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Review

Bamboo as Sustainable Building Materials: A Systematic Review of Properties, Treatment Methods, and Standards

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Abstract: Bamboo is the building material of the past and future. It offers numerous properties that make it versatile for various applications, including construction. Its impressive strength-to-weight ratio enables it to bear substantial loads and stresses, while its good elasticity allows efficient energy absorption. However, its mechanical properties can vary based on factors such as species, age, locations, methods, and treatment. Treating bamboo is essential to enhance its properties and durability. The literature provides various natural and chemical treatments that enhance some of the properties but also reported drawbacks regarding higher temperature, content, and duration. This paper reviewed 57 articles from the Scopus database, specifically focusing on article–document-type publications from the years 2003 to 2023. Additional references were also incorporated to address concerns in properties, treatment, and standards to provide systematic understanding. With extensive assessment of the articles, the following gaps and concerns were observed, and recommendations for further study and assessment were made: the bamboo's properties, the development of centralized guidelines and procedures for the preparation and processing; the exploration of alternative materials to reinforce bamboo without compromising its ductility; and the development of joint connections, and testing of mechanical properties considering seismic, wind and vibration. For treatment methods, the standardization of procedures using natural, chemical, or a combination. Lastly, for bamboo codes and standards, the assessment of existing codes and standards for testing the mechanical properties of bamboo, highlighting the potential limitations and areas, uniformity, and differences with all existing similar standards. By filling these gaps, it can support the reliability and robustness of bamboo as a sustainable material, fostering its promotion and adoption in the construction industry.

Keywords: bamboo; bamboo culms; building materials; construction

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1. Introduction

The use of bamboo culms in the construction industry presents an environmental advantage because of the reduction in carbon dioxide generation compared to conventional structural materials [1]. Bamboo exhibits numerous notable physical properties that play a vital role in its diverse applications. These properties include size, color, dimension, texture, grain, density, moisture content, thermal conductivity, and absorption. The dimensions and length of bamboo can differ based on the species and the maturity of the plant [2]; in comparison to timber, bamboo achieves maturity at a faster rate, typically taking only three to four years to reach maturity [3], while the former ages more slowly over 6 years and lacks its strength-up to 12 years old [4]. Physical properties can vary considerably among different species due to their distinct cellular structures and varying fiber proportions, which can influence their density. Some bamboo species may have a higher density, while others may have a lower density [5–8]. Remarkable mechanical properties characterize bamboo, rendering it a versatile and sustainable material. With an impressive strength-to-weight ratio, bamboo possesses excellent flexural ductility compared to wood by 3.06 times [5]. Singh et al. [9] tested the mechanical properties of different bamboo species such as *Dendrocalamus hamitonii*, *Bambusa tulda*, *Bambusa nutans*, and *Bambusa balcoa*, and found that *Bambusa nutans* has the highest compressive and bending strength of 98.24 MPa and 7.669 MPa, respectively. *Bambusa tulda* has the strongest tensile strength of 226.28 MPa, and the highest shear strength of 19.56 MPa was obtained by *Dendrocalamus hamiltonii*. Krause et al. [10] mentioned that the tensile behavior of *Dendrocalamus gigantus* is dictated by the fiber volume fractions and independent of the position of the culm wall. Cui et al. [11] observed that the tensile strength of bamboo fiber bundles gradually decreases with increasing temperature, which is mainly influenced by the decrease in the relative content of cellulose and hemicellulose. Wu et al. [12] confirmed that the tensile strength of an outer bamboo sliver treated with alkali at 60 °C and an inner bamboo sliver treated with alkali at 40 °C will increase up to a maximum of 86.6% and 132%, respectively, compared to untreated bamboo. Lorenzo et al. [13] performed both an experimental test and finite element simulation on Moso bamboo and found that the nonlinear behavior is mainly caused by the incremental development of cracks to the locations where the circumferential tensile capacity of bamboo is exceeded, leading to the eventual failure of the pole. Bamboo material is also excellent in compressive strength. Awalludin et al. [14] confirmed that the compressive strength of bamboo increases as the moisture content decreases. Bahtiar et al. [15] developed the structural grading of Guadua culms under axial compression and concluded that the strongest coefficients of determinations for structural grading were related to density. Five different bamboo species were studied by Drury et al. [16] such as Moso, Guadua, Tali, Black Java, and Madake. The compressive strength of these species was found to be greater than 50 MPa, which makes them excellent for construction use. Gauss et al. [17] stated that the presence of nodes has a local stiffening effect with respect to compression and shear. Shawana et al. [18] investigated the strength characteristics of bamboo along the length of the culm and observed that the size of the culm governs the ultimate load capacity. The larger culm and thicker wall obtained more load. Lo et al. [19] conducted a strength analysis of Mao Zhu and Kao Zhu bamboo species that are basically used for scaffoldings in China. They observed that the compressive strength of both species ranges from 45 to 65 MPa, and the top section of the culm has higher strength than its bottom section. Suarez et al. [20] studied the influence of weathering on the mechanical properties of bamboo culm from Guadua species with and without nodes. There was a 9% decrease in the compressive strength, but they had no influence on the tension and bending performance when the silica layer was placed on the compression face. Also, nodes have a positive effect on the stiffness near the points of load application when tested for bending. Bamboo material is also outstanding in flexural strength [1,5,21,22], allowing it to bear substantial loads and stresses. Its good elasticity enables efficient absorption and distribution of impact energy. Bamboo's mechanical properties vary based on factors such as species, age, and culm regions [23]. It is highly regarded for its strength, flexibility, and resilience, making it suitable for various applications, including construction, furniture, and engineered products. Bamboo composite or engineered bamboo is widely explored to optimize the utilization of bamboo. These mechanical properties of engineered bamboo products can be influenced by processing methods [24].

Despite the excellent potential of bamboo, its durability and resistance to weathering actions might be compromised because it decays compared to conventionally manufactured materials [25]. That is why treatment is basically considered. Treating bamboo is widely studied nowadays, and this continues to develop an effective and optimal treatment. Bamboo can be treated by natural methods such as drying, heating (boil, fired, oven), steaming, soaking, smoking, oil application, and impregnation of natural resin (e.g., rosin). The use of natural treatment for bamboo is environmentally friendly compared to chemical treatment, especially for the local communities who better understand the workings of bamboo [26]. Chemical treatment is used by various researchers since it can be done in less time compared to the natural method. However, a fraction of the chemicals introduce environmental and safety issues. Some chemicals used in treating bamboo are boric acid, copper naphthenate (CuN), polycarboxylic acids (CA), butanetetracarboxylic acid (BTCA), disodium octaborate tetrahydrate (DOT) aqueous, boron-based preservatives, epoxy resin, deltamethrin, and alkali with sodium hydroxide. These components were used by the literature reviewed in this paper. Sharma et al. [24] observed that the thermal processing technique influences the mechanical strength of materials, notably affecting their bending behavior and properties, as evidenced by the enhanced compressive and shear strength parallel to the grain following treatment. Cid et al. [27] studied the influence of hornification on the physical and flexural properties of Moso and found that the process through the wetting and drying cycle lead to a reduction in the water retention capacity of the bamboo at the end of treatment. With regards to the flexure, the hornification process leads to reductions of the ultimate deflection and increased stiffness and strength. Yang et al. [28] proved that rosin impregnation improved the dimensional stability and hydrophobicity of bamboo. Marasigan et al. [29] studied the effect of thermal treatment on the wettability of giant bamboo (*Dendrocalamus asper*) and Kawayan Tinik (*Bambusa blumeana*) in the Philippines, and found that thermal treatment changed the color of both bamboo species, the density decreased, and improved the wettability.

Bamboo is a sustainable material that is used in construction; however, it has limited application [30] and global adoption, especially in medium and high construction. In Bangladesh, bamboo was utilized in the construction of a low-height telecom tower located on a rooftop [31]. The Barajas International Airport in Madrid, Spain, used engineered bamboo for ceilings [32]. Bamboo is also used in scaffoldings in Japan in high-rise buildings [33]. The existing codes and standards may not be sufficient to optimize the usage since there are many variations with regard to species, age, locations, methods of preparation and testing, and others. It could be potentially interesting to assess the variations of the result from the available standard methods from international and other national standards.

This paper provides a review of the use of bamboo culms as building materials in construction with regard to the species, physical and mechanical properties, treatment, applications, and codes and standards tackled by the gathered literature, and determines the research gaps and challenges which could be addressed for future work. The paper highlights several research gaps in bamboo's physical and mechanical properties. These include the need for centralized guidelines in preparation and processing, exploring sustainable filling materials, advancement of culm connections, testing under different loads, standardizing treatment methods, and assessing existing codes and standards for bamboo. Addressing these gaps will optimize bamboo's potential as a sustainable construction material.

2. Methodology

The collection of relevant literature or articles is a crucial step in conducting a comprehensive review paper. A summary of the research methodology is shown in Figure 1. In this paper, the Scopus database was utilized as a primary resource for gathering scholarly articles. Scopus is widely recognized as a comprehensive abstract and citation database encompassing a vast range of disciplines [34]. Furthermore, Scopus offers advanced search functionalities, citation analysis, and author metrics, enabling the researcher to conduct thorough and efficient literature searches, evaluate the impact of previous studies, and identify influential authors.

The general topic for the review had already been recognized as "Use of bamboo culms as building materials in construction". Presently, Scopus provides 14,456 articles for "bamboo", 1753 articles for "bamboo culms", 86,867 for "building materials", and 437,526 for "construction". These keywords were combined and used the advance search and Boolean operators. The search was filtered to articles only and limited to subject areas such as engineering, material science, environmental engineering, chemical engineering, agricultural and biological sciences.

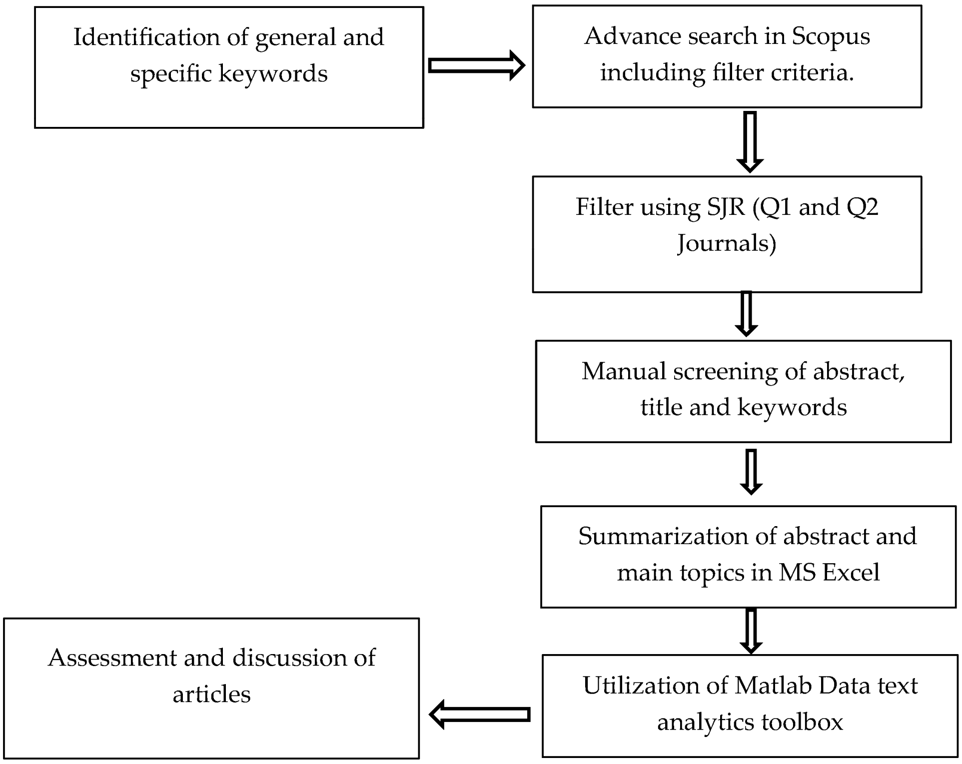

Figure 1. Research methodology.

To ensure a wider range of studies to be reviewed and synthesized, the inclusive years for the publications included were from 2003 to 2023. A total of 793 documents were found. The articles were filtered based on high-ranking journals from the SCImago Journal Ranking (SJR) selecting only those Q1 and Q2 journals such as *Construction and Building Materials*, *Buildings*, *Journal of Materials in Civil Engineering*, *Materials*, and *Royal Society Open Science*. The SCImago journal rank indicator is a novel instrument for the evaluation of the scientific journals that may challenge the established premiership of the impact factor (IF) in ranking scientific journals, and the primary strength of SCImago is that it uses Scopus as the data source for the development of the SJR indicator [35]. Choosing only the highly-ranked journals, the articles were narrowed to 138.

These articles underwent a rigorous manual screening, wherein they were assessed based on specific author and index keywords. Only those articles that contained relevant terms such as "bamboo", "bamboo culms", "bamboo poles", "bamboo species", "bamboo properties", "bamboo construction", "building materials", or a combination of these were considered for inclusion. Subsequently, the abstracts of the identified articles were scrutinized to evaluate their relevance to the study. Only those abstracts that provided a clear and concise discussion of essential aspects of bamboo properties, species, testing, treatments, and a key summary of findings in relation to bamboo performance and properties were selected. As a result of this thorough approach, a total of 57 articles were meticulously reviewed and systematically assessed to gather comprehensive insights on the subject matter. However, additional references were also incorporated to address issues on topics regarding properties, treatments, applications, and standards to provide a methodical and in-depth understanding. The 57 articles were imported into Matlab software (R2023a) for Text Analytics. The Matlab Text Data Analytics provides an overview of the topic by word clouds, topic mixtures, journal distribution, and publication year. The text analytics with Matlab can be useful in automating the process of extracting information from text, significantly reducing the time required for manual processing [36]. This method is similar to the studies of Ongpeng et al. [37,38], where Matlab Text Data Analytics was utilized for generating the topics. Figure 2 shows the word cloud generated, which contains regularly occurring words from the documents extracted. It can be seen that the distinct word is "bamboo" which is basically the general keyword of the study. The validation perplexity is shown in Figure 3, from 1 to 10 topics; the results show that of the three topics, the validation perplexity has the lowest value. For this graph, the lowest perplexity validation has the most suggested number of topics to be used [36]. Figure 4 presents the topic mixture generated, which shows the percentage of topic occurrence on each document through colors. Topic 1 (the blue color) highlights the words "properties, materials, strength, density, and test". Topic 2 (the red color) emphasized the words "effect, structural, method, specimen, and high". Lastly, Topic 3 (the yellow color) pointed to the words "mechanical, treatment, increase, show, and modulus". These groups of words were interpreted and developed a specific topic for this study. For topic 1, the corresponding interpretation is the "Physical and mechanical properties of different bamboo species". Topic 2 was interpreted as "Bamboo standards and structural applications", and topic 3 was interpreted as "Bamboo culm treatment methods". These three topics are discussed qualitatively in this paper. The publication year distribution of the collected articles is presented in Figure 5. The publication behavior shows an increasing and decreasing pattern. Few articles were published in 2006 to 2010 and 2014. The number of highest publications was in 2021, but decreased in 2022 and the present year. However, this is justifiable since we are still in the middle of the year 2023. Figure 6 shows the countries that have bamboo studies, of which 46% belong to China.

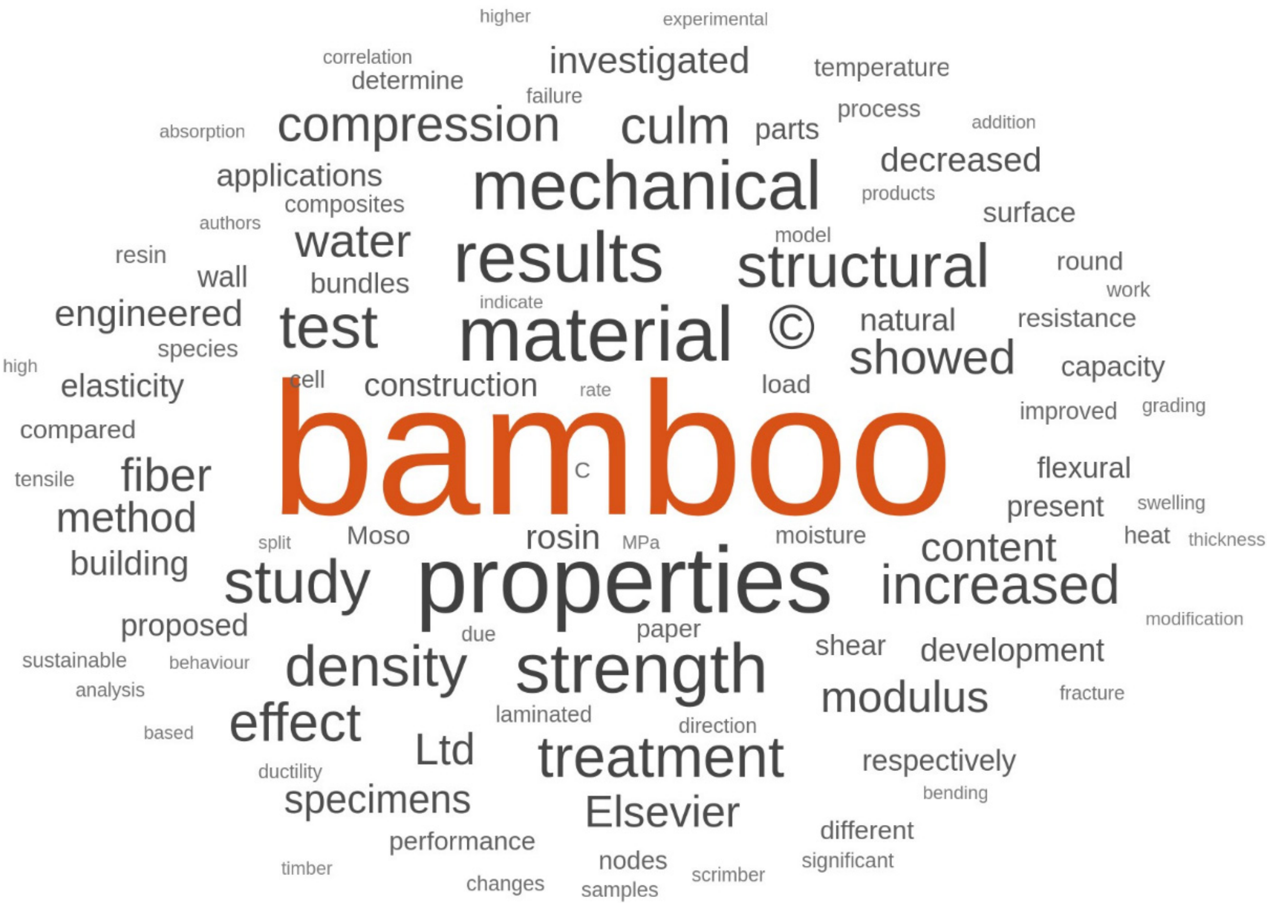

Figure 2. Word cloud generated by Matlab Software (R2023a).

