

Review

Bamboo as a sustainable alternative construction material: A review

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ABSTRACT

Bamboo is one of the fastest-growing plants in the world, naturally abundant, and recognized as a highly sustainable and renewable material resource. Although the existing literature highlights its potential in the construction industry, bamboo's use remains largely confined to temporary applications such as scaffolding, props and ladders, as well as decorative elements. The recent rise in the cost of conventional building materials has intensified the need to explore alternative, sustainable and cost-effective options. We present a synthesis of current research, practical applications and future prospects of bamboo as a viable and sustainable alternative to conventional construction materials, given the rising global demand for eco-friendly building practices and the need to reduce the environmental footprint of the construction sector. We evaluate bamboo's mechanical properties, environmental benefits and its role in achieving sustainability goals. We find strong evidence supporting bamboo not only as a substitute for traditional wooden elements but also, when appropriately treated, as a potential alternative to mild steel reinforcement in concrete. Based on these insights, we provide specific recommendations to promote the use of bamboo in sustainable, resilient and environmentally friendly construction practices.

1. Introduction

All over the world, the building industry uses three main resources to carry out its activities: Material resources, labour resources, and plant and equipment resources. Among these resources, materials have been identified as accounting for 60–65% of the total cost of projects (Opoku et al., 2015). The recent escalating cost of building materials has resulted in a search for alternatives for sustainable construction. Moreover, research has shown that less than 60 years from now, steel production will have declined, resulting in the need to provide alternative materials in the construction industry (Ingole et al., 2022). This strengthens the need to conduct research into the use of alternative sustainable materials to replace steel in concrete.

Over the years, the massive harvesting of wood has gradually depleted natural vegetation leading to severe environmental degradation in many areas. The unsustainable exploitation of wood and the unsustainable use of wood products in the construction industry has prompted some countries to pass laws to ban indiscriminate logging (e.g., Kenyan National Bamboo Policy, 2019).

In October 2007, the first-ever international conference on modern bamboo structures was organized in China (Yan, 2022; Yan et al., 2008). The objective was to bring experts from all over the world together to discuss topics related to the design, analysis, testing, manufacturing and construction of modern bamboo structures and other natural or non-conventional construction materials. Since then, many researchers have worked on the development of stable and modern structures and products from bamboo (Yan et al., 2010). This reflects the numerous benefits derived from the use of bamboo.

Bamboo has many advantages, including its ready availability, light weight, higher tensile strength compared to traditional wood, and its status as an easily renewable resource (Anto et al., 2023; Varma, 2016). However, its use in the construction industry is mostly limited to architectural applications and temporary works. This limitation is due to several factors: Governmental inaction (the limited development and implementation of policies, standards and regulatory frameworks that support the adoption of bamboo as a mainstream construction material), geometric variability of the product (variety of culm sizes, not standardized), inherent irregularities in shapes and sizes that are not always

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suitable for consistent use (Lorenzo et al., 2021; Sharma et al., 2015; Zhang et al., 2019) as well as its susceptibility to water absorption, fungal attack and chemical decomposition (Hebel et al., 2016). To mitigate these limitations, bamboo needs to be treated and modified for use in construction. Unfortunately, the initial setup of the equipment used to produce laminated bamboo is capital-intensive, serving as a disincentive for the production of state-of-the-art bamboo materials (Asmah et al., 2016).

In this review, we synthesize existing research, practical applications and emerging developments with a view to evaluating bamboo's potential as a viable and sustainable alternative to conventional construction materials. This is consistent with the rise of global demand for eco-friendly building practices and the need to reduce the environmental footprint of the construction sector. We evaluate bamboo's mechanical properties, environmental benefits and its role in achieving sustainability goals. To achieve this, we conducted a comprehensive literature review, with emphasis placed on the most relevant studies for this review paper.

The review is particularly relevant as it addresses contemporary issues in sustainable infrastructure, green materials and innovations in construction technology. We believe it will be of interest to a broad spectrum of readers, including researchers, practitioners, policymakers and materials science students, as it consolidates various ideas and research findings on bamboo to support informed and decisive policy making.

2. General importance of bamboo

The importance of bamboo can be categorized into three main areas: environmental, social and economic. Environmentally, bamboo can be highly effective in preventing erosion, absorbing carbon dioxide from the air, and growing faster than most tree species, providing vegetation cover within three to four years (Hossain et al., 2015; Sharma et al., 2015; Tekpetey, 2011).

Bamboo has many uses in the construction industry, including scaffolding, plywood, beams and wall plates, flooring, walls, foundation, ceiling, windows, doors, roofs, trusses and rafters in buildings, as well as bridge girders (Chaowana et al., 2021; Madhura and Mathur, 2021; Marueng et al., 2021; Occupational Health and Safety, 2017; Yan et al., 2010). There are approximately 1000 documented uses (Li et al., 2020). According to the Kenyan National Bamboo Policy (2019), about 10,000 general products are made from bamboo, including timber substitutes, composite plastics, textiles, fibres, food and beverages, cosmetics and health products. Bamboo is also widely used for bioenergy, ecosystem protection, protection of water bodies and general environmental protection due to its fast growth rate.

Bamboo is lightweight compared to the timber used in the construction industry. When used as a reinforcement in concrete, it reduces the material's weight and improves the tensile strength of the concrete by 400% (Tutorial Tips Civil, 2020; Varma, 2016).

Bamboo grows very rapidly compared to other woody plants and, when treated, can replace timber in the construction industry (Addo-Danso, 2018; Asmah et al., 2016; Kumar and Gupta, 2008). It is also a major source of job creation, economic development, poverty eradication and environmental management through activities such as cultivation, harvesting, transportation, processing, manufacturing of bamboo-based products and its use in construction. These activities bring about employment opportunities across rural and urban areas, provide income for smallholder farmers and artisans and stimulate local economies, thereby supporting poverty alleviation and economic development (Kenyan National Bamboo Policy, 2019). It is a highly sustainable material compared to wood and steel (Trujillo, López, 2020).

Although Bonsi (2009) suggested that further research is needed into the type of soil best suited for bamboo cultivation, Tekpetey (2011) indicated that bamboo grows easily in almost every soil but thrives particularly well in swampy areas where most trees struggle. This is

confirmed by Obiri et al. (2020), who state that bamboo is very versatile in its cultivation and can thrive in a wide range of agricultural conditions.

