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A Sustainable Solution for Track Construction

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Review

The Application of Bamboo in the Railway Industry: A Sustainable Solution for Track Construction

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Abstract: The railway industry has shown a strong interest in utilizing sustainable materials, including recycled materials and composites, in construction. Bamboo, as a highly renewable natural resource, has been proposed as a construction material for the railway industry. This material offers several advantages, such as high strength and durability, sustainability, low embodied energy, and ease of handling. It has been used in various construction materials like plywood, scrimber, laminates, and fibers. This paper aims to review the application of bamboo as a material in the railway industry and provide suggestions for its future use as railway sleepers. The mechanical properties of bamboo and its desirable features for sleeper construction, such as versatility, durability, low embodied energy and carbon footprint, lightweight, and ease of handling, are discussed. Bamboo-based products like plywood and scrimber can offer higher mechanical properties compared to traditional timber sleepers. Moreover, due to its rapid growth rate, bamboo is considered an environmentally friendly material. However, there are certain factors that limit the widespread deployment of bamboo in the railway industry. For instance, the lightweight nature of bamboo can reduce the lateral resistance of sleepers. Additionally, long-term performance studies and its performance in regions with varying weather conditions need to be further investigated. This review paper aims to promote the increased utilization of bamboo in the railway industry, contributing to the development of sustainable railway tracks. By considering the mechanical properties and advantageous characteristics of bamboo, it is possible to explore its potential as a viable and eco-friendly material for railway sleepers.

Keywords: bamboo; railway; bamboo railway sleepers; sustainable construction material; low embodied energy

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1. Introduction

Recently, the demand for composite materials as an alternative to existing timber sleepers has risen due to the increasing resource requirements in today's modern industrialized world [1]. However, the availability and quality of wood resources from forests have declined, necessitating the exploration of alternative construction materials to replace traditional wood utilization [2]. Consequently, there is growing interest in identifying promising alternatives to wood as a raw material [3]. In parallel, bamboo is being cultivated as a plantation crop in addition to its natural occurrence in various countries like China and India [4]. This cultivation provides significant benefits to local farmers, as they can process bamboo into diverse products, improving their livelihoods [5]. The large production of bamboo, for instance, in China, which produces approximately 10,000 types of bamboo products, can provide a long-term resource for railway sleeper manufacturing [6]. However, the bamboo culm does not meet the mechanical properties needed for railway sleeper manufacturing, but by developing recent technologies to produce bamboo products, this material is suggested for employment in the railway industry [7]. Those features of bamboo suitable for railway sleepers are listed and discussed in the following sections.

1.1. Versatility and Durability

Bamboo exhibits remarkable versatility and durability, making it an attractive material for various applications [8]. Bamboo can be utilized in construction for a wide range of applications, including structural elements, flooring, walls, roofs, and even entire buildings [9]. It can be used as a primary material or in composite forms with other substances [10,11]. Its natural beauty and flexibility allow for diverse design possibilities [12]. Bamboo fibers are used for producing paper and textiles [13]. Bamboo can also be utilized as a biomass fuel source, providing renewable energy in the form of heat and electricity [14]. Bamboo has an impressive strength-to-weight ratio, making it comparable to steel in terms of tensile strength [15]. It can withstand heavy loads and has excellent structural integrity [16]. Bamboo possesses inherent flexibility, allowing it to withstand bending and vibrations without breaking [17]. This flexibility helps it resist damage from wind, earthquakes, or other external forces [18]. Bamboo has natural resistance to water, making it less prone to rot or decay [19]. Additionally, it contains natural silica, which acts as a deterrent to pests such as insects and fungi [20]. When properly treated and maintained, bamboo products can have a long lifespan [21]. With appropriate preservation techniques, bamboo can withstand outdoor conditions and retain its durability for many years [22]. The versatility and durability of bamboo products are two of the features needed for railway sleeper manufacturing.

1.2. Low Embodied Energy and Carbon Footprint

With appropriate preservation techniques, bamboo can withstand outdoor conditions and retain its durability for many years [23]. Bamboo is considered an environmentally friendly material due to its rapid growth rate, high yield per acre, and minimal need for pesticides or fertilizers [24]. It is a renewable resource that can be harvested without causing deforestation, as bamboo plants rapidly regenerate from their root systems [25]. However, bamboo cultivation practices such as irrigation, fertilization, and respiration during the planting stage contribute to CO_2 emissions (Figure 1a). The production phase is the largest contributor to CO_2 emissions, accounting for approximately 83% of carbon emissions (Figure 1b), which at its maximum is 1070 kg CO_2 emissions, which is higher than concrete sleeper production with 420.26 kg CO_2 emissions [26]. This is mainly due to the involvement of numerous complex processes that require high-power machinery (e.g., sanding machines, hot plate presses, and vacuum bumpers) and materials (e.g., antimold preservatives and adhesives). CO_2 emissions during the transport phase primarily range between 100 and 200 kg and are significantly influenced by the distance of transportation (Figure 1c). These bamboo CO_2 emissions are much lower than those of concrete sleepers because of the lower weight and size of bamboo products. The construction phase generates a lower amount of CO_2 compared to the production and transport phases (Figure 1d). The emitted amount is significantly smaller compared to the CO_2 uptake through manufacturing raw materials for concrete sleepers, which is about 306.4 kg [26].