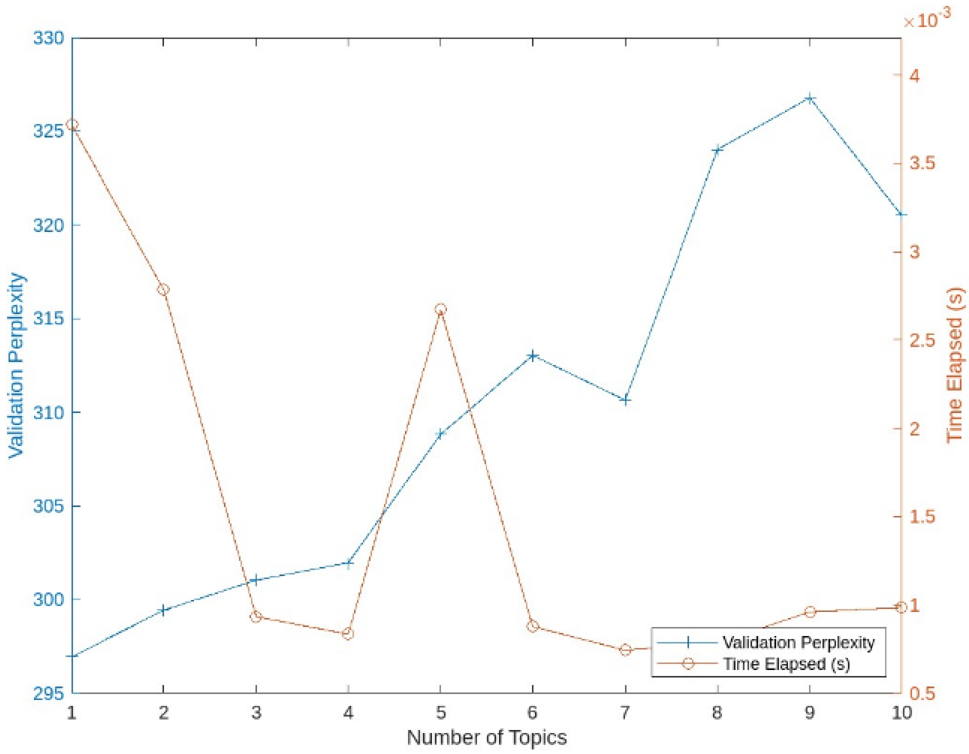

Figure 3. The number of topics.

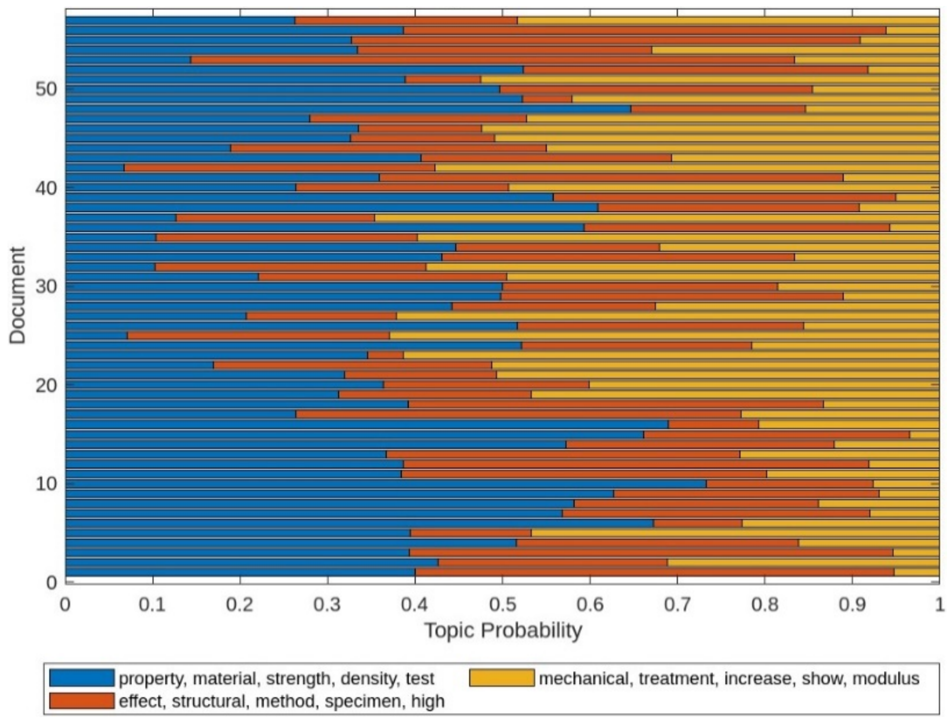

Figure 4. Topic mixtures.

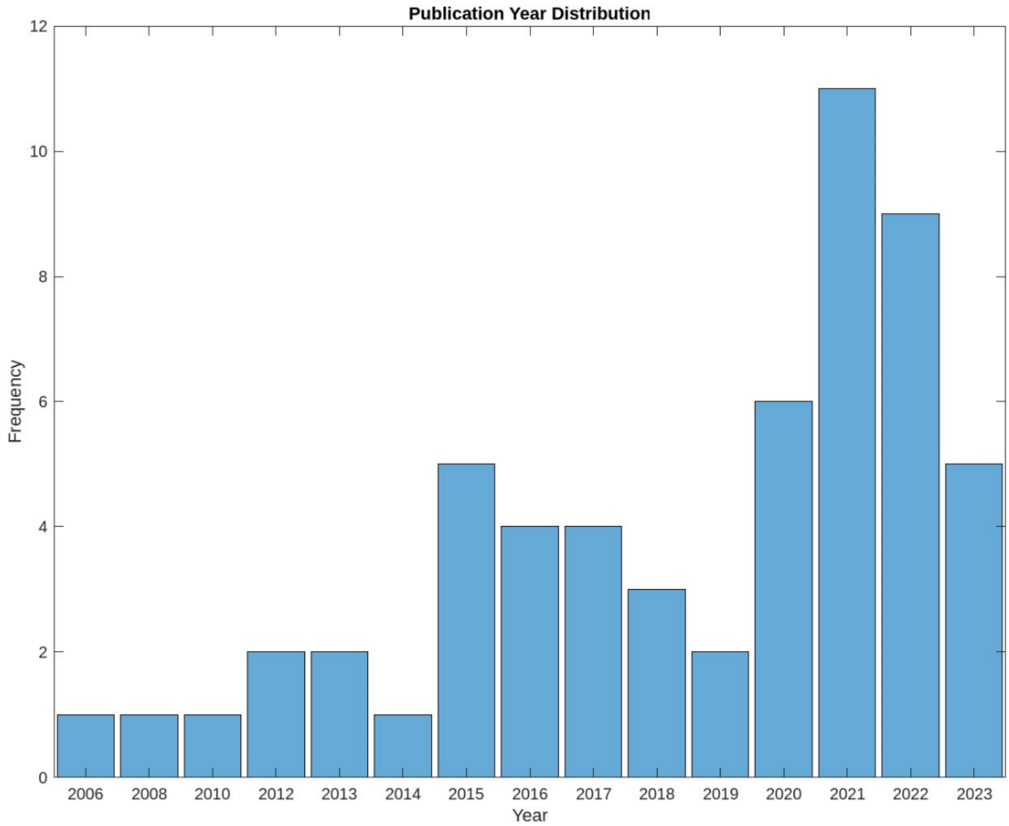

Figure 5. Publication year distribution.

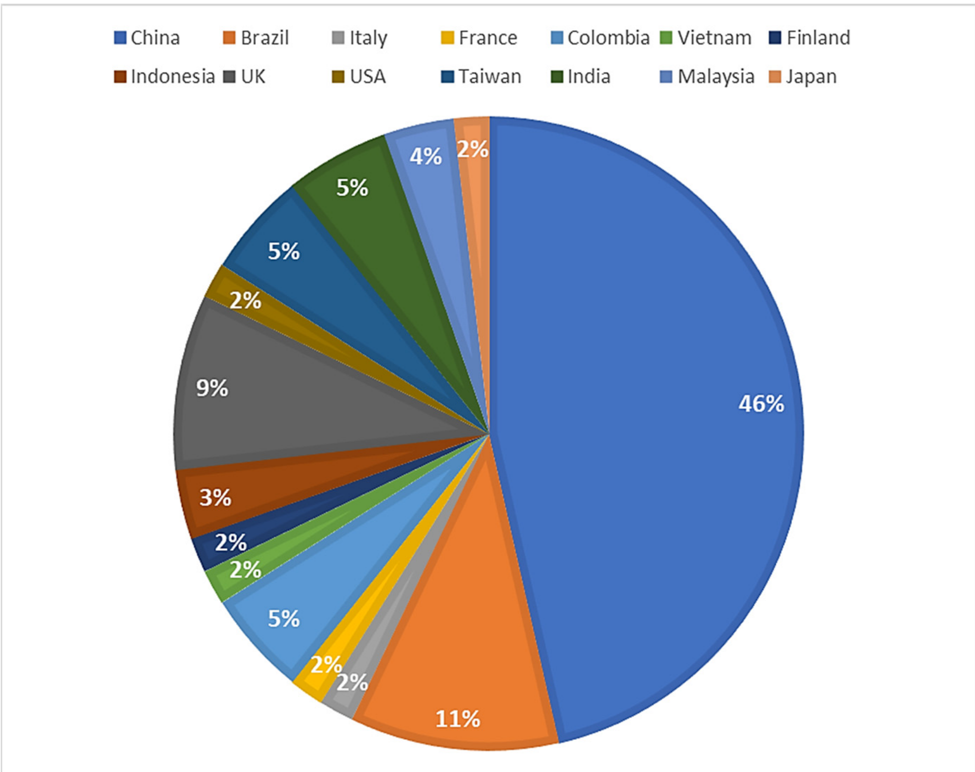

Figure 6. Countries with bamboo studies.

3. Results and Discussion

The objective of this paper is to provide a review of the use of bamboo culms as building materials and identify the research gap that could be addressed. This section assesses the different bamboo species used in construction, the physical and mechanical properties of bamboo, the treatment methods used, how this affects the properties of bamboo, and the standards and applications of bamboo culms and composites. There are various species of bamboo used in gathered literature with different locations. Since most of the studies were oriented from China, the majority of the bamboo samples were situated in this country.

3.1. Bamboo Species

The globalization of bamboo's potential as a construction material is enormous due to its lightweight nature, abundant renewability, and rapid growth [39]. With its wide advantageous properties, bamboo presents an environmentally friendly and sustainable alternative for various construction applications across the world. Bamboo belongs to the *Poaceae* family of grasses, exhibits remarkable lightweight characteristics, and stands as one of the most rapidly growing plants found on our planet [40]. A total of 1662 bamboo species are known to exist, distributed across 121 genera; among these, 232 species have been introduced to areas beyond their native ranges and have become invasive [41]. In Asia, China boasts the greatest diversity of bamboo, having 500 native species. Japan follows with 139 species, while India, Indonesia, and Myanmar have 119, 118, and 97 species, respectively [42].

Bamboo exhibits a wide array of applications, including construction, furniture, food, biofuel, textiles, paper, charcoal production, ornamental gardening, and environmental benefits like carbon sequestration and phytoremediation capabilities that enhance soil quality and mitigate erosion [33]. The most used species for structural construction is given in Table 1. Most of these species are found in Asia.

Table 1. List of bamboo species commonly used in construction. Data are adapted from [43], The Institution of Structural Engineers, 2016.

Scientific Name (Local Name)	Areas Found	Diameter (mm)
Guadua angustifolia Kunth	South America	120–160
Dendrocalamus strictus (Calcutta)	Asia	25–80
Bambusa vulgaris	Africa, Asia, South America	80–150
Phyllostachys edulis (Moso)	Asia	120–180
Dendrocalamus asper (Petung)	Asia, South America	80–200
Bambusa blumeana (Spiny/ThornyBamboo)	Asia, Asia–Pacific	60–150
Gigantochloa apus	Asia	40–100

Figure 7 shows 18 different species that were used by the researchers in this study, such as (1) Moso (*Phyllostachys pubescens*/*Phyllostachys edulis*), (2) Hong (*Phyllostachys iridencens*), (3) *Phyllostachys viridiglaucecsens*, (4) *Phyllostachys family*, (5) *Guadua angustifolia kunth a.k.*, (6) *Bambusa vulgaris*, (7) *Tregai (Bambusa stenostachya)*, (8) *Dendrocalamus strictus*, (9) Ater (*G. atter*), (10) Makino (*Phyllostachys makinoi*), (11) *Pseudosasa amabilis*, (12) *Bambusa Balcoa*, (13) Madake (*Phyllostachys bambusoides*), (14) *P. aurea*, (15) *Dendrocalamus giganteus*, (16) *Dendrocalamus asper*, (17) *Schizostachyum Grande*, and (18) *Gigantochloa Scortechinii*. It can be seen that most of the researchers used Moso bamboo in their study. This paper will use "S" to stand for species and numbers "1–18" for the specific type as discussed (e.g., S-1, *Moso (Phyllostachys pubescens*/*Phyllostachys edulis*). Moso bamboo stands out as the globally predominant bamboo species in terms of widespread harvesting [22], temperate bamboo species which basically grows in China [41] and performs better compared to other species both environmentally and mechanically [44].

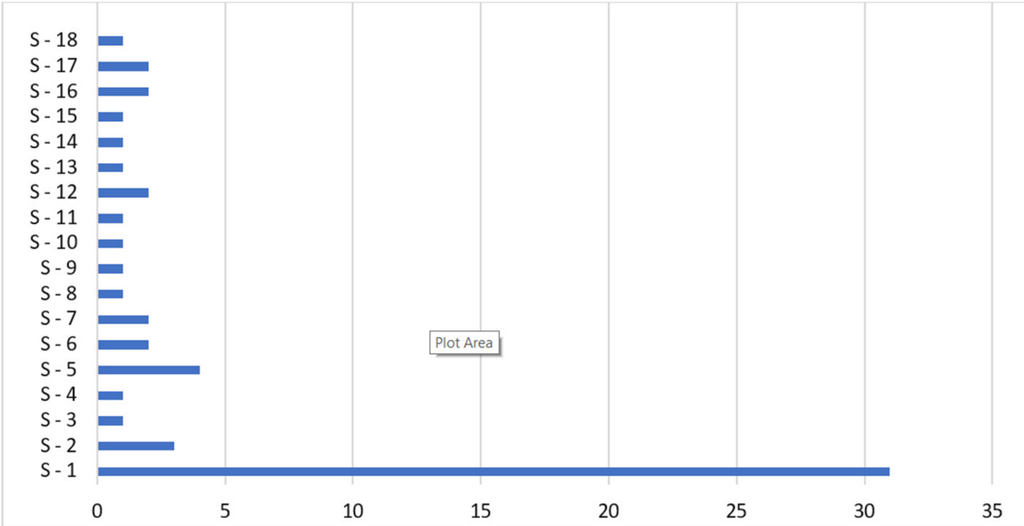

Figure 7. Species used by the researchers.

3.2. Physical Properties

Bamboo possesses several noteworthy physical properties that contribute to its wide range of applications. These properties include size, color, dimension, texture and grain, density, moisture content, thermal conductivity, and absorption. The dimensions and length of bamboo can differ based on the species and the maturity of the plant [2], in comparison to timber, bamboo achieves maturity at a faster rate, typically taking only three to four years to reach maturity [3], while the latter ages more slowly, over 6 years and lacks strength up to 12 years old [4]. The bamboo culm is composed of vascular bundles and parenchymal base tissue. Within the vascular bundles, fiber caps or sheaths enclose conducting elements such as vessels, sieve tubes, and companion cells, all of which collectively influence bamboo's characteristics [2,40]. It has been observed that vascular bundles are distributed unevenly throughout the culm, ranging from the outer to the inner layer [45,46]. Additionally, the shape and size of vascular bundles within the culm exhibit variability.

In Figure 8, Lee et al. [3] provide a detailed look at the anatomy of a typical bamboo: (a) shows a mature bamboo culm ready for harvesting, with internodes and nodes. The nodes have internal diaphragms and an external ridge; (b) displays a cross-section of the bamboo culm; (c) presents an enlarged cross-section (2 mm to 4 mm scale) highlighting the distribution of vascular bundles, which are more concentrated towards the outer diameter. In (d), a microscopic view (0.2 mm to 0.3 mm scale) reveals the bamboo culm wall in detail, with its main components being the parenchyma cells and vascular bundles. The vascular bundles, with their four-winged structure, consist of fiber strands that determine the mechanical properties of the bamboo.