3. Importance of bamboo in the construction industry

Socio-economically, bamboo is one of the important building materials that is readily available and can be used by skilled and unskilled labour in the construction industry (Varma, 2016). It can be used in several ways, including ceiling panels, furniture, artifacts, flooring, window blinds, props and reinforcement (Bonsi, 2009). Bamboo can also be used for making veneers for plywood, decorative boards, panel boards and other building materials (Kumar and Gupta, 2008). The cultivation, processing and application of bamboo in the construction industry also help provide employment opportunities for people in the industry.

Despite bamboo being abundant, inexpensive and readily available to meet the economic housing needs, especially in tropical regions, its current use is usually limited to temporary construction (Kumar and Gupta, 2008; Opoku et al., 2015). Its lightweight characteristic also helps reduce the weight of the construction elements. More importantly, treated bamboo construction is very durable and can have a structural lifespan of more than 50 years (Forest Research Centre for Livelihood Extension, 2022).

4. Sustainable bamboo production

Sustainability, as defined by Asheim (1994), can be explained as the responsibility of the present generation to use and manage available resources in a way that meets their needs, without compromising the ability of future generations to meet their own needs. It involves the spontaneous pursuit of socio-economic and environmental objectives. Wood resource sustainability has been declining worldwide over the years, but bamboo has been recognized as a renewable, abundantly available and highly sustainable natural resource. It is very cost-effective and environmentally friendly, with a fast growth rate compared to most trees (Kumar and Gupta, 2008; Lorenzo et al., 2020). Due to its shorter life cycle (maturing in three to four years) compared to most woody plants (Sharma et al., 2015), it is considered the most sustainable natural construction material resource that can be managed for the benefit of future generations. This is supported by the Kenyan National Bamboo Policy (2019), which emphasizes that bamboo is highly sustainable because its annual harvesting does not result in environmental degradation, deforestation or depletion of natural resources. Bamboo continues to produce new shoots annually, and if the older ones are not harvested, they die off and decay. Selective harvesting of mature bamboo culms not only helps reduce structural clutter but also improves the regenerative capacity, and quality and quantity of culms, allowing cultivation to last for many years (Kenyan National Bamboo Policy, 2019).

Unfortunately, the initial capital required to install advanced bamboo processing and treatment plants is very high, which has been a major disincentive to local production and use of bamboo products in developing countries (Asmah et al., 2016; Bonsi, 2009). It would, therefore, be prudent to develop simple but effective equipment for local and commercial production. Additionally, Bonsi (2009) has noted that some countries are not technologically ready for bamboo processing, suggesting that incentives, such as tax holidays, should be given for importing processing machines. Ranjan and Gupta (2016) report that the Indian Center for Green Building has initiated technological training for its manpower to promote bamboo technology in India.

5. State of the art bamboo technology

Bamboo has traditionally been used for props, sheds, fence walls, window/door frames, ladders, scaffolds and other products. As a result

of technological advances, bamboo is now used to produce substitutes for wood, composite materials, plywood, fiberboards and many other advanced products such as prefabricated houses (African Pacific Network for Global Change, 2016). Moreover, bamboo is widely recognized as a renewable natural material that may in future replace steel and reinforced concrete structures (Lapina and Zakieva, 2021; Mbazor et al., 2023). However, to maintain or improve the state of the art in bamboo technology, there is a need for standardization, a code of practice, and standard procedures for testing bamboo products to ensure product quality (Amede et al., 2021).

Although India, which has the second-highest bamboo cultivation after China, has established some standards for testing the flexural strength and compressive strength of bamboo (Bureau of Indian Standards, 2008), as well as a code of practice for preserving bamboo (Bureau of Indian Standards, 2006), there is a need for an international standard for the codification of bamboo that would serve as a reliable reference for architects and engineers in construction. This standardization would facilitate bamboo's acceptance as a standard construction material by policymakers, architects and engineers worldwide (Amede et al., 2021).

6. Mechanical and physical properties of bamboo

6.1. Physical properties of bamboo

Bamboos belong to the grass family, the Poaceae (Ahmad et al., 2017; Kenyan National Bamboo Policy, 2019). They generally have hollow culms separated by nodal diaphragms, with the culm diameter decreasing from the base to the top. The culm of bamboo is generally soft inside but hardened with cellulose, pectin, and a wax coating on the outside (Tekpetey, 2011), as shown in Fig. 1 below. Its lightweight characteristics, specifically its strength-to-weight ratio, along with its flexible nature, enable it to perform very well during earthquakes (Kaminski et al., 2016a).

Although there is extensive research on the physical properties,

anatomical properties and preservation needs of bamboo, further research is necessary to explore other properties when developing prototype products for different market segments (Obiri and Oteng-Amoako, 2007).

Ghavami (2005) examined bamboo reinforcement in concrete after 15 years and compared it to steel reinforcement bars in concrete after 10 years, concluding that properly treated bamboo reinforcement is more durable than steel. Unfortunately, the species used in the experiment was not reported. Supporting this observation, Ghandehari et al. (2016) conducted an experiment on accelerated corrosion of steel reinforcement in concrete, which resulted in massive cracks in the concrete, unlike the use of treated bamboo. Here again, the species used for the experiment was not reported. Another experiment further showed that untreated bamboo used as reinforcement in concrete swells due to water absorption from the fresh concrete. Subsequently, shrinkage occurs when the concrete dries, creating voids between the bamboo and the concrete matrix (Neenu, 2021).

To prevent the swelling issue, Su et al. (2021) conducted an experiment by impregnating bamboo with a rosin ethanol-based solution using vacuum pressure. The ethanol evaporated after drying, leaving the rosin to fill the culm's pores, resulting in over 50% reduction in the bamboo's water absorption. Furthermore, Yu et al. (2021) demonstrated that heating the bamboo structure to a temperature of 180 °C reduced its water absorption. Reducing bamboo's water absorption prevents bamboo strips from swelling during concrete casting and shrinking during curing, which can create gaps between the concrete and bamboo strips, ultimately reducing their bonding strength, as explained by Javadian et al. (2016). Treating bamboo to reduce its water absorption could potentially help to improve its bonding properties, enabling it to replace steel reinforcement in concrete. This has also been suggested by Jafarnia and Mofidi (2025) in their systematic literature review on the mechanical properties of bamboo.