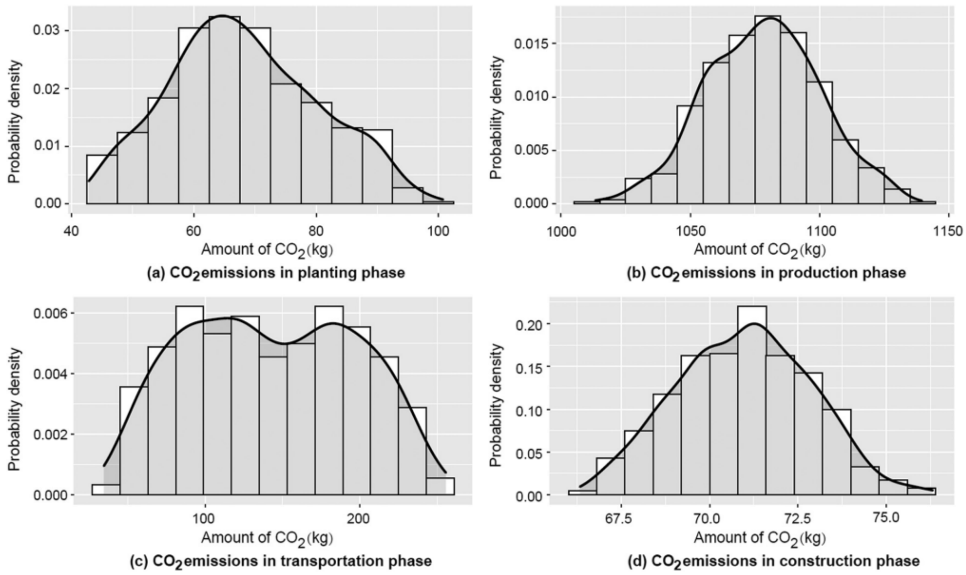


Figure 1. Bamboo CO_2 emissions by phases in (**a**) planting phase, (**b**) production phase, (**c**) transportation phase, and (**d**) construction phase [27].

1.3. Lightweight and Easy to Handle

Bamboo possesses inherent characteristics and physical properties that make it lightweight and easy to handle [28]. Its unique hollow structure, consisting of interconnected chambers called "internodes" [29], separated by solid segments called "nodes," significantly reduces its weight while maintaining strength [30]. This distinguishes bamboo as a much lighter material compared to others [31]. Additionally, bamboo has a low density relative to traditional building materials like wood, metal, or concrete, further contributing to its lightweight nature [32]. Despite its lightness, bamboo exhibits an impressive strength-to-weight ratio, enabling it to support heavy loads [33]. Bamboo can also be readily cut, drilled, or modified using standard tools, enhancing its convenience in various projects or installing fastening systems in railway tracks [34]. The lightweight nature of bamboo additionally contributes to its portability and ease of transportation [35]. It can be carried or loaded onto vehicles without the need for heavy machinery or specialized equipment [36]. This makes bamboo a practical choice for projects requiring mobility and efficient logistics, such as railway track construction.

1.4. Bamboo Life Cycle Assessment

Life cycle assessment (LCA) is a method used to assess the environmental impacts associated with all stages of a product or process, starting from raw material extraction to its end-of-life [37]. Numerous researchers have conducted LCA studies on bamboo products, examining their entire life cycle [38,39]. When comparing the CO_2 emissions of bamboo products, timber is often chosen as a reference point [40]. During the growth phase of bamboo, carbon is absorbed through photosynthesis as the culms mature [38]. Fertilizers may be used to enhance biomass yield. The amount of CO_2 stored in the aboveground bamboo biomass is calculated by multiplying the mass of the aboveground bamboo, the carbon content, and the molecular weight ratio between CO_2 and carbon [41]. Harvested bamboo culms are transported to nearby processing facilities, where they undergo drying and cutting processes. They may also be further processed into composite materials using adhesives [42]. Air drying is the most common method, requiring minimal energy consumption, which is often overlooked in LCA assessments. However, the production of glued laminated composites involves energy-intensive drying and carbonization steaming treatments, in contrast to air drying [43]. In the disposal stage of bamboo products, three common scenarios are considered: landfill, incineration, and recycling [44]. In landfill scenarios, post-consumer waste is transported to landfills located at distances ranging from 20 to 60 km [45]. Incineration scenarios involve burning waste bamboo products, generating approximately 19 MJ of heat per kilogram, which can be recovered and used as a heat source, displacing the need for heat from other sources [42].

1.5. Limitations

Despite the presence of over 1200 bamboo species worldwide, the variations in geometric and mechanical properties of bamboo culms [46] show limitations to producing railway sleepers with sensitivity in material quality use [47]. Additionally, making connections and joints for round sections can be challenging, rendering the use of tubes impractical in certain applications; therefore, more treatment processes are needed for the application of bamboo [48]. Furthermore, some bamboo culms exhibit several other limitations, including small diameter, longitudinal variations in diameter, thin and hollow walls, and a susceptibility to corrosion and cracking [49]. Therefore, high conservation in choosing bamboo for construction applications is needed. As a result, bamboo has primarily been utilized in applications with low technological complexity and limited added value [50] until bamboo treatment and fabrication technologies have been developed [51]. Furthermore, bamboo standards are outdated, with the most recent publications occurring more than 10 years ago, lacking updates to incorporate new technologies in bamboo product manufacturing, for instance, JG/T 428 [52] for composite ply bamboo forms with steel frames, GB/T 30762 [53] for quality grading standards of main bamboo shoots, JG/T 199 [54] for testing methods of physical and mechanical properties of bamboo used in building, GB/T 2690 [55] for bamboo timber, and GB/T 15780 [56] for testing methods of physical and mechanical properties of bamboo [57].

1.6. Current Number of Research about Bamboo

More than 1000 authors have written about bamboo applications in structures in more than 4119 papers (Figure 2). These authors co-authorship is divided into 82 clusters, which shows authors on this topic have contributed to a lot of joint projects. When it comes to categorization based on countries, we can see that more than 104 countries have contributed to bamboo publications (Figure 3). China has the highest co-authorship with other countries of any of these countries. These countries co-authorship is divided into 21 clusters. Figure 4 illustrates the trend of publications related to the application of bamboo in structures from 2000 to 2022. The graph demonstrates a steady and gradual increase in the number of publications over the course of 22 years. This upward trend indicates the growing popularity and interest among researchers in exploring and utilizing bamboo for structural applications. The most frequently mentioned keywords are species, forest, carbon, area, diversity, building, specimen, tensile strength, synthesis, and adsorption. More than 1710 publications about the application of bamboo in construction are published by Elsevier, 342 by MDPI, 649 by Springer Nature, 331 by Wiley, 193 by Taylor & Francis, and other publishers. The most publications in bamboo belong to the International Center for Bamboo and Rattan, with more than 353 publications, followed by Nanjing Forestry University, the Chinese Academy of Sciences, the Chinese Academy of Forestry, etc.