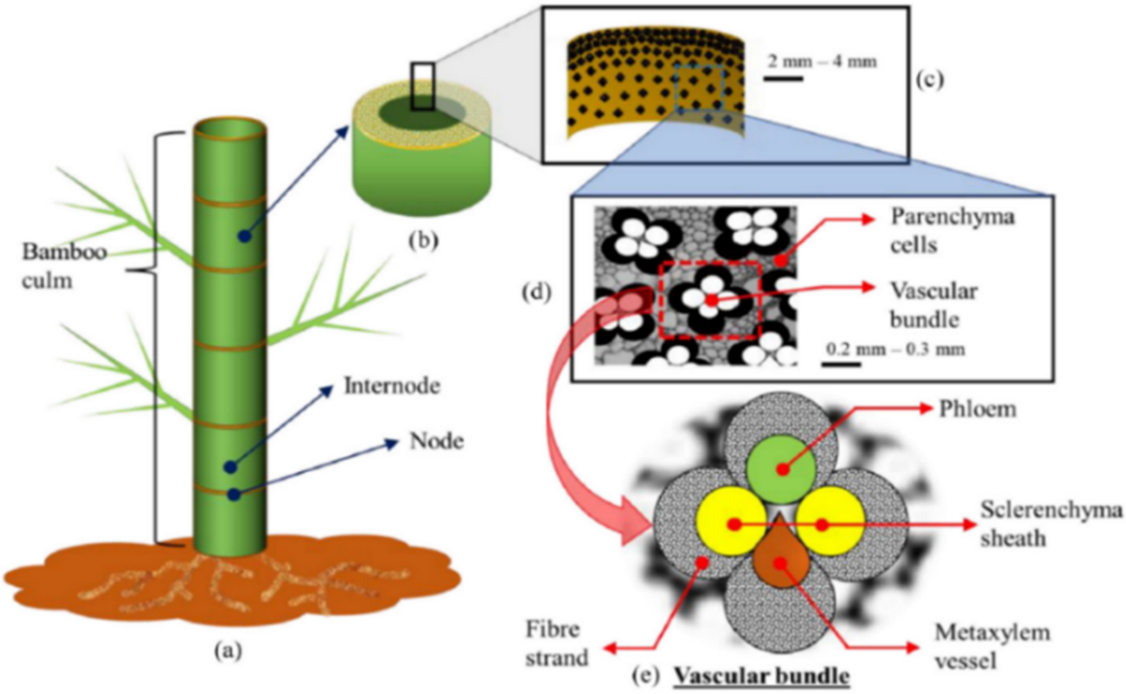

Figure 8. Typical bamboo anatomy: (**a**) the whole bamboo culm in its natural state, (**b**) a cross-section of the bamboo showing its internal structure, (**c**) a close-up view of the cross-section area, (**d**) a magnified view of the parenchyma cells and vascular bundles, and (**e**) an enlarged view of a vascular bundle, Figure is reproduced with permission from [3], Elsevier, 2022.

The culm internode length has an increasing pattern from the bottom to the mid-section and then decreases towards the top, while the culm's conical shape decreases in the outer diameter from bottom to top; furthermore, the inner diameter of the mid-section decreases both towards the bottom and the top, which results in the reduction of culm thickness [46]. The properties of bamboo can vary significantly among different species. Different bamboo species have distinct cellular structures and varying proportions of fibers, which can impact their density. Some bamboo species may have a higher density, while others may have a lower density. *P. edulis* has a density of 796 kg/m^3 [5], and *Bambusa balcoa* has a density of 685 kg/m^3 [6], tending to have higher densities compared to species like *Phyllostachys pubescens* that have 601–640 kg/m^3 [7], but these densities can be modified through treatment and mechanical processes. Other species, like *Bambusa vulgaris*, have a density ranging from 630 kg/m^3 to 680 kg/m^3 and do not vary significantly with location [8]. Table 2 shows the articles that highlight the physical properties of different species. It can be seen that most of the studies highlighted the density and moisture content of bamboo. The average age was between 3 to 4 years, where 6 years is the oldest and 2 years is the youngest sample used. Various types of samples have been used for density testing, as shown in Figure 9. These are bamboo strand composite lumber (BSCL), bamboo culm, modified bamboo splits, bamboo scrimber, outdoor bamboo-fiber re-inforced composite (OBFRC), bamboo slivers, laminated bamboo timber (LBT), and unidirectional round bamboo stick boards (UBSBs). UBSBs undergo processes such as splitting and peeling, converting it to a round bamboo stick, drying and heating treatment, immersion in PF resin, then a flattening process to form UBSBs [22]. Bamboo culm samples is just cut from the whole culm, where basically, the length is twice the diameter [15]. MBS is a product of flattening and densification of natural bamboo splits. Bamboo scrimber undergoes processes such as splitting, flattening, crushing, and steam carbonizing at 170 °C for 100 min, then it is impregnated with PF resin (15–17%) and undergoes cold molding; finally a bamboo scrimber is formed after activation of resin for 12 h at 80–120° [23]. OBFRC processes include mechanical fluffing (splitting, peeling, or skin removal) to produce bamboo fiber mats; these mats are impregnated by PF resin and then assembled for hot pressing to finally form OBFRC slabs [47]. The LBT processes include splitting, treating with borax, air-drying, then splitting into strips, strips arere then glued and pressed horizontally at a temperature of 140 °C and a pressure of 1.47 MPa for 30 min [44]. The BSCL processes involve splitting of the bamboo culm, peeling of the outer skin, cutting into parts, and then is followed by dripping and drying. After drying, it will then be assembled and hot-pressed to form BSCL [48].

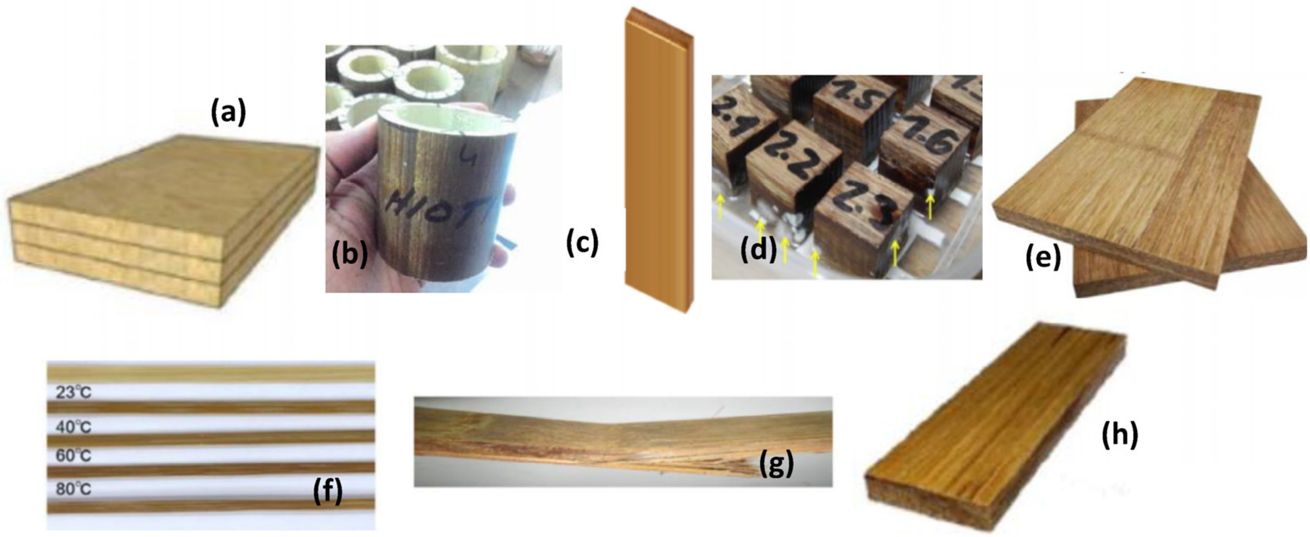

Figure 9. Samples used for testing the bamboo properties: (**a**) BSCL [49], (**b**) bamboo tube [50], (**c**) MBS, (**d**) scrimber, (**e**) OBFRC, (**f**) bamboo slivers, (**g**) LBL, (**h**) UBSBs. All figures are reproduced with permission from (**a**) BSCL [49], Elsevier, 2021; (**b**) bamboo tube [50], Elsevier 2019; (**c**) MBS [51], Elsevier, 2023; (**d**) Scrimber [23], Elsevier, 2016; (**e**) OBFRC [47], Elsevier, 2020; (**f**) bamboo slivers [12], Springer Nature, 2023; (**g**) LBL [44], Elsevier, 2016; and (**h**) UBSBs [22], Elsevier, 2018.

Table 2. Summary of the study on the physical properties of bamboo.

Reference	Species	Age	Density	Moisture Content	Water Absorption	Porosity	Thermal	Microstructure
[1]	S-1, S-5	NA	✓					
[52]	S-1	5			✓	✓		
[49]	S-1	4	✓					
[8]	S-6	4	✓	✓				
[53]	S-1, S-5, S-7	3–6	✓	✓				✓
[15]	S-5	NA	✓	✓				
[54]	S-1	4	✓					
[7]	S-1	NA	✓					
[48]	S-1	3	✓	✓				
[51]	S-1	4	✓					
[55]	S-1	4						✓
[23]	S-1	NA	✓	✓	✓			
[56]	S-1	4					✓	
[57]	S-1	NA		✓		✓		✓

Table 2. *Cont.*

Reference	Species	Age	Density	Moisture Content	Water Absorption	Porosity	Thermal	Microstructure
[28]	S-11	4	✓			✓		✓
[42]	S-5	2 to 5		✓				
[27]	S-1	3			✓			
[58]	S-13	3		✓	✓			
[59]	S-1	2, 4, 6						✓
[12]	S-1	NA	✓					
[10]	S-15	6	✓					✓
[60]	S-16	3 to 5	✓				✓	
[47]	S-1	4	✓	✓				
[61]	S-1	5			✓	✓		
[44]	S-18	NA	✓					
[62]	S-7	NA		✓				
[63]	S-9	2–3	✓	✓				
[14]	S-1, S-6, S-17, S-18	NA		✓				
[64]	S-1	3–5	✓	✓				
[65]	S-1	5	✓					

3.2.1. Density of Bamboo

One of the most important physical properties of bamboo is its density; some studies noted the density of the bamboo, as shown in Table 3. It is important to determine the density of the bamboo culm that will be used because it is one of the key parameters that influence the performance of the material [2,40]. The dry density of bamboo commonly used in structures ranges from 500 kg/m^3 to 800 kg/m^3 [43]. Various studies have confirmed that the density of bamboo has a significant influence on the mechanical properties [22,23,49,54,66], water absorption [23,67], and a higher density means the bamboo fibers are more compacted together [23]. Density is the most relevant parameter of the mechanical properties of the original bamboo parallel to the grain [54]. Sun et al. [49] observed in Moso bamboo that the higher density of 900 kg/m^3 has a significant influence on shear strength and modulus of rupture under natural drying treatment; soaking time affects density and higher density swells after boiling.

Table 3. Summary of studies on the density of bamboo.

Reference	Age	Species	Sample	Density (kg/m^3)	Remarks
[49]	4	S-1	Bamboo strand composite lumber (BSCL)	730–1320	soaking time affects density, higher density swells after boiling
[1]	NA	S-1, S-5	Bamboo tube	684 ^{1} 730 ^{2}	Moso ^{1} Guadua ^{2}
[8]	4	S-6	Bamboo tube	646	average
[53]	3–6	S-1, S-5, S-7	Bamboo tube	400–850 ^{1,3} 500–100 ^{2}	Moso ^{1}, Guadua ^{2}, Tregai ^{3}

Table 3. *Cont.*

Reference	Age	Species	Sample	Density (kg/m^3)	Remarks
[15]	NA	S-5	Bamboo tube	794.5 [1] 1099.4 [2]	w/o node [1], w/node [2]
[54]	4	S-1	Bamboo tube	586–982	density is a relevant parameter to mechanical properties
[22]	3	S-1	Unidirectional round bamboo stick boards (UBSBs)	918–975	density has positive relationship w/flexural strength
[51]	4	S-1	Modified bamboo Split (MBS)	1080–1130	density increased after treatment
[23]	NA	S-1	Bamboo scrimber	1054–1215	density influenced the absorption and mechanical properties
[12]	NA	S-1	Bamboo slivers	550–1100	density increased after treatment by 45.6–88.3% treated at 40 °C
[60]	3–5	S-16	Bamboo tube	1600	maximum
[44]	NA	S-18	Laminated bamboo timber (LBL)		low density is attributed to nodes
[57]	NA	S-1	Bamboo tube		internode has uniform density, density fluctuation at nodal parts
[63]	2–3	S-9	Laminated bamboo	762 [1] 747 [2]	hydraulic press [1], manual press [2]
[24]	NA	S-1	Laminated bamboo (LB)	644 [1], 673 [2]	Bleached [1], Semi-caramelised [2]
[10]	6	S-15	Bamboo split	710–940	
[47]	4	S-1	Outdoor bamboo-fiber-reinforced composite OBFRC	1160	average
[64]	3–5	S-1	Laminated bamboo	800–980	
[65]	5	S-1	Bamboo strip	600–690	

Superscript on the density corresponds with the identifications indicated in "Remarks" to categorized each value.

In a study conducted by Dixon et al. [53], a comparison was made of the structure and flexural properties of Moso, Guadua, and Tre Gai bamboo. The results revealed that, at a given density, Guadua exhibited a higher axial modulus of elasticity compared to Moso and Tre Gai, which showed similar properties. Additionally, the ultrastructural analysis indicated that Guadua has a higher stiffness in its solid cell wall. The density of Moso bamboo decreases from the external surface to the internal surface of the culm wall in the radial direction, both in the internodes and nodes parts [7]. The internode has uniform density, and it fluctuates at the nodal parts. The weakness in nodes is the influence of low density and the irregular vascular bundle arrangements [44]. Luan et al. [51] observed that for bamboo split, the density of the inner part was tremendously increased to over 1.0 g/cm^3 and is consistent with that of the outer part under steamed treatment. The density of specimens containing nodes is consistently higher than that of specimens without nodes [15]. This observation is considered trivial because diaphragms contribute to the overall mass but are not taken into account in the measurement of volume or length. Kadivar et al. [60] observed that density increased in bamboo after DOT treatment. An increase in density also of bamboo splits was observed by Luan et al. [51] after-steam after steam treatment. Wu et al. [12] tested the bamboo slivers and confirmed that after treatment, density increased by 45.6–88.3% and treated at 40 °C.

3.2.2. Moisture Content of Bamboo

Table 4 shows a few of the literature in this paper that noted the moisture content (MC) of bamboo. Bamboo is considered suitable for use when its moisture content is around 8% to 12% [44,58,63,65]. The mechanical properties and durability of bamboo are dependent on its moisture level, therefore, MC must be kept below 20% [31]. This range is often preferred for construction purposes, furniture making, and other applications where dimensional stability and resistance to warping or cracking are important.

Table 4. Summary of moisture content.

Reference	Age	Species	Sample	Moisture Content	Remarks
[15]	NA	S-5	Bamboo tube	7.3–10.9%	Nodal and internodal is similar
[8]	4	S-6	Bamboo tube	12.95%	average
[23]	NA	S-1	Bamboo scrimber	7%	average
[61]	4	S-1	Bamboo split		water uptake reduced by 24.7% after rosin treatment
[47]	4	S-1	Outdoor bamboo-fiber-reinforced composite OBFRC	6.95%	average
[53]	3–6	S-1, S-5, S-7	Bamboo tube	4%, 6%, 6%	Moso, Guadya, Tregai
[62]	NA	S-7	Bamboo tube	12%	average
[63]	2–3	S-9	Laminated bamboo	17.2% 16.0%	Hydraulic press Manual press
[24]	NA	S-1	Laminated bamboo (LB)	8% 7%	Bleached LB Semi-caramelized LB
[22]	3	S-1	UBSBs	5.2–10.3%	
[14]	NA	S-1, S-6, S-17, S-18	Bamboo split	19.63%	Maximum, S-17
[64]	3–5	S-1	Laminated bamboo	7%	average

Most of the studies stored their bamboo culm specimens and allowed them to reach the equilibrium MC before they were tested [52,55,65]. It is known that bamboo culm shrinks when dry and swells when wet [15]; therefore, it is important to attain the equilibrium moisture content of bamboo before undergoing testing and processing. Some studies managed the moisture content of the bamboo by undergoing treatments and process modifications. Su et al. [52] used the rosin treatment in Hong bamboo and found that equilibrium moisture content decreased across relative humidity values. The test found that the film formed on the surface of the bamboo culms might greatly weaken the surface wettability and moisture absorption of bamboo culms. The study of Bahtiar et al. [15] on the structural grading of *Guadua angustifolia* demonstrated that the correlation between moisture content and mechanical properties of bamboo bears a striking resemblance to that of wood, with compression resistance of short members as the grading foundation. The moisture content of *Guadua angustifolia kunth* species typically falls within the range of 9% to 10% [42], a similar range to that of [15], having a higher MC at the nodal section but considered insignificant. Sa Riberio et al. [8] studied the MC of untreated *Bambusa vulgaris* and found that the average MC was 12.95% higher than that obtained by Dixon et al. after borax treatment for three species Moso, Guadua, and Tregai, which were 4%, 6%, and 6%, respectively.

3.2.3. Porosity and Absorption of Bamboo

Bamboo is considerably porous due to the presence of small open spaces or pores within its structure, and has a certain capacity to absorb and retain moisture [68]. The absorption characteristics of bamboo are influenced by its porosity, as well as the structure and composition of its cell walls, which consist of cellulose, hemicellulose, and lignin [69]. When bamboo is exposed to moisture, it can absorb water into its cell walls, causing it to swell and increase in dimensions. The porosity of bamboo culm may be improved by treatment and processing procedures. Huang et al. [57] addressed that the hygrothermal properties show a stronger correlation with open porosity than with bulk density.