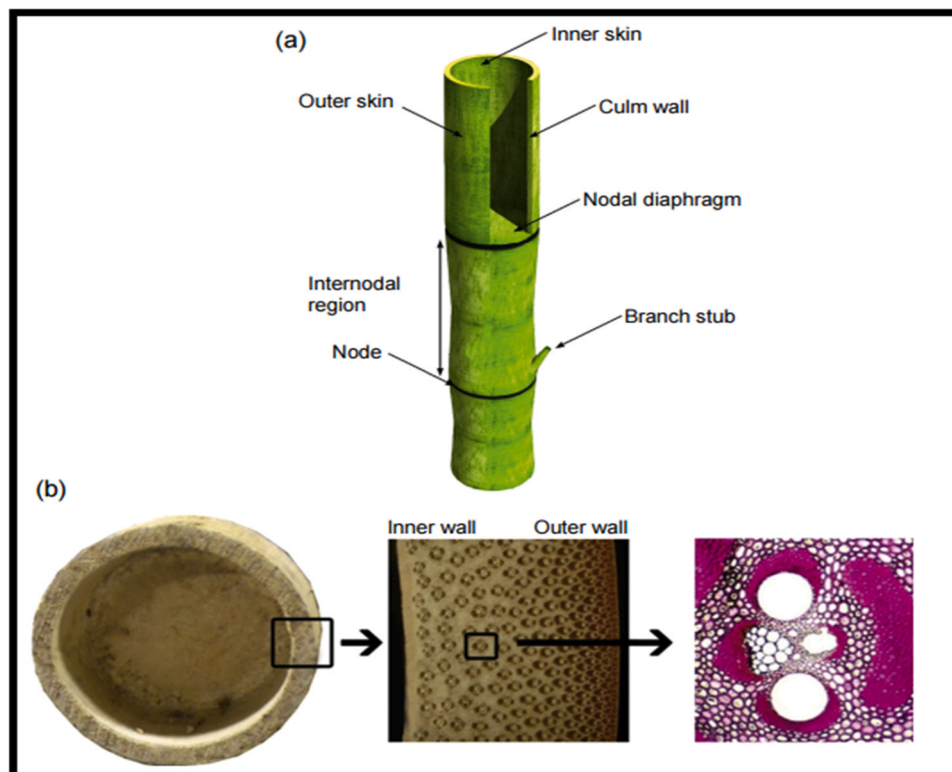


Fig. 1. Anatomy of a bamboo culm. (a) Schematic view of a bamboo segment and (b) sections of the culm wall (Trujillo, López, 2020).

6.2. Mechanical properties

The mechanical properties of a bamboo culm vary throughout its length and increase proportionately with its density, from the inner part of the culm to the outer surface. These properties further vary with the age and species of the bamboo (Ahmad et al., 2017), but in the large ‘timber’ bamboos, the best mechanical properties are obtained when the culms are 3–5 years old (Das et al., 2025). For instance, Li et al., (2021) experimented with Moso bamboo (*Phyllostachys edulis* (Carrière) J. Houz.) strips from the outer surface, which yielded a tensile strength of 100 MPa, whereas the inner culm exhibited lower strength.

Bamboo demonstrates approximately 200% greater strength in tension and about 20% greater strength in compression when compared to wood (Table 1) (Yuan and Feng, 2015).

Although Kaminski et al. (2016c) provided technical notes for determining characteristic strength values and methods for calculating the limit state design, the existence of approximately 1660 bamboo species (Yan, 2022), each potentially possessing varying properties, means that further research is required to provide more accurate design values and coefficient data.

The variation in properties has been further confirmed by Xu et al. (2019), who tested the tensile and compressive strengths of laminated bamboo subjected to temperatures ranging from 20 °C to 230 °C (Fig. 2).

Akmaluddin et al. (2015) in an experiment used *Gigantochloa atter* (Hassk.) Kurz ex Munro as a permanent formwork for slabs and allowed the reinforcement to continue after the bamboo's service life, resulting in increased slab strength.

A detailed experiment conducted by Terai and Minami (2011), using Black Bamboo (*Phyllostachys nigra* (Lodd. ex Lindl.) Munro) and Japanese Timber Bamboo (*Phyllostachys bambusoides* Siebold & Zucc.) compared the flexural strength and uniaxial strength of mild steel reinforced concrete to bamboo reinforced concrete. The results demonstrated that bamboo reinforced concrete can effectively replace steel reinforcement in the construction industry, as corroborated by Khan et al. (2025). The same conclusion has been reached by Himasree et al. (2017), who used *Bambusa bambos* (L.) Voss to reinforce wall panels in the form of floor slabs which were then subjected to in-plane loading. The results were excellent, leading them to conclude that steel reinforcement could be replaced with bamboo in wall panels (Himasree et al., 2017).

A critical element in load transfer within buildings is RC beams. To investigate the feasibility of using bamboo in beams, Anto et al. (2023) compared steel-reinforced concrete (RCC) with untreated concrete reinforced with *Dendrocalamus strictus* (Roxb.) Nees (BRC) and found the results to be very impressive as shown in Fig. 3 and 4.

They observed that the ultimate load recorded for RCC was 50 kN with 5.45 mm deflection, while untreated BRC recorded 46 kN with 8.09 mm deflection. Consequently, they concluded that when bamboo strips are properly treated, the resulting BRC beams can achieve comparable or even greater ultimate failure strength, indicating that

bamboo can effectively replace steel reinforcement in beams (Anto et al., 2023).

In a similar experiment, the shear and flexural performance of beams reinforced with *Bambusa bambos* (syn. *Bambusa arundinacea* (Retz.) Willd.) were comparable to that of conventional RCC beams with 1.23% steel reinforcement (Mali and Datta, 2020). The same conclusion was reached by Bhonde et al. (2014) who recorded the average tensile strength of bamboo to be 95.781 MPa, and compressive strength across the culm to be 77–79 MPa, with a shear strength of 99.71 MPa.

In an investigation by Chaowana et al. (2021) into the mechanical and physical properties of 5 bamboo species (*Dendrocalamus asper* (Schult. & Schult.f.) Backer), *Dendrocalamus sericeus* Munro, *Dendrocalamus membranaceus* Munro, *Thyrsostachys oliveri* Gamble and *Phyllostachys makinoi* Hayata), the shear strength parallel to the grain in the bamboos varied from 13 to 50.2 MPa, the tensile strength parallel to the grain varied from 71 to 216 MPa, and the compressive strength parallel to the grain varied from 56 to 132.9 MPa. Their testing set-up is shown in Fig. 5.

Chaowana et al. (2021) concluded that although the bamboo nodes along the culm increase its shear strength, they negatively affect its tensile strength compared to the internodes, a phenomenon confirmed in an experiment by Nie et al. (2021). A review by Prashant et al. (2025) concluded that although bamboo nodes are weak in tension, they help to improve the bond strength between bamboo and concrete.

In an experiment using *Guadua angustifolia* Kunth strips conducted by Omaliko and Uzodimma (2021), the strips had higher compressive strength at the nodes compared to the internodes, as shown in Fig. 6.