1.7. Paper Outline

Here, in this section, a flowchart is presented to show the paper approach for a better understanding of how bamboo can be employed as a railway sleeper (Figure 5). Four steps are designed to provide enough information about new types of bamboo products suitable for sleeper construction. In the first step, the main target is to show that bamboo materials are gaining importance as an alternative to timber and other materials due to several compelling reasons. Afterwards, it is explained that, first, bamboo is an incredibly sustainable resource. It is one of the fastest-growing plants on Earth, with some species maturing in just a few years. In contrast, trees used for timber can take decades, or even centuries, to reach maturity. This rapid growth rate makes bamboo a highly renewable and eco-friendly option for construction and manufacturing. In comparison with other materials such as concrete and steel, bamboo possesses impressive strength and durability, making it a viable alternative to traditional materials like concrete or timber for railway sleepers. Bamboo has excellent load-bearing capacity and can withstand heavy weights and constant stress, making it suitable for the high pressure exerted by trains and maintaining track stability. Then, in the third section, bamboo products are introduced with related features. In the fourth section, the current application of bamboo is reviewed and limitations, numerical modeling, and some suggestions are presented. Finally, future prospects and studies needed for more employment of bamboo in the railway industry are discussed.

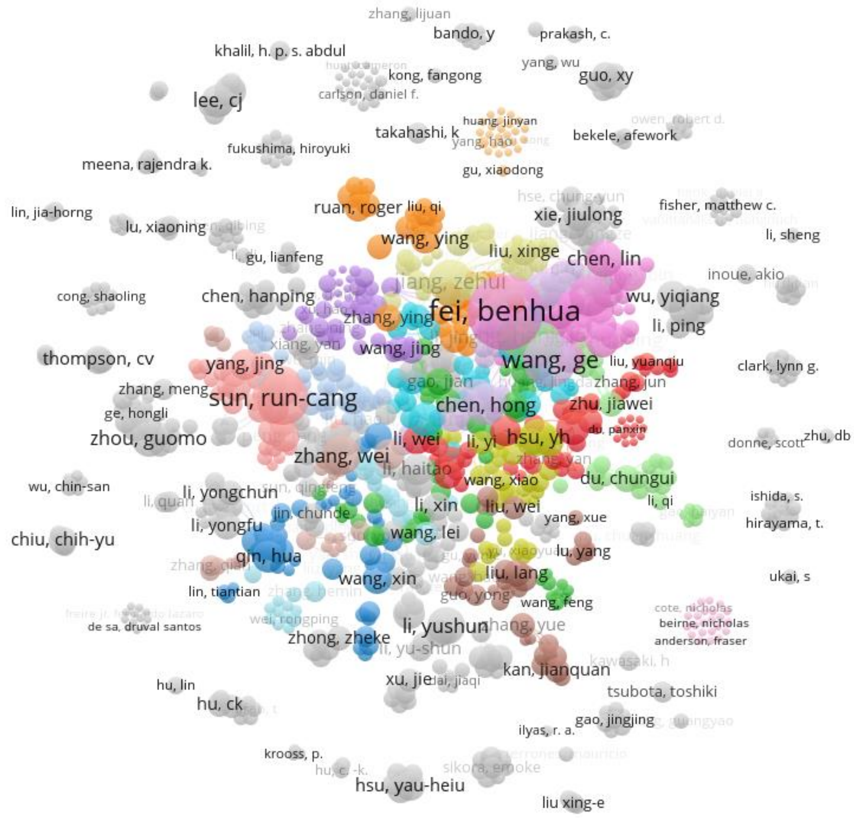
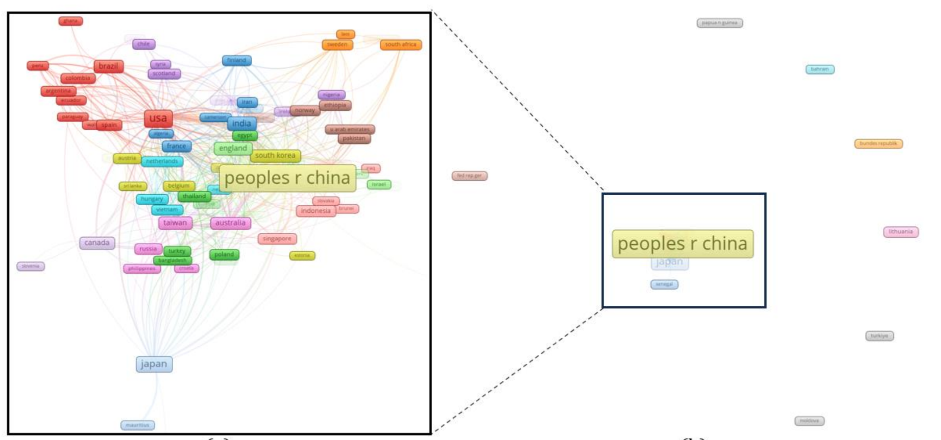


Figure 2. Bibliometric analysis of 1000 researchers worked on bamboo application in structures extracted from VOSviewer from a Web of Science data source.



(a) (b)

Figure 3. Bibliometric analysis of 104 countries worked on the application of bamboo in structures extracted from VOSviewer from a Web of Science data source; (**a**) group of countries with joint collaboration, and (**b**) the connection between countries with joint colaboration.