The determination of the porosity of bamboo is presently less advanced compared with the equivalent research conducted on wood. Well-recognized and established approaches for quantifying porosity within the domain of wood research includes mercury intrusion porosimetry (MIP), gas pycnometry (GP), microscopy image processing, and computed tomography (CT scan). MIP is known to be effective for wood, but high pressure can cause deformation of the pores. GP is considered highly accurate, but sample preparation and displacement media need to be treated carefully [70]. The average values of the measurement will be utilized as the bulk density in calculating the porosity, as shown in Equation (1). ρ_{bulk} is the bulk density, ρ_s is the skeletal density, Ø is the porosity, and ρ_{air} is the air density (1.184 kg/m^3 at 1 atm, 25 °C). With an unknown bulk and skeletal density, the porosity value can be obtained. The bulk density is obtained by CT scanning measurement [71].

$$\rho_{bulk} = \rho_s \times (1 - \text{Ø}) + \rho_{air}\, \text{Ø} \quad (1)$$

3.2.4. Thermal Performance of Bamboo

Few studies from the literature emphasized the thermal performance of bamboo. Dong et al. [56] evaluated the anti-mold termite resistance and properties of Moso bamboo cross-linking utilizing polycarboxylic acids, and observed that the thermal stability of bamboo is enhanced by cross-linking modification. Polycarboxylic acid treatment is an eco-friendly, low-cost, and versatile method to improve bamboo properties. Another study [61], observed that surface color and contact angle of bamboo were notably influenced by the treatment temperature and duration. Higher treatment temperatures resulted in darker surface colors and larger contact angles, ensuring favorable hydrophobicity of the bamboo [55]. The exposure of bamboo to water or high humidity tends for the cell walls of the bamboo fibers to absorb moisture, causing them to expand or swell [52]. The thermal conductivity of a material has a crucial role in determining how quickly the temperature rises within the material, which affects how rapidly the material's mechanical properties deteriorate when exposed to high temperatures and is significant in terms of fire safety [72]. Wu et al. [69] and Yang et al. [70] stated that the thermal conductivity of bamboo is influenced by the combined effect of final moisture content, the structure of cellulose, and the density of bamboo. Some methods for determining the thermal conductivity are steady-state platforms [70], hot disk thermal constant analyzers [72], and thermal conductivity testers [69]. The thermal conductivity can be calculated using Equation (2) where k is the thermal conductivity (W/(m·K)), μ is the thermal effusivity (W/(m^2·K)), ρ is the density (kg/m^3), and C_p is the specific heat capacity (J/(kg·K)) [73].

$$k = \frac{\mu^2}{\rho\, C_p} \quad (2)$$

3.2.5. Microstructure of Bamboo

Bamboo microstructure was widely studied by the different researchers. Bamboo is a radially graded, transversely isotropic composite material [7]. The microstructure of bamboo can vary among different bamboo species and culm regions. The arrangement and characteristics of the vascular bundles, parenchyma cells, and fiber strands impact the overall mechanical behavior and physical properties of bamboo. Figure 10 shows the scanning electron microscope (SEM) images of raw bamboo culm with different constituents [73]. It is a zoom-in view of the vascular bundles of bamboo along with the parenchyma cells. The SEM images of bamboo are shown in Figure 10. Dixon et al. [53] investigated three different bamboo species: Moso, Guadua, and Tregai. They observed that Moso and Tre Gai exhibited similar volume fractions of fibers and similar variations across the culm wall, whereas Guadua generally had a higher fiber volume fraction but a similar distribution. The average fiber volume fractions obtained for each species were 0.20 for Moso, 0.33 for Guadua, and 0.16 for Tre Gai. The variation in the density of Moso bamboo can be attributed to the distinct proportions and growth patterns of its vascular bundle tissues and parenchyma ground tissues [7]. The volume of lumen in parenchyma tissue was significantly reduced, resulting in a nearly uniform distribution instead of gradually changing along the thickness direction [51]. Lee et al. [55] examined the structure of Moso bamboo subjected to heating treatment and found that bamboo treated at higher temperatures experienced significant damage to its tissue structures, especially the parenchyma cells. Through FTIR spectroscopy, they observed that as the treatment temperatures increased, the intensity of characteristic absorption peaks of polysaccharides decreased while the intensity of lignin peaks increased. Yang et al. [28] performed an alkali pre-treatment method of 6% Sodium hydroxide (NaOH) on Moso bamboo, which aimed to remove the hydrophobic layer from bamboo surface and improve the permeability for the main treatment which is the impregnation of two types of rosin such as epoxy-modified and natural rosin. The study found that by modifying rosin with epoxy, it was possible to fill the cell lumens of bamboo, including the small nanopores in cell walls and spaces between cells. This filling of the bamboo's structure resulted in improved dimensional stability, with a decrease in swelling by 33.74%. The modified rosin also enhanced the hydrophobicity of the bamboo, as indicated by an increased contact angle and a reduction in water absorption by 24.73%. The modified rosin physically filled the vessels, parenchyma cells, and other structures of the bamboo after impregnation. Ramful et al. [58] studied Madake bamboo and conducted smoke treatment to the culms and found that bamboo showed an increase in lignin content at a specific peak of 1114 cm^{-1}. This increase was due to the thermal effect of temperatures above 100 °C, resulting in poly-condensation reactions.

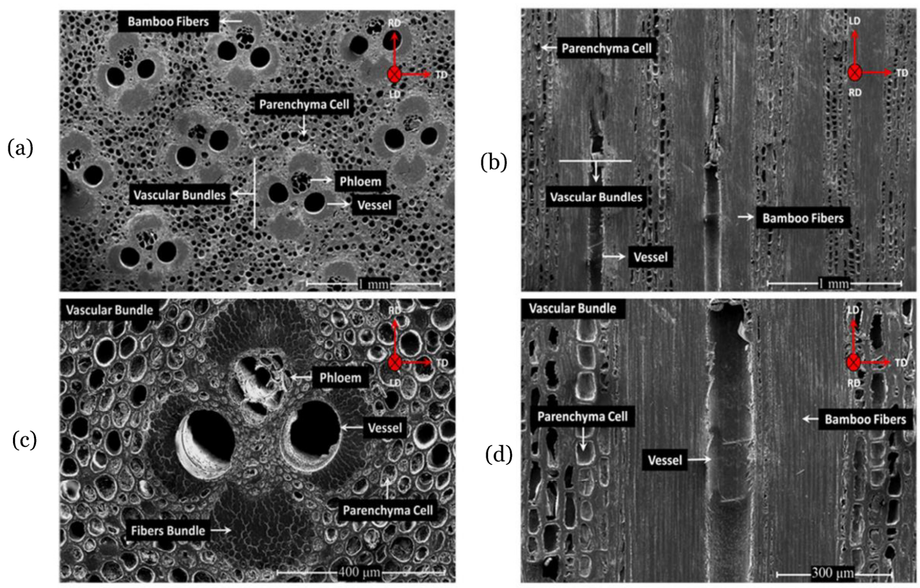

Figure 10. *Cont.*

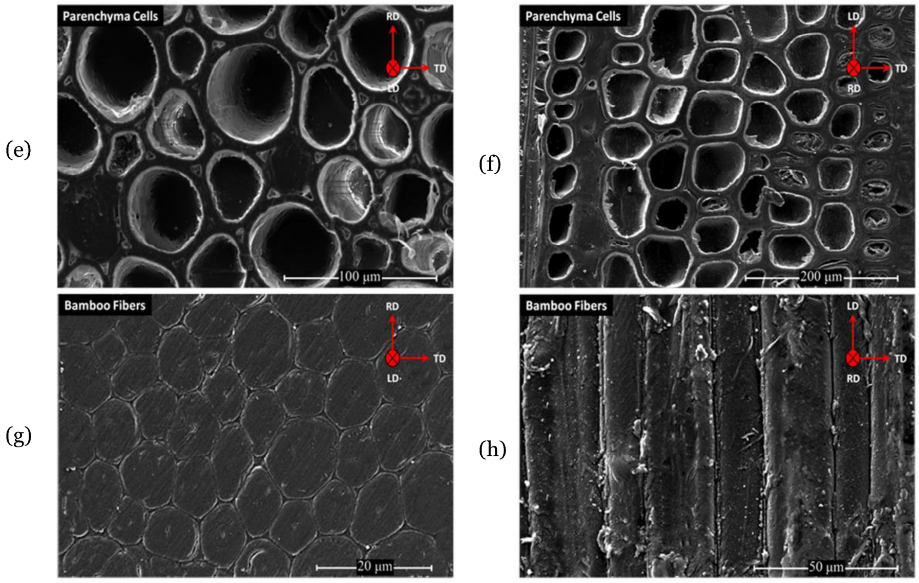

Figure 10. SEM micrographs of the raw bamboo culm with different constituents. Transversal direction (**a**,**c**,**e**,**g**), and longitudinal direction (**b**,**d**,**f**,**h**). All figures are adapted with permission from [73], Scientific Reports, 2014.

3.3. Mechanical Properties

Bamboo exhibits remarkable mechanical properties that make it a versatile and sustainable material. Bamboo composite or engineered bamboo is widely explored to optimize the utilization of bamboo. The mechanical properties of engineered bamboo products can be influenced by processing methods [24]. Table 5 shows the summary of the studies that highlighted the mechanical properties of bamboo. Compressive strength (CS), tensile strength (TS), flexural strength (FS), shear strength (SS), modulus of rupture (MOR), and modulus of elasticity (MOE), hardness, ultimate bearing capacity, and durability. Figure 11 shows the test set-up for mechanical testing of bamboo specimens for compression, bending, shear, and tensile parallel to the grain.

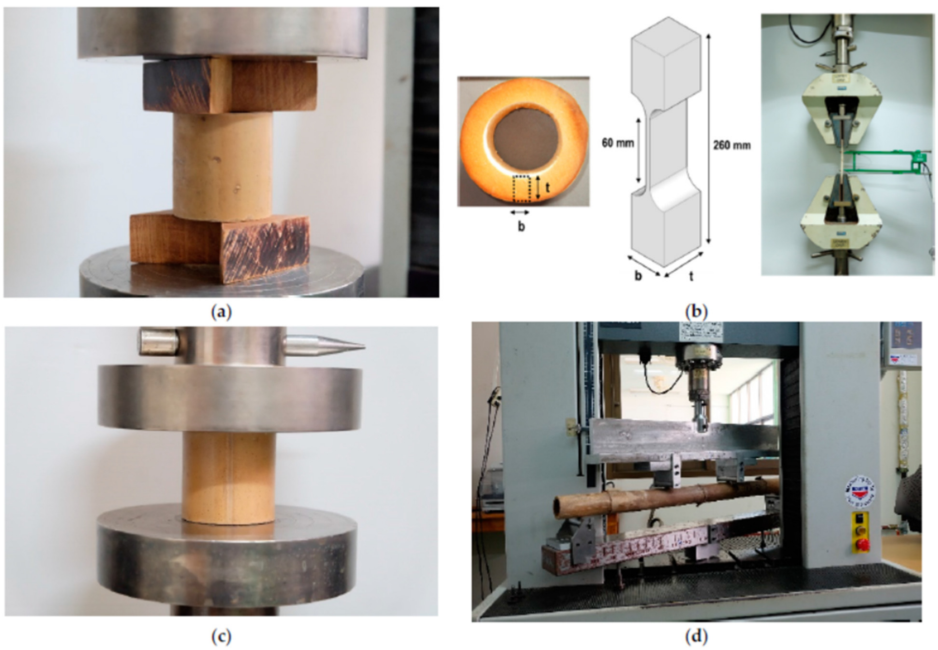

Figure 11. (**a**) shear strength test, (**b**) tensile strength test, (**c**) compressive strength test, (**d**) four-point bending test. All figures are adapted with permission from [18], MDPI, 2021.

Table 5. Summary of the study on mechanical properties of bamboo.

Reference	Bamboo Species	Age	CS	TS	FS	SS	MOR	MOE	Hardness	Ultimate Bearing Capacity	Durability
[11]	S-1	3		✓				✓	✓		✓
[74]	S-1, S-15	4	✓	✓	✓						
[75]	S-3	3			✓						✓
[76]	S-4	NA	✓								✓
[21]	S-5	NA			✓						
[45]	S-1	NA	✓	✓						✓	
[49]	S-1	4	✓	✓			✓	✓			
[8]	S-6	4					✓	✓			
[77]	S-7	NA				✓					
[53]	S-1, S-5, S-7	3–6		✓	✓		✓	✓			
[15]	S-5	NA	✓								
[54]	S-1	4	✓					✓			
[62]	S-7	NA					✓	✓			
[63]	S-9	2–3					✓	✓			
[78]	S-1	4–5	✓	✓		✓					
[24]	S-1	NA	✓	✓	✓		✓	✓			
[22]	S-1	3	✓	✓	✓	✓	✓	✓			
[51]	S-1	4		✓	✓						
[23]	S-1	NA	✓	✓		✓					
[56]	S-1	4	✓		✓		✓	✓			
[5]	S-1	4			✓		✓	✓			
[42]	S-5	2–5	✓		✓	✓					
[27]	S-1	3			✓	✓	✓	✓			
[79]	S-1	NA		✓							
[80]	S-12	3–4	✓								
[58]	S-13	3							✓		✓
[81]	S-12	NA			✓		✓	✓			
[59]	S-1	2, 4, 6		✓	✓						
[13]	S-1	NA			✓						
[1]	S-1, S-5	NA	✓		✓	✓					
[16,67]	S-1, S-5, S-18, S-13	NA	✓								
[12]	S-1	NA		✓				✓			
[10]	S-15	6	✓								
[60]	S-16	3 to 5				✓					
[47]	S-1	4	✓		✓	✓	✓	✓			
[14]	S-6, S-16, S-17, S-18	NA	✓	✓							
[48]	S-1	3			✓		✓	✓			
[64]	S-1	3–5	✓				✓				
[65]	S-1	5			✓	✓	✓	✓			
[44]	S-18	NA	✓		✓	✓	✓	✓			
[17]	S-1	3–5	✓			✓					
[59]	S-1	NA			✓		✓	✓			
[82]	S-1	NA								✓	
[83]	S-6	NA								✓	
[84]	S-7, S-14	NA						✓			

3.3.1. Compressive Strength

Among all the species studied in this article, Drury et al. [16] reported that Moso bamboo from China had the highest compressive strength of 69.9 MPa tested with nodes in their study comparing four bamboo species such as Moso, Guadua, Madake, and Tali, which were obtained from three different countries. Awalludin et al. [14] observed in their comparative study of the mechanical properties of the different species that *Bambusa vulgaris*, *D. asper*, and *Gigantochloa scortechii* have excellent mechanical properties in compression as well as tensile strength.

Bamboo Culms

Generally, compressive strength is correlated with density [1,10,54]. Bahtiar et al. [15] studied the structural grading of Guadua angustifolia on short members to determine the compression resistance and developed a prediction model. The grading capacity could be predicted through the linear mass, and the density is the indicating predictor for the compressive strength. Here, the compressive strength of samples that have nodes was higher compared to non-node samples although the difference was not significant (82.2 MPa and 75 MPa). Still, the result differed from some of the studies that observed nodal samples had lower strength than those without nodes [45,82]. According to Nie et al. [82], the influence of bamboo nodes on compressive behavior increases with an increasing nominal diameter. Specifically, specimens with relatively larger diameters and without nodes can experience an increase of up to 18.2% in ultimate stress compared to bamboo tubes with nodes. The influence of bamboo nodes on the compressive behavior of bamboo tubes should be considered during the design of practical structures, especially for bamboo columns with relatively larger diameters. But with respect to ultimate bearing capacity, nodal samples are better. In addition, Drury et al. [16] observed that the compressive strength of culm is not affected by the nodes because, in his study of the comparison of strength of different species, the highest compressive strength was obtained by the sample that had nodes, i.e., both Moso and Madake species. However, in the result of Guadua, Tali, and Black Java specimens, the highest compressive strength was obtained from the internodal specimens. Gauss et al. [17] identified that nodes have a significant local effect on the behavior of the tensile, but it can be disregarded in compression and shear. The failure mode is also a general concern in bamboo specimens tested in axial loading. Zhou et al. [54] observed a ductile failure characteristic in *Phyllostachys edulis* bamboo tested in parallel to grain, similar to the observation of Cui et al. [11] on bamboo fiber bundles. Basically, the common mode of failure of bamboo culms tested in parallel to the grain is splitting and end bearing [14,45,82,85]. The end-bearing failure is mostly influenced by high moisture content [85]. In the study conducted by Nie et al. in 2022 [82], it was observed that in full-culm bamboo tubes with bamboo nodes, longitudinal cracks appeared first on the bamboo nodes, followed by the tearing of the inner diaphragm into multiple sections. Various research findings have led different researchers to conflicting conclusions regarding the variation of bamboo strength along its culm length. Mukhopadhyay et al. [80] confirmed higher compressive and cleavage strengths in the relatively upper parts of culms, which aligns with the findings of Jusoh et al. [86]. But Chung et al. [85] observed that both physical and mechanical properties are constant along the bamboo culm length. The compressive strength of bamboo can be improved with treatments. The bamboo treated with polycarboxylic acid increased compressive strength up to 17–20% [56].

Concrete-Filled Bamboo Culms

Aside from treatment, the strength of bamboo culm can be further improved, and failure will be delayed by filling materials inside it. The compressive strength of bamboo filled with concrete and mortar was investigated by Li et al. [45]. Culm specimens are comprised of nodes, without nodes, with and without stiffener, with and without reinforcement, and the combinations of these parameters. It was observed that both concrete and mortar–filled culm had a higher axial load-bearing capacity and initial stiffness. But concrete fill was more efficient than mortar. This coincides with the study of Nie et al. [82], which also utilized a concrete filler in bamboo culm and proved that by adopting the method of internal concrete filling, the ultimate bearing capacity of full-culm bamboo tubes could be significantly enhanced. Also, Li et al. [45] observed that the concrete-filled specimen's failure occurred in splitting mode; the splitting failure can be delayed by the nodes and stiffener. The horizontal stiffener on the bamboo that passes through the bamboo internodes had a good effect on the ultimate bearing capacity (UBC) and axial strains of both concrete and mortar filler, but for the stiffener that passes through the node, it is not advisable since it decreases bearing capacity. The average UBC of concrete filled culm was increased to a maximum of 65.3% compared with no-fill bamboo culms. But this UBC of the bamboo was further improved by [82] by using bamboo sheet-strengthened concrete-filled full-culm bamboo tubes (BSCBs) in which the bamboo sheets are wrapped to bamboo tubes with epoxy resin adhesive. This method improves the ultimate bearing capacity by more than 2.5 times higher than the concrete-filled bamboo alone. However, ref. [82] did not include in their study the effect of nodes on both concrete filled and sheet-strengthened concrete-filled bamboo culm. For these studies, different filling materials could have different effects also, such as geopolymer concrete, recycled concrete with ash, or a combination, which is a possible future interest.