Data summarized from a number of different experiments are presented in Table 2.

6.2.1. Bamboo and concrete bonding

One critical property required in a concrete-bamboo composite is strong bonding between the two materials. Amede et al. (2021) found that certain characteristics of bamboo, such as hygroscopic swelling and shrinkage, hinder the formation of a strong bond with concrete. Archila et al. (2018) emphasized the poor bonding characteristic of bamboo, arguing that additional surface treatment was required before using it for reinforcement.

Ogirigbo et al. (2024) determined the bond properties of three reinforced concrete samples. They used finite element modelling in ABAQUS to simulate the failure modes of the samples, which included steel reinforced concrete (SRC), bamboo reinforced concrete (BRC), and hybrid reinforced concrete (HRC). In the finite element simulations, the SRC exhibited the highest bond strength, followed by HRC and then BRC. The authors concluded that further research is required to enhance the bond strength of BRC.

Research has been conducted on ways to process and treat bamboo that would overcome such shortcomings and improve its mechanical properties when used in composite concrete (Ahmad et al., 2017; Varma, 2016). There has been some success with this, and both Mali et al. (2020) and Ashshiddiq et al. (2024) recorded almost the same flexural and shear stresses in experiments comparing treated bamboo-reinforced concrete with steel-reinforced concrete. Neenu (2021) recommended using split bamboo rather than whole culm bamboo in concrete as split bamboo has a rougher surface.

Another critical reason why bamboo reinforcement may not bond well is that, split bamboo reinforcement absorbs water from the concrete mix. When the concrete dries, the bamboo shrinks, creating a gap between the bamboo and concrete mix, as illustrated in Fig. 7 (Javadian et al., 2016).

To prevent this situation, several researchers have investigated the use of various substances to coat the surfaces of the dispersed bamboo phases before casting them into the concrete matrix. However, data on the long-term effects of these substances are not available (Javadian et al., 2016).

Pullout tests are conducted to investigate proper bonding, ensuring

Table 1
Comparison of the strength of bamboo and wood (from Yuan and Feng, 2015).

Types		Tensile strength		Compressive strength	
		Intensity (MPa)	Mean Value (MPa)	Resistant to compression (MPa)	Mean value (MPa)
Bamboo	Moso bamboo	194.8	213.9	64.0	48.8
	<i>Phyllostachys</i>	283.3		54.0	
	Henon bamboo	182.1		35.9	
	<i>Dendrocalamus latiflorus</i>	195.1		41.1	
Wood	Fir	77.2	100.8	40.6	42.9
	Korean pine	98.1		32.8	
	German Oak	143.2		57.7	
	Sassafrass	110.8		46.5	

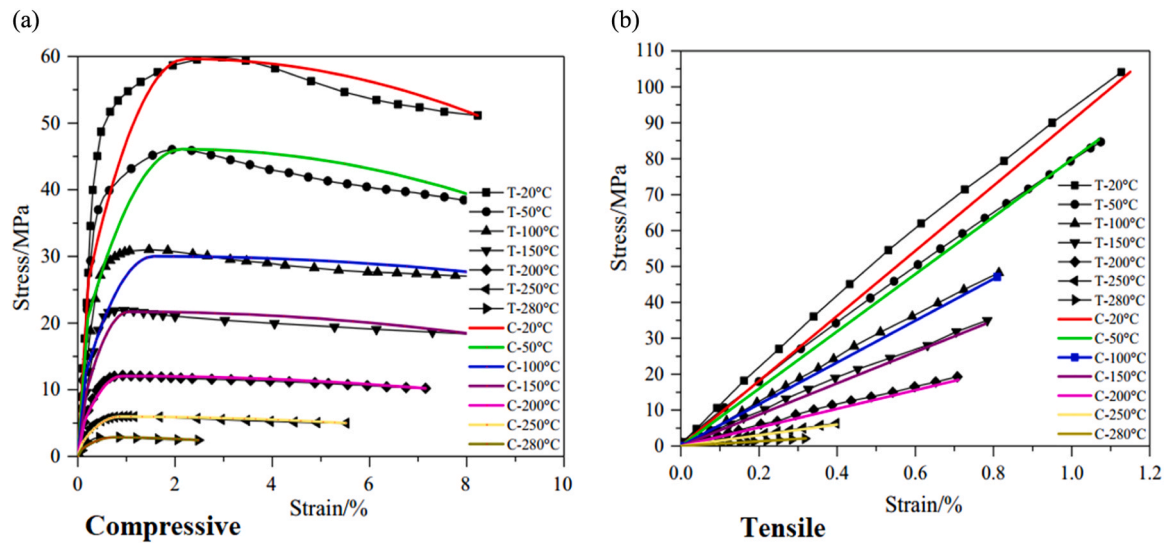


Fig. 2. (a) Compressive and (b) tensile strengths of laminated bamboo exposed to different temperatures (from Xu et al., 2019).

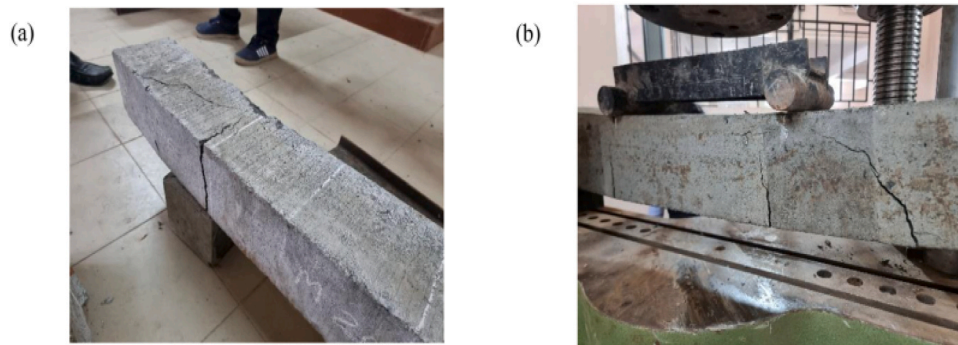


Fig. 3. (a) Crack development in bamboo-reinforced concrete at 14-days. (b) Crack development in bamboo reinforced concrete at 28-days (from Anto et al., 2023).

