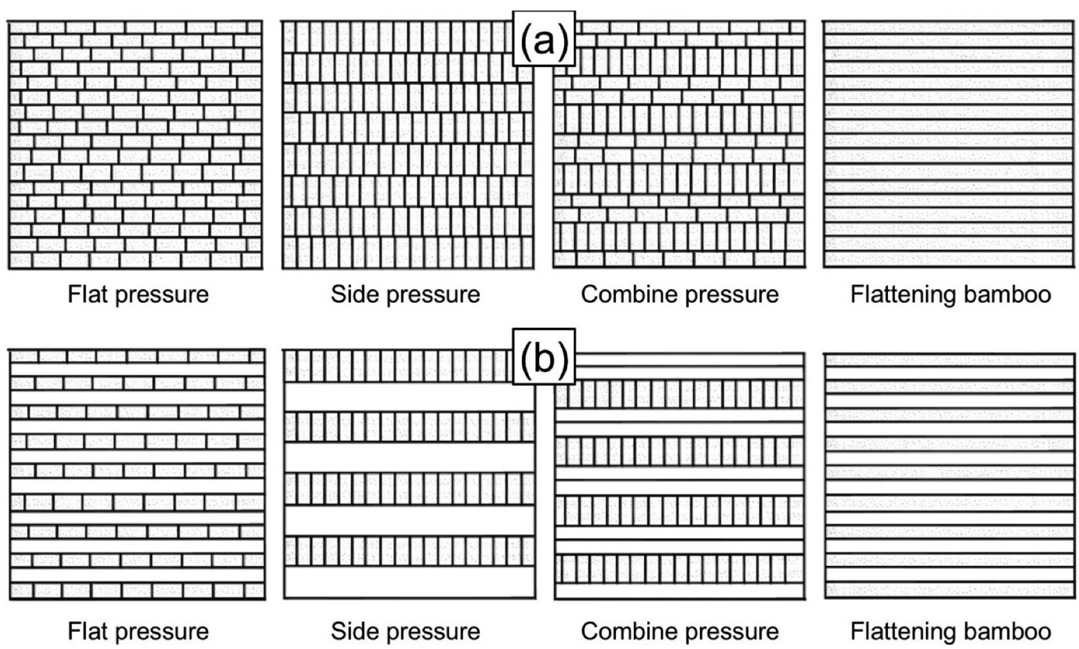

Figure 11. (a) Parallel-laminated and (b) Cross-laminated bamboo lumber (reproduced under terms of the CC-BY license (Dauletbek, Li, and Lorenzo 2023), copyright 2021, sustainable development press limited).

stiff and brittle compared to wood connections. Due to their density, LBLs cope with energy distribution better than conventional materials, making them best suited for use in seismically hazardous areas (Dauletbek, Li, and Lorenzo 2023). The use of bamboo in structural applications has been shown to have the lowest environmental burden and costs, by a large margin (Mahdavi, Clouston, and Arwade 2011).

As a building material, the strength of bamboo is an important consideration. Heat treatment of bamboo can increase its strength at certain temperatures. At moderate temperatures (140°C), this heat treatment improves the performance of bamboo composites by increasing porosity and resin absorption capacity. However, higher temperatures (~200°C) damage the microstructure, reduce resin absorption, and weaken bond performance (Shan et al. 2025). One solution to address this issue is to make the bamboo more flame-retardant. Zhang et al. (2025) reported that a core-shell synergistic method provides high flame retardancy and smoke inhibition properties while maintaining its original mechanical properties. The use of the core-shell synergistic strategy significantly improved the flame retardancy and smoke suppression properties of bamboo scrimber-giving it fire safety advantages and making it suitable for modern construction applications (Zhang et al. 2025). LBL has great potential and can serve as a viable alternative to conventional building materials. An example of a construction using LBL is shown in Figure 12.

Cross-laminated bamboo (CLB)

One type of laminated bamboo that is often used is cross-laminated bamboo (CLB). CLB is a two-way laminated bamboo made by arranging bamboo laminae in two directions to improve the performance of bamboo perpendicular to the grain direction (Figure 11b) (Dauletbek, Li, and Lorenzo 2023). Although bamboo-based construction products have many advantages, such as being environmentally friendly and sustainable, they are also easily cracked. Wu et al. have investigated the translaminar fracture properties of CLB. The results showed that bidirectional fiber arrangement has a remarkable

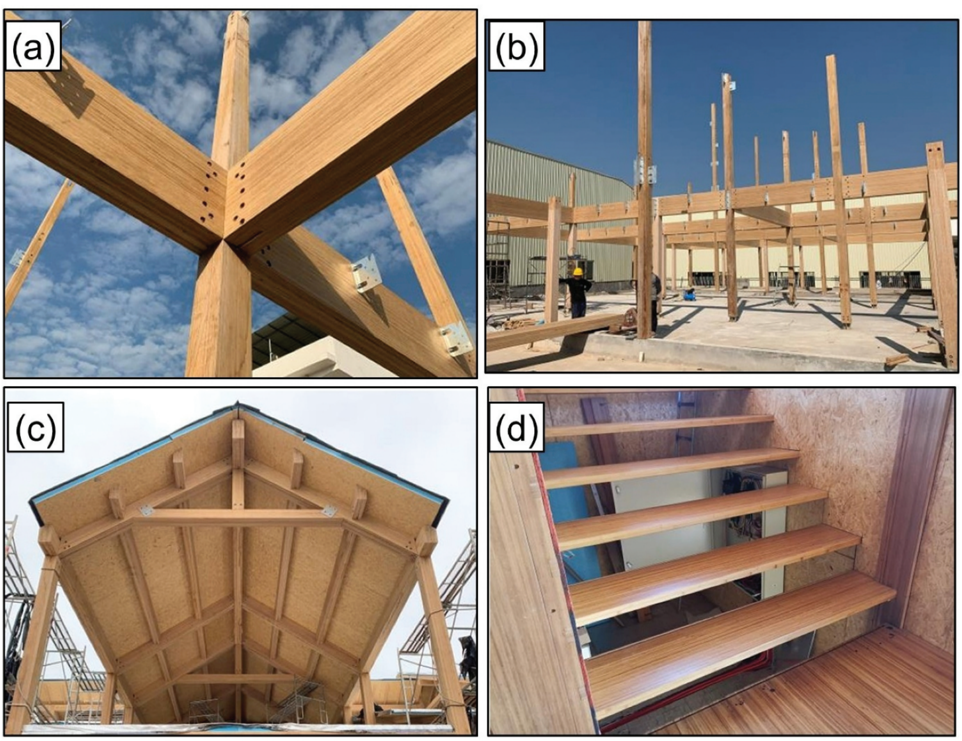

Figure 12. LBL building construction of (a) connections between columns and beams, (b) structural system for the first floor, (c) inner side of the roof, and (d) stairs (reproduced under terms of the CC-BY license (Dauletbek, Li, and Lorenzo 2023), copyright 2021, sustainable development press limited).

improvement in the toughness of laminated bamboo at and after crack initiation. It was also found that fiber pullout/bridging caused by 90° crack propagation around the fiber bundle is the dominant toughening mechanism of CLB (Wu et al. 2023). In addition, the interlaminar shear behavior of CLB has also been studied by Li et al. The test results showed that the shear properties of CLB can meet the strength and modulus requirements of current cross-laminated wood standards. It has promising potential for bamboo and CLB or cross-laminated wood panels with good shear resistance (Li et al. 2022).

In other species of bamboo, study conducted by Chaowana et al. describes the characteristics and properties of three-year-old bamboo stems of five species (*Dendrocalamus asper*, *Dendrocalamus sericeus*, *Dendrocalamus membranaceus*, *Thyrsostachys oliveri*, and *Phyllostachys makinoi*). The density of the five bamboo species varied from 594–933 kg/m^3. The density of bamboo affects the strength of the bamboo stem. With increasing density, the strength value also increases. Based on its mechanical properties, *P. makinoi* has the highest grades in shear, tensile, compressive, and flexural strength due to its highest density. However, *D. asper* can receive the highest ultimate load due to its stem size (Chaowana, Wisadsatorn, and Chaowana 2021).

In addition to bamboo, cross-lamination is also combining bamboo with wood. 5-layer cross-laminated bamboo and timber (CLBT) were tested under in-plane compression loading, and compared with cross-laminated timber (CLT) specimens. Figure 13 shows the configurations in CLT and CLBT. Compared with CLT, CLBT with scrimber bamboo layers resulted in a 90% increase in compressive strength and a 20% increase in compressive modulus in the principal strength direction (Li et al. 2023). Evaluation of the rolling shear properties of CLBT also showed that the rolling shear modulus and strength of scrimber bamboo were 92.81% and 98.64% higher than those of CLT, respectively (Dong et al. 2021). Therefore, cross-laminated bamboo and timber (CLBT) is considered capable of improving some of the deficiencies in laminated bamboo lumber (CLB).

Bamboo lumber-based composites

Bamboo is often made into composite form to increase the benefits of bamboo material efficiently and with high value (Sewar et al. 2024). Sun et al. have added resin to bamboo lumber. The results indicated that board density and resin content significantly affect bamboo's water resistance properties. The resulting mechanical properties can be comparable to or exceed those of wood or bamboo products (Sun et al. 2021). Another method that can be used to strengthen the physical and mechanical properties of bamboo is by using the roller-pressing impregnation method that effectively increases the density, strength, and stability of bamboo scrimber while supporting industrial-scale production through an efficient mechanized approach. This strengthens bamboo scrimber's position as a high-performance biomass material alternative for construction, furniture, and other structural applications (Zhang et al. 2025).

In another study, laminated bamboo lumber (LBL) was coated with solvent-based and water-based polyurethane (PUS and PUW) surface protectors against natural weathering. LBL was processed using phenol-formaldehyde (PF) adhesive. Figure 14 shows before and after 90 days of exposure to natural weathering conditions. It is known that uncoated bamboo and LBL specimens showed a tendency to become darker after exposure to weathering conditions. Meanwhile, LBL coated with PUS and PUW showed better color retention. FTIR spectroscopy results revealed that lignin present in uncoated LBL deteriorated rapidly under natural weathering conditions (Kelkar et al. 2023). Other improvements were made with modification with furfuryl alcohol, a biobased compound that strengthens the cellulose structure of bamboo. Through furfuryl alcohol modification, the bamboo scrimber becomes more resistant to mold and moisture changes, improving its functional performance in outdoor applications. This method offers a strong, durable, and sustainable biocomposite solution for the construction sector (Tan et al. 2025).

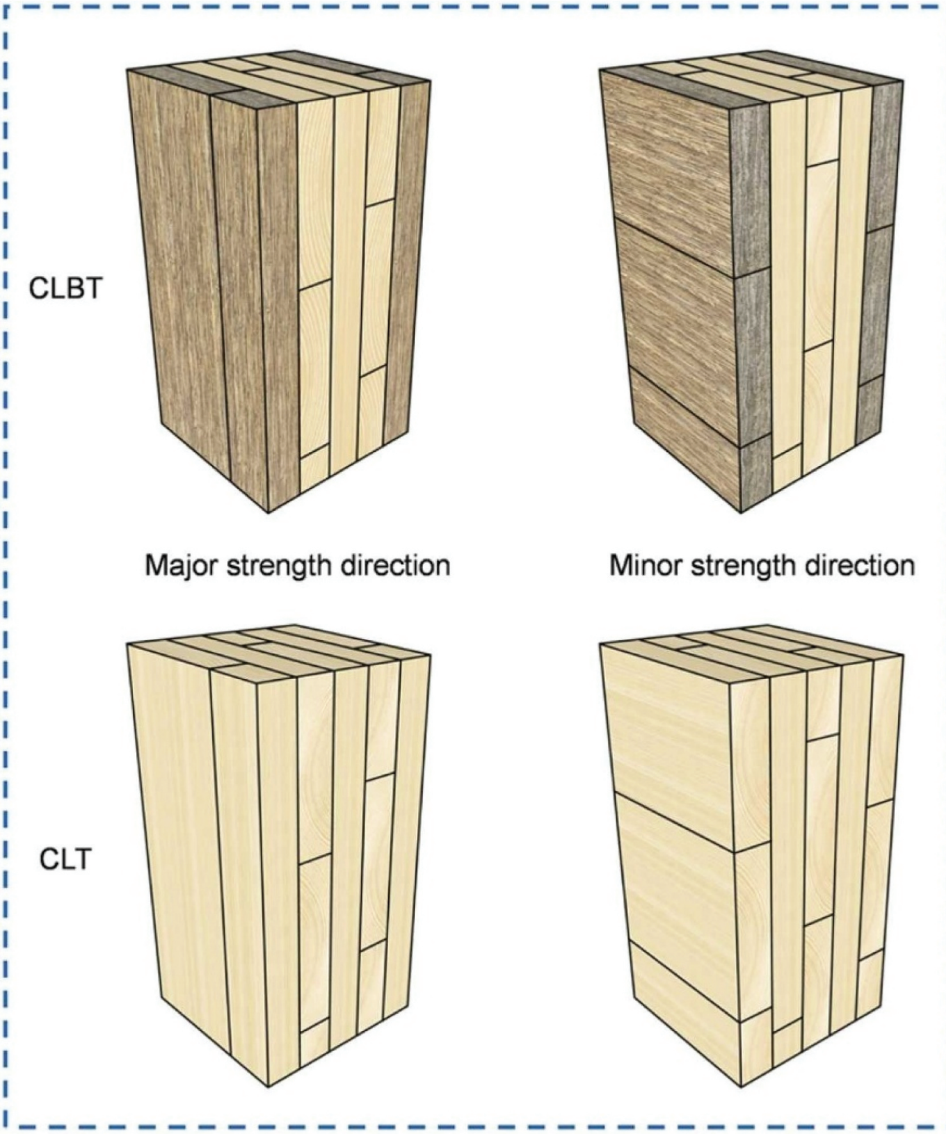

Figure 13. Configuration of cross-laminated timber (CLT) and cross-laminated bamboo and timber (CLBT) (reproduced with permission (Li et al. 2023), copyright 2023, Elsevier).

Binder materials

Bamboo leaf ash (BLA) was used as a supplementary cementitious material (SCM). The results showed that the composite with cement replacement by BLA presented excellent mechanical properties and increased durability (Silva et al. 2023). BLA was more reactive than commercial silica fume, with $Ca(OH)_2$ almost completely consumed in three days. This indicates that cement replacement of up to 20% of BLA met the required physical and mechanical properties (Villar-Cociña et al. 2011). Environmental and economic benefit analysis of SCM usage has also been reported. Energy savings of 15%, CO_2 emission reduction of 19%, and cost reduction of 10% can be obtained from the usage of 10% BLA and 10% ceramic brick waste (Rodier et al. 2019). In addition, it was reported that BLA was also used in soil stabilization. The results showed the potential of BLA stabilization on laterite soil for highway construction, if added at optimum level (Amu and Adetuberu 2010).

Figure 14. Effect of natural weathering on color change of (a) Bamboo, (b) Uncoated LBL, (c) PU coated LBL, and (d) PUW coated LBL. (suffixes 0 and 1 represent spectra taken before and after exposure to natural weathering). (reproduced with permission (Kelkar et al. 2023), copyright 2023, Elsevier).

Another study reported the effect of BLA on lime-stabilized laterite soil for highway construction. The strength test results showed that BLA increased the strength of all lime-stabilized samples. The unsoaked CBR value increased from 2–11%, which was lime-stabilized with the addition of BLA. The shear strength increased substantially, from 42.16 to 398.96 kN/m^2. Therefore, BLA is a good complement for lime stabilization of laterite soil (Amu and Babajide 2011).

Biomedical and food innovations

Antioxidant

Although bamboo is an agricultural product worth billions of dollars in international trade, only its shoots are used in fiber and food production. The potential use of young bamboo flour as a new ingredient for food products, increases the intake of insoluble fiber and considers consumer demand for healthier products. The total fiber content in young bamboo culm flour is lower than that of white wheat fiber, which can be explained by the presence of starch in young bamboo culms (10 g/100 g) (Felisberto, Beraldo, and Clerici 2017). Three varieties of bamboo; *Dendrocalamus asper*, *Bambusa tuldoides* and *Bambusa vulgaris* contains potential fiber and starch, which can be used in the food and non-food industries. The flour obtained would be an alternative to traditional whole flours used in cake and bread formulations, with the advantage of not discoloring the final product. Bamboo starch could be an alternative source for starches traditionally used as thickeners, fat substitutes, or in food and cosmetic formulations (Felisberto et al. 2017).

Bamboo has a greater abundance of phenolic compounds. Flavonoids are the most widely reported phenolics found in bamboo. The main antioxidants in bamboo leaves and shoots are phenols, vitamins C & E and mineral elements such as selenium, copper, zinc, iron and manganese. Bamboo leaves and shoots are a good source of natural antioxidants and can play an important role in the food and pharmaceutical industries (Nirmala et al. 2018). Leaf extracts *Phyllostachys nigra* showed anti-inflammatory activity when tested in vitro. In an in vivo comparative study conducted on Wistar albino rats, leaf extracts of *Bambusa arundinacea* (Retz.) showed higher antithrombotic activity compared with phytomenadione (vitamin K). Bamboo has metabolites that are important for medicinal applications, but it is important to evaluate whether the yield of these compounds or extracts is sufficient to make an herbal medicine (Gagliano et al. 2022).

Antioxidant of bamboo leaves (AOB), a brownish-yellow powder extracted from bamboo leaves, includes three main functional components: flavonoids, lactones, and phenolic acids. As a natural antioxidant officially certified in China, AOB has been widely used in various food preservation fields, such as fish, meat, and edible oil (Liu et al. 2021). Bamboo leaf extract has shown positive effects in controlling various degenerative diseases such as diabetes, cancer, as well as heart problems. Bamboo leaves are loaded with antioxidants and flavonoids that can help delay aging with their anti-inflammatory activity. Products made from bamboo leaves such as bamboo beer and bamboo wine are now a new-age discovery as alcoholic beverages due to their potential health benefits. Antioxidant of bamboo leaves (AOB) extracted from *genus Phyllostachys Sieb*. et Zucc., while six phenolic acids namely chlorogenic, ferulic, coumeric, protocatechuic, vanillic and coffeic acids were extracted from the leaves of *Bambusa arundinacea*. In another study, bamboo leaf extracts from *Phyllostachys praecox* can exhibit antioxidant activity at concentrations higher than 400 mg/L (Singhal 2023). Bamboo species like *Bambusa vulgaris* has recently been found to have significant levels of secondary metabolites in all parts of the plant, especially the leaves, which may be used as natural components in skincare products. The essential oil from bamboo leaf extract contains high levels of biological activity, including antioxidant, antimicrobial, antibacterial, and anti-inflammatory properties (Alias et al. 2023).

In addition to leaf utilization, bamboo shoots also have many benefits, especially in health and food ingredients. Bamboo shoots have historically been used in medicines and identified with diverse health benefits such as hypolipidemic, prebiotic, and anti-diabetic activities. Bamboo shoots are also a reservoir of bioactive substances, such as phytosterols, polyphenols, polysaccharides, and dietary fiber. Given these key components, bamboo shoots are evidenced with antioxidant, hypolipidaemic, prebiotic, anti-diabetic, anti-obesity, anti-inflammatory, and anti-hypertensive activities, as well as anti-microbial activities (Behera and Balaji 2021). The antioxidant activity of bamboo shoots is mainly derived from ascorbic acid and phenolic compounds, which show strong prevention against lipid oxidation, which is excellent for various radicals and comparable reduction ability to oxidative compounds, such as Fe^{3+}. Due to its high nutritional quality, diverse health benefits, and low pollution, bamboo shoots have become more popular in recent years (Wang et al. 2020). About 2 million tonnes of bamboo shoots are consumed every year. Fresh young bamboo shoots are delicious, crunchy and healthy, with a high content of nutrients, bioactive and antioxidants. Freshly harvested bamboo shoots are a good source of protein, fiber, minerals, vitamins and amino acids (Bajwa, Santosh, and Nirmala 2021).

Most of the dietary fiber from bamboo shoots is insoluble and only a small proportion is soluble, which plays a potential role in health and provides protection against many chronic diseases. Physicochemical and physiological properties of soluble dietary fiber (SDF) and insoluble dietary fiber (IDF) from bamboo shoots *Fargesia spathacea* relatively higher than other species. Both SDF and IDF of *F. spathacea* showed potential prebiotic effects, although effects of the *Lactobacillus* dan *Bifidobacterium* of SDF is relatively stronger than IDF. Dietary fiber *F. spathacea* with strong cholesterol adsorption activity and prebiotic potential (Wu et al. 2020). Fermented bamboo shoots are a storehouse of microorganisms, many of which are probiotic in nature. Fermentation is an important ancient biotechnological procedure used for the preservation of food products; fermented bamboo shoots are referred to as India’s “green gold” (Behera and Balaji 2021).

Antimicrobial

Antimicrobial activity can generally be prevented by utilizing the content present in a plant substance, such as bamboo. Some parts of bamboo, namely bamboo shoots and leaves, contain substances that are useful to inhibit the activity and become antimicrobial agents. Bamboo shoots promote health in many aspects, including improving digestion, relieving hypertension, and preventing cardiovascular disease and cancer. Insoluble fiber from bamboo shoots performed best among all tested fibers and its effects, as well as modulation with gut microbiota. Insoluble fiber from bamboo shoots was the most effective in suppressing high-fat diet-induced obesity and accompanying metabolic changes (Li et al.

2016). The addition antioxidant of bamboo leaves (AOB) combined with polyphenols can also inhibit bacterial growth and decarboxylase positive spoilage activity as it acts as an antimicrobial agent (Nirmala et al. 2018).

In addition to bamboo shoots, bamboo leaves can be used to treat spasmodic disorders and for the treatment of stomach problems such as killing intestinal worms, such as threadworms by fermentation (Behera and Balaji 2021). The utilization of fermented bamboo leaves as an antimicrobial agent has been tested on several types of microorganisms as shown in Table 4.

The content in bamboo leaves such as alkaloids, flavonoids, phytates, oxalates, tannins, terpenoids, and saponins where these bioactive constituents are related to antimicrobial activity. Antioxidant of bamboo leaves (AOB) and ZnO nanoparticles synergistically increase antibacterial activity against *Escherichia* dan *S. aureus*. AOB has a synergistic effect with ZnO nanoparticles in increasing the antimicrobial activity of chitosan films against gram-positive (*S. aureus*) and gram-negative bacteria (*Escherichia*) (Liu et al. 2021). Alkaloids can increase antimicrobial activity of antibiotics while saponin compounds are effective for inhibiting gram-positive bacteria such as *Staphylococcus aureus*. Bamboo leaves have the potential to be used as a natural plant-based ingredient in formulated skin care products and promote benefits for human health and the environment (Alias et al. 2023). Another use as an antimicrobial agent is done by extracting essential oils (EO) from bamboo. Leaves from *Phyllostachys pubescens* can be used as an essential oil that can interfere with the integrity of pathogenic membranes and thus can be a potential antimicrobial agent for future use (Singhal 2023).

Environmental and energy solutions

Environmental uses

The potential use of bamboo is not limited to certain organs and extracts of its substance content, but to the environment and surrounding conditions. All bamboo forests generate more ecosystem services and have lower growth and maintenance costs compared to the ecosystem services in other same plant ecosystem. Given global environmental challenges and climate change, bamboo forest management has received greater attention and is now a fundamental aspect of sustainable development (Shah et al. 2025). In the research conducted by Zeng et al. (2020), shows that bamboo forests can be used as a form of therapy that is able to relieve physical stress and stabilize emotions. The environmental experience of the bamboo forest was more conducive to the reduction of systolic blood pressure and heart rate of female subjects and maintained peripheral oxygen saturation at a higher level. This shows that the bamboo forest environment can effectively reduce the pressure on the human body, relieve emotions, and increase energy. The same was done in research by Lyu et. al. that by looking at the landscape and taking a walk around the bamboo forest environment for 15 min it increases the positive mood state and reduces the negative mood state (Lyu et al. 2019).

The aspect of physical use of bamboo in the environment is the use of fibers and their structure. Bamboo fibers have micro-slits, which makes them softer than cotton and improves their ability to absorb moisture. Another interesting property of bamboo fiber is that it is highly elastic, bacteriostatic, resistant to ultraviolet rays, and biodegradable which makes bamboo fiber products environmentally friendly. Due to its versatile nature, bamboo fiber is used primarily in the textile industry to make

Table 4. Application of microorganisms commonly found in bamboo shoot fermentation (reproduced under terms of the CC-BY license (Behera and Balaji 2021), copyright 2021, Springer nature).

Microorganisms	Applications
Lactobacillus plantarum	Can inhibit the adhesion of pathogens onto the gastrointestinal tract or urinary tract, thus inhibiting infection; also acts as probiotic; maintain intestinal microbe balance
Lactobacillus brevis	Produces gamma-aminobutyric acid (GABA), which has anti-depressant property
Leuconostoc fallax	Present in the heterofermentative stage of sauerkraut fermentation, found in the fermentation of vegetables
Lactococcus lactis	Food bacterium with industrial importance; used for production of industrial metabolites, enzymes, therapeutics, used as vaccine delivery system, production of heterologous plant-based and membrane-based proteins

clothing, bathrobes, and towels (Hakeem, Jawaid, and Alothman 2015). On the other hand, bamboo is beneficial for energy conservation and reduction of CO_2 emissions. Bamboo is considered a potential substitute for hardwood, and it exhibits high tensile strength with a value of 3.59×10^8 N/m^2, which is comparable to steel. As shown in the Figure 15, Glue-laminated bamboo boards store more carbon than other materials. The negative carbon emission value of glue-laminated bamboo boards results in lower gross carbon emissions compared to other materials. Therefore, the use of glue laminated bamboo board provides a positive environmental effect (Chang et al. 2018).

To reduce CO_2 gas emissions to be lower, bamboo has the potential to be used as the main material to replace plastic. Replacing plastic with biodegradable, compostable, and environmentally friendly materials is an urgent need. CO_2 emissions from the production of tableware made from bamboo pulp are lower than the manufacture of plastic products and traditional paper making from wood pulp, so it has the potential to replace plastic, especially in food packaging (Liu et al. 2020). Recent research shows that bamboo can be converted into a strong, moldable, and biodegradable cellulose-based material, designed as an alternative to plastic. The key approach is "multiscale interface engineering," which involves processing bamboo into macrofibers and nanofibers and then reconfiguring them through a combination of physical and chemical techniques. This innovative approach successfully transforms bamboo into a strong, moldable, biodegradable structural material with mechanical properties that equal or surpass those of modern plastics. The flexibility of the mechanical design, along with its positive environmental impact, makes this research important for the development of plastic alternative materials (Hu et al. 2025).

Other research in Ethiopia shows the potential of bamboo as a sustainable alternative to plastic and wood in the horticultural sector. The innovation involves creating and promoting new bamboo boxes/ cardboard boxes made from a type of mountain bamboo (Oldeania alpina). Bamboo products offer significant environmental and economic advantages over plastic and wood alternatives, contributing to reduced pollution and better waste management (Alamerew et al. 2025). Another positive impact that can be obtained by utilizing bamboo is preventing landslides. With fibrous roots, interconnected rhizomes, and relatively dense foliage that protects from heavy rainfall and produces new culms from underground. Ecologically, bamboo gardens also benefit from maintaining the hydrological cycle of groundwater, bamboo clumps can hold up to 25% of rainwater that falls to the ground; This percentage is much greater than that of conifers and pines (Timko et al. 2024).

In composition, bamboo dry materials are mainly composed of lignin, cellulose, and hemicellulose. Lignin can be converted into charcoal and used for carbon sequestration either at the mining site or elsewhere. Alternatively, bamboo can be used as a construction material. Wooden bamboo, especially

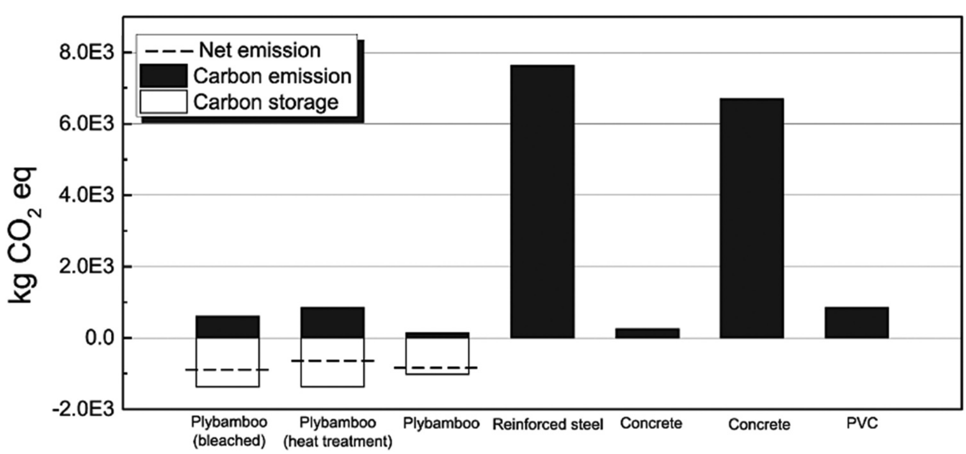

Figure 15. Greenhouse gas (GHG) emissions produced per kilogram of various materials (reproduced with permission (Chang et al. 2018), copyright 2018, Elsevier).

Phyllostachys, very promising for soil transformation and biodiversity improvement. *Bambusa vulgaris*, offering excellent soil holding ability, it is perfect for maintaining soil structures on banks. Bamboo through a strong root system that spreads more vertically than horizontally, effectively anchoring the soil to prevent erosion (Mahdavi, Clouston, and Arwade 2011). In addition, Bamboo has also long been widely used in building structures, such as in the manufacture of bamboo houses and composite plates. Biomass bamboo aggregate concrete (BAC) is improved with age. Compared with normal concrete, the mechanical properties of bamboo aggregate concrete decrease as the replacement ratio of modified bamboo aggregate increases, the compressive strength of modified bamboo aggregate concrete can still reach 74% of normal concrete (Zhou et al. 2024). Other implementation is used to reduce insect with Vacuum thermal modification that environmentally friendly method to improve durability and reduce insect infestation on bamboo, which has the advantages of preventing deformation, preventing oxidation of bamboo surface (Zhang et al. 2024).

Bamboo as wind turbine

Bamboo has many engineering attributes, making it an attractive material for wind turbine blades. Bamboo-based composites are rapidly emerging for use in wind turbine structural applications. In a study by Holmes et al., a low-cost bamboo-based composite was developed for wind turbine blade applications. The bamboo-poplar composite showed potential for reducing production costs compared to other bamboo-based composites. The tensile strength was 175–191 MPa with an average tensile modulus of 21.6 GPa. The fracture toughness along the weakest orientation of the laminate was approximately 0.13 kJ/m^2. The strength and modulus values found for the laminates exceeded those of birch (Holmes et al. 2009).

In addition to its strength, the advantages of using bamboo for turbine blades are its recyclability, low cost, high strength, and biodegradability compared to synthetic composites. In the study of Bora et al., the bamboo-epoxy composite was used for vertical-axis wind turbine (VAWT) blades. The Darrieus VAWT model, consisting of three blades, is shown in Figure 16a. These blades are connected to the main rotating shaft with the help of six radial support arms. The 3D model of the blade with chord length, span height, and two boundary conditions constrained at equal distances from both ends is shown in Figure 16b. The 2D cross-sections of the two wings are shown in Figure 16c, d. In addition, the aspect ratio of the blade plays an important role in the overall performance. The turbine performance decreases as the aspect ratio is reduced. The results show that the blade with two shear webs exhibits minimum stress and deflection values. The stress and deflection of the observed non-symmetric bamboo-epoxy composite blade are reduced by 70.98% (stress) and 1.11% (deflection) respectively compared to the glass-epoxy blade (Bora et al. 2023). The use of bamboo in moving structures such as wind turbines requires mechanical conditions that can withstand existing conditions. A solution that can be applied for this is innovative research using metal-reinforced bamboo composite (MRBC) production methods, using bamboo waste and metal nanoparticles as reinforcements. It has been proven that reinforcing bamboo waste with metal nanoparticles produces strong composites with high bonding strength, without the use of synthetic chemical adhesives. This offers a sustainable material solution for structural applications such as wind turbines by utilizing bamboo waste and enhancing the value of both base materials (Yu et al. 2025).

Bioethanol production

Bioethanol production from bamboo is a growing sustainable energy source with great potential due to its rapid growth rate, high cellulose content, and sustainability. Some processes involved in producing bioethanol from bamboo are bamboo selection and pretreatment, hydrolysis, fermentation, and distillation or purification (Deshmukh and Pathan 2024; Zhan et al. 2022). One of the most important processes in bioethanol production from bamboo is pretreatment. Wang et al. have reported using three pretreatment technologies such as hot liquid water (LHW), dilute acid (DA), and soaking in aqueous ammonia (SAA). The minimum ethanol selling price (MESP) of these pretreatment processes was 0.554, 0.484, and

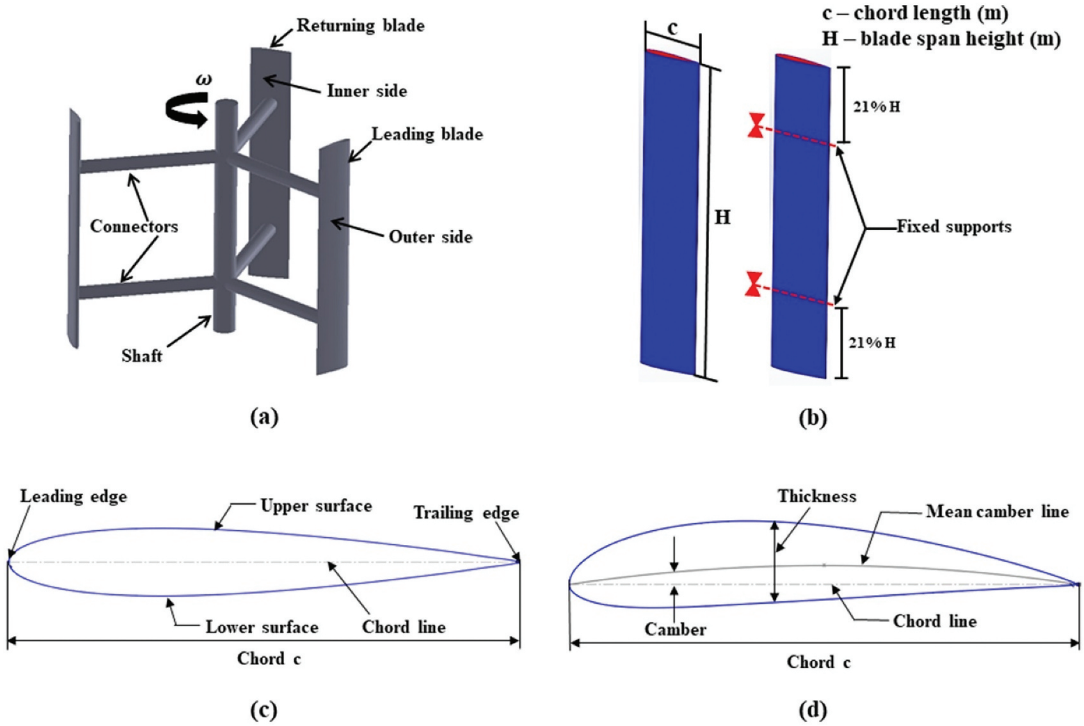

Figure 16. Geometry of blade profiles (a) Darrieus vertical axis wind turbine (VAWT) model, (b) Blade model for simulation, (c) Symmetric cross-section of the blade, and (d) Non-symmetric blade cross-section (reproduced with permission (Bora et al. 2023), copyright 2012, Elsevier).

1.014 $ per liter for DA, LHW, and SAA pretreatments, respectively. Bioethanol produced through DA and LHW pretreatments can be economically competitive with gasoline. Bioethanol synthesized through this method is also known to be more environmentally friendly with greenhouse gas emissions reduced by 45–93% (Wang, Littlewood, and Murphy 2014).

In India, *Dendrocalamus* bamboo species is developed as a raw material for bioethanol production with the help of enzymatic saccharification. Dilute alkali pretreatment resulted in the removal of lignin which effectively increased the cellulose concentration from 46.7% to 63.1%. It is known that enzymatic fermentation is efficient with ethanol production of 71.34% of the theoretical maximum. This process has the potential to produce 143 L of ethanol per dry ton of bamboo waste (Kuttiraja et al. 2013).

In another study, LHW pretreatment was used and found to keep the economic and environmental costs to a minimum. LHW pretreatment at 190°C for 10 min could release 69% of sugar under the loading of commercial enzyme Cellic CTec2. The techno-economic evaluation revealed that the production cost was $0.484 per liter (data calculated in China). Therefore, bioethanol from bamboo is proven to be technically and economically feasible, and competitive with gasoline in China (Littlewood et al. 2013).

Biomass production

Several countries are updating their bioenergy strategies to include bamboo. A bamboo-fueled power plant is being built in Mizoram, India to help meet the energy needs of northeastern India. Bamboo is thought to be key to combating Africa's energy woes. Among the advantages of bamboo that make this innovation possible is that the entire bamboo plant, including the culm, branches, and rhizomes, can produce charcoal, making it extremely resource-efficient with limited waste (Ogunwusi and Onwualu 2013).

Bamboo as biomass for energy sources has also been explored. Purbasari et al. have studied three bamboo species, namely *Gigantochloa apus*, *Gigantochloa levis*, and *Gigantochloa atroviolacea* (Purbasari, Samadhi, and Bindar 2016). The three bamboo species underwent four stages of thermal decomposition (Figure 17), indicating that bamboo contains lignin (20–30%), cellulose (40–50%), hemicellulose (25–30%), extractives, and ash (Kumar and Chandrashekar 2014). These results indicate that the selected bamboo species have calorific values comparable to wood, suggesting that it can be used as a sustainable energy source (Table 5). *G. atroviolacea* has the highest ash content and the lowest calorific value, while the ash content and calorific value in *G. apus* and *G. levis* are relatively the same. In addition, bamboo ash contains high silica and has the potential to be further used as a building material or for engineering purposes. Bamboo ash contains mineral phases, namely arcanite (K_2SO_4), sylvite (KCl), and quartz (SiO_2). This result is in accordance with the oxide composition analysis that silicon and potassium are dominant in bamboo.

While the calorific value and chemical composition of bamboo support its potential as a renewable energy source, scalability for bioethanol production still faces significant challenges. One major obstacle is the efficiency of lignin removal during the pretreatment process, as lignin forms a protective matrix around cellulose and hemicellulose, limiting enzymatic access. In addition, enzymatic hydrolysis for the release of fermentable sugars remains expensive, especially when using unoptimized or highly lignified biomass. However, certain bamboo species, such as *Gigantochloa apus*, with relatively high hemicellulose content and moderate lignin content, are more suitable for hydrothermal or dilute acid pretreatment, which facilitates faster hydrolysis and increases fermentation rates (Saini et al. 2016; Sun and Cheng 2002). The high natural hemicellulose fraction in *G. apus* can produce more xylose and other fermentable sugars, making it a promising candidate for second-generation bioethanol production. Therefore, specific species selection and tailored pretreatment

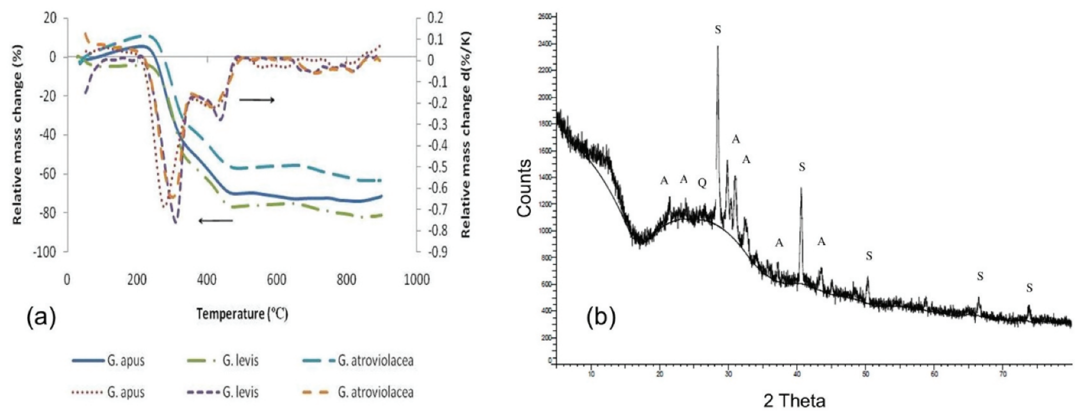

Figure 17. (a) Combustion profiles of selected bamboo and (b) XRD pattern for bamboo (G. apus) ash (A = arcanite (K_2SO_4), S = sylvite (KCl), Q = quartz (SiO_2)) (reproduced under terms of the CC-BY license (Purbasari, Samadhi, and Bindar 2016), copyright 2016, CBIORE).

Table 5. Proximate analysis and calorific value of selected bamboo and wood.

	Proximate analysis (%)				
Species	Moisture	Ash	Volatile matter	Fixed carbon	Calorific value (cal/g)
G. apus	8.89	2.45	70.31	18.35	4151
G. levis	8.76	2.46	72.71	16.07	4161
G. atroviolacea	8.13	3.29	71.70	16.88	4086

strategies are critical to overcome technical and economic barriers in scaling up bamboo-based bioenergy.

Advanced materials

Cellulose fibers crystal

Although natural fibers are not as strong as synthetic fibers, they are abundant, low-density, low-cost, renewable, and biodegradable. Natural cellulose fiber-reinforced polymer composites have been developed to be environmentally friendly materials (Venkatarajan and Athijayamani 2021). Natural fibers such as highly aligned lignocellulosic bamboo have been extracted and densified to obtain structural materials with excellent tensile strength. This performance is obtained from the strong fiber alignment and high fiber volume (Song et al. 2018). Bamboo is a cheap biomass resource and has abundant long fibers with a theoretical strength of 1200–1930 MPa (Yu et al. 2014).

Lin et al. have reported the use of bamboo cellulose fiber as a structural material with antifungal properties and for electrodes. Figure 18a shows the design concept and fabrication process of bamboo fiber composite and supercapacitor derived from natural bamboo cellulose fiber. Long and parallel cellulose fibers were isolated from bamboo vascular bundles by removing the hemicellulose and lignin matrix (Figure 18b,c). The results showed that the composite had a high tensile strength of up to 571

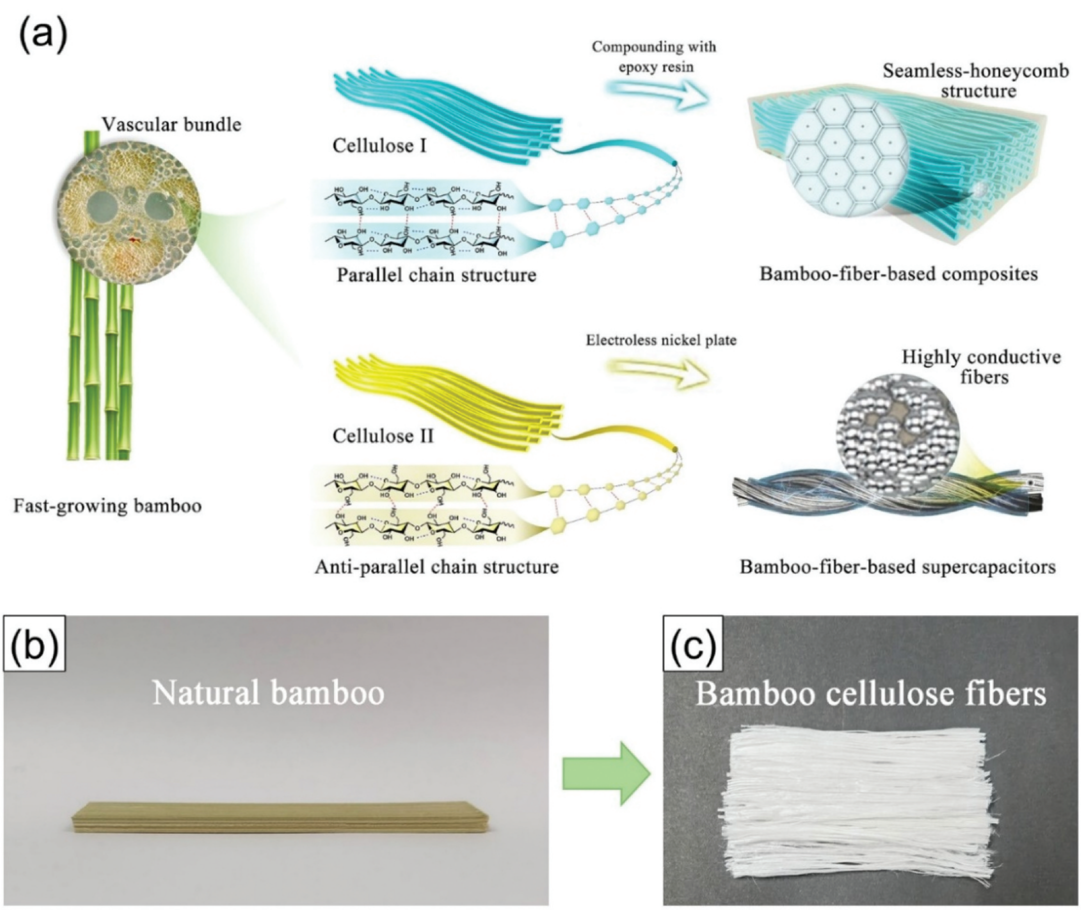

Figure 18. (a) Schematic showing the design concept and fabrication process of bamboo fiber-based composites and supercapacitors, and (b) Photographs of natural bamboo and (c) the extracted bamboo cellulose fibers (reproduced with permission (Lin et al. 2022), copyright 2022, Elsevier).

MPa. In addition, cellulose was also used to fabricate a supercapacitor with an areal capacitance of 2032 mF cm^{-2} and a linear capacitance of 670 F cm^{-1} (Lin et al. 2022). A similar study was reported by Shan et al. (2022), who used bamboo cellulose fiber as an antibacterial agent. The aim is to understand adsorption mechanism of tannic acid (TA) on bamboo cellulose fibers (BCFs) with potential applications such as antibacterial agents, preservatives, or other functional properties. The result proves that TA can attach to bamboo cellulose through strong yet reversible multi-molecular physical adsorption, mainly sustained by hydrogen bonding. This finding opens a method of adaptively and sustainably functionalizing bamboo fibers, with broad potential in textile, packaging, and eco-friendly material applications (S. Shan et al. 2022).

In another study, bamboo fibers (BFs) were prepared into microfibrillated cellulose (MFC) by alkali treatment combined with bleaching and sulfuric acid hydrolysis. FTIR spectroscopy analysis of untreated BFs, alkali-treated BFs, bleached BFs, and hydrolyzed BFs showed that compositional changes occurred in the fibers during hydrolysis. Figure 19a shows that hemicellulose and lignin were mostly removed in MFC. Figure 19b,c show the microscopic images of the original BFs and alkali-treated BFs. The original BFs were covered by a massive cementitious material, which was reduced after the BFs were treated with an alkaline solution. The obtained MFCs may have potential

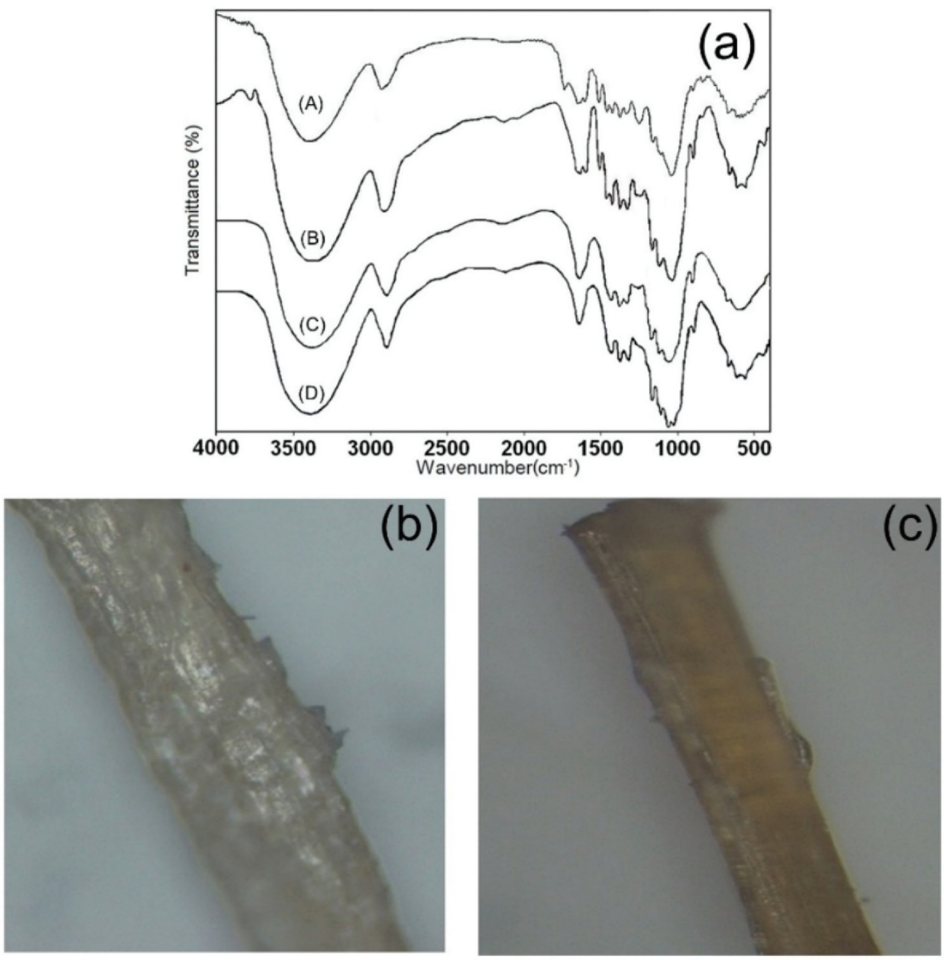

Figure 19. (a) FTIR spectra of BFs after different treatments: (a) Raw BFs, (b) 2 wt% alkali treated BFs, (c) Bleached BFs, (d) Hydrolyzed BFs, (b) Optical microscopy images of raw BFs, and (c) Alkali treated BFs (reproduced under terms of the CC-BY license (Sewar et al. 2024), copyright 2013, IOP publishing).

applications in alternative resources such as biomass, pharmaceutical, and optical industries as additives, and in the composite field as reinforcing phase (Nguyen et al. 2013).

Similar results were reported by Zhang et al., MFC was obtained by crushing bleached bamboo kraft pulp (*Phyllostachys pubescens*) with chemical pretreatment and high-pressure homogenization procedures (Zhang et al. 2012). Scanning electron microscope (SEM) images of the effect of homogenization time were evaluated (Figure 20). Pronounced differences in the volumes of pulp and MFC were observed. There were rod-like structures with diameters of about tens of millimeters on the surface of the original bamboo fibers. The fibers were crushed into nanoscale microfibrils after 2, 3, and 6 times of homogenization.

Cellulose-based functional hydrogel

Hydrogel products are a group of polymeric materials, whose hydrophilic structure enables them to retain large amounts of water in their three-dimensional network. The widespread use of these products in many industrial and environmental application areas is considered to be of great importance. Hydrogels have great research and application prospects in the field of product design (Ahmed 2015).

Bamboo cellulose-based hydrogels have been reported, and have potential applications in food packaging and plant agriculture, such as fertilizer release and crop production. Researchers have extracted cellulose from bamboo and produced various cellulose-based functional hydrogels with excellent properties through cross-linking methods (Cao et al. 2022). Various approaches

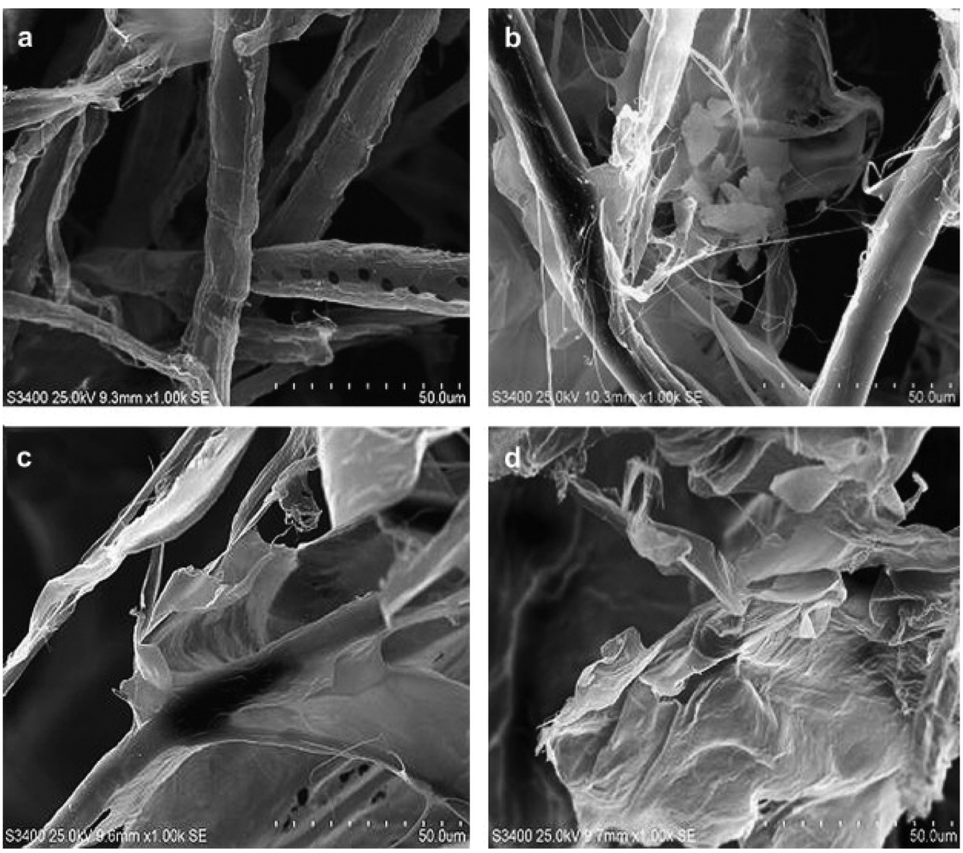

Figure 20. Scanning electron micrographs of pulp and MFC of (a) Untreated kraft pulp fiber, (b) Homogenized twice, (c) Homogenized three rounds, and (d) Homogenized 6 times (reproduced with permission (Zhang et al. 2012), copyright 2012, Elsevier).

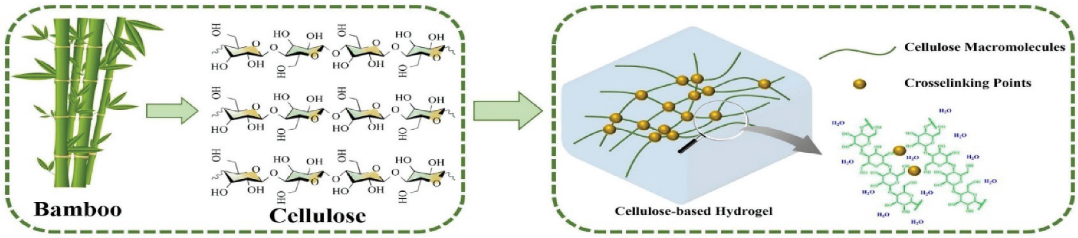

Figure 21. Schematic illustration of the structures of cellulose and cellulose-based hydrogels as well as the preparation process of cellulose-based hydrogels (reproduced under terms of the CC-BY license (Huber et al. 2019), copyright 2022, frontiers).

have been used to prepare hydrogels from cellulose, which shows the great application value of bamboo in the production of cellulose-based hydrogels. Figure 21 shows that cellulose can be used to produce cellulose-based hydrogels with cross-linking agents having a three-dimensional network structure (Shen et al. 2016). Hydrogels can be designed and synthesized with fine-scale control of various hydrogel properties, such as structure, cross-linking density, biodegradability, mechanical strength, chemical response, and hydrology of hydrogels to stimuli (Huber et al. 2019).

Several steps in making cellulose-based hydrogel from bamboo include (1) extraction of cellulose from bamboo and (2) synthesis of hydrogel from cellulose. In many reports, the bleach-alkali treatment method is the most common method for extracting cellulose from bamboo (Bhaladhare and Das 2022). This method uses bleach and alkali to remove lignin and hemicellulose to obtain high-purity cellulose. Under certain temperature conditions, lignin is removed by soaking it in an alkali solution. Commonly used bleaches are chlorite, hypochlorite, or chlorine, while the alkali reagents used are usually sodium hydroxide or potassium hydroxide (Lu, Zou, and Fang 2021).

After obtaining pure cellulose, the next step is hydrogel synthesis. Cellulose-based hydrogels are generally prepared through physical cross-linking, chemical cross-linking, and polymerization technologies (Cao et al. 2022). Physical cross-linking methods can be used to improve the structure of hydrogels. This method is carried out using freeze-thaw technology, photoinitiator technology, and radiation-induced technology (González-Torres et al. 2018). Chemical cross-linking methods are used to form bonds between polymers and cross-linking agents (Yu et al. 2017).

Fiber composites

Bamboo is also used as a composite fiber. Bamboo fiber-reinforced polymer (BFRP) is designed as an alternative to carbon fiber-reinforced polymer (CFRP). BFRP is made using fine lace made of bamboo filaments presented in a bonded frame. CFRP commonly uses non-consumable oil raw materials that have high prices. BFRP has become an option for planning sustainable and environmentally friendly goods. Some BFRP applications that have been reported are for construction, interior design, furniture, and automotive applications. Compared to synthetic composites, BFRP as a natural fiber composite is a renewable substitute material and is cheaper than synthetic fibers (Kaur et al. 2017).

Research form Wang et al. (2025) introduces a transparent and flexible bamboo-based composite material, utilizing a dual-resin blending strategy. The aim is to combine the mechanical strength of bamboo with flexibility and optical clarity on a commercial material scale, and the result is a transparent and flexible variant of bamboo composite through dual-resin blending, paving the way for polymer-based plastic substitutes with a better environmental impact. This is an innovative step that combines the mechanical strength of Bamboo and the optical clarity of a resin, meeting the needs of modern materials with a sustainable approach. This research utilizes the natural structure of bamboo as the base material for transparent and flexible composites (Wang et al. 2025). In another study, bamboo has been used as a blend with polyester in knitted fabrics. It was observed that with increasing bamboo content, the roughness and unevenness of the yarn increased and its tenacity decreased. It was also found that increasing bamboo content in the blend increased the ultraviolet protection factor, water vapor permeability, and absorbency (Mahish, Patra, and Thakur 2012).

Bamboo charcoal is also used as a thermoplastic composite by mixing it with polyester (PET) and polypropylene (PP) by melt compounding and then injection molding. The results showed that the mechanical properties of PET/PP_{ext} (extrusion grade polypropylene) composites were better than PET/PP_{inj} (injection grade polypropylene) composites. It is also known that the mechanical properties of PET/PP_{inj} composites are not significantly affected by the addition of bamboo charcoal (Lou et al. 2007).

Compared to plastic products, bamboo offers several advantages, including sustainable, carbon dioxide absorption, pollution-free products, and biodegradability. In September 2024, China released the "Special Standard System for Bamboo in Lieu of the Plastic Initiative," The purpose of this policy is to reduce the utilization of plastic products, reduce environmental pollution and facilitate the economic progress of bamboo. Of the many bamboo species, three stand out as the most cultivated in China: *Phyllostachys edulis*, *Bambusa multiplex* (Lour.) Raeusch. Ex Schult.f. and *Dendrocalamus latiflorus* Munro. It is widely used in various fields, including construction, furniture, and handicrafts (Li, Wang, and Latiff 2025). In addition, modeling using artificial intelligence (AI) also helps accelerate the process of breeding superior bamboo for plastic replacement needs through faster breeding and more precise phenotyping and genotyping predictions. This is important for realizing specifically in the global Bamboo as a Substitute for Plastic (BASP) initiative with high industrial-scale efficiency (Sun, Di, and Gao 2025).

Conclusions

Bamboo is a sustainable resource with unique properties that support its wide range of applications across industries. This review has explored the geographical distribution, traditional uses, anatomical, and chemical properties of bamboo, highlighting its uses in construction, biomedical and food, environmental engineering, energy solutions, and advanced materials.

Engineered bamboo lumber, such as laminated bamboo lumber (LBL), cross-laminated bamboo (CLB), and modified composites show satisfactory strength for construction applications. Bamboo ash is also used as a mixture of additional cement materials (SCM) in construction applications. In the health and food sector, bamboo leaves and shoots have a large abundance of phenolic compounds, especially flavonoids. This makes bamboo a good source of natural antioxidants and can play an important role in the food and pharmaceutical industries. In addition, bamboo leaves can also inhibit bacterial growth and positive decarboxylase decay activity which functions as an antimicrobial agent. In the environmental sector, bamboo fibers have micro-gaps, which allow them to absorb moisture. In addition, bamboo fibers are highly elastic, bacteriostatic, resistant to ultraviolet light, and biodegradable, making them environmentally friendly. In the energy sector, bamboo has the potential to be applied to wind turbine blades. In addition, bamboo is rich in cellulose, which can potentially be a source of bioethanol and biomass production. In the material sector, bamboo cellulose fibers are used as composites have antifungal properties, and can be applied as electrodes, hydrogels, and biodegradable inexpensive plastic.

Beyond these findings, future research should adopt a more interdisciplinary approach to fully harness bamboo's potential. Integrating genetic and molecular studies, for instance, could accelerate selective breeding for optimized lignin and cellulose content, enhancing bamboo's suitability for bioenergy and composite materials. Additionally, advances in nanotechnology open promising avenues, such as utilizing bamboo-derived nanocellulose for flexible electronics, wearable devices, and sustainable packaging. Exploring these directions can expand the boundaries of bamboo research, driving innovation at the intersection of biotechnology, materials science, and environmental sustainability. This integrative perspective is essential for maximizing bamboo's impact across scientific and industrial domains.

This review contributes to understanding the characteristics of bamboo species, components, and applications in detail. The guidance provided in this review can be the basis for further research in developing the potential and understanding bamboo species that are suitable for their applications. Thus, a better understanding of this is the key to optimizing bamboo, opening up wider application potential in various fields of science and technology.

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