Bamboo Composite

Bamboo culm is also utilized to produce composite materials or used as reinforcement in which the application could be optimized. Sayed et al. [87] studied bamboo sticks and used it as reinforcement for concrete, Fabricating a concrete tube with bamboo sticks. Using bamboo sticks as reinforcement improves the compressive strength of concrete. The test result shows that with the addition of 0.6% of sticks, the BSRC compressive strength rose by 3.24 and 17.33% for length-to-diameter ratios 20 and 30, respectively. The compressive strength of specimens was enhanced by adding 1.2% and 2.4% bamboo sticks with a length-to-diameter ratio of 10 by 21.38 and 20.94%, respectively. For laminated bamboo lumber made from Moso bamboo, the bamboo nodes have a beneficial effect when tested perpendicular and parallel to the grain because they increase the compressive strength by 11.25% and 27%, respectively [78]. A semi-caramelized laminated bamboo demonstrated a slightly higher capacity in compression for both perpendicular and parallel to the grain [24]. Rao et al. [47] studied a composite bamboo material, which was the outdoor bamboo-fiber-reinforced composite (OBFRC) to be used in flooring. This study utilized resin and observed the 20% content is effective. The compressive strength of the specimen decreases gradually as the resin content increases. Yang et al. [22] fabricated a unidirectional round bamboo stick boards (USBS) from bamboo culm and recognized the improvement of compressive strength under heat treatment of 155 °C, and not advised to increase the temperature more. An engineered bamboo scrimber was fabricated and tested by Kumar et al. [23] from Moso species and observed that the compressive strength of bamboo is comparable to that of the commonly used grade of concrete in residential buildings and can be further improved by treatment because treated bamboo performed better. In laminated bamboo lumber, nodes have a beneficial effect in compression tested in parallel to the grain, which seemed to increase the compressive strength by 11.25% and 27% for perpendicular to the grain.

3.3.2. Hardness of Bamboo

The hardness of bamboo is not the main concern of most of the studies in this article. The study of Dong et al. [56] on bamboo scrimber treated with three methods, such as heating, polycarboxylic acid (citric acid), and butanetetracarboxylic acid (BTCA), observed that the hardness of bamboo after heat treatment was dramatically reduced. However, in other treatments, such as CA and BTCA, they had no significant impact and noted that the hemicelluloses degradation of bamboo caused by heating could be the main factor in the decrease of the surface hardness. Another study, which also differentiates the hardness with respect to different treatments, was conducted in [58]. In their study, the methods were smoke, dried, and dyed treatments. The hardness of the specimen was measured from the radial–longitudinal section, and they observed that smoked treatment resulted in greater hardness ranging from 75 MPa to 250 MPa. This obtained value is two-fold higher compared to the untreated samples. Furthermore, Cui et al. [11] attributed the increase in hardness of Moso bamboo fiber bundles to a change in chemical structure resulting from treatment modification, and their observations revealed a positive correlation between temperature and the hardness of the fiber cell walls, with an increase from 0.36 to 0.47 GPa.

3.3.3. Tensile Strength

Culms

Like compressive strength, the tensile strength of bamboo can vary depending on several factors, including the species, age, growing conditions, processing methods, and treatment. The comparative study of Awalludin et al. [14] observed that *Bambusa vulgaris*, *D. asper*, and *Gigantochloa scortechii* have excellent tensile strength. Zhou et al. [54] observed that the tensile strength of bamboo culm is correlated with the density; as the density increases, the tensile strength also increases. This is similar to the findings of [23] on density and strength with a typical brittle failure. Gauss et al. [17] identified that nodes have a significant local effect on behavior on the tensile properties. On the other hand, the tensile behavior of the bamboo culm is dictated by the fiber volume fractions [10]. The integrated process of flattening and densification on the gradient structure of bamboo improves the tensile properties across the gradient, which was observed by [51]. Also, the tensile properties of full-thickness bamboo splits were improved, and the change in stress distribution led to a stable structure. Cui et al. [11] examined Moso bamboo fiber bundles (BFB) obtained manually from Moso bamboo culms. The fiber bundles underwent heat treatment at temperatures ranging from 160 °C to 220 °C. The initial average tensile strength of the unheated specimens was measured at 423.29 MPa. As the temperature increased, the tensile strength gradually decreased, reaching 191.61 MPa at 220 °C. In a parallel study by Wang et al. [59], the mean tensile strength of bamboo fiber bundles (BFB) ranged from 653.3 MPa to 766.2 MPa.

Composite

Sun et al. [49] determined the tensile strength of bamboo strand-based structural composite lumber that underwent rosin treatment. The study confirmed that there was a decrease in the tensile strength of the high-density board with the content of rosin. The thickness of the strand has no impact on the mechanical properties of composite material with different densities. The mechanical properties of laminated bamboo lumber (LBL) from Moso species under a drying treatment were determined by [78] in both perpendicular and parallel to the grain. The presence of nodes had a negative impact on the tensile resistance of the bamboo, indicating that the strength against pulling forces was reduced. A similar study on laminated bamboo lumber (LBL) and that also tested both perpendicular and parallel to the grain, but with different treatments, was conducted by [24]. The material subjected to bleaching exhibited a slightly higher tensile strength compared to the caramelized and semi–caramelized treated bamboo. However, the tensile strength of non-treated sample is still higher. The effect of node in the result of the test was not indicated in this study.

The tensile and bending performance of the bamboo sliver were tested by Wu et al. [12]. After treating the specimens with alkali, the outer bamboo slivers showed the highest tensile strength at 60 °C, while the inner bamboo slivers achieved their highest tensile strength at 40 °C, with both values being 86.6% and 132.0% higher, respectively, than the tensile strength of the untreated ones.

Concrete-Filled

Tensile testing was primarily conducted by Li et al. [45] in their study on the bamboo culm filled with concrete and cement mortar, as one of the baselines for the evaluation of the ultimate bearing capacity. The average *longitudinal* tensile strength, longitudinal tensile modulus, and longitudinal ultimate tensile stain of bamboo obtained from these coupon tests were 147.06 MPa, 13.70 Gpa, and 1.07%, respectively. The samples tested in transverse, obtained average values of 8.36 MPa for circumferential tensile strength, 2.11 GPa for circumferential tensile modulus, and 0.40% for circumferential ultimate tensile strain. It was observed that the ultimate bearing capacity of bamboo filled with concrete and mortar increased by 226% and 86%, respectively, compared to the hollow specimens. Another study on bamboo filled with concrete by Nie et al. [82], performed a tensile test for the evaluation of the ultimate bearing capacity of the bamboo culms filled with concrete. The average tensile strength, tensile modulus, and ultimate tensile strain were 184.28 MPa, 14.74 Gpa, and 1.26%, respectively, were obtained from testing parallel to the grain. For the test of perpendicular to the grain, only the average hoop tensile strength of bamboo was indicated, which was 9.38 MPa. Both studies used Moso bamboo species. It can be observed that between these two studies, the bamboo culm that was used by the previous study has higher tensile properties compared to the later. But it would have been better if the later study also indicated the sets of tensile properties obtained in testing perpendicular to the grain.

3.3.4. Shear Strength

Bamboo possesses a unique fibrous structure with interconnected fibers that contribute to its mechanical properties [3,45,46], including shear resistance. The shear stress behavior of bamboo is a critical aspect in understanding its mechanical properties and suitability for various applications. Bamboo, known for its remarkable strength and flexibility, exhibits distinct shear characteristics due to its unique fibrous structure [45]. Regarding the shear property of a composite bamboo material, the existence of a node in the test specimen leads to a localized stiffening effect. Additionally, the type of adhesive used and its spread rate were found to have a significant impact on the compression and shear bond strengths of LBL [44]. Similar to the study of Zhang et al. [78] in Moso bamboo, which underwent drying treatment, the presence of nodes did not affect the shear strength of LBL units but had an obvious negative impact on the shear modulus, causing an average reduction of 34.62%. In the study of Kumar et al. [23], which determined the effect of density on the mechanical properties of bamboo scrimber, the shear strength of bamboo was found to range from 4.09 to 5.86 N/mm^2, which is comparable to concrete. However, this strength can be further enhanced by transforming bamboo into a composite material or applying appropriate treatment methods. Bamboo's eco-friendly nature is evident as it decomposes faster than other construction materials and does not generate harmful waste that could harm ecosystems.

3.3.5. Flexural and Bending

The flexural strength of bamboo is on par with other timber, and compared to wood, the strength in flexure of bamboo is better [21], which may be further influenced by different treatment methods. Similar to other mechanical properties of bamboo, the flexural strength of bamboo has a positive relationship with its density [48]. On the other hand, Chen et al. [5] confirmed that the flexural strength of bamboo exhibited a direct correlation with the vascular bundle content, while the flexural ductility showed a direct correlation with the parenchyma composition. However, there was a contradictory association between the flexural strength and ductility in bamboo. Also, bamboo outperforms wood with respect to flexural ductility.

Greco et al. [75] investigated the impact of ultraviolet (UV) irradiation on the mechanical properties of bamboo culm, in both dried and untreated samples. The research revealed that UV exposure for up to 360 h resulted in a decrease in the lignin content and surface changes, but it did not compromise the longitudinal fiber structure. Therefore, the study confirms that UV exposure lasting 360 h has no significant effect on the bending properties of bamboo. Cid et al. [27] determined the effect of hornification treatment on the flexural behavior of bamboo. Distinct mechanisms were observed for each orientation examined:

a brittle response was observed when the inner face was subjected to tension, while a ductile response was observed when the outer face was under tension. The treatment, in general, resulted in decreased ultimate deflection and increased stiffness and strength. However, the effect on strength was not significant when the inner wall was subjected to tension. Lorenzo et al. [13] used prestressed stainless-steel bands to reinforce the bamboo pole when tested in bending stress. However, the result showed that the reinforcement has no significant effect in counteracting the development of significant circumferential tensile stresses in the pole. This was extensively tested through simulation, but the result remains the same. A laminated veneer lumber (LVL) was tested by Wang et al. [59], and they observed that the bending strength and modulus were significantly increased with the addition of bamboo fiber bundles (BFB). Another composite is the laminated bamboo lumber (LBL), which was fabricated from a bamboo culm with and without nodes to determine the effect of nodes on the mechanical properties of composite material. Increasing the intervals between nodes in LBL resulted in improved flexural performance. The study findings also indicated that most bending failures occurred at the nodes.

3.3.6. Modulus of Rupture

The modulus of rupture is a mechanical property of bamboo that measures its resistance to breaking or fracturing under bending stress. The modulus of rupture represents the maximum stress that bamboo can withstand before it fails or fractures when subjected to a bending load. The modulus of rupture of Moso, Tregai, and Guadua bamboo species are similar at a given density [53]. Sa Ribeiro et al. [8] determined the MOR of culm of *Bambusa vulgaris*, which ranged from 48 MPa to 132 MPa. For the bamboo composite, such as Bamboo strand composite lumber (BSCL), the MOR was as high as 300 MPa. The MOR of a single glue line (SGL) bamboo composite has a higher value than the DGL or the double glue line, and the MOR value also had a wider brushed surface for a given assembly time limit [63].

3.3.7. Modulus of Elasticity

The MOE of bamboo is higher than that of wood by about 0.84 times [5]. Guadua exhibits a higher axial modulus of elasticity compared to Moso or Tre Gai, with the latter two showing similar values. Additionally, ultrastructural results indicate that Guadua has a higher solid cell wall stiffness. At a given density, their moduli of rupture are also similar [53]. The modulus of elasticity of bamboo improves when it undergoes treatment methods [11,24,53,56]. Gottron et al. [62] stated that the orientation of the specimen significantly influenced both the creep behavior and residual strength of creep-conditioned specimens; specimens loaded with the outer culm-wall in tension exhibited a larger modulus of elasticity. Sa Ribeiro et al. [8] investigated the modulus of elasticity of *Bambusa vulgaris* culm, which ranged from 6.1 GPa to 14.2 GPa. The analysis of the results revealed that bamboo culm density and dynamic modulus of elasticity are useful indicators for determining its strength and stiffness. Thin-walled bamboo laminated bamboo esterilla sheets (LBES) showed higher MOE, which is superior for the flexural member [63]. For bamboo composite, such as Bamboo strand composite lumber, the MOE is as high as 30,000 MPa [49]. BSCLs have the potential to be considered as a high-performance alternative to wood-based structural composite lumber.

Table 6 provides a comprehensive summary of the mechanical properties of bamboo; this includes compressive strength, tensile strength, flexural strength, shear strength, corresponding modulus of elasticity and modulus of rupture, hardness, and ultimate bearing capacity. While some studies presented their findings in terms of percentage increase and overall improvement without specific numerical values, those results were not incorporated into the summary. Table 7 shows some of the mechanical properties of wood. David et al. [88] presented some physical and mechanical properties of various types of wood grown in America, which include basswood, cherry back, black cottonwood, hackberry, and chestnut oak. The average tensile strength of bamboo is very much higher compared to these woods, as well as the compressive strength. Tumenjargal et al. [89] studied *Larix sibirica* wood species and obtained a high compressive and shear strength; however, the availability of this wood worldwide is limited compared to bamboo. Bamboo stands out as a readily accessible and rapidly growing plant worldwide compared to other types of wood.

Table 6. Summary of findings on mechanical properties of bamboo.

Reference	CS (MPa)	TS (MPa)	FS (MPa)	SS (MPa)	MOR (MPa)	MOE (GPa)	Hardness	Ultimate Bearing Capacity, kN	Remarks
[11]		191.61–423.29 ‖				21.29–27.53	360–470 MPa		
[74]	42.50–52.73 ‖	159.01 ‖ ^{1} 164.30 ‖ ^{2}	148.69 ‖ ^{1} 153.31 ‖ ^{2}						^{1} S-1, 2 ^{2} S-15
[75]			130–160 ‖						
[76]	57 ‖								
[45]	32.72 ‖	147.0 ‖, 8.36 ⊥						171.44–210.14 ^{1} 326.25–550.87 ^{2}	^{1} mortar, ^{2} concrete
[49]	24.27–158.26 ‖			5.48–36.22	64.63–328.18	13.35–29.34			
[8]					48–132	6.1–14.2			
[53]					50–220	5.0–20.0			
[15]	75–82.2 ‖								
[61]	38.46–162.82 ‖					8.30–17.15			
[62]					76.7–107.6	26.82–36.24			
[63]					74.56 ^{1}, 82.72 ^{2}	18.93 ^{1}, 18.74 ^{2}			^{1} manual, ^{2} hydraulic
[78]	50.57 ‖, 14.82 ⊥	112.56 ‖	118.0 ‖	17.34		9.90			
[24]	55–60 ‖, 22 ⊥	116–124 ‖	76–79 ‖, 3.0 ⊥	14–17		10.20–10.50			
[22]	114 ‖, 19.3 ⊥	136–294 ‖		13.5–14.8	225.0	21.0			
[51]		156.43–397.96 ‖	188.04–361.75 ‖						
[23]	104.71–115.7 ‖ 49.33–77.0 ⊥	111–144.75 ‖, 4.18–6.70 ⊥	131–83–166.5 ‖	11.89–17					
[56]	58.1–66.3 ‖				194.9–225.5	22.3–23.8	3.0–3.76 kN		
[5]			85.0–230.0 ‖		80–210.0	8.0–12.5			
[27]					122.0	18.5			
[79]		211.0 ‖							
[80]	38.40–92.37 ‖								
[58]							243.4 ^{1}, 76.0 ^{2}, 266.6 ^{3} MPa		^{1} smoked, ^{2} dried, ^{3} dyed
[81]			81.43–124.30 ‖			3.76			
[84]						2.11			
[59]		653.3–766.2 ‖				22.5–26.7			
[13]	43.9–72.2‖			15.9–21.8		8.81–13.2			
[1]	54–58.0 ‖			12.0–16.0		11.93–20.68			
[16]	59.1–69.9 ‖								
[12]		204.76–382.01 ^{1} 62.96–146.07 ^{2}							^{1} outer, ^{2} inner
[10]	67.3–94.7 ‖					0.60–0.70			
[60]				18.0					
[47]	95.26–107.09 ‖		178.35 ‖	19.21	165.65–178.35	16.6–18.16			
[14]	78.74	233.0				20.0			S-6, optimum
[64]	51.0 ‖	82.0 ‖	99.0 ‖		94.0	10.40			
[65]			123.62–149.84 ‖		106.39–128.14	7.24–7.60			
[44]	54.01–64.01 ‖			3.12					
[82]								619.54	
[83]								130.0	

‖—parallel to the grain; ⊥—perpendicular to the grain. Superscript on the mechanical properties corresponds with the identifications indicated in "Remarks" to categorized each value.

Table 7. Mechanical properties of other types of wood.

Reference	CS (MPa)	TS (MPa)	FS (MPa)	SS (MPa)	MOR (MPa)	MOE (GPa)	Hardness	Ultimate Bearing Capacity, kN	Remarks
[89]	46.3–51.1 ‖			10.4–13.0	79.8–13.9	7.03–9.51			Larix sibirica
[88]	15.3 ‖	1.9		4.1	34	7.2			Basswood
[88]	24.4 ‖	3.6		7.8	55	9.0			Cherry black
[88]	15.2 ‖	1.9		4.2	34	7.4			Black cottonwood
[88]	18.3 ‖	4.3		7.4	45	6.6			Hackberry
[88]	24.3 ‖	4.8		8.3	55	9.4			Chestnut oak
[90]					54.78	5.53			Persian silk wood (heartwood)
[90]					50.12	4.80			Persian silk wood (sapwood)

‖—parallel to the grain.

4. Bamboo Culm Treatment Methods

Bamboo is a natural material with impressive mechanical strengths; however, its long-term performance as a construction material is often questioned due to sensitivity to moisture and durability concerns, requiring further research for sustainable treatment solutions [52,61,76]. Hence, most of the studies on the mechanical properties of bamboo emphasized the treatments and methods used. This paper discusses the treatments used by the collected literature. Bamboo culms could be naturally or chemically treated, or a combination. Tables 8 and 9 show the summary of the treatments used by different articles collected in the respective bamboo species used. Natural treatments used in these papers are heating or thermal treatment with different methods (air and sun drying, boiling, oven), smoked, rosin impregnation, fire or flame, soaking or saturation (salt, seawater), oil treatment, and hornification. The chemical treatment includes the use of borax, alkali, epoxy resin, boron-based preservatives, polycarboxylic acids (citric acid and butanetetracarboxylic acid), disodium octaborate tetrahydrate (DOT) aqueous, rosin impregnation, copper naphthenate (CuN) impregnation, and or a combination.

Table 8. Summary of natural treatment on bamboo.