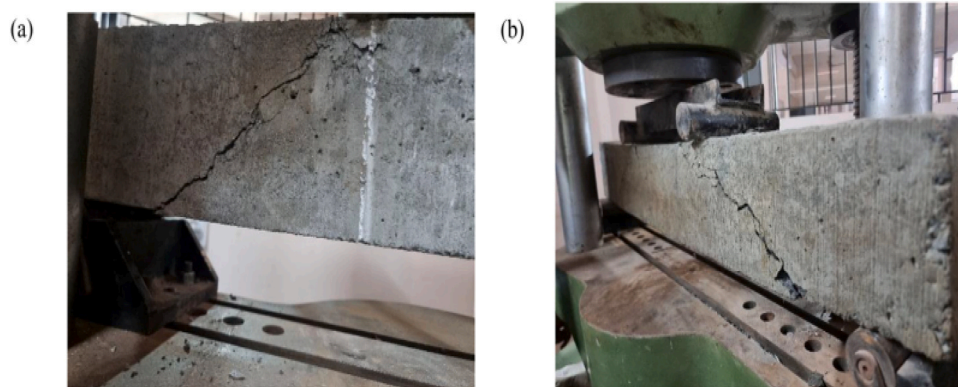


Fig. 4. (a) crack development in mild steel reinforced steel at 14-days. (b) Crack development in mild steel reinforced steel at 28-days (from Anto et al., 2023).

that the load on the member can be safely transmitted from the matrix through the dispersed members to the other structural elements. Several experiments have been carried out to ascertain the best bonding properties, including the use of epoxy-based coatings and sprinkling bitumen with sand (Mohammed et al., 2024; Trujillo, López, 2020), painting with oil, and wrapping binding wire around the bamboo (Javadian et al., 2016). The pullout test (bonding strength) of bamboo concrete reinforcement has been improved with the use of epoxy (Mohammed et al., 2024). Wairagade, Sonar (2019) used oil on split bamboo and wrapped it with binding wire before casting the concrete around it. The pullout

test results showed almost a 200% improvement in bonding compared to the use of plain bamboo in concrete. Alyousef et al. (2020) also compared binding wire wrapped on bamboo strips with corrugated bamboo strips and discovered that the latter improved the bond between bamboo and concrete by 79%. Kumar et al. (2021) concluded in their review that the use of thermoset polymer resin improved the bond strength from 1.34 MPa to 3.42 MPa.

In other materials, Zhang et al. (2025) conducted experiment using bamboo fibres in a high density polyethylene matrix and found that the bamboo fibres bonded very well to the surface, with the product

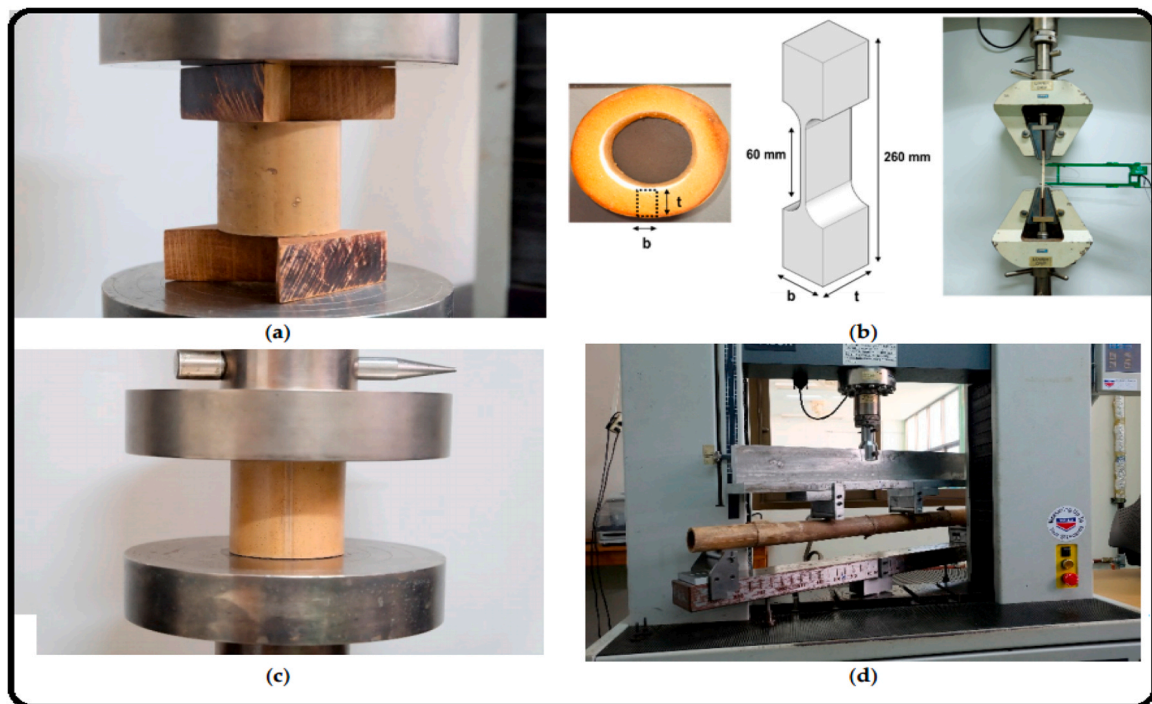


Fig. 5. Testing of bamboo to determine its properties. (a) Shear strength (b) tensile strength (c) compressive strength and (d) bending strength (from Chaowana et al., 2021).

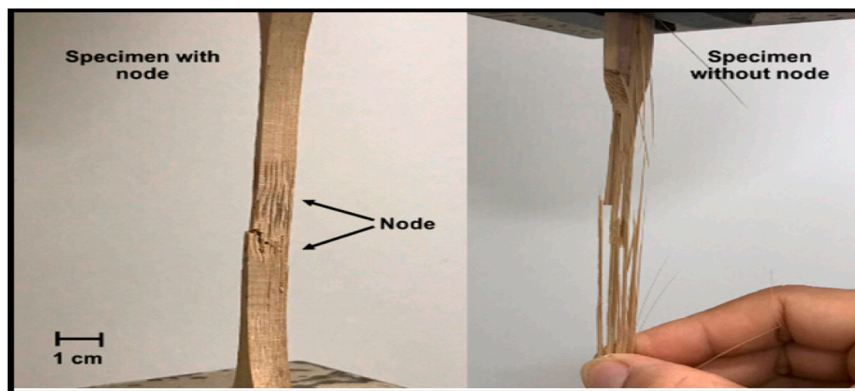


Fig. 6. Fracture of tensile specimens parallel to the grain, with node and without nodes (from Omaliko and Uzodimma, 2021).

Table 2

Summary of bamboo strength analysis in the published literature.

SN	Author	Sample	Ultimate tensile strength (MPa)	Compressive strength (MPa)	Shear strength (MPa)	Flexural strength (MPa)
1	Chaowana, et al. (2021)	Different bamboo species	120–216	56–132.9	13–50.2	
2	Anto et al. (2023)	Bamboo reinforced concrete (untreated)	340			5.01
3	Anto et al. (2023)	Steel reinforced concrete	510			6.31
4	Bhonde et al. (2014)	Raw bamboo	95.78	95.781	99.71	
5	Molari et al. (2020)	Raw bamboo culm	150–230	60–80		
6	Molari et al. (2020)	Bamboo strips	100			
7	Yuan and Feng, (2015)	Raw Bamboo	213	117.5		172
8	Rahim et al. (2020)	Bamboo strips	177.45	44.93		
9	Himasree et al. (2017)	Raw RC wall	120	40		
10	Hebel et al. (2016)	Bamboo strips	135	65		134
11	Wei et al. (2020)	Bamboo Scrimbers	131.9	105.2		
12	Li et al. (2018)	Laminated Bamboo lumber	84.53	68.8		
13	Neenu (2021)	Raw Bamboo	124.1	55.2		

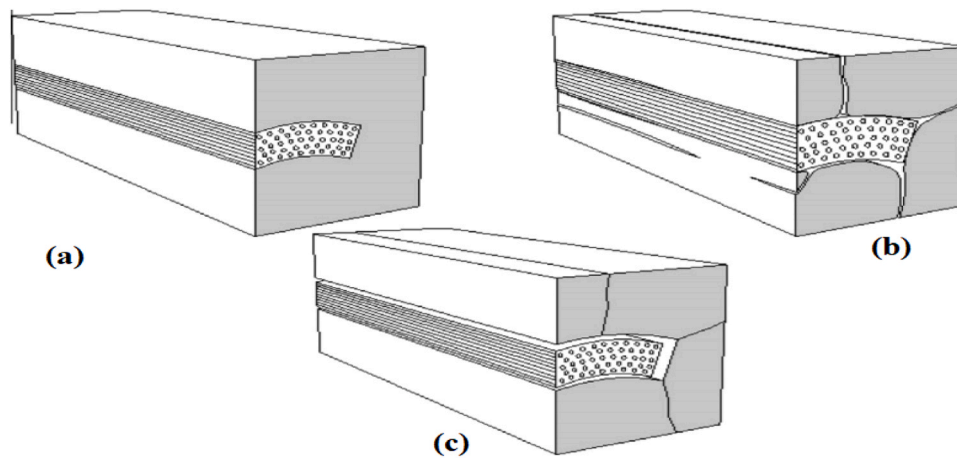


Fig. 7. (a) Bamboo in fresh concrete, (b) swollen bamboo in concrete, (c) shrunken bamboo in dry concrete (from Javadian et al., 2016).

exhibiting superior performance in ductility, strength and energy performance. This confirms that bamboo can not only bond very well with ceramic materials and exhibit good tensile strength, but can also do the same with polymeric materials.

6.2.2. Ductile properties of bamboo

Another property required of bamboo to perform well is its ductility. An experiment conducted by Bhagat et al. (2021), which involved using epoxy to glue bamboo together and subjecting the product to load until fracture, showed that the beams displayed a plastic response post-peak behaviour. They held the peak load during prolonged additional deformations, displaying effective ductility. After removal of the loads, the beam almost returned to its original shape, indicating excellent ductile behavior (Bhagat et al., 2021). This was further confirmed by Arifin et al., (2025) in research comparing bamboo reinforced concrete with mild steel reinforced concrete in a flexural test experiment.

7. Structural bamboo processing technology

Raw bamboo can be engineered to produce structural construction elements with properties equal to or better than conventional construction materials (Mertens, 2019). For instance, research by the Green Pacific Network for Global Change Research has indicated that the tensile strength of bamboo was recorded as 193.05 MPa while that of mild steel was 158.6 MPa (African Pacific Network for Global Change, 2016). Okokpujie et al. (2020) tested bamboo as a structural reinforcement material in concrete. The results showed significant potential for bamboo to replace steel reinforcement in concrete when treated.

Wang et al. (2018) concluded that bamboo has slightly lower thermal resistance properties than normal wood. However, they did not report any influence of thermal resistance on tensile strength. Based on experimental work, Huang and Sun (2021) suggested that bamboo has the potential to be a locally climate-adaptive building material and that it is competitive compared to corresponding timber products.

To ensure the sustainable use of bamboo, two types of treatment have been identified: (a) treatment against insect attack and (b) treatment against fire. The treatments vary from country to country. Whereas some use traditional methods of treatment such as immersion in water, some use mechanical means by pressure impregnation, which is vacuum pressure method used to force preservative into the bamboo. According to de Vries (2002), the technology for bamboo processing and construction is very basic and temporary, including traditional treatments such as soaking in water for about 14 days, preservative treatment using boron, modern copper-based preservative treatment, and bath/soaking.

The Bureau of Indian Standards (2006) has developed treatment procedures and processes using different chemicals for treating bamboo

for structural use, based on the area of application. In all these processes, the nodal diaphragm must be punctured to allow ingress of the chemicals. Subsequently, the culms are air-dried, after which it becomes ready for application (Kaminski et al., 2016b) (Figs. 8a and 8b).

Boric acid treatment is recommended against insect and microbial attack, while borates are recommended as a fire-retardant treatment (Kassa, 2009; Ubidia, 2020). Both treatments are recommended if there is a need for protection against both insects and fire. However, the use of chemicals for treatment must be carefully applied to avoid affecting the health of the user and the environment (Ubidia, 2020).

Although Ng (2022) indicated that alkaline treatment weakens the strength of bamboo, further studies may be required to determine the long-term effects of boron and boric acid treatments on the mechanical properties of bamboo (Sharma and van der Vegte, 2020). This observation has been emphasized in a review paper by Prashant et al. (2025).

On the other hand, bamboo can be technologically processed at an advanced level to produce modern structural members using the process described by Mertens (2019) in Fig. 9 below.

In this process, the bamboo is split into parts after treatment and dried. It is then mixed with resin, compressed, and heat-cured. Finally, it is planed to the desired shape as shown in Fig. 10 (Mertens, 2019). Bamboo scrimbers can equally be used as wooden columns, veneer and other wooden members in the construction industry (Hong et al., 2021; Mertens, 2019).

Li et al. (2018) conducted an experiment to confirm the mechanical properties of laminated bamboo lumber and recorded averages of 84.53 MPa and 68.8 MPa for tensile and compressive strengths, respectively, while Wei et al. (2020) recorded impressive tensile strengths of 131.9 MPa and compressive strengths of 105.2 MPa. Wei et al. (2020) produced and tested novel reinforced bamboo scrimbers. The nature of failure was mainly due to splitting, but the reinforcement could sustain the load after initial failure.