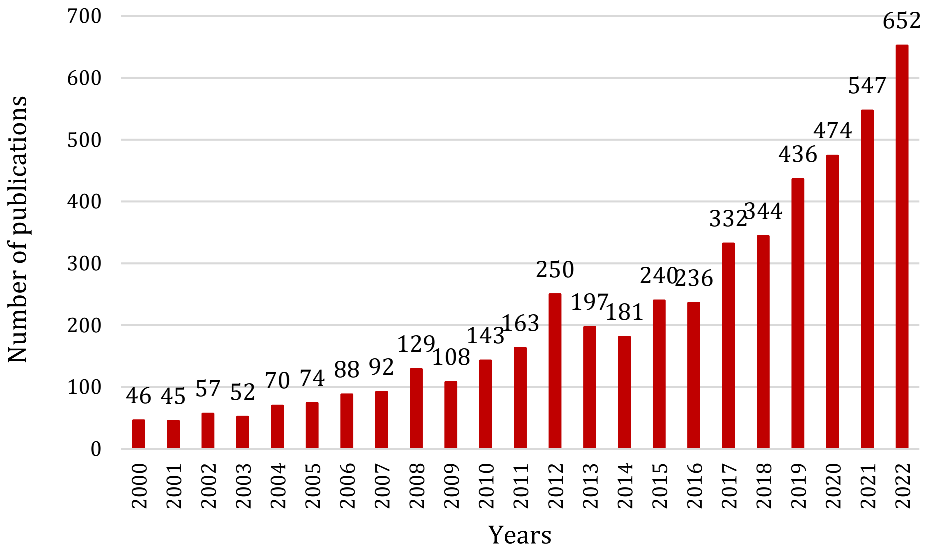


Figure 4. Number of publications about the application of bamboo in structures over 22 years.

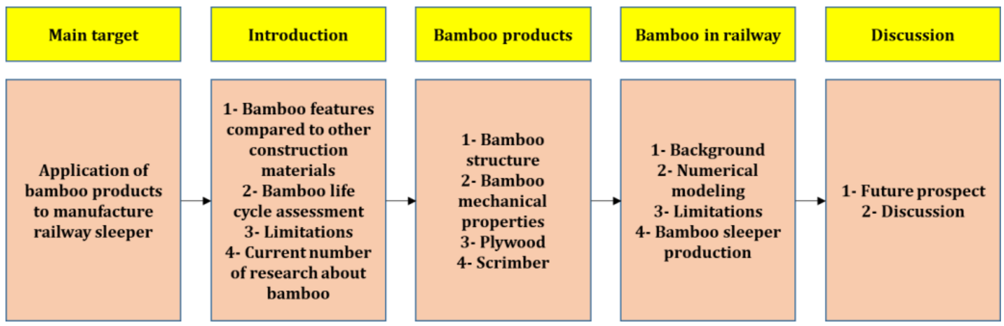


Figure 5. Paper outline, including each step to review the potential of bamboo products for railway sleeper deployment.

2. Bamboo Construction Material Fabrication

Bamboo culm has been treated before application as construction materials such as scrimber [58], plywood [59], panels [60], lumber [61], and laminated [33]. Bamboo products can compete with other railway sleeper materials such as concrete, wood, and steel because they have high strength and stiffness compared to their weight [62]. As shown in Figure 6, stiffness and strength divided by mass per volume of four common construction materials, such as concrete, steel, wood, and bamboo, are compared. Bamboo shows higher performance compared to concrete and wood in terms of stiffness/mass per volume and higher strength than concrete, steel, and wood in terms of strength/mass per volume. In the following sections, more specifications are presented about bamboo products.

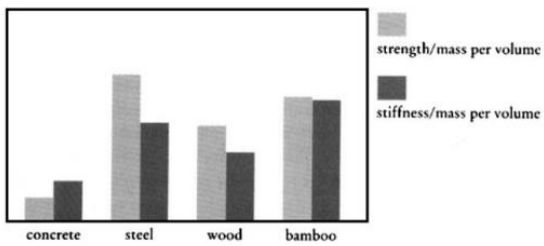


Figure 6. Stiffness and strength/mass per volume of various materials used for railway sleeper manufacturing [63].

2.1. Bamboo Structure

Bamboo exhibits a hollow internal structure with tube-like sections between the nodes, where longitudinal fibers are aligned within a matrix of lignin (see Figure 7a) [64,65]. The thickness of the culm wall gradually decreases from the base to the top of the bamboo culm [66]. The slender bamboo fibers, which are long, tapered at both ends, and sometimes forked, also vary in density within the culm wall, with a decrease in density from the outer wall to the inner wall [67]. A cross-section micrograph of bamboo is presented in Figure 7b. Based on the distribution density of longitudinal vascular bundles and corresponding chemical components, bamboo can be divided into four components: the outer layer, the fresh layer, the inner layer, and the nodal area (Figure 7c,d). The size of the vascular bundles gradually increases from the outer layer to the fresh layer, reaching its maximum size in the inner layer [68]. Consequently, the mechanical strength of bamboo gradually decreases from the outer to the inner regions [69]. The high density and hardness of the outer layer make it difficult to compress, while the softness of the inner layer makes it prone to stretching and cracking [70].

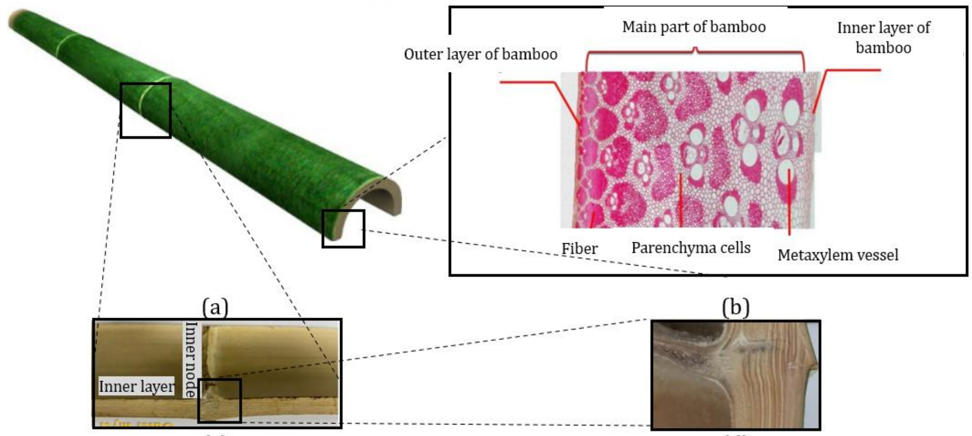


Figure 7. Bamboo structure: (**a**) culm, (**b**) microstructure, (**c**) node, and (**d**) node structure [71,72].