Reference	Age	Bamboo Species	Treatment
[11]	3	S-1	Heating
[75]	3	S-3	Abura–Nuki technique (Flame)
[51]	4	S-1	Steaming
[81]	NA	S-12	Lime water (slaked lime)
[91]	2, 4, 6	S-1	Heating
[58]	3	S-13	Smoked
[49]	4	S-1	Drying
[78]	4 to 5	S-1	Drying
[61]	5	S-1	Rosin impregnation
[52]	4	S-2	Steamed and rosin
[48]	3	S-1	Heating
[59]	NA	S-1	High-temperature saturated steamed treatment
[65]	5	S-1	Tung oil and heat
[22]	3	S-10	Heating

Table 8. *Cont.*

Reference	Age	Bamboo Species	Treatment
[55]	4	S-1	Heating
[76]	NA	S-4	Oil
[23]	NA	S-1	Thermal treatment using saturated steam (SST)
[64]	3–5	S-1	Boiling and air-drying
[21]	NA	S-5	Drying
[92]	NA	S-6	Hornification

Table 9. Summary of chemical treatment on bamboo.

Reference	Age	Bamboo Species	Treatment
[28]	4	S-11	Alkali pretreatment plus rosin (epoxy-modified rosin and natural rosin)
[16]	NA	S-1, S-5, S-13	Borax
[12]	NA	S-1, S-5	Alkali
[93]	4	S-2	Copper naphthenate (CuN) impregnation
[56]	4	S-1	Polycarboxylic acids [citric acid (CA butane tetracarboxylic acid (BTCA) plus heating
[60]	3 to 5	S-16	Disodium octaborate tetrahydrate (DOT) aqueous
[15]	NA	S-5	Boron-based preservative
[27]	3	S-1	Hornification phenomenon, cold impregnation w/epoxy resin
[1]	NA	S-1, S-5	Borax
[47]	4	S-1	PF resin post-treatment
[14]	NA	S-6, S-16, S-17, S-18	Borax
[94]	NA	S-8	Akali
[10]	6	S-15	Chemical treatment (deltamethrin)
[44]	NA	S-18	Borax
[53]	NA	S-1, S-5, S-7	Borax
[24]	NA	S-1	Steamed and bleaching
[79]	NA	S-1	Alkali
[84]	NA	S-14, S-7	Borax
[77]	NA	S-7	Borax

4.1. Natural Treatment Methods

The use of natural treatments on bamboo is more environmentally advantageous, making it a preferred choice for enhancing its properties and durability; natural treatments are also more economical. There were 20 studies that used natural treatment on bamboo, and most of them found that treatments have a beneficial impact on the improvement of the properties of bamboo. Some of the studies did not emphasize the impact of treatment on the physical and mechanical properties of bamboo; only a few have been discussed. The number of studies used heat treatment and discovered that it has a positive impact on the properties of bamboo [3,11,21,48,58,59], but the performance is affected by temperature in which higher temperature will result in a decrease in the properties [21,28,65,76]. The heat treatment had a notable impact on the surface color of the bamboo.

Cui et al. [11] used heat treatment and observed that with a heat treatment of 180 °C, the fracture surfaces of both bamboo bundles and single fibers exhibited a smoother appearance, which is a favorable outcome because smoother fracture surfaces observed after heat treatment on bamboo bundles and single fibers are indicative of positive effects, suggesting an enhancement in the mechanical properties and structural performance of the bamboo material. A similar method was used by Wang et al. [59], except that they performed mechanical modification. The thermal-mechanical method effectively extracted the fiber bundles from bamboo culms with little damage to the microstructure of bamboo fibers. This method did the isolation of the fiber bundles while preserving the integrity of the bamboo fibers' microstructure.

For a composite bamboo, the compressive strength, shear strength, and modulus of rupture values of Unidirectional bamboo stick boards (UBSBs) significantly improved when using bamboo sticks heat-treated at 155 °C, but higher heat treatment temperatures above 155 °C resulted in a decrease in the mechanical properties of UBSBs [48]. Temperature has a significant impact on all treatments that utilize temperatures in which there is a ceiling value of temperature. The study of Mena et al. [21], which used drying treatment, found that the flexural strength decreases if the temperature increases more than 15 °C. Heating with sunflower and vegetable oil treatment was performed by Bui et al. [76] who noticed that the maximum temperature of positive impact on compressive strength is up to 180 °C only, higher than it will decrease the compressive strength. Also, the oil is best if applied after heating, which they refer to as a "cooling" stage only. Tang et al. [65] applied Tung oil treatment to bamboo at temperatures ranging from 100 °C to 200 °C. Their findings indicated that the mechanical properties of bamboo, such as ultimate stress, modulus of elasticity, and modulus of rupture, remained unaffected when heat-treated below 200 °C, in comparison to untreated bamboo. The ceiling temperature in their study will not be determined because 200 °C is the highest temperature that they used. Maybe the result will be different with the temperature higher than 200 °C; this could be a call for a future study.

The density of bamboo culm improved after the steamed treatment [51]. Wang et al. [59] verified the difference between steam and heat treatment and observed that the equilibrium moisture content (EMC) of bamboo culms was effectively reduced through high-temperature saturated steam treatment. The smoke treatment has good performance, according to Ramful et al. [58], because smoke treatment on bamboo resulted in a hydrophobic surface with improved water-repelling ability. The treatment led to reduced hygroscopicity and increased lignin content due to thermal effects and poly-condensation reactions. Another advantage of the smoke treatment is it improves the hardness ranging from 75 MPa to 250 MPa, which is two-fold higher than untreated. Another treatment that is relatively new is the rosin treatment. Here, rosin is impregnated with the bamboo culm or bamboo composite. The effect of rosin on the porosity of bamboo is significant in that it decreased up to 14.43%, as verified by [52] using Hong bamboo species. The moisture absorption of the rosin–treated culms is significantly lower compared to the untreated culms.

4.2. Chemical Treatment Methods

Chemical treatment on bamboo enhanced its physical and mechanical properties [12,24,27,48,56,78]. Compared to the natural treatment methods, using chemicals will obtain faster results. However, some of the drawbacks are its environmental, health, and safety factors. There are 19 studies that applied chemical treatments on bamboo culms and composites in their methodologies. The chemical treatment includes the use of borax, alkali, epoxy resin, boron-based preservatives, polycarboxylic acids (citric acid and butanetetracarboxylic acid), disodium octaborate tetrahydrate (DOT) aqueous, rosin impregnation, copper naphthenate (CuN) impregnation, and or a combination. Some of the studies did not discuss the impact of treatments used to the properties of bamboo. None of the research that used the borax treatment specifically detailed how the treatment affected the characteristics of bamboo. However, these studies found that the compressive, tensile, and bending strength have significant performance during testing [14,16,47,54]. But on the literature available and other studies like Handana et al. [95], using borax treatment is an excellent choice. Borax solution, being environmentally friendly and water-soluble, is an ideal choice for preservation in both cold and hot soaking techniques. Its effectiveness in protecting bamboo from insect and fungal attacks has been well-established. Yang et al. [28] used alkali treatment and observed that as the alkali concentration increased, the weight loss rate of the bamboo samples also increased gradually. The contact angle decreased with higher alkali concentration, indicating a more effective removal of wax and silica from the outer and inner layers of bamboo. These changes significantly improved bamboo's permeability, making it a favorable environment for subsequent modification. As the alkali treatment temperature increased, the parenchyma cells in bamboo experienced greater collapse, leading to a significant reduction in width and thickness, resulting in a denser structure, especially in the inner bamboo slivers. The highest density for both outer and inner slivers was achieved at 40 °C, increasing by 45.6% and 88.3%, respectively, compared to untreated slivers [12]. A similar treatment was used by Zhang et al. [78], which also observed a similar result on the improvement on the mechanical properties of bamboo using alkali treatment. Sharma et al. [24] differentiate the effect of using bleached to heat treatment. In heat treatment, it is classified into two categories; caramelized and semi-caramelized. The mean shear strength of the semi-caramelized bamboo is higher than the bleached bamboo. They found that the specimens that had undergone bleaching had a slightly higher tensile strength. An improvement in the tensile strength of bamboo is similar to the findings of Cid et al. [27], except that they used a different treatment; here, they used Epoxy resin. Dong et al. [56] conducted a study showing that polycarboxylic acid treatment is an eco-friendly and cost-effective method to enhance bamboo properties. Treated samples exhibited high termite resistance and minimal mass loss. The compression strength of bamboo increased by 17–20% after treatment. However, heat treatment reduced the surface hardness significantly, whereas CA and BTCA treatments had no evident impact. The decrease in surface hardness is likely due to hemicellulose degradation caused by heating. Jiang et al. [93] performed Copper naphthenate (CuN) impregnation and oil on bamboo specimens and observed that the application of CuN during heat-cold impregnation enhanced the termite resistance of bamboo significantly. Compared to the untreated control, heat oil treatment, and heat-cold impregnation of mineral oil alone, the CuN-treated round bamboo showed notable improvements in decay and mold resistance.

5. Bamboo Codes, Standards and Application

Bamboo can be utilized in all parts of the house, including structural columns, beams and walls, flooring, doors, and windows [96]. It is a sustainable building material. However, its application is still limited [30]. In the early ages, it is already used as a building material for the construction of light houses. This material is also used as bracings and temporary scaffoldings for light construction in Asian countries. However, the application of this material cannot be optimized because of some constraints, such as preservation and connections. It is known that the weakness of bamboo is its decay over time and that it will be attacked by termites and other insects if not treated [25]. Bamboo connection is also a concern, especially the use of whole culm. Many researchers nowadays are still working on the development of bamboo connections to maximize its performance. The codes and standards available regarding the requirements and procedures are also insufficient to fully adapt the use of bamboo as a structural material [30].

5.1. Codes and Standards Utilized by References

The significant impact of testing methods on results has prompted most industries to establish standardized testing procedures [39]. There are available International Standards, requirements, and testing procedures for bamboo. However, there are variations in the result [97], which may be because of different variables such as methods, species, origin, type of testing machines, and others. Among the various variables, the testing standard emerged as the most influential factor affecting the mechanical property values of bamboo [39]. Some of the literature in this paper did not mention the codes and standards used in their studies. Table 10 shows the different codes and standards used in this paper.

Table 10. Codes and standards used.

Reference	Codes and Standards	International	National	Country	bamboo	Wood	Composites	General Guidelines	Testing (Physical)	Testing (Mechanical)	Structural Design	Characteristics Value	Grading	Treatment
[1,15,50,64,74]	ISO 22157-2019;	✓			✓			✓	✓	✓				
[8,14,15,17,24,27,92]	ISO 22157-2004;	✓			✓			✓	✓	✓				
[77,98]	ISO 22156	✓			✓			✓			✓			
[42]	ISO 12122–1	✓			✓	✓		✓				✓		
[15,42]	ISO 19624	✓						✓					✓	
[44,63,64,84]	ASTM D143	✓			✓	✓				✓				
[91]	ASTM D3379	✓				✓				✓				
[91]	ISO 9427	✓				✓	✓		✓					
[59]	ISO 16979	✓				✓			✓					
[48,91]	ASTM D1037-12	✓					✓		✓	✓				
[10]	ASTM D3039	✓					✓			✓				
[44]	ASTM 3043	✓					✓			✓				
[44]	ASTM D7078	✓					✓			✓				
[44]	ASTM 5266-99	✓				✓				✓				
[78]	ASTM D3822-07	✓				✓				✓				
[12,56]	GB/T 15780		✓	China	✓				✓	✓				
[1,13,54,78]	JG/T 199:2007		✓	China	✓			✓	✓	✓	✓			
[52]	GB/T 1928-2009		✓	China		✓		✓	✓	✓				
[47]	GB/T 17657-2013		✓	China		✓			✓	✓				
[47]	GB/T 30364-2013		✓		✓		✓	✓						
[98]	EN 12512		✓	Europe		✓		✓	✓	✓		✓		
[24]	EN 408		✓	Europe		✓		✓	✓	✓				
[75]	UNI 11842-2021		✓	Italy	✓				✓	✓				
[75]	JIS-A		✓	Japan	✓									✓
[80]	NBC SP7-2005		✓	India				✓						

The International Standards used includes (1) ISO 22157-2019 [1,16,54,74,75]: 2004 [8,14,15,17,24,27,92]: test methods for determination of physical and mechanical properties of bamboo culms; (2) ISO 22156 [77,98]: bamboo–structural design which basically concerned with the requirements for the mechanical resistance, service and durability of bamboo structures; (3) ISO 12122-1 [42]: determination of the characteristic values for a defined population of timber products; (4) ISO 19624 [15,42]: basic principles and procedures of the grading of bamboo culms for bamboo structures; (5) ASTM D143 [44,63,64,84]: standard test methods for small clear specimens of timber; (6) ASTM D3379-75 [91]: standard test method for tensile and young's modulus for high–modulus single filament materials; (7) ISO 9427 [91]: methods of determining the density of wood–based panels; (8) ISO 16979 [59]: determination of the moisture content of wood–based panels; (9) ASTM D1037-12 [48,91]: standard test methods for evaluating properties of wood–based fiber and particle panel materials; (10) ASTM D3039 [10]: standard method for tensile testing composites; (11) ASTM 3043-00 [44]: standard test for structural panels in flexure; (12) ASTM D7078-12 [44]: standard test method for shear properties of composite materials by V-notched rail shear method; (13) ASTM 5266-99 [44] standard practice for estimating the percentage of wood failure in adhesive joints; and (14) ASTM D3822-07 [78]: standard test method for tensile properties of single textile fibers.

China has their own codes in standards of bamboo. The earliest is the (1) GB/T 15780 [12,56]: testing methods for physical and mechanical properties of bamboos; (2) JG/T 199:2007 [1,13,54,78]: testing methods for physical and mechanical properties of bamboo used in building; (3) GB/T 1928-2009 [52]: general requirements for physical and mechanical tests of wood; (4) GB/T 17657-2013 [47]: test methods for evaluating the properties of wood-based panels and surface decorated wood-based panels; (5) GB/T 30364-2013 [47]: guidelines for bamboo scrimber; and (6) GB/T 20241-2006 [47]: a guidelines of the laminated veneer lumber.

There are studies in the literature that used European standards such as (1) EN 12512, and (2) BS EN 408. The EN 12512 [98] governs the requirements and test methods for materials, geometry, strength, stiffness, and durability aspects of dowel fasteners used in load-bearing timber structures. Another is the BS EN 408 [24], which guides the determination of some physical and mechanical properties of timber structures and glued laminated timber. Italy has UNI 11842-2021 [75], which governs the test procedures for the mechanical characterization of bamboo culms. Greco et al. [75] used this in their investigation of the photodegradation of bamboo in UV rays. The JIS is the Japanese International Standard, which was used by Bui et al. [76] in their study on the effect of heat and oil treatment on the mechanical properties of bamboo. They observed that the compressive strength of bamboo was improved after heat treatment and oil application (after heating). They noted that the maximum temperature is 180C because larger than it will degrade the strength. Lastly, Mukhopadhay et al. [80] used the National Building Code NBC SP7–2005 of India in their investigation of the compressive and cleavage strengths of Indian bamboo species. It is observed that most of the studies utilized International Standards. Based on the articles gathered in this paper, there is no study that has common parameters that can be used to differentiate the standards because they differ in methods, preparations, treatment, and species. This could be an avenue for future interest. Putting more interest on the codification and standardization of bamboo usage is needed for the growing interest in this material [99]. Kumar et al. [23] pointed out that there are still no codes and standards in characterizing engineered bamboo composites; thus, comparing it with the literature is the best they can do to assess the results, each of which also utilized different standards. There is available literature outside the articles gathered, which conducted an assessment on the tensile strength of bamboo, which assessed the result obtained between ISO 22157 and modified ASTM D143 [100]. They observed that the result of tensile strength obtained from modified ASTM has obtained a higher value compared to ISO 22157. This could be a leading option for the designer in considering standard test for tensile. The further assessment and comparison of different properties might be a subject for future study. Furthermore, it would be better if there were centralized Standard Guidelines for the usage of bamboo considering different variations such as species, locations, treatments, and others. There is no existing standard procedure for treating bamboo, maybe it could be another future interest to promote standardization for bamboo optimization.

5.2. Bamboo Applications

Bamboo is a sustainable material. In old times, bamboo was considered a material for the poor since it is mostly used by marginalized people in remote areas; However, at present, it is known worldwide due to its good properties as a building material and its aesthetic purpose [30]. However, the bamboo needs to be treated and properly processed to optimize it and have a long service life. That is why engineered and or bamboo composite arises. In which bamboo is mixed and or combined with other materials to perform better. This section briefly discusses some of the bamboo applications presented and mentioned in the gathered literature. [22] used bamboo sticks in reinforced concrete mix for structural columns. The other way around was the study of [45,82,83], in which they used concrete to reinforce the bamboo and determined the ultimate load-bearing capacity of bamboo culm, which can be used for structural columns. Sun et al. [49] studied bamboo strand composite lumber (BSCL) for building material application. A laminated bamboo lumber was the focus of Liliefna et al. [63] and Zhang et al. [79] to be used in flexural members. A bamboo stick board was introduced by Yang et al. [22], which they recommended for structural construction. Bamboo–based panels were explored by Huang et al. [57] and Wang et al. [91], which they suggested to be used in structural construction. Xiao et al. [64] and Anokye et al. [44] studied glued laminated bamboo, commonly known as "glubam". Both studies addressed that glubam can be used in general structure applications. Flooring application was the recommendation of Rao et al. [47] in their study on outdoor bamboo-fiber-reinforced composites (OBFRC). They concluded that the OBFRC is good for outdoor purposes not only it has good strength but also aesthetics, and its use as a building material is one of the many applications of bamboo. This material is excellent in many ways. Engineered or bamboo composite is indeed improved and widened the application of bamboo; however, it is difficult and expensive. The use of bamboo culms as building materials in construction still interests many researchers today. The common weakness of bamboo culms or bamboo poles that needs further study is the preservation and the connection. Figure 12a shows how bamboo was used to construct the ceiling at the Madrid-Barajas Airport in Spain, Figure 12b a laminated bamboo curtain wall in Germany, and Figure 12c an aesthetic footbridge in China.

(a) (b) (c)

Figure 12. (**a**) Engineered bamboo ceiling, Barajas International Airport in Madrid, Spain. (**b**) Laminated bamboo curtain wall, Germany, (**c**) bamboo footbridge in China. All figures are reproduced with permission from (**a**,**b**) [32], Elsevier, 2015; and (**c**) [45], Elsevier, 2017.

6. Research Gaps and Challenges

The literature review comprehensively studied the physical and mechanical properties of bamboo, treatment methods, some applications, codes, and standards. However, there are still challenges that need to be address in these different aspects. Figure 13 shows the summary of recommendations for research topics that may be addressed for future studies.

6.1. Properties of Bamboo

The identification of optimal harvesting, curing, and storage practices must be standardized and establish criteria for selecting species and maturity levels. The selection of nodal and internodal specimens should also be indicated since there are variations in the performance testing results [15,45,82,101]; the use of both nodal and internodal should always be considered since the nodes cannot be disregarded [82]. Another thing is the exploration of the improvement of the properties of bamboo, which includes modification of treatments, processing for composite products, and incorporation of other materials, particularly sustainable materials. Furthermore, the continuing trend issue in bamboo as a structural material is the development of connections in different applications. A single article in this paper discussed the nailed connection using Moso [98], which was laterally loaded. Various researchers involved in modifications of bamboo connection include plate with bolt [31], steel cap with lashing [102], buckle plate connection [103], modified steel clamps [104], bolted with sleeves and inserts [105], and wooden block joint with hose clams [106]. The mechanical testing performed for bamboo specimens in the literature is mostly static in nature; factors such as seismic, wind, and vibration were not performed. This is a major concern if the material will be used in structures, especially in outdoor settings. Generally, these gaps and challenges are summarized as follows: (1) develop centralized guidelines and procedures for the preparation and processing of bamboo with respect to species, age, and locations; (2) explore alternative sustainable filling materials for bamboo aside from concrete and mortar in which the strength will be increased but not compromise the ductility; (3) further development of the bamboo culm connections for different structural applications; and (4) testing of mechanical properties of bamboo subjected to seismic, wind and vibrations in relation to structural applications.

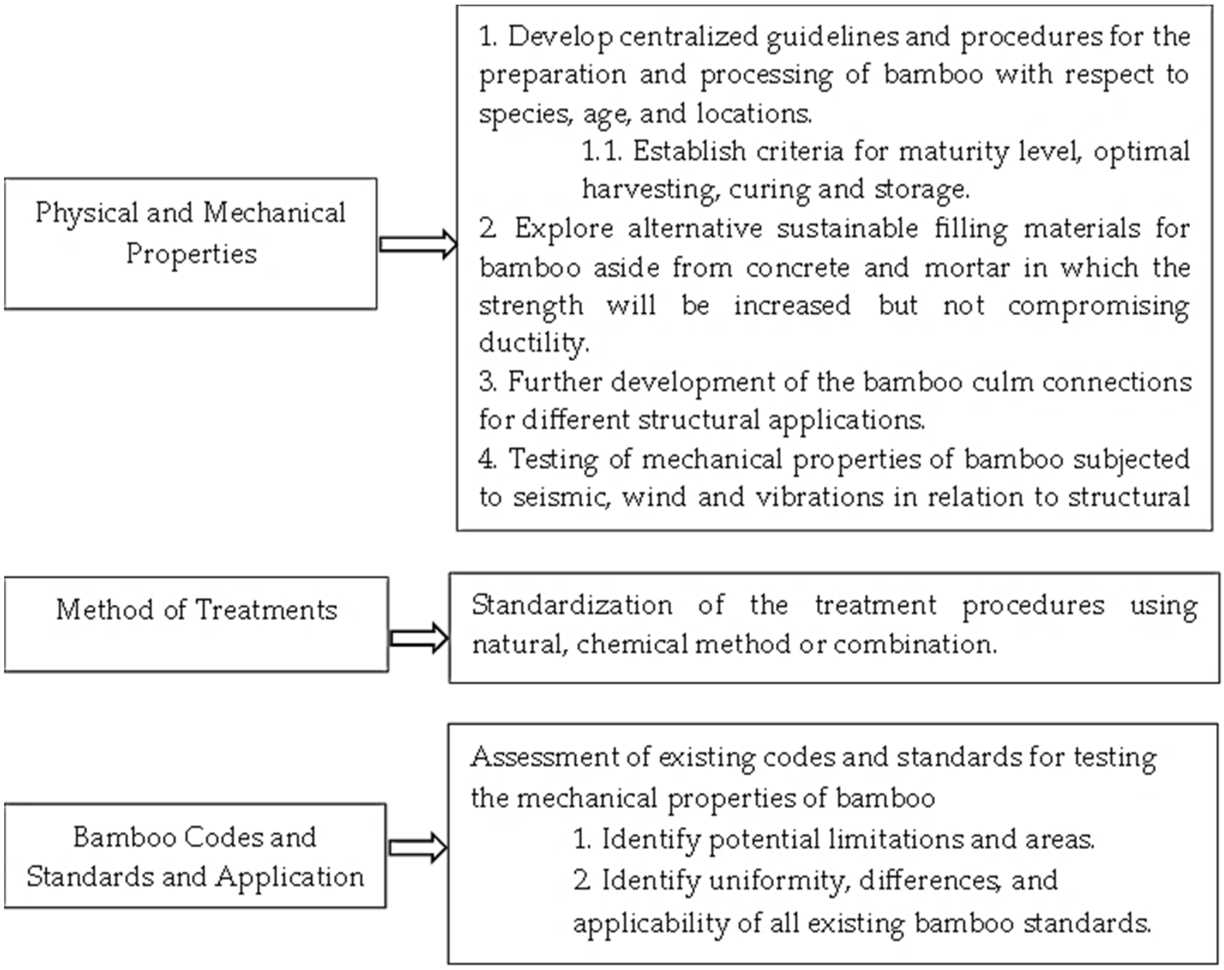

Figure 13. Research topic recommendations.

6.2. Treatment Methods

The treatment of bamboo is one of the factors in the improvement of its properties. The various treatment presented in the literature has their own modification. It would be a great contribution if there were a standard procedure to be used in treating bamboo naturally or chemically, with respect to its species, age, and location. Further modification of treatment methods, such as investigation of potential natural materials to be used as treatment, like rosin [28,52] mango sap [107], or a combination of natural and chemical treatments, and development of a standard procedure from it.

6.3. Bamboo Codes and Standards

Codes and standards play a crucial role in the use of bamboo as a sustainable material in construction and other applications; they are essential for gaining confidence and trust in the reliability and safety of bamboo-based structures. Gatoo et al. [99] emphasized that codification and standardization of bamboo use are needed for the increasing interest in this sustainable material. Kumar et al. [23] also emphasized that there is still a need for codes and standards in characterizing engineered bamboo composites because comparison with the existing literature is what most researchers do. In this literature, some studies used different codes and standards in testing the mechanical properties of bamboo [8], refs. [12,56,63] though in this literature, there is no direct similar parameter that could differentiate the result because they vary in species, age, location, treatment, and sample specimen used. This challenge might be addressed in future work.

7. Conclusions

As a sustainable material, bamboo has consistently demonstrated its environmental credentials throughout history and in contemporary times, from being used as a temporary structure to becoming a structural material. Presently, the Scopus database provides thousands of documents related to bamboo use in construction, and these are still progressing. The most widely studied aspects of bamboo are its physical and mechanical properties, and few are in the areas of connections and applications, especially in applications to tall building construction. The gathered literature provided widespread data regarding the generated three topics: (1) physical and mechanical properties of different bamboo species, (2) bamboo treatment methods, and (3) bamboo applications and standards. Most of the physical and mechanical properties of bamboo surpasses all other types of wood and are comparable to steel with respect to tensile strength. Its properties can be further enhanced by various types of treatment and processing methods. The decaying weakness of bamboo can be addressed with proper treatment. Natural treatment is better and environmentally friendly compared to the chemical treatment available. However, chemical treatment provides results in less time. The availability and sustainability of bamboo material is optimum compared to other construction materials. There are still gaps and key points that need further study and assessment. For the physical and mechanical properties: (1) develop centralized guidelines and procedures for the preparation and processing of bamboo with respect to species, age, and locations that have established criteria for bamboo maturity, level, optimal harvesting, curing, and storage. (2) Explore alternative sustainable filling materials for bamboo aside from concrete and mortar in which the strength will be increased but not compromising ductility. (3) Further development of the bamboo culm connections for different structural applications. (4) Testing of mechanical properties of bamboo subjected to seismic, wind, and vibrations in relation to structural applications. For methods of treatment: (5) standardization of the treatment procedures using natural or chemical methods, or a combination; and for bamboo codes and standards: (6) assessment of existing codes and standards for testing the mechanical properties of bamboo, highlighting the potential limitations and areas, uniformity, differences with all existing similar standards. By filling these gaps and future study recommendations, it can support the reliability and robustness of bamboo as a sustainable material, fostering its promotion and adoption in the construction industry.

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References

1. Lorenzo, R.; Godina, M.; Mimendi, L.; Li, H. Determination of the physical and mechanical properties of moso, guadua and oldhamii bamboo assisted by robotic fabrication. *J. Wood Sci.* **2020**, *66*, 20. [CrossRef]
2. Liu, P.; Zhou, Q.; Fu, F.; Li, W. Effect of bamboo nodes on the mechanical properties of p. Edulis (*Phyllostachys edulis*) bamboo. *Forests* **2021**, *12*, 1309. [CrossRef]
3. Lee, G.; Looi, D.; Choo, C.; Tsang, H.-H. A reconnaissance study on tensile strength of bamboo based on global database. *Mater. Today Proc.* **2022**, *64*, 1109–1115. [CrossRef]
4. Yadav, M.; Mathur, A. Bamboo as a sustainable material in the construction industry: An overview. *Mater. Today Proc.* **2021**, *43*, 2872–2876. [CrossRef]
5. Chen, M.; Ye, L.; Li, H.; Wang, G.; Chen, Q.; Fang, C.; Dai, C.; Fei, B. Flexural strength and ductility of moso bamboo. *Constr. Build. Mater.* **2020**, *246*, 118418. [CrossRef]
6. Rusch, F.; Ceolin, G.B.; Hillig, E. Morphology, density and dimensions of bamboo fibers: A bibliographical compilation. *Pesqui. Agropecu. Trop.* **2019**, *49*, 3. [CrossRef]
7. Huang, P.; Chang, W.-S.; Ansell, M.P.; Chew, Y.J.; Shea, A. Density distribution profile for internodes and nodes of *Phyllostachys edulis* (Moso bamboo) by computer tomography scanning. *Constr. Build. Mater.* **2015**, *93*, 197–204. [CrossRef]
8. Ribeiro, R.A.S.; Ribeiro, M.G.S.; Miranda, I.P. Bending strength and nondestructive evaluation of structural bamboo. *Constr. Build. Mater.* **2017**, *146*, 38–42. [CrossRef]
9. Singh, K.; Garg, H.; Pabla, B.S. Evaluation of mechanical properties of different bamboo species for structural applications. *Int. J. Innov. Technol. Explor. Eng.* **2019**, *8*, 2927–2935. [CrossRef]
10. Krause, J.Q.; Silva, F.d.A.; Ghavami, K.; Gomes, O.d.F.M.; Filho, R.D.T. On the influence of *Dendrocalamus giganteus* bamboo microstructure on its mechanical behavior. *Constr. Build. Mater.* **2016**, *127*, 199–209. [CrossRef]
11. Cui, J.; Fu, D.; Mi, L.; Li, L.; Liu, Y.; Wang, C.; He, C.; Zhang, H.; Chen, Y.; Wang, Q. Effects of Thermal Treatment on the Mechanical Properties of Bamboo Fiber Bundles. *Materials* **2023**, *16*, 1239. [CrossRef] [PubMed]
12. Wu, J.; Yixiu, Z.; Zhong, T.; Zhang, W.; Chen, H. Bamboo slivers with high strength and toughness prepared by alkali treatment at a proper temperature. *J. Wood Sci.* **2023**, *69*, 13. [CrossRef]
13. Lorenzo, R.; Mimendi, L.; Yang, D.; Li, H.; Mouka, T.; Dimitrakopoulos, E.G. Non-linear behaviour and failure mechanism of bamboo poles in bending. *Constr. Build. Mater.* **2021**, *305*, 124747. [CrossRef]
14. Awalluddin, D.; Mohd Ariffin, M.A.; Osman, M.H.; Hussin, M.W.; Ismail, M.A.; Lee, H.S.; Abdul Shukor Lim, N.H. Mechanical properties of different bamboo species. *Proc. MATEC Web Conf.* **2017**, *138*, 01024. [CrossRef]
15. Bahtiar, E.T.; Trujillo, D.; Nugroho, N. Compression resistance of short members as the basis for structural grading of *Guadua angustifolia*. *Constr. Build. Mater.* **2020**, *249*, 118759. [CrossRef]
16. Drury, B.; Padfield, C.; Russo, M.; Swygart, L.; Spalton, O.; Froggatt, S.; Mofidi, A. Assessment of the Compression Properties of Different Giant Bamboo Species for Sustainable Construction. *Sustainability* **2023**, *15*, 6472. [CrossRef]
17. Gauss, C.; Savastano, H.; Harries, K.A. Use of ISO 22157 mechanical test methods and the characterisation of Brazilian *P. edulis* bamboo. *Constr. Build. Mater.* **2019**, *228*, 116728. [CrossRef]
18. Chaowana, K.; Wisadsatorn, S.; Chaowana, P. Bamboo as a sustainable building material—Culm characteristics and properties. *Sustainability* **2021**, *13*, 7376. [CrossRef]
19. Lo, T.Y.; Cui, H.; Tang, P.; Leung, H. Strength analysis of bamboo by microscopic investigation of bamboo fibre. *Constr. Build. Mater.* **2008**, *22*, 1532–1535. [CrossRef]
20. Suarez, E.; Rescalvo, F.J.; Fernandez, A.; Cruz, A.; Gallego, A. Influence of weathering on mechanical properties of culm samples of *Guadua angustifolia Kunth* bamboo with and without nodes. *Wood Mater. Sci. Eng.* **2022**, *18*, 434–445. [CrossRef]
21. Mena, J.; Vera, S.; Correal, J.F.; Lopez, M. Assessment of fire reaction and fire resistance of *Guadua angustifolia* kunth bamboo. *Constr. Build. Mater.* **2012**, *27*, 60–65. [CrossRef]
22. Yang, T.-C.; Lee, T.-Y. Effects of density and heat treatment on the physico-mechanical properties of unidirectional round bamboo stick boards (UBSBs) made of Makino bamboo (*Phyllostachys makinoi*). *Constr. Build. Mater.* **2018**, *187*, 406–413. [CrossRef]
23. Kumar, A.; Vlach, T.; Laiblova, L.; Hrouda, M.; Kasal, B.; Tywoniak, J.; Hajek, P. Engineered bamboo scrimber: Influence of density on the mechanical and water absorption properties. *Constr. Build. Mater.* **2016**, *127*, 815–827. [CrossRef]
24. Sharma, B.; Gatóo, A.; Ramage, M.H. Effect of processing methods on the mechanical properties of engineered bamboo. *Constr. Build. Mater.* **2015**, *83*, 95–101. [CrossRef]
25. Subekti, N.; Yoshimura, T.; Rokhman, F.; Mastur, Z. Potential for Subterranean Termite Attack against Five Bamboo Speciesin Correlation with Chemical Components. *Procedia Environ. Sci.* **2015**, *28*, 783–788. [CrossRef]
26. Setiyowati, E.; Mappaturi, A.B. Comparison between chemical and natural treatments for bamboo as building material towards sustainable construction method. *IOP Conf. Series Earth Environ. Sci.* **2020**, *456*, 012043. [CrossRef]
27. Cid, S.C.G.; Cardoso, D.C.T.; Silva, F.d.A.; Krause, J.Q. Influence of hornification on the physical and flexural properties of Moso bamboo. *Constr. Build. Mater.* **2020**, *248*, 118701. [CrossRef]
28. Yang, X.; Huang, Y.; Ye, C.; Lin, X.; Su, N.; Fei, B. Improving the dimensional stability of round bamboo by environment-friendly modified rosin. *Constr. Build. Mater.* **2023**, *365*, 130078. [CrossRef]
29. Marasigan, O.S.; Razal, R.A.; Alipon, M.A. Effect of thermal treatment on the wettability of giant bamboo (*Dendrocalamus asper*) and Kawayan tinik (*Bambusa blumeana*) in the Philippines. *J. Trop. For. Sci.* **2020**, *32*, 369–378. [CrossRef]

30. Amede, E.A.; Hailemariama, E.K.; Hailemariam, L.M.; Nuramo, D.A. A Review of Codes and Standards for Bamboo Structural Design. *Adv. Mater. Sci. Eng.* **2021**, *2021*, 4788381. [CrossRef]
31. Ahmad, S.I.; Alam, S.; Alam, J. Structural and Life-Cycle Economic Feasibility of Rooftop Low-Height Bamboo Telecom Tower Considering a Case Study from Bangladesh. *Pract. Period. Struct. Des. Constr.* **2020**, *25*, 05020007. [CrossRef]
32. Sharma, B.; Van Der Vegte, A. Engineered bamboo for structural applications. In *Nonconventional and Vernacular Construction Materials: Characterisation, Properties and Applications*; Woodhead Publishing: Sawston, UK, 2019; ISBN 9780081027042. [CrossRef]
33. Van der Lugt, P.; Van den Dobbelsteen, A.A.J.F.; Janssen, J.J.A. An environmental, economic and practical assessment of bamboo as a building material for supporting structures. *Constr. Build. Mater.* **2006**, *20*, 648–656. [CrossRef]
34. Burnham, J.F. Scopus database: A review. *Biomed. Digit. Libr.* **2006**, *3*, 1. [CrossRef] [PubMed]
35. SCImago. "SJR—SCImago Journal & Country Rank," SJR—SCImago J. Ctry. Rank. 2016. Available online: https://www.scimagojr.com/journalrank.php?area=2200 (accessed on 14 June 2023).
36. MatlabR2022b. Available online: https://www.mathworks.com/products/text-analytics.html%0A (accessed on 20 July 2023).
37. Roxas, C.L.C.; Bautista, C.R.; Dela Cruz, O.G.; Dela Cruz, R.L.C.; De Pedro, J.P.Q.; Dungca, J.R.; Lejano, B.A.; Ongpeng, J.M.C. Design for Manufacturing and Assembly (DfMA) and Design for Deconstruction (DfD) in the Construction Industry: Challenges, Trends and Developments. *Buildings* **2023**, *13*, 1164. [CrossRef]
38. Cruz, O.G.D.; Ongpeng, J.M.C. Building Information Modeling on Construction Safety: A Literature Review. *Adv. Sci. Technol. Innov.* **2022**, 89–102. [CrossRef]
39. Vivas, L.S.; Costello, K.; Mobley, S.; Mihelcic, J.R.; Mullins, G. Determination of safety factors for structural bamboo design applications. *Arch. Eng. Des. Manag.* **2020**, *18*, 26–37. [CrossRef]
40. Liese, W.; Weiner, G. Ageing of bamboo culms. A review. *Wood Sci. Technol.* **1996**, *30*, 77–89. [CrossRef]
41. Canavan, S.; Richardson, D.M.; Visser, V.; Le Roux, J.J.; Vorontsova, M.S.; Wilson, J.R.U. The global distribution of bamboos: Assessing correlates of introduction and invasion. *AoB Plants* **2016**, *9*, plw078. [CrossRef]
42. Correal, J.F.; Calvo, A.F.; Trujillo, D.J.; Echeverry, J.S. Inference of mechanical properties and structural grades of bamboo by machine learning methods. *Constr. Build. Mater.* **2022**, *354*, 129116. [CrossRef]
43. Kaminski, S.; Lawrence, A.; Trujillo, D. Structural use of bamboo Part 1: Introduction to bamboo. *Struct. Eng.* **2016**, *98*, 40–43.
44. Anokye, R.; Bakar, E.S.; Ratnasingam, J.; Yong, A.C.C.; Bakar, N.N. The effects of nodes and resin on the mechanical properties of laminated bamboo timber produced from *Gigantochloa scortechinii*. *Constr. Build. Mater.* **2016**, *105*, 285–290. [CrossRef]
45. Li, W.-T.; Long, Y.-L.; Huang, J.; Lin, Y. Axial load behavior of structural bamboo filled with concrete and cement mortar. *Constr. Build. Mater.* **2017**, *148*, 273–287. [CrossRef]
46. Darwis, A.; Iswanto, A.H. Morphological Characteristics of *Bambusa vulgaris* and the Distribution and Shape of Vascular Bundles therein. *J. Korean Wood Sci. Technol.* **2018**, *46*, 315–322. [CrossRef]
47. Rao, F.; Ji, Y.; Li, N.; Zhang, Y.; Chen, Y.; Yu, W. Outdoor bamboo-fiber-reinforced composite: Influence of resin content on water resistance and mechanical properties. *Constr. Build. Mater.* **2020**, *261*, 120022. [CrossRef]
48. Yang, T.-C.; Chung, M.-J.; Wu, T.-L.; Yeh, C.-H. Physicomechanical properties and water resistance of heat-modified moso bamboo (*Phyllostachys pubescens*) as a function of density. *Constr. Build. Mater.* **2021**, *306*, 124897. [CrossRef]
49. Sun, Y.; Yu, W.; Wei, X.; Ge, L.; Guo, Z.; Zhang, Y. Bamboo strand-based structural composite lumber: Influence of technological parameters on physico-mechanical properties. *Constr. Build. Mater.* **2021**, *271*, 121795. [CrossRef]
50. Bahtiar, E.T.; Imanullah, A.P.; Hermawan, D.; Nugroho, N. Abdurachman Structural grading of three sympodial bamboo culms (Hitam, Andong, and Tali) subjected to axial compressive load. *Eng. Struct.* **2019**, *181*, 233–245. [CrossRef]
51. Luan, Y.; Yang, Y.; Chen, L.; Ma, Y.; Jiang, M.; Fei, B.; Liu, H.; Ma, X.; Zhang, X.; Fang, C.; et al. Effects of integrated process of flattening and densification on the gradient structure and properties of Moso Bamboo. *Constr. Build. Mater.* **2023**, *392*, 132073. [CrossRef]
52. Su, N.; Fang, C.; Yu, Z.; Zhou, H.; Wang, X.; Tang, T.; Zhang, S.; Fei, B. Effects of rosin treatment on hygroscopicity, dimensional stability, and pore structure of round bamboo culm. *Constr. Build. Mater.* **2021**, *287*, 123037. [CrossRef]
53. Dixon, P.; Ahvenainen, P.; Aijazi, A.; Chen, S.; Lin, S.; Augusciak, P.; Borrega, M.; Svedström, K.; Gibson, L. Comparison of the structure and flexural properties of Moso, Guadua and Tre Gai bamboo. *Constr. Build. Mater.* **2015**, *90*, 11–17. [CrossRef]
54. Zhou, X.; Liu, P.; Zhou, Q.; Xiang, P.; Zhang, H.; Tian, J. Study on the tension and compression stress-strain relationship of Phyllostachys Edulis bamboo parallel to the grain. *Ind. Crop. Prod.* **2022**, *177*, 114548. [CrossRef]
55. Lee, C.-H.; Yang, T.-H.; Cheng, Y.-W.; Lee, C.-J. Effects of thermal modification on the surface and chemical properties of moso bamboo. *Constr. Build. Mater.* **2018**, *178*, 59–71. [CrossRef]
56. Dong, Y.; Liu, X.; Liu, J.; Yan, Y.; Liu, X.; Wang, K.; Li, J. Evaluation of anti-mold, termite resistance and physical-mechanical properties of bamboo cross-linking modified by polycarboxylic acids. *Constr. Build. Mater.* **2021**, *272*, 121953. [CrossRef]
57. Huang, Z.; Sun, Y.; Musso, F. Experimental study on bamboo hygrothermal properties and the impact of bamboo-based panel process. *Constr. Build. Mater.* **2017**, *155*, 1112–1125. [CrossRef]
58. Ramful, R.; Sunthar, T.P.M.; Marin, E.; Zhu, W.; Pezzotti, G. Investigating the Effect of Smoke Treatment on Hygroscopic Characteristics of Bamboo by FTIR and Raman Spectroscopy. *Materials* **2022**, *15*, 1544. [CrossRef]
59. Wang, X.; Yuan, Z.; Zhan, X.; Li, Y.; Li, M.; Shen, L.; Cheng, D.; Li, Y.; Xu, B. Multi-scale characterization of the thermal—Mechanically isolated bamboo fiber bundles and its potential application on engineered composites. *Constr. Build. Mater.* **2020**, *262*, 120866. [CrossRef]

60. Kadivar, M.; Gauss, C.; Tomazello-Filho, M.; Ahrar, A.J.; Ghavami, K.; Savastano, H. Optimization of thermo-mechanical densification of bamboo. *Constr. Build. Mater.* **2021**, *298*, 123860. [CrossRef]
61. Su, N.; Fang, C.; Zhou, H.; Tang, T.; Zhang, S.; Fei, B. Hydrophobic treatment of bamboo with rosin. *Constr. Build. Mater.* **2020**, *271*, 121507. [CrossRef]
62. Gottron, J.; Harries, K.A.; Xu, Q. Creep behaviour of bamboo. *Constr. Build. Mater.* **2014**, *66*, 79–88. [CrossRef]
63. Liliefna, L.D.; Nugroho, N.; Karlinasari, L.; Sadiyo, S. Development of low-tech laminated bamboo esterilla sheet made of thin-wall bamboo culm. *Constr. Build. Mater.* **2020**, *242*, 118181. [CrossRef]
64. Xiao, Y.; Yang, R.; Shan, B. Production, environmental impact and mechanical properties of glubam. *Constr. Build. Mater.* **2013**, *44*, 765–773. [CrossRef]
65. Tang, T.; Chen, X.; Zhang, B.; Liu, X.; Fei, B. Research on the physico-mechanical properties of moso bamboo with thermal treatment in tung oil and its influencing factors. *Materials* **2019**, *12*, 599. [CrossRef] [PubMed]
66. Xie, J.; Qi, J.; Hu, T.; De Hoop, C.F.; Hse, C.Y.; Shupe, T.F. Effect of fabricated density and bamboo species on physical–mechanical properties of bamboo fiber bundle reinforced composites. *J. Mater. Sci.* **2016**, *51*, 7480–7490. [CrossRef]
67. Guo, A.; Liu, C.; Li, S.; Zhou, X.; Wang, J.; Wang, S.; Qu, P.; Hu, Y. Water absorption rates and mechanical properties of material extrusion-printed continuous carbon fiber-reinforced nylon composites. *J. Mater. Res. Technol.* **2022**, *21*, 3098–3112. [CrossRef]
68. Ren, W.; Cao, M.; Zhou, Y.; Zhu, J.; Wang, H.; Yu, Y. Pore structure evolution of bamboo fiber and parenchyma cell wall during sequential chemical removal. *Ind. Crop. Prod.* **2023**, *193*, 116165. [CrossRef]
69. Wu, J.; Wang, X.; Fei, B.; Xu, X.; Lian, C.; Chen, H. The mechanical properties and thermal conductivity of bamboo with freeze–thaw treatment. *J. Wood Sci.* **2021**, *67*, 66. [CrossRef]
70. Yang, M.X.; Zhang, Y.; Liu, H.W.; Zheng, Q.T. Factors affecting thermal and moisture comfort of bamboo fabric. *Adv. Mater. Res.* **2011**, *332–334*, 808–811. [CrossRef]
71. Huang, P.; Chang, W.-S.; Ansell, M.P.; John, C.Y.M.; Shea, A. Porosity estimation of *Phyllostachys edulis* (Moso bamboo) by computed tomography and backscattered electron imaging. *Wood Sci. Technol.* **2016**, *51*, 11–27. [CrossRef]
72. Shah, D.U.; Bock, M.C.D.; Mulligan, H.; Ramage, M.H. Thermal conductivity of engineered bamboo composites. *J. Mater. Sci.* **2016**, *51*, 2991–3002. [CrossRef]
73. Habibi, M.K.; Lu, Y. Crack propagation in bamboo's hierarchical cellular structure. *Sci. Rep.* **2014**, *4*, srep05598. [CrossRef]
74. Gomes, B.M.d.C.; da Silva, N.A.; Saraiva, A.B.; Caldas, L.R.; Filho, R.D.T. Environmental and mechanical performance assessment of bamboo culms and strips for structural use: Evaluation of *Phyllostachys pubescens* and *Dendrocalamus giganteus* species. *Constr. Build. Mater.* **2022**, *353*, 129078. [CrossRef]
75. Greco, S.; Manzi, S.; Molari, L.; Saccani, A.; Ulian, G.; Valdrè, G. Photodegradation of Bamboo: A Study on Changes in Mechanical Performances. *Materials* **2023**, *16*, 285. [CrossRef]
76. Bui, Q.-B.; Grillet, A.-C.; Tran, H.-D. A bamboo treatment procedure: Effects on the durability and mechanical performance. *Sustainability* **2017**, *9*, 1444. [CrossRef]
77. Mitch, D.; Harries, K.A.; Sharma, B. Characterization of Splitting Behavior of Bamboo Culms. *J. Mater. Civ. Eng.* **2010**, *22*, 1195–1199. [CrossRef]
78. Zhang, H.; Li, H.; Li, Y.; Xiong, Z.; Zhang, N.; Lorenzo, R.; Ashraf, M. Effect of nodes on mechanical properties and microstructure of laminated bamboo lumber units. *Constr. Build. Mater.* **2021**, *304*, 124427. [CrossRef]
79. Zhang, X.; Wang, F.; Keer, L.M. Influence of surface modification on the microstructure and thermo-mechanical properties of bamboo fibers. *Materials* **2015**, *8*, 6597–6608. [CrossRef]
80. Mukhopadhyay, P.; Dutta, S.C. Investigating Compressive and Cleavage Strengths of an Indian Bamboo Species. *J. Mater. Civ. Eng.* **2015**, *27*, 06014029. [CrossRef]
81. Chatterjee, A.; Bhowmik, R. Experimental determination of flexural strength of Bholuka bamboo (*Bambusa balcooa*) of Assam, India. *Mater. Today Proc.* **2023**, *76*, 585–589. [CrossRef]
82. Nie, Y.; Wei, Y.; Miao, K.; Zhao, K.; Huang, L. Experimental investigation of full-culm bamboo tubes strengthened by filled concrete and bamboo sheets under axial compression. *J. Build. Eng.* **2022**, *45*, 103548. [CrossRef]
83. Stephen, S.; Bernadette, S.; Bruce, K. Structural Behavior of Concrete Filled Bamboo Columns under Axial Loads. *Civ. Environ. Res.* **2020**, *12*, 62–67. [CrossRef]
84. Sharma, B.; Harries, K.A.; Ghavami, K. Methods of determining transverse mechanical properties of full-culm bamboo. *Constr. Build. Mater.* **2013**, *38*, 627–637. [CrossRef]
85. Chung, K.; Yu, W. Mechanical properties of structural bamboo for bamboo scaffoldings. *Eng. Struct.* **2001**, *24*, 429–442. [CrossRef]
86. Jusoh, N.Z.; Ahmad, M.; Azmi, I. Study on compressive strength of semantan bamboo culm (*Gigantochloa scortechinii*). *Appl. Mech. Mater.* **2013**, *330*, 96–100. [CrossRef]
87. Sayed, U.; Li, H.; Dauletbek, A.; Ali, M.; Yang, D.; Lorenzo, R.; Ashraf, M.; Feng, Z.; Wang, Z.; Xue, X. Bamboo stick diameter, volume and aspect ratios effect on the compressive behavior of bamboo sticks reinforced concrete mixed with sea sand and seawater. *Constr. Build. Mater.* **2023**, *369*, 130437. [CrossRef]
88. David, W.; Green, J.E.; Winandy, D.E.K. Mechanical Properties of Wood. In *Wood Handbook—Wood as an Engineering Material*; Forest Products Laboratory, Forest Service: Madison, WI, USA, 1999; p. 463.

89. Tumenjargal, B.; Ishiguri, F.; Aiso, H.; Takahashi, Y.; Nezu, I.; Takashima, Y.; Baasan, B.; Chultem, G.; Ohshima, J.; Yokota, S. Physical and mechanical properties of wood and their geographic variations in *Larix sibirica* trees naturally grown in Mongolia. *Sci. Rep.* **2020**, *10*, 12936. [CrossRef]
90. Qing-Xian, Y. Theoretical expressions of thermal conductivity of wood. *J. For. Res.* **2001**, *12*, 43–46. [CrossRef]
91. Wang, X.; Yao, Y.; Xie, X.; Yuan, Z.; Li, W.; Yuan, T.; Huang, Y.; Li, Y. Investigation of the microstructure, chemical structure, and bonding interfacial properties of thermal-treated bamboo. *Int. J. Adhes. Adhes.* **2023**, *125*, 103400. [CrossRef]
92. García, J.J.; Rangel, C.; Ghavami, K. Experiments with rings to determine the anisotropic elastic constants of bamboo. *Constr. Build. Mater.* **2012**, *31*, 52–57. [CrossRef]
93. Jiang, J.; Han, S.; Ren, X.; Wang, H.; Yu, H.; Sun, F. Enhanced durability of round bamboo treated with copper naphthenate under heat-cold impregnation. *R. Soc. Open Sci.* **2022**, *9*, 220247. [CrossRef] [PubMed]
94. Mannan, S.; Paul Knox, J.; Basu, S. Correlations between axial stiffness and microstructure of a species of bamboo. *R. Soc. Open Sci.* **2017**, *4*, 160412. [CrossRef] [PubMed]
95. Handana, M.; Surbakti, B.; Karolina, R. The effect of borax solution as preservative to the mechanical properties of bamboo. *Int. J. Sustain. Constr. Eng. Technol.* **2020**, *11*, 79–88. [CrossRef]
96. McClure, F.A. Bamboo as a Building Material. Peace Corps. Appropriate Technologies for Development. Reprint-33; 1981. Available online: http://files.eric.ed.gov/fulltext/ED242878.pdf%5Cnhttps://babel.hathitrust.org/cgi/pt?id=umn.31951d014156933;view=1up;seq=5 (accessed on 18 July 2023).
97. Gnanaharan, R.; Janssen, O. Bending Strength of Guadua Bamboo. *Information* **1995**.
98. Malkowska, D.; Norman, J.; Trujillo, D. Theoretical and experimental study on laterally loaded nailed bamboo connection. *Constr. Build. Mater.* **2022**, *342*, 127971. [CrossRef]
99. Gatóo, A.; Sharma, B.; Bock, M.; Mulligan, H.; Ramage, M.H. Sustainable structures: Bamboo standards and building codes. *Proc. Inst. Civ. Eng. Eng. Sustain.* **2014**, *167*, 189–196. [CrossRef]
100. De La Cruz, M. Assessment of testing protocols for bamboo for tension parallel to fiber. *Int. J. GEOMATE* **2020**, *19*, 31–36. [CrossRef]
101. Nie, Y.; Wei, Y.; Zhao, K.; Ding, M.; Huang, L. Compressive performance of bamboo sheet twining tube-confined recycled aggregate concrete columns. *Constr. Build. Mater.* **2022**, *323*, 126544. [CrossRef]
102. Adhikari, R.C.; Wood, D.H.; Sudak, L. Design procedure for tubular lattice towers for small wind turbines. *Wind. Eng.* **2014**, *38*, 359–376. [CrossRef]
103. Paraskeva, T.; Grigoropoulos, G.; Dimitrakopoulos, E. Design and experimental verification of easily constructible bamboo footbridges for rural areas. *Eng. Struct.* **2017**, *143*, 540–548. [CrossRef]
104. Moran, R.; García, J.J. Bamboo joints with steel clamps capable of transmitting moment. *Constr. Build. Mater.* **2019**, *216*, 249–260. [CrossRef]
105. Salim, S.; Nor, A.H.M.; Sanik, M.; Osman, M.H.; Abdullah, M.; bin Sarif, A.; Kumil, J. Bolts Connection Technique of Bamboo in Construction Work. *IOSR J. Mech. Civ. Eng.* **2017**, *14*, 54–60. [CrossRef]
106. Lefevre, B.; West, R.; O'Reilly, P.; Taylor, D. A new method for joining bamboo culms. *Eng. Struct.* **2019**, *190*, 1–8. [CrossRef]
107. Bacosa Cesario, A., Jr.; Loretero, M. Naturally Treated Philippine Bamboo Species as an Alternative Concrete Reinforcement Materials Substitute for Steel Bars. *Soc. Cult. Stud. Soc. Sci.* **2023**, *34*, 188–201. [CrossRef]