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Review

# A systematic literature review of bamboo as reinforcement in concrete

**Ipsitaa Priyadarsini Das**[1] · **Pradeep G. Kini**[1] · **Shreelaxmi Prashant**[2]

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**Abstract**
The building industry is a major contributor to global greenhouse gas emissions, particularly $CO_2$, accounting for about 30%. With an expected world population growth of over 2 billion by 2030, the demand for 300 million new housing units will escalate the consumption of non-renewable building materials. Within industrialized nations, the share of primary energy consumption by the construction sector hovers around 40%, while energy-related $CO_2$ emissions account for 36% of the total. Material production and construction processes significantly amplify greenhouse gas emissions, raising their atmospheric concentrations. Conventional materials like cement, steel, and glass are major $CO_2$ emitters, posing challenges to the Paris Agreement's goals of limiting temperature rise and achieving zero emissions by 2050. To meet these goals and align with Sustainable Development Goal 9, adopting alternative materials is crucial. Bamboo, recognized for its durability, renewability, and eco-friendliness, is emerging as a viable substitute for steel in reinforced concrete structures. This study analyzes the feasibility of bamboo as a sustainable alternative to steel reinforcement, focusing on its mechanical properties and applications in construction. The review, conducted using the PRISMA 2020 method, screened 467 papers, narrowing down to 48 research papers and 2 Indian Standard codes. Findings show that *Bambusa balcoa*, *Bambusa vulgaris*, *Dendrocalmus asper*, and *Bambusa bamboo* are the most commonly examined species, demonstrating average tensile strength of 118.578 MPa and modulus of elasticity of 15.529 GPa. Bamboo reinforcement also offers significant cost savings (approximately 36.78%) and lower carbon emissions, making it a promising eco-friendly alternative to steel in concrete structures.
*Clinical trial registration*: Not applicable.

**Keywords** Bamboo reinforced concrete · Housing · Sustainable · Life cycle assessment · Structural strength · Bamboo treatment

**Abbreviations**

| | |
|---|---|
| ANN | Artificial neural network |
| AR | Aspect ratio |
| BRC | Bamboo reinforced concrete |
| $CO_2$ | Carbon dioxide |
| COP27 | The Paris Agreement |
| EE | Embodied energy |
| FEM | Finite element modelling |
| FICSEB | Fibre reinforced hollow interlocking compressed stabilized earth masonry |

✉ Pradeep G. Kini, pradeep.kini@manipal.edu; ✉ Shreelaxmi Prashant, shreelaxmi.p@manipal.edu; Ipsitaa Priyadarsini Das, ipsita.das@manipal.edu | [1]Manipal School of Architecture and Planning, Manipal Academy of Higher Education, Manipal 576104, Karnataka, India. [2]Department of Civil Engineering, Manipal Institution of Technology, Manipal Academy of Higher Education, Manipal 576104, Karnataka, India.

| | |
|---|---|
| FTM | Flexural testing machine |
| GGBS | Ground granulated blast furnace slag |
| GTBRC | Grooved treated bamboo reinforced concrete slab |
| GHG | Greenhouse gas |
| NBC | National Building Code |
| NBM | National Bamboo Mission |
| INBAR | International Bamboo and Rattan Organization |
| IPITRI | Indian Plywood Industries Research & Training Institute |
| ISFR | India State of Forest Report |
| IS Code | Indian Standard Code |
| PCC | Plain cement concrete |
| PRISMA | Preferred reporting items for systematic reviews and meta-analyses |
| PTBRC | Plain treated bamboo reinforced concrete slab |
| PUNDIT | Portable ultrasonic non-destructive digital indicating tester |
| RCC | Reinforced cement concrete |
| SDG | Sustainable development goal |
| SLR | Sustainable literature review |
| TR | Thinness ratio |
| UTBRC | Untreated bamboo reinforced concrete slab |
| UTM | Universal testing machine |
| LRFD | Load & resistance factor development |

## 1 Introduction

The construction industry contributes significantly to global greenhouse emissions, especially the $CO_2$ [1] which makes up about 30%. This impact is greatly driven by the ever-increasing population. It is expected that by 2030 population growth will increase by more than 2000 million which may result in around 300 million new housing units would be required to accommodate the huge population [2] and adequate infrastructure required to support this demand. This demand is expected to consume about 60% of the conventional building materials, many of which are non-renewable in nature [3], and also account to approximately 40% energy demand [4, 5], while energy-related $CO_2$ emissions account for 36% of the total energy demand [6]. In India, the yearly consumption of building materials exceeds 2 billion tons, where it contributes about 20–25% of India's total energy demand and emits about 30% of greenhouse gas (GHG); where cement industry contributes about 7.5%, while the steel industry contributes about 6.8% [7].

The process of manufacturing steel products requires a substantial amount of energy, which contributes to environmental concerns such as climate change and the release of greenhouse gases. The production of building materials, like concrete and steel, utilizes 20–25% of India's total energy demand, resulting in significant emissions and environmental contamination. Steel products have an embodied energy (EE) of 32.24 MJ/kg. The requirement of thermal energy accounts for nearly 97% of the EE of steel. The direct energy consumed for primary processes for the production of steel represents about 92.5% of total EE [7]. The EE values of cement vary depending on the industry, with values ranging between 2.38 and 3.72 MJ/kg for different cement industries. The EE of cement is estimated by considering the indirect energy component (mainly extraction of limestone) and the direct energy component (transportation and process energy). Steel, compared to cement, exhibits higher embodied energy, carbon footprint, greenhouse gas (GHG) emissions, and environmental impact. Steel production involves substantial environmental impacts due to direct emissions, intensive resource use, wastewater contamination, and harmful waste generation in large quantities [8–12]. Furthermore, considering the recyclability of both cement concrete and steel reinforcement, cement concrete can serve as filler material in infrastructure projects. This practice reduces emissions compared to sourcing filler materials from quarries and also aids in $CO_2$ absorption through recarbonation processes. Moreover, though cement has a high impact in terms of embodied energy and carbon footprint, it can significantly help in reducing emissions and contribute to a more eco-efficient approach in construction when used as infill material. This process requires minimal energy input and results in significantly lower $CO_2$ emissions. However, steel reinforcement, despite its recyclability, demands higher energy consumption and contributes to greater $CO_2$ emissions than cement concrete. Although secondary steel production prevents the emission of 1.2 kg $CO_2$eEq per kilogram (a 74% reduction compared to primary steel), its overall carbon footprint remains considerably

higher [5, 7]. Considering cement and steel are major constituent materials of the building industry, finding an alternative sustainable material to either of them can significantly contribute to the reduction of GHG emissions, $CO_2$ emissions and lower embodied energy of buildings. When compared to steel, cement has lower EE values, indicating a relatively lower impact on GHG and carbon emissions [8, 13]. Hence, replacing steel reinforcements with sustainable alternatives in RCC structures is a better solution to lower the environmental impact.

The Paris Agreement (COP27), an international treaty on climate change, states that limiting the temperature escalation by 1.5 °C above preindustrial levels by significantly reducing carbon emissions by 2030 and achieving zero emissions by 2050, allows the reduction of environmental impact of the utmost importance [14]. With the focus of achieving the requirements of Paris agreement and SDG-9, there is an urgent requirement to utilize alternative building materials and technologies in the building industry to decrease the dependency on the conventional building materials which are responsible for high $CO_2$ emissions, while boosting cost effectiveness, and promoting environmental sustainability by reducing carbon footprint of buildings. The incorporation of natural fibers (NFs) such as hemp, bamboo, vegetable fibers (leaf, bast, fruit, and grass fibers), animal fibers (wool, silk, hair), and mineral fibers (wollastonite, polygarosike) in concrete has exhibited potential in enhancing strength and durability while significantly reducing the environmental impact [15, 16]. These fibers contribute to improved crack resistance, ductility, and energy absorption, making them a viable eco-friendly alternative to synthetic reinforcements. For structural applications, timber has been widely recognized as a reinforcement material in RCC structures [17]. Among the commercially available timber species, bamboo stands out as a superior reinforcement option, offering higher tensile strength, rapid renewability, and cost-effectiveness compared to conventional timber [18], making it an ideal substitute for steel reinforcement in concrete. The unique characteristics of bamboo, including its lower self-weight, resilience, renewability, and affordability, have propelled its rising use for both structural and nonstructural applications. Studies indicate that bamboo presents a viable substitute for steel in reinforcing concrete, providing an eco-friendly and economical solution. With a notably high tensile strength, reaching levels of up to 370 MPa, bamboo stands as a promising choice for reinforcing the structural stability of concrete components [19]. Therefore, bamboo emerges as a favorable choice over wood for reinforcing concrete structures due to its remarkable mechanical properties and eco-friendly nature [20–23].

This study aims to provide a systematic review of existing research on bamboo species suitable for structural applications, particularly as an alternative to steel reinforcement in reinforced cement concrete (RCC) structures. Through an extensive literature review, the study identifies bamboo species commonly used in construction and evaluates their mechanical properties in structural applications and their performance, durability, and feasibility in modern building construction. To achieve these objectives, the study follows a comprehensive review of literature published in past 10 years, extracted from Scopus database on bamboo reinforced concrete. The study was conducted focusing on three objectives. First, to identify different bamboo species used in various structural elements; second, to analyze the bamboo's mechanical properties in reinforced concrete; and finally, to conduct an in-depth study on BRC to understand its properties and its applications in building construction. The study analyzes 48 eligible research papers along with 2 IS codes where the results were filtered using PRISMA method and VOSviewer. By critically examining the benefits, limitations, and practical challenges of using bamboo in RCC structures, this research contributes to the advancement of sustainable construction practices. The findings aim to enhance knowledge about bamboo's structural capabilities and provide insights into improving its application in modern construction. Ultimately, this study seeks to support the development of innovative and eco-friendly reinforcement solutions, promoting bamboo as a viable alternative for sustainable architecture.

## 2 Overview of bamboo as reinforcement in concrete

### 2.1 A brief historical review of bamboo as reinforcement in concrete

Bamboo is widely accepted as a suitable alternative to timber and sometimes also as a practical substitute for steel as reinforcement in RCC structures [24]. Bamboo is a sturdy, durable, renewable, and eco-friendly material. Apart from the bamboo products, they are used in formwork as well as for framework. In framed structure, bamboo is used in two different ways—as reinforcement material (BRC) and as exposed pole frame structure. Pier Luigi Nervi, a prominent figure in structural design, stated that reinforced concrete is the "most fruitful and generous of all building materials" [25]. While steel reinforcement has been the primary choice for decades due to its versatility, the issue of corrosion and cost remains a significant drawback. However, there exists a promising alternative in bamboo, a renewable natural resource abundant

in tropical regions, offering a sustainable solution for structural applications. Inspired by the superior tensile strength and its abundance in his native country of China, Mr. H K Chow conducted a series of landmark research on the utilization of bamboo as a suitable reinforcement material in RCC structures in the beginning of the twentieth century [26]. One of the major arguments in favour of Bamboo, as a suitable reinforcement in RCC structures has been the significant reduction in the cost of construction. The ever-increasing population demands an equal increase in built structures and concurrently, an increase in demand for construction materials, rise of construction costs as well as material cost. Currently, the significance of utilizing ecologically sustainable materials that are also cost-effective is of utmost importance, considering that the building industry uses nearly half of all the raw materials globally [27].

Rashmi Manandhar et al. [28] has critically reviewed previous studies on the acceptance of utilizing bamboo as a building material in the construction industry and the sustainable impact that it has towards the environment, along with social and economic sectors The bamboo here is referred as "poor man's timber", as it has turned out to be the first material of preference for the construction of low-cost structures. Numerous researches conducted to this point have emphasized that the application of bamboo in construction sector will advance sustainable building practices due to its several environmental benefits. Furthermore, there are many socio-economic benefits that serve to incentivize people to adopt bamboo construction.

## 2.2 Bamboo properties

Bamboo is fast-growing grass, that has several appealing properties that advocate it as an alternative to steel in constructing the concrete jungle. Due to exceptional mechanics, bamboo has high strength-to-weight ratio, higher flexibility, and exhibits good tensile strength, making it suitable for structural application. Thus, an understanding of the various properties of bamboo for each of the species that can be suitably applied in various design applications in the building industry is essential.

### 2.2.1 Physical properties

Unlike trees which have a solid core, bamboo has hollow core, making them comparatively lower in density and subsequently the weight. Commonly tested bamboo species like *Bambusa arundinacea*, *B. tulda*, *B. vulgaris*, *Dendrocalamus giganteus*, *D. strictus* have average fiber length about 2.7 mm, 3.0 mm, 2.3 mm, 3.2 mm, 2.4 mm respectively [29]. The fibers run along the length of bamboo and are concentrated over the outer surface, giving it a higher tensile strength and load bearing capacity [30]. Furthermore, the girth of bamboo stem stops increasing after a certain period, giving them a relatively uniform trunk size.

### 2.2.2 Chemical properties

In India, 36 species of pathogenic fungi have been reported to affect bamboo, with only a few posing significant threats to the bamboo industry and rural economy [31]. Bamboo does not contain any naturally occurring toxic compounds for defending against pest attack or biodegradation. The presence of resins, tannins and wax in their stem is not strong enough to resist pest attacks. This makes them vulnerable to infections from borers, fungus, beetles, moulds and termites which feed on the rich stems of bamboo starch [32]. This can lead to material degradation, impacting its structural applications. Therefore, the durability of bamboo untreated forms extremely low, which restricts its applications.

### 2.2.3 Mechanical properties

Bamboo possesses high compressive and tensile strength even in untreated conditions. The tensile strength is comparatively greater than that of the few commercially available grades of steel [33]. The density of bamboo varies across its cross-section, typically ranging from 500 to 800 kg/m$^3$ [34], with higher values found towards the outer culm wall compared to the inner layers. This variation results in improved strength-to-weight ratios [24]. Compared to aluminum, steel, and galvanized iron, bamboo has a substantially greater strength to weight ratio as shown in Table 1. Additionally, they are highly flexible while exhibiting sufficiently high resistance to wind loads.

**Table 1** Comparative analysis between bamboo and steel properties [35]

| Sl. no. | Property | Steel | Bamboo |
|---|---|---|---|
| 1 | Density (kg/m$^3$) | 7850 | (515–817) for different species in green condition<br>(640–758) for different species in air dry condition [36] |
| 2 | Modulus of elasticity (N/mm$^2$) | $2.1 \times 10^6$ [37] | $(0.61–15.01) \times 10^3$ for different species in green condition $(3.77–21.41) \times 10^3$ for different species in air dry condition [36] |
| 3 | Grading for structural Utilization | As per its yield stress, ultimate tensile stress, elongation | As per diameter, taper, straightness, inter nodal length, wall thickness, density and strength, durability and seasoning [38] |
| 4 | Compression strength | Mild steel—compression in column bars:130 MPa | 25–100 MPa [38]<br>150 MPa (for *D. strictus*) [37] |
| 5 | Tensile strength | Mild steel—permissible stress in tension<br>140 MPa (upto 20 mm dia)<br>130 MPa (over 20 mm dia)<br>420 MPa (hot rolled deformed steel bar) [39] | 100–400 MPa [38]<br>550 MPa [39] |
| 6 | Bending strength | 0.66*yield stress | 70–300 MPa [38] |
| 7 | Factor of safety (F.O.S.) | 1.15–Structural member for limit state of collapse | For safe working stresses of bamboo [37]<br>4–Extreme fiber stress in beams<br>4.5–Modulus of elasticity<br>3.5–Maximum compressive stress parallel to fibers |
| 8 | Ratio of tensile Strength (N/m$^2$) to specific weight (N/m$^3$) | 5326 | Six times greater than steel [40] |

### 2.3 Bamboo species used for structural application

The ISFR 2021 report indicates that there are 1200 species of bamboo, available globally, across 90 genera, with India housing approximately 125 indigenous species and 11 exotic species across 23 genera. [41]. Depending upon the climate and topography different forms of bamboo along with bamboo species are available. Bamboo stands as the 5th largest flowering plant on the earth which can grow in different forms like Tree form, Reed forms, Straggler form and Shrub Form [42]. IS 15914:2018 categorizes solid bamboo with thicker walls and closely spaced nodes as suitable for structural use. As per the IS code, sixteen bamboo species, suggested for structural use in building construction (Table 2) are categorized based on their physical and mechanical properties during green & air-dried condition [43].

### 2.4 Carbon footprint of bamboo

The construction industry stands as the largest contributor to carbon dioxide ($CO_2$) emissions [44], largely due to the use of fossil fuel-intensive manufacturing processes for the production of materials like steel and cement. A notable advantage of bamboo lies in its capacity to absorb $CO_2$ and release oxygen as it is a naturally grown product [45], making it an environmentally sustainable building material. The whole life cycle of bamboo-based construction material helps to improve global warming as they are carbon sinks [46]. Research indicates that the embodied energy of medium carbon steel ranges from 29 to 35 MJ/kg, whereas bamboo culms have a significantly lower embodied energy of 4–6 MJ/kg. Furthermore, the carbon footprint of steel vastly surpasses that of bamboo, with medium carbon steel emitting 2.2–2.8 kg of $CO_2$/kg, compared to just 0.25 kg of $CO_2$/kg for bamboo [24, 47]. To produce one ton of steel, approximately two tons of $CO_2$ is released, whereas planting one ton of bamboo absorbs one ton of $CO_2$, making bamboo an effective $CO_2$ fixator. Several studies have highlighted the low-carbon footprint of bamboo in construction, emphasizing its potential to reduce $CO_2$ emissions compared to conventional materials like concrete and steel [48]. Life cycle assessment (LCA) studies indicate that bamboo-reinforced structures not only have a lower environmental impact but also offer a cost-effective alternative to steel-reinforced structures [49]. Hector et al. [50] and Luisa et al. [51] underscores the need for further exploration into LCA methodologies and bamboo-based low-carbon housing solutions to advance sustainable and affordable construction practices.

**Table 2** Properties of Indian bamboo (in round form) [37, 43]

| Sl. No. | Bamboo Species | Properties | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | During Green Condition | | | | During Air Dry Condition | | | |
| | | Density (kg/m$^3$) | Modulus of Rupture N/mm$^2$ | Modulus of Elasticity X 10$^3$ N/mm$^2$ | Maximum Compressive Strength N/mm$^2$ | Density (kg/m$^3$) | Modulus of Rupture N/mm$^2$ | Modulus of Elasticity X 10$^3$ N/mm$^2$ | Maximum Compressive Strength N/mm$^2$ |
| 1 | Bambusa auriculata | 594 | 65.1 | 15.01 | 36.7 | 670 | 89.1 | 21.41 | 54.3 |
| 2 | Bambusa balcooa | 783 | 65.4 | 7.31 | 46.7 | – | – | – | 60.6 |
| 3 | Bambusa bambos (Syn. B. arundinacea) | 559 | 58.3 | 5.95 | 35.3 | 663 | 80.1 | 8.96 | 53.4 |
| 4 | Bambusa burmanica | 570 | 59.7 | 11.01 | 39.9 | 672 | 105.0 | 17.81 | 65.2 |
| 5 | B. glancescens (Syn. B. nana) | 691 | 82.8 | 14.77 | 53.9 | – | – | – | – |
| 6 | B. nutans | 603 | 52.9 | 6.62 | 45.6 | 673 | 52.4 | 10.72 | 47.9 |
| 7 | B. pallida | 731 | 55.2 | 12.90 | 54.0 | – | – | – | – |
| 8 | Bambusa tulda | 658 | 51.1 | 7.98 | 40.7 | 722 | 66.7 | 10.07 | 68.0 |
| 9 | Bambusa ventricosa | 626 | 34.1 | 3.38 | 36.1 | – | – | – | – |
| 10 | Bambusa vulgaris | 626 | 41.5 | 2.87 | 38.6 | – | – | – | – |
| 11 | Cephalostachyum pergracile | 601 | 52.6 | 11.16 | 36.7 | 640 | 71.3 | 19.22 | 49.4 |
| 12 | Dendrocalamus longispathus | 711 | 33.1 | 5.51 | 42.1 | 684 | 47.8 | 6.06 | 61.1 |
| 13 | Dendrocalamus strictus | 631 | 73.4 | 11.98 | 35.9 | 728 | 119.1 | 15.00 | 69.1 |
| 14 | Melocanna baccifera | 817 | 53.2 | 11.39 | 53.8 | 751 | 57.6 | 12.93 | 69.9 |
| 15 | Oxytenanthera abyssinicia | 688 | 83.6 | 14.96 | 46.6 | – | – | – | – |
| 16 | Thyrsostachys oliveri | 733 | 61.9 | 9.72 | 46.9 | 758 | 90.0 | 12.15 | 58.0 |

## 3 Review methodology

The review was systematically conducted using the PRISMA 2020 methodology, enabling the rigorous examination of relevant literature while filtering out irrelevant studies [52]. The review drew from online databases including Scopus, IEEE, and Indian Standards (IS) Codes. Using the keyword "bamboo" AND "reinforced" AND "concrete", 462 papers were identified in Scopus and 5 in IEEE. The focus was on engineering applications from 2014 to 2023, considering only peer-reviewed journal publications in English. The initial search yielded 116 papers from Scopus and 4 from IEEE, along with 7 relevant IS codes. However, 14 papers from Scopus and 4 from IEEE were inaccessible via original sources or email requests. Additionally, 53 Scopus-indexed papers were excluded for being outside the scope of this study, with some focusing on unrelated areas like transportation, telecommunications, bamboo fiber, coir, leaf ash, engineered laminated wood, earthen blocks, and large-scale infrastructure projects. After applying the exclusion criteria, 48 research papers were selected for a systematic literature review (SLR). These papers were chosen based on their focus on various aspects critical to the performance of bamboo reinforced concrete (BRC). The selected studies examined mechanical properties such as flexural strength, modules of elasticity and physical properties including the shape and size of bamboo for use in structural components like beams, columns, slabs, and walls. Additionally, the review covered the treatment processes for different bamboo species, the embodied energy (EE) of BRC, life cycle assessment (LCA) of BRC, overall strength and durability, crack behavior in BRC structural elements, and the bonding strength between bamboo and concrete, different types of testing used for various structural components. Additionally, the review incorporated relevant IS codes, such as IS 15912: 2018 (Structural Design Using Bamboo—Code of Practice—First Revision) [43] and IS 6874: 2008 [53]. However, other IS codes, including IS 9096: 2006 [54], IS 22156: 2021 [55], IS 22157: 2004 (Part 1) [56] IS 22157: 2004 (Part 2) [57], and IS 8242: 1976 [58], were not publicly accessible, posing a challenge to conduct a comprehensive review of bamboo standards (Fig. 1).

## 4 General characteristics of the reviewed papers

The search engine shows the unchanged interest in bamboo as an alternative to steel reinforcement in concrete was observed between 2014 and 2016 and there was a rise of research on the topic from 2016 to 2018 and 2021 to 2023. Additionally, a notable surge in citation numbers occurred from 2016 to 2018, coinciding with increased interest in unconventional building materials. However, scientific production experienced a slowdown in 2020 due to the COVID-19 pandemic, with a resurgence observed from 2021 onwards (Fig. 2a, b).

To understand the current trends in the BRC research, a co-occurrence analysis is performed by using VOS viewer version 1.6.20 (a bibliometric mapping software) to generate the knowledge maps with different clusters with sizes according to the co-occurrence of the keywords used in the published research documents. Figure 3 shows that there are seven different clusters generated where the circle represents a term whose size is proportional to the number of published articles. Each cluster are marked in different colour which shows the different thematic category on which the study is made. Red Cluster: Mechanical properties, Green Cluster: LCA and Structural Element, Blue Cluster: Bamboo reinforcement properties, Yellow Cluster: Mechanical performance, Purple and Orange Cluster: Bond Strength, Cyan Cluster: Physical Properties. The analysis reveals that researchers have investigated several aspects of bamboo reinforcement in concrete, including bond strength, composite structures, life cycle assessments, flexural strength through pull-out tests, and durability tests. However, the research appears to be incomplete across these stages, as indicated by the similar sizes of the clusters in Fig. 3. This suggests a need for further discussion and testing to address these gaps.

## 5 Analysis

Based on systematic literature analysis, four aspects that were established are bamboo species used for structural applications, structural elements designed bamboo as a reinforcing material for bamboo, mechanical properties of the BRC elements, bonding strength between bamboo and surrounding concrete.

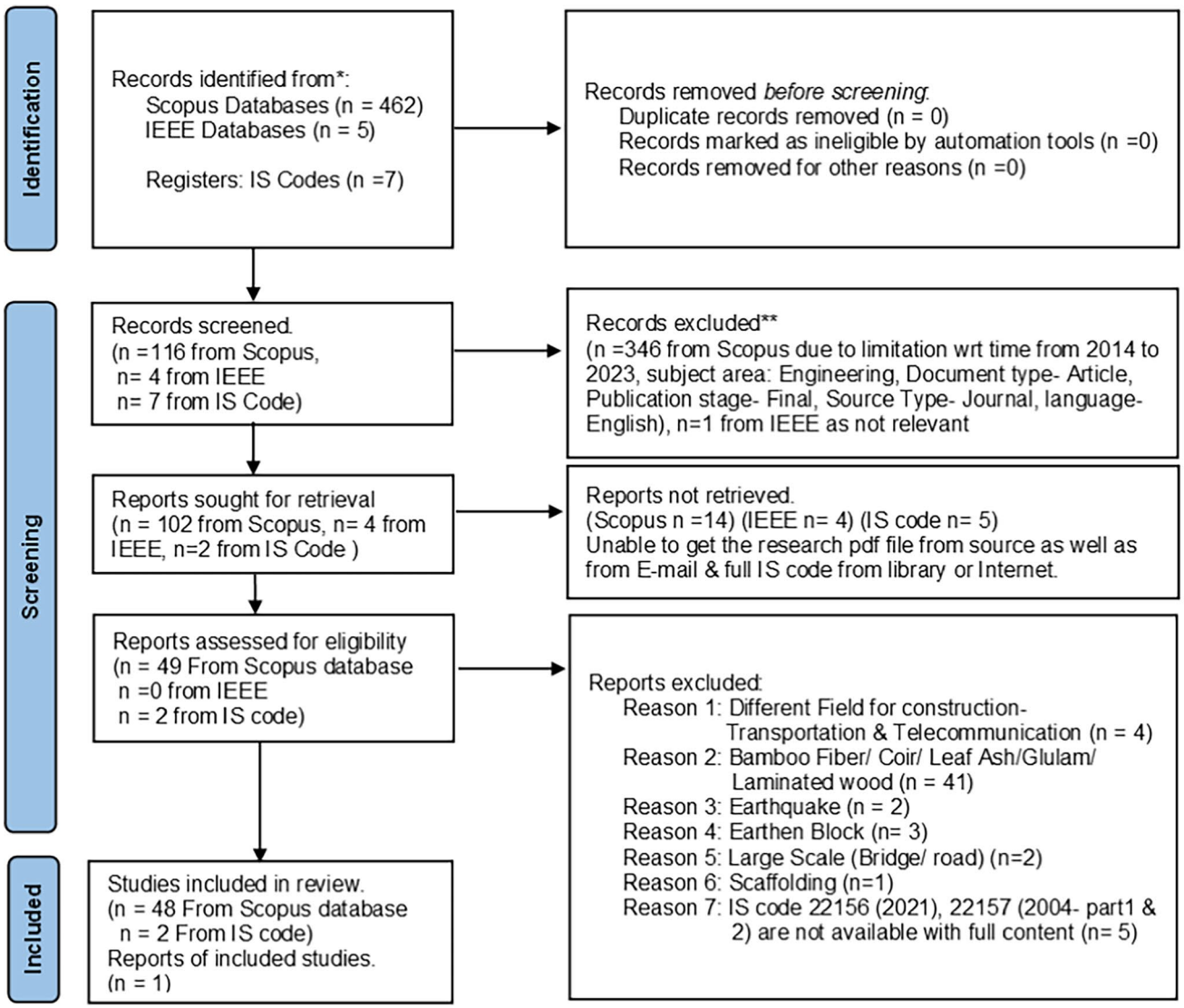



**Fig. 1** PRISMA flow chart

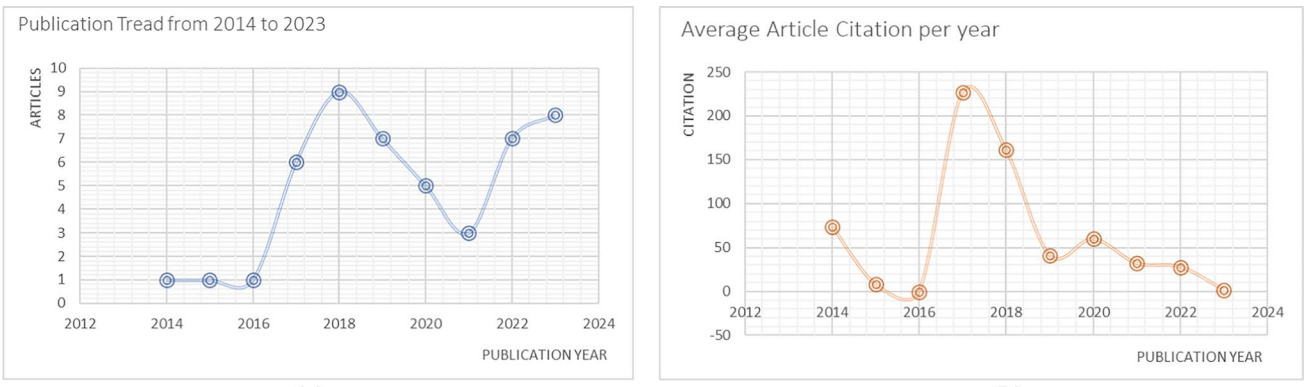



**Fig. 2** **a** Publication trend from the year 2014 to 2023 on bamboo reinforced concrete based on search criteria in Scopus database. **b** Publication citation from the year 2014 to 2023

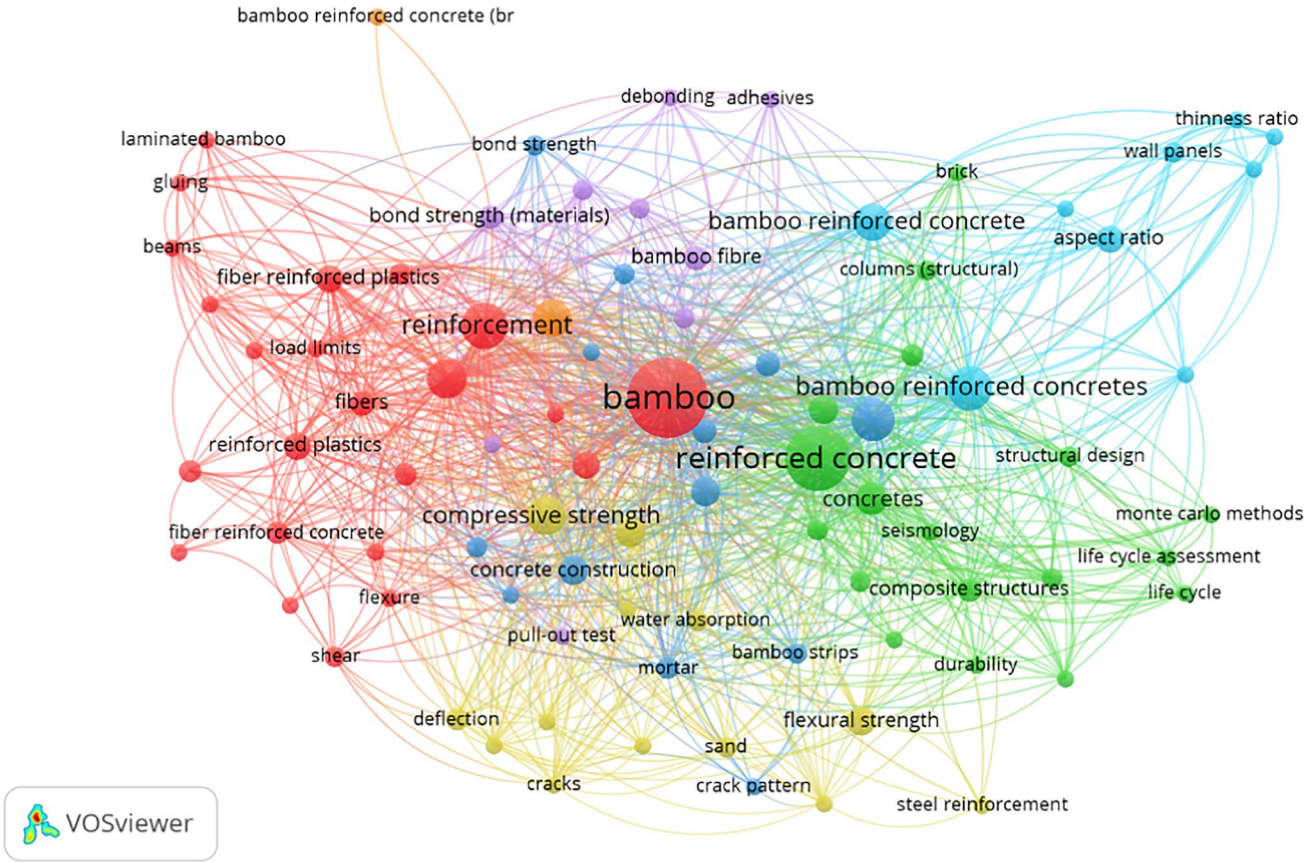



**Fig. 3** Co-occurrence analysis map using keywords based on BRC

### 5.1 Use of bamboo species as reinforcement

In the systematic literature review of 48 research papers, 26 researchers have identified the bamboo species utilized in their studies. Predominantly cited species include *Bambusa balcoa* (locally called Barak) [59–62], *Bambusa arundinacea* (locally called katang) [63, 64], *Petung bamboo* (*Dendrocalamus asper*) [65–67], *Bambusa vulgaris* [44, 68] and *Bambusa vulgaris vittate* (Yellow bamboo) [69]. Apart from these species other species like *Muli bamboo*, *Bambusa*, *Bambusa tudla*, *Dendrocalamus strictus*, *Brachystachyum densiflorum*, *Bambusa heterostachya*, *Schizostachyum brachycladum* yellow, *Gigantochloa scortechinii*, *Moso bamboo* were also utilized by researchers (Fig. 4). *Bambusa Balcoa* is recognized by INBAR and NBM as a bamboo species suitable for structural use in India [70].

### 5.2 Structural element

Research for alternative materials for building construction have been underway since the 1960s [64]. Bamboo's adaptability enables its use as both whole culms and strips for reinforcement, offering environmentally friendly alternatives, across various structural elements like foundations, columns, beams, slabs, and walls. A systematic literature study reveals a focus on bamboo's utilization in building structures, particularly in beams (Fig. 5), and explores aspects such as mechanical strength, bond strength, durability, behavior as reinforcement in concrete, and design with different stirrups arrangements. However, recent studies often overlook crucial details such as the types of bamboo species used and the testing climate, limiting our understanding of the material's intricacies.

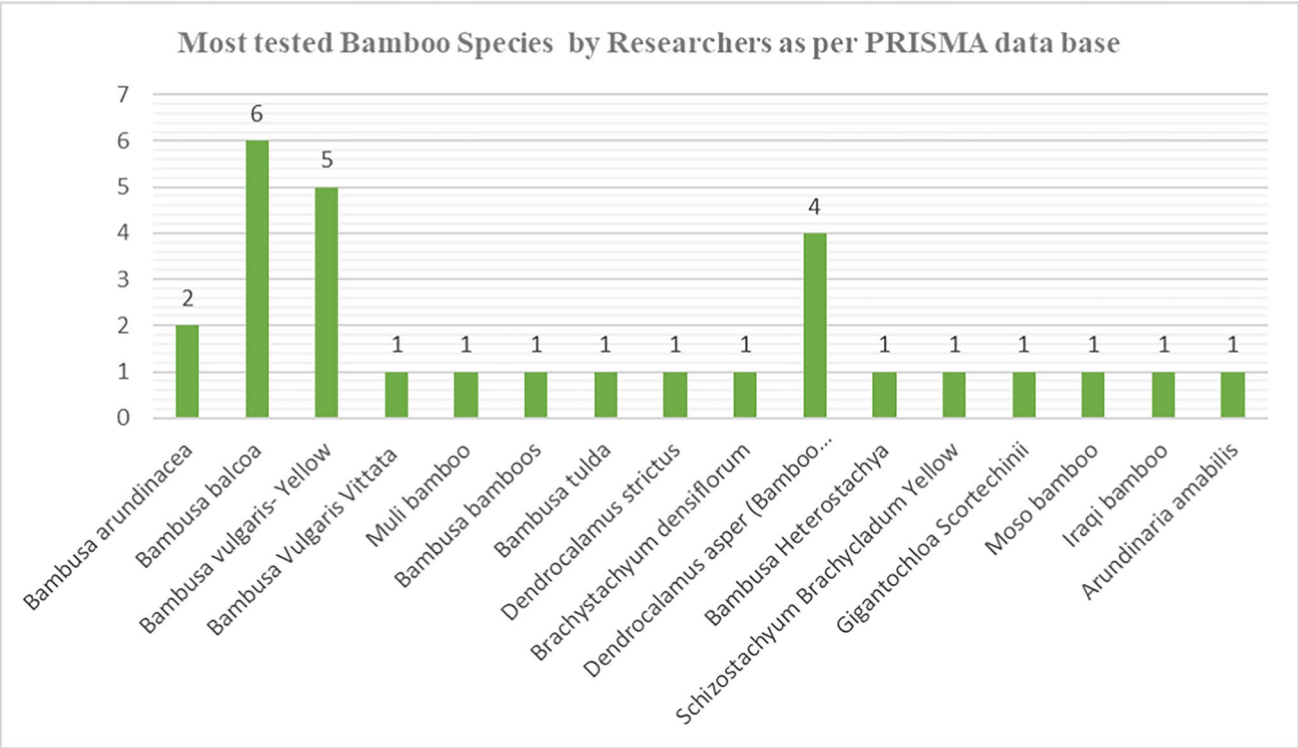
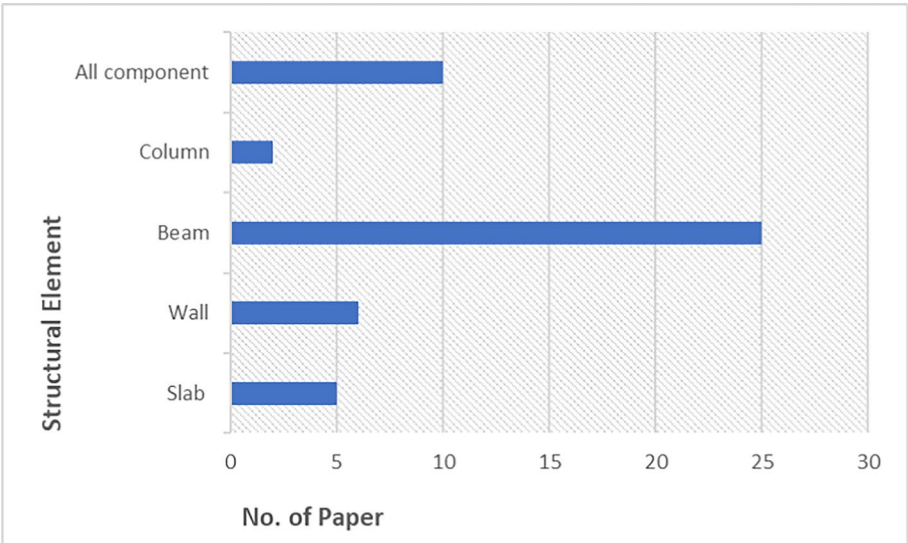



**Fig. 4** Most tested bamboo species as reinforcement in concrete by PRISMA analysis

**Fig. 5** Most testing on structural component PRISMA analysis




### 5.2.1 Wall

In rural areas, bamboo has traditionally been used for wall construction combined with mud plaster, known as wattle and daub walls. However, this type of construction is not durable in areas with heavy rainfall hence researchers have suggested various methods incorporating bamboo strips to enhance wall strength and durability. Researchers like Vengala et al. [71], Puri et al. [35] and IPITRI have developed prefabricated bamboo-based wall system where bamboo strips were used as grid along with steel wire mess and plaster. For this study researchers have taken 50 mm-thick wall panels with *Bambusa balcoa* mesh, which possessed high strength and flexibility. This also resulted in reduced carbon emissions with 40% construction cost savings, which is substantial. Such panels are suitable for earthquake-prone areas [35]. To

understand the impact of opening on the strength and behavior of BRC wall, experimental study was conducted where *Bambusa bamboo* with 20 mm splint was varnished and sandblasted before it was used for reinforcement in concrete. Grid layout of 20 mm bamboo splint was done as per the specification suggested by NBC- 2016 Part 6. It was found that the aspect ratio (AR) and thinness ratio (TR) for a load carrying capacity is very important for BRC wall panel. Lateral deflection of wall panels decreases with an increasing aspect ratio in panels with openings but increases in panels without openings, while ultimate load decreases with higher aspect ratio and increases with greater thickness ratio, regardless of openings [47]. Kasinikota et al. has discussed a study done on FICSEB walls where bamboo was used as reinforcement vertically, which enhances the ultimate load carrying capacity of about 114.84–184.91%, lateral deformation by about 19–27.6%, and energy absorption capacity by 168.9–317.43% [72]. Therefore, it can be used for load bearing structure for one- or two-story buildings based on the seismicity of the region. Whereas special care required to be taken while using bamboo in cementitious matrix to prevent cracking due to swelling due to moisture absorption [73].

#### 5.2.2 Slab

*B. vulgaris*- yellow, B. arundinacea, was mostly used species for roof slab casting (both one-way and two-way slab) where mostly slab thickness was taken as 75 mm and 100 mm thickness. It was observed that BRC slab possessed higher flexural strength, along with lower value of deflection and improved bonding performance by replacing polyvinyl waste (PW) to the concrete mixture as a partial replacement to cement [74]. Mali et al. has tested the treated bamboo strips as plain along length wise and bamboo strips with 10 mm diameter semicircular grooved along thickness wise where it was detected that the energy absorption capacity of grooved treated bamboo strips, used as reinforcement was higher than plain treated bamboo strips and untreated bamboo strips slab specimen [63]. Researchers stated that BRC slab is the most economical and affordable roofing system which can be adopted for rural or low-cost construction units where steel is costly [44, 63, 74–76]. Precast BRC slabs can reduce costs by 36.78% compared to RCC slabs whereas the slab is comparatively lighter and that can be lifted by two to three masons [75].

#### 5.2.3 Beams

Various methods of use of Bamboo, particularly for