2.2. Bamboo Mechanical Properties

Raw bamboo has significantly lower mechanical properties than treated bamboo products. Table 1 shows that each bamboo product has mechanical properties suitable for being used in construction. However, a wide range of differences in the mechanical properties of bamboo can be seen in this table. It can be a disadvantage to employ bamboo as a construction material for railway sleepers. Among all listed bamboo products, bamboo scrimber shows the highest mechanical properties, higher than wood.

Table 1. Mechanical properties of different bamboo products [73–80].

Material	Compressive Strength	Tensile Strength	Elasticity Modulus	Rupture Modulus	Density	Water Absorption
Unit		MPa			g/cm^3	(%)
Bamboo (treated)	31.47–34.03	90–145	9.37–14.27	130–205	1–1.22	6–19
Bamboo (untreated)	18.96–22.28	40–83	-	-	1–1.3	12–26
Bamboo scrimber	70.5–199.3	227.6–364.8	13.5–32.3	178.5–398	0.72–1.3	-
Bamboo plywood	57.7–86	3.2–205	8.8–15.37	-	0.66–1.12	-
Bamboo bar	55	120–370	10–17	-	-	-

2.3. Bamboo Plywood

The development of the bamboo plywood production process stemmed from the need for a simple bamboo processing technology that could enhance the performance of bamboo products without altering their original thickness and width [81]. This process aimed to reduce costs and increase the added value of bamboo products [82]. Various methods have been proposed for bamboo plywood production, including the technique known as "bamboo fattening" [83]. This method involves constructing fattened bamboo boards to create strong and highly rigid bamboo plywood [84]. Examples of this type of plywood include curtain-ply, woven compressed wood, crisscross mat, bamboo curtain sheet, and compressed wood, among others [85]. Producing plywood from bamboo enhances its qualities, such as moisture-proofing, water resistance, corrosion resistance, and resistance to salt damage [86]. Bamboo plywood becomes significantly harder and stronger than standard wood, exhibiting a tensile strength that is 1.5 to 2 times greater than that of wood [87]. Another method for producing bamboo plywood is through bamboo lamination (Figure 8) [74]. In this process, bamboo culms are split into splits using a sizing and splitting machine [88]. These splits are then refined into strips, which are subsequently bonded together using resin to create a laminate [89]. These laminates can be further bonded together to produce bamboo plywood [90]. Hot pressing and the application of pressure are commonly employed to treat the laminates and ensure their cohesion [91].

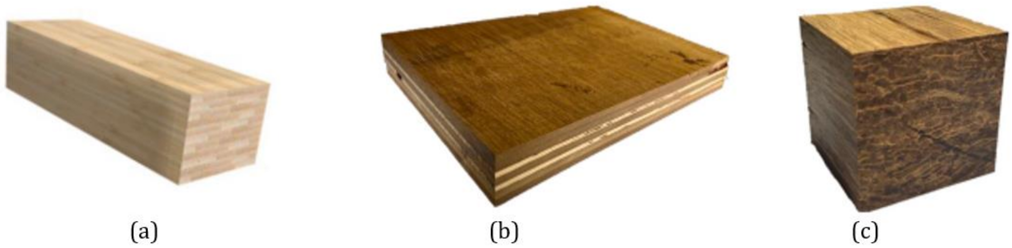


Figure 8. An overview of bamboo plywood with different laminate layers (**a**) laminated bamboo, (**b**) laminated flattened bamboo, (**c**) Bamboo scrimber [78].

2.4. Bamboo Scrimber Fabrication

In response to the growing industry and demand for sustainable construction products, bamboo is being utilized to create engineered bamboo composites, which aim to standardize the shape and reduce material property variations [92]. One specific type of engineered bamboo composite is bamboo scrimber, which involves crushed bundles of bamboo fibers saturated in resin and compacted into a dense block [93]. This rectangular structural element possesses exceptional qualities, including a high bamboo utilization ratio (over 80%), an appealing grain pattern, and similar hardness and color to that of hardwood [94]. These characteristics make bamboo scrimber a competitive option among commonly used construction materials [95]. The production process of bamboo scrimber typically involves several steps, as illustrated in Figure 9. These steps include truncation and splitting of bamboo, softening, removal of the bamboo's outer skin, drying, sizing, assembly, and hot-pressing [72]. However, with advancements in technology, certain steps have been omitted in the large-scale production of bamboo scrimber [96]. The main processes involved now include truncation and splitting, defibering, drying, dipping, assembly, cold-pressing, and heat curing or hot-pressing [97].