Concrete is good in compression, and bamboo scrimbers are good in tension (Wei et al., 2020). To produce a stronger composite material from these, Wei et al. (2021) produced and experimented with novel bamboo and concrete composites joined with wooden dowels and tested under flexural compression. The bamboo performed very well under tension and failed only due to continuous delamination, while the concrete failed by crushing, as shown in Fig. 11 below.

This form of failure was further confirmed by Li et al. (2020) during an experiment to evaluate the bearing capacity of laminated bamboo under axial loading. This in itself was a confirmation of an earlier experiment to determine mechanical properties of laminated bamboo columns under radial eccentric compression (Li et al., 2016).

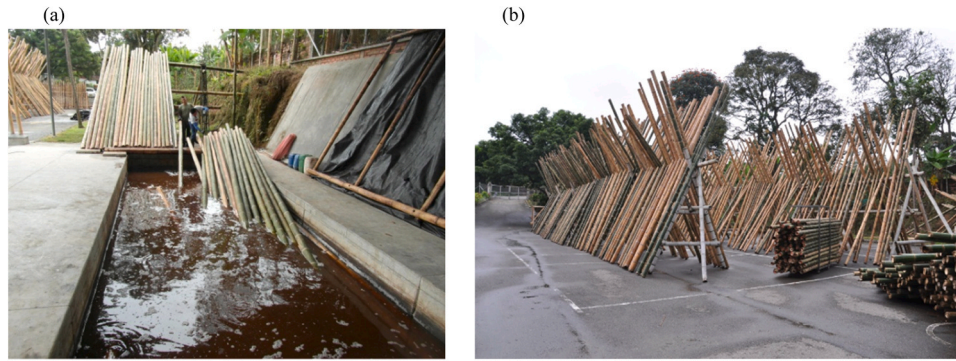


Fig. 8. (a) Bath method for boron treatment of bamboo culms and (b) seasoning of treated bamboo (from Kaminski et al., 2016b).

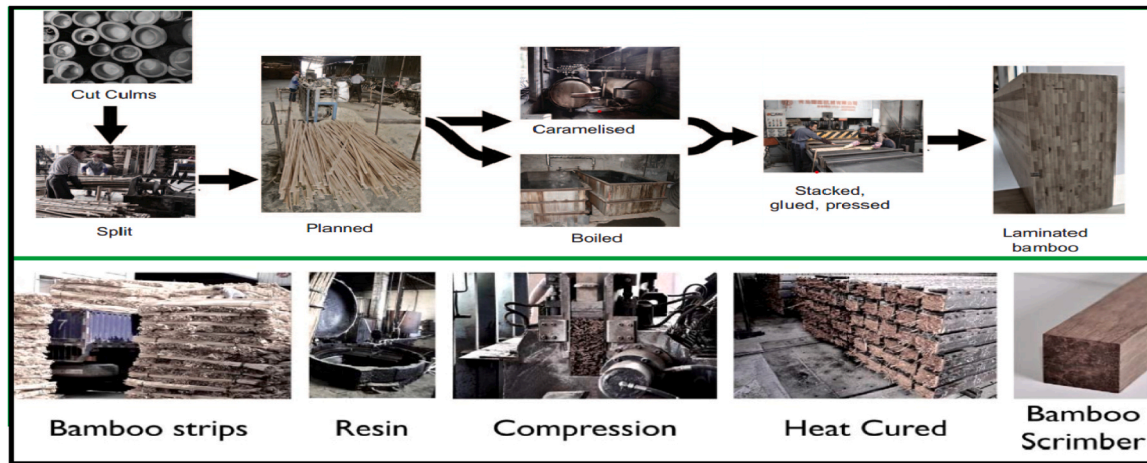


Fig. 9. Processing of laminated bamboo (from Mertens et al., 2019) and bamboo scrimbers production (from Sharma et al., 2015).



Fig. 10. Finished bamboo scrimbers (from Amede et al., 2021).

8. The use of bamboo in the construction industry

Traditionally, the scarcity of traditional wooden members used for props, such as wawa scantling, has resulted in the use of bamboo as props to support formworks (Asmah et al., 2016). However, today, the use of bamboo extends far beyond props (Opoku et al., 2015). Despite the availability of sophisticated bamboo products in developed countries, Opoku et al. (2016) asserted that several factors inhibit the use of bamboo in the construction industry in developing countries. These factors include the absence of specifications by architects in design, inadequate bamboo processing factories and a lack of technological knowledge, among others.

Using bamboo as a construction material reduces the reliance on traditional wood and cement in the construction industry, making it an economical alternative. We also believe that the use of bamboo will significantly reduce the reliance on steel, as bamboo provides viable alternative to steel reinforcement in concrete (Das et al., 2025). This belief is further supported by research conducted by a group of scientists in the years 2010, 2013 and 2014, which showed that the elasticity and tensile strengths of bamboo are nearly equivalent to those of steel (Ranjan and Gupta, 2016).

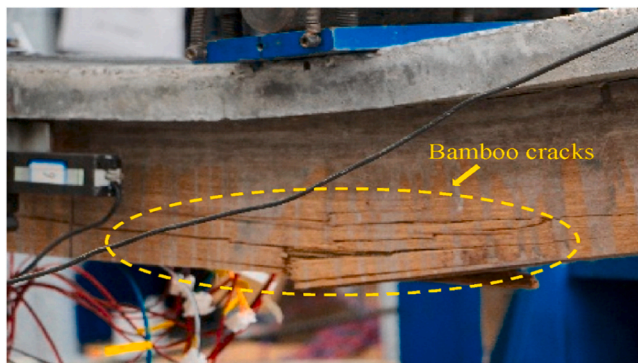


Fig. 11. Failure mode of bamboo scrimbers through tensile fracture (from Wei et al., 2021).

9. Future development

Bamboo construction is recognized for its earthquake resistance, resilience against tremors and potential for seismic retrofitting (Terai and Minami, 2011). Considering the recent earthquake recorded in Thailand with 7.7–7.9 magnitude that claimed thousands of lives within minutes and acknowledging bamboo's environmentally friendly, sustainable and renewable qualities, along with its excellent mechanical properties (Anto et al., 2023; Bhonde et al., 2014; Molari et al., 2020), we believe that as bamboo processing and application technology become more readily available, future developments will not only be dominated by bamboo but also by bamboo-reinforced concretes.

While Chattaraj (2022) proposed that bamboo's fracture properties might not be suitable for heavy structural works, Rahim et al. (2020) conducted experiments to determine the flexural strength of bamboo-reinforced concrete, as well as the compressive strength, pull-out strength and tensile strength of the bamboo. The results were impressive, leading to the conclusion that bamboo can effectively replace steel reinforcement in concrete based on the properties exhibited in the experiment. This was further supported by Bijapure and Patil (2020) who emphasized that the tensile strength of bamboo fibres surpasses that of steel, and again, this is further confirmed in several review papers (Das et al., 2025; Gowri et al., 2015). However, the use of bamboo in this capacity will be enhanced if it is treated (Gowri et al., 2015).

10. Discussion

Our review of bamboo as a construction material highlights its remarkable potential as a sustainable, eco-friendly alternative to conventional materials such as steel and timber. Here, we integrate the evidence presented in previous sections and critically evaluate the implications for future adoption of bamboo products in the construction industry.

10.1. Bamboo as a sustainable construction material

Bamboo's rapid growth rate, renewability and ability to sequester carbon make it an environmentally attractive material. Unlike traditional woody plants, which can take decades to mature, bamboo reaches harvestable size within three to four years, enabling sustainable cultivation without contributing to deforestation (Sharma et al., 2015; Tekpetey, 2011). Its versatility, spanning from structural applications to everyday products, underscores its socio-economic importance, particularly in providing employment opportunities and supporting local economies in both rural and urban contexts (Kenyan National Bamboo Policy, 2019). The environmental and economic benefits of bamboo complement its practical utility in construction, indicating that its adoption can align with global sustainability goals.

10.2. Mechanical properties and structural performance

Extensive research indicates that bamboo exhibits excellent mechanical properties, including high tensile and compressive strength, which in many cases rival those of steel and surpass those of conventional timber (Yuan and Feng, 2015; Wei et al., 2020). Experiments on bamboo-reinforced concrete (BRC) beams and wall panels have demonstrated load-bearing capacities comparable to steel-reinforced concrete (Anto et al., 2023; Himasree et al., 2017; Mali and Datta, 2020). These findings suggest that, with appropriate treatment and processing, bamboo can be utilized effectively in structural applications, including beams, slabs, and columns, supporting its potential to reduce reliance on steel reinforcement.

The variability in mechanical properties due to species, age and culm section (inner vs. outer) underscores the importance of careful selection and standardization of bamboo materials for structural purposes (Ahmad et al., 2017; Li et al., 2021). While the nodes increase shear strength, they may reduce tensile performance, highlighting the need for targeted treatment or selection strategies when designing bamboo-based structural elements (Chaowana et al., 2021; Nie et al., 2021).

10.3. Bonding with concrete

A critical factor in bamboo-reinforced concrete is the bonding between bamboo and the concrete matrix. Untreated bamboo absorbs water from fresh concrete, swells and subsequently shrinks during curing, leading to voids and reduced bond strength (Javadian et al., 2016; Amede et al., 2021). Experimental studies indicate that treatment methods, such as vacuum-pressure impregnation, resin coating, epoxy wrapping or sand-bitumen coatings, significantly improve bonding and overall structural performance (Mohammed et al., 2024; Neenu, 2021; Alyousef et al., 2020). Such treatments mitigate the inherent hygroscopic nature of bamboo and enhance its applicability in reinforced concrete applications, suggesting that technological interventions are critical for successful adoption.

10.4. Technological advances and standardization

Modern bamboo processing techniques, such as laminated bamboo lumber and bamboo scrimbers, demonstrate that bamboo can achieve mechanical performance comparable to or exceeding that of traditional timber and, in some cases, mild steel (Mertens, 2019; Wei et al., 2020). However, widespread adoption is hindered by high capital costs, lack of technological readiness in many developing countries, and the absence of international standards for structural design and testing (Amede et al., 2021; Bonsi, 2009). Establishing codified standards and low-cost local processing technologies could accelerate global acceptance of bamboo as a mainstream construction material.

10.5. Ductility and earthquake performance

The ductile behavior of bamboo, particularly when treated and engineered appropriately, allows it to perform effectively under dynamic and seismic loading conditions (Bhagat et al., 2021; Arifin et al., 2025). Its high strength-to-weight ratio, combined with flexibility, makes bamboo a promising material for earthquake-resistant construction. These properties, along with its environmental sustainability, support bamboo's role in both temporary and permanent construction, particularly in regions prone to seismic activity.

10.6. Challenges and future prospects

Despite the clear advantages, challenges remain in the large-scale adoption of bamboo. These include variability in species and properties, susceptibility to moisture and pests, the need for effective treatment and the high initial investment for advanced processing equipment.

Nonetheless, the growing body of experimental research on treated bamboo-reinforced concrete, laminated bamboo products and composite systems demonstrates that these challenges are surmountable. Future development will likely focus on improving treatment methods, establishing standardized testing and design codes, and integrating bamboo with modern construction technologies (Das et al., 2025; Gowri et al., 2015).

Bamboo's potential in reducing steel usage in reinforced concrete aligns with the global need to minimize the environmental footprint of construction. With proper technological interventions, training, and policy support, bamboo can transition from a niche material to a mainstream, sustainable construction alternative.

11. Conclusion and recommendations

In conclusion, bamboo possesses significant potential as a sustainable, high-performance construction material. Its mechanical strength, ductility and renewability, combined with appropriate treatment and processing, make it a viable alternative to traditional timber and steel. Bamboo, when treated appropriately, can be viable and sustainable replacement for steel reinforcement in concrete. Challenges such as standardization, treatment and technological readiness need to be addressed through research, policy and industry initiatives. The convergence of these factors points toward a promising future for bamboo in sustainable and resilient construction.

Three main types of product have been examined: Raw bamboo culms (both treated and untreated), reinforced bamboo concrete and engineered bamboo products (such as scrimbers and laminated bamboo). All these products can serve as convenient alternatives to conventional construction materials currently in use, provided appropriate treatments are applied. Further research is needed on the long-term effects of chemically treated bamboo before its mass production and use. This should be accompanied by technological transfer to end-users and hands-on training to ensure efficient utilization, offering a sustainable alternative to conventional wood, mild steel and other materials used in the construction industry.

CRedit authorship contribution statement

Wonder Salami Davor: Writing – original draft. **Benjamin Agyei-Tuffour:** Writing – review & editing, Supervision. **Lucas Nana Wiredu Damoah:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors of this publication have no known interests whatsoever, whether financial or personal, that could influence the work published in *Advances in Bamboo Science Journal*.

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Data availability

Data used have been properly referenced

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