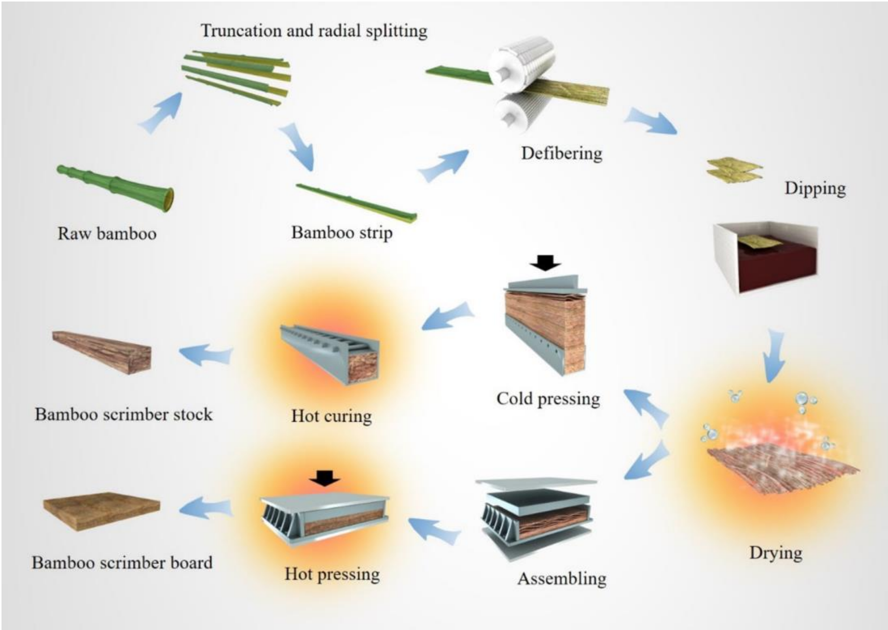


Figure 9. Process of bamboo scrimber production line [72].

3. Application of Bamboo in the Railway Industry

3.1. Background

Bamboo has been increasingly applied in various aspects of the railway industry, showcasing its versatility and potential benefits. For instance, Erlangga et al. [98] used bamboo nets to improve soil density, offering an environmentally friendly alternative for soil enhancement (Figure 10a). The bamboo nets, measuring 10 cm in diameter and 5 m in length, achieved a density degree of 96.5% based on sand cone density tests. Xiao et al. [77] developed a composite railway sleeper using a combination of wood and bamboo (Figure 10b). Through their study, they found that by using a resin content of 15.5%, targeting a density of 0.8 g/cm^3, applying a hot-pressing time of 0.65 min/mm, and setting a hot-pressing temperature of 170 °C, an optimal modulus of rupture value of 70.08 MPa was achieved. Sasmayaputra et al. [99] explored the use of bamboo mats as temporary reinforced soil retaining walls in railway beds. Bamboo mats were investigated as an alternative to geosynthetics for temporary mechanically stabilized earth (MSE) walls. These mats proved cost-effective and biodegradable, offering advantages for temporary MSE walls. Numerical simulations showed that the bamboo mat MSE walls were safe against internal and external collapses, with the lowest safety factor recorded at 1.53, primarily due to the potential of global slope stability leading to collapse. Wang et al. [76] conducted a theoretical evaluation to determine optimal material combinations for a newly developed composite railway sleeper. The composite material consisted of polyvinyl chloride, chalk, and bamboo fiber.

In their research, Han et al. [71] investigated the use of a bamboo laminate composite for railroad car flooring. The study findings revealed that this laminated composite exhibited a low density of 0.73 g/cm^3, resulting in a specific modulus of 13.03 GPa cm^3/g. Moreover, it demonstrated a vibration damping ratio of 6.61% and an impact toughness of 14.16 J/cm^2. These characteristics were significantly superior to those of other wood-based composites, such as Birch plywood (BP), which is commonly used for high-speed rail floors (Figure 10c). In a separate study, Xue et al. [60] developed laminated bamboo–wood composite lumber for railway applications. This composite lumber consists of two thin curtain boards with a thickness of 3–4 mm as the surface material, along with three layers of wood boards with a thickness of 10–15 mm forming the interior structure. This composite lumber offers several advantages over solid bamboo boards, including increased strength, improved resistance to abrasion, lower density, better nail holding capacity, and cost-effectiveness. Currently, the product is undergoing testing on railway flat wagons.

Liu et al. [100] proposed a novel type of thin-walled circular tubes (CTs) inspired by the energy absorption capabilities of bamboo. The intention behind these bamboo-inspired bionic tubes (BT) was to use them as energy absorbers in rail vehicles (Figure 10d). The research results indicated that the BT specimens exhibited significantly enhanced energy absorption (EA) compared to the CT specimens. In experimental tests, the BT specimens showed an increase of 93.1% in EA, while simulated tests demonstrated an increase of 101.8% in EA. Additionally, the mean load values rose from 74.2 kN and 68.3 kN to 143.4 kN and 137.9 kN for the BT specimens, respectively, indicating a substantial improvement in crashworthiness (Figure 10e).

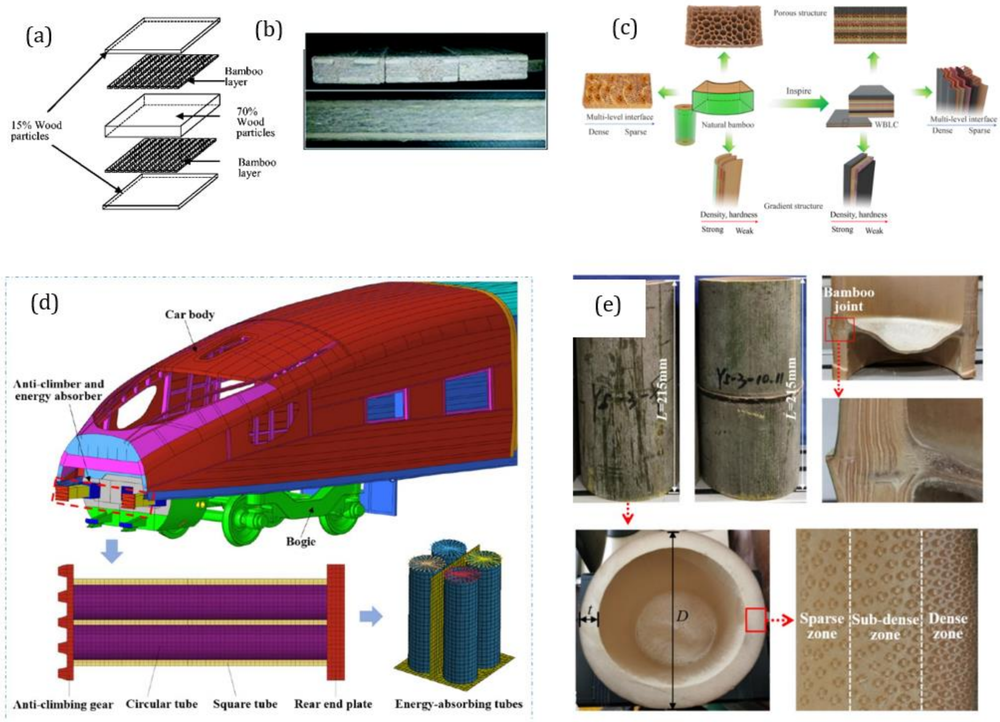


Figure 10. (**a**) Preparation and (**b**) cross-section of a real composite sleeper, (**c**) process to produce a bamboo laminate composite for the flooring of railroad cars, (**d**) application of energy-absorbing CTs in rail vehicles, and (**e**) bamboo samples and the detailed structures [71,77,98,100].

3.2. Numerical Modeling

Bamboo is composed of vascular bundles and ground tissues, both of which contribute to its mechanical properties, similar to unidirectional composites [101]. However, a notable distinction between wood and bamboo is the absence of horizontal tissue, such as rays, in bamboo [102]. As a result, bamboo is often simplified as a transversely isotropic material in modeling [103]. There are some standard methods for measuring the elastic constants of anisotropic materials [104]. However, bamboo presents challenges in determining the elasticity constants due to its inherent anisotropy, hollow culm structure, and gradient distribution [105]. Various mathematical models have been developed to predict the structural behavior of bamboo as a construction material, including analytical solutions [106] and finite element methods implemented by researchers using software such as ANSYS [107] and ABAQUS [108]. Iynkaran et al. [79] studied a hybrid reinforcement for concrete slabs, including steel and bamboo bars (Figure 11a). Reinforcement bamboos were modeled by two-node, three-dimensional truss elements. FEM results showed that hybrid slab behavior shows more flexibility to the load than steel reinforcement slabs and lower weight (Figure 11b). Al-Rukaibawi et al. [109] conducted an assessment of the mechanical behavior of a bamboo–steel composite beam subjected to pure bending. Bamboo was characterized as an anisotropic material, with greater tensile and compressive strengths in the longitudinal direction compared to the transverse directions. Using FEM, it was observed that the computational model developed closely predicted the experimental results, with an average difference as low as 3%.

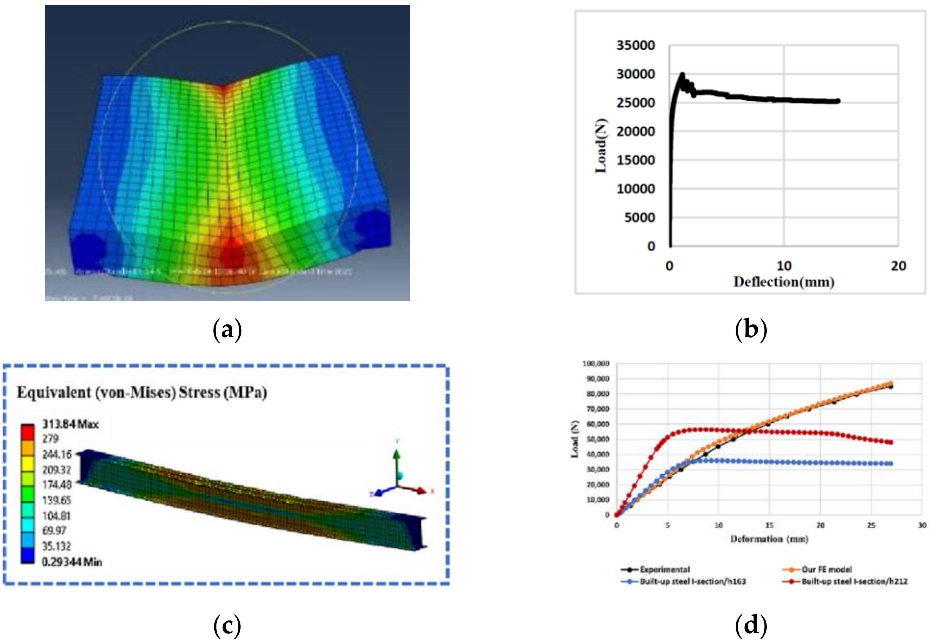


Figure 11. An overview of bamboo numerical modeling: (**a**) FEM modeling of bamboo slab, (**b**) load-deflection results of concrete slab reinforced by bamboo [79], (**c**) FEM study of a bamboo–steel composite beam, and (**d**) load-deflection results of different types of bamboo–steel composite [109].

3.3. Bamboo Sleeper Production

3.3.1. Background

Railway sleepers, also known as railroad ties or crossties, play a crucial role in the functioning and stability of railway tracks [110,111]. Their primary purpose is to provide support, stability, and secure alignment for the rails [112]. This railway track component has several roles, such as supporting rails, absorbing loads coming from trains, maintaining track alignment, reducing vibration, and maintaining track stability [1]. Railway sleepers are subject to train dynamic loads [113]. Bad ballast support conditions may cause ununified load support distribution for sleepers, which results in cracks in the rail seat and middle of the sleeper [114]. Track owners have tried to replace wood sleepers with different types of composite railway sleepers, such as TieTek, Axion, and KLP [115]. So far, the application of bamboo to construct railway sleepers has been studied [71,76]. This type of sleeper can be an alternative to timber railway sleepers. Xiao et al. [77] studied the manufacturing process of a wood–bamboo hybrid composite sleeper. Three parameters, including resin content, density, and hot-press time of the sleeper manufacturing process, are defined, and their relationship with the modulus of elasticity (MOE) is assessed. Results showed that more resin in bamboo composite sleepers increases MOE, while more density than 0.8 g/cm^3 decreases sleeper MOE. Longer hot-press times slightly decrease MOE.

However, the authors have started a comprehensive study regarding the application of bamboo in railway sleeper production with different types of bamboo construction materials, such as bamboo plywood and fibers. Here are some examples of bamboo sleeper production: two different processes of using bamboo fibers mixed with concrete and using bamboo plywood are followed. These sleepers are studied under bending tests, and their mechanical results are compared with those of normal concrete and timber sleepers.

3.3.2. Bamboo Sleeper Application Challenges

Bamboo, despite its many advantages, may present several disadvantages when used as a sleeper on railway tracks. One notable drawback is its light weight, which can lead to reduced lateral resistance [116]. This can potentially affect the stability and integrity of the railway track, especially under heavy loads or during high-speed train operations [117]. Another concern related to bamboo sleepers is their durability, particularly in regions with variable weathering action [118]. Bamboo is susceptible to weather-induced deterioration, such as fungal decay, cracking, or rotting, which can compromise its structural integrity over time [119]. This vulnerability to weathering raises concerns about the long-term performance and reliability of bamboo sleepers on railway tracks. Furthermore, limited data exists on the long-term performance of bamboo sleepers in railway applications. Comprehensive studies and field trials assessing the durability, maintenance requirements, and overall performance of bamboo sleepers are relatively scarce. This lack of available data makes it challenging to accurately assess their suitability and longevity in railway track systems. It is crucial to address these disadvantages and thoroughly evaluate the feasibility and practicality of bamboo sleepers before incorporating them extensively in railway infrastructure. Table 2 shows a comparison between different types of sleepers. It can be seen that bamboo plywood sleepers have the lightest weight between 60 and 75 kg, and their middle bending strength is equal to that of high-quality timber sleepers by 100 MPa. The results for the fiber bamboo sleeper and the plywood sleeper are reported from the authors' experiments. Application of bamboo fiber reduces the bending strength of concrete sleepers; however, it lightens the weight of concrete sleepers by 10%. The bamboo plywood sleeper is the cheapest among other types of sleepers. All prices are extracted from a sleeper-selling website [120].

Table 2. A comparison of the flexural strength and total weight of different types of sleepers.

Sleeper Type	Middle Flexural Strength (MPa)	Average Amount for a Sleeper (kg)	Ref.	Price $
Timber	70–110	60	[1]	20
steel	120	64	[121]	500
Concrete	110	375	[112]	28
FFU composite	142	100–120	[113]	45
Plastic sleeper	68	100	[122]	6/kg
Bamboo fiber concrete sleeper	70	345	_	25
Bamboo plywood sleeper	100	60–75	_	15

4. Future Prospects and Discussion

Bamboo products, such as plywood and bamboo scrimber, have shown promising mechanical features that make them potential alternatives to timber sleepers [123]. However, further studies are necessary to assess their long-term performance, resistance to temperature variance, and weathering effects. Additionally, more research, both numerical and experimental, is needed to explore the application of bamboo products in ballast mats and under sleeper pads, particularly in terms of their damping properties when combined with elastic materials like recycled tires. The use of bamboo in sleeper construction can provide benefits such as protecting the elastic layer from abrasion caused by ballast particles and contributing to vibration attenuation. However, when considering bamboo as a fiber mixed with conventional concrete or as laminates, certain concerns arise. The mechanical performance of railway concrete sleepers may be compromised when using bamboo fibers, as they are typically extracted from culms and may not provide sufficient reinforcement [124]. Moreover, the bonding and stress between laminate layers in bamboo plywood sleepers may lead to premature failure. To address these concerns, various methods have been suggested, including the use of high-strength resin and carbon fiber-reinforced polymer (CFRP) reinforcement in similar structures [1]. These approaches aim to enhance the bonding and stress distribution within bamboo laminates, ensuring the durability and longevity of bamboo sleepers. Therefore, while bamboo products offer potential as alternatives to timber sleepers in terms of their mechanical features and damping properties, further research is necessary to investigate their long-term performance, resistance to environmental factors, and bonding characteristics. Addressing these aspects will contribute to the successful incorporation of bamboo in railway sleeper construction.

5. Conclusions

This paper aims to study the potential and properties of bamboo products to manufacture a railway sleeper. Therefore, the mechanical properties of bamboo products and their manufacturing methods are discussed. The application of bamboo in the railway industry has been reviewed, and numerical modeling of bamboo is presented. A brief overview of the authors in bamboo sleeper production is also shown in this review paper. Bamboo sleepers' static behavior is compared with current railway sleepers. The key findings of this paper are as follows:

1. Bamboo has been considered a low-quality product for construction by emerging new technologies to manufacture bamboo products such as plywood, bamboo scrimber, and laminates. This material provides better properties than wood and composites with high stiffness, strength/mass per volume, and low carbon emission features.
2. More than 104 countries have contributed to bamboo publications with around 4119 papers. These contributions have increased in recent years, which shows the attention given by researchers even in those countries without bamboo as a local plant.
3. One of the main defects regarding the application of bamboo is the wide range of properties that can be found in the same bamboo products. However, the mechanical properties of bamboo products greatly increase, but the high difference between the mechanical properties of the elements of the structures may cause failure.
4. Bamboo plywood and scrimber are the main products that are suitable for railway sleeper production in terms of their durability and mechanical performance. These products can provide moisture-proofing, water resistance, corrosion resistance, and resistance to salt damage.
5. The application of bamboo in the railway industry has not been well extended compared with other parts of structural science. This material has mostly been used for soil improvement. However, considering its properties, it has the potential to be widely used in railway sleeper manufacturing, as has been studied so far. The shortcoming for more application of bamboo in the railway industry is the concerns about its weathering and long-term performance, as there are no such studies.
6. To model bamboo, it is mostly characterized as an anisotropic material, with greater tensile and compressive strengths in the longitudinal direction compared to the transverse directions. The literature has proven that most FEM models can be validated with experimental results with low differences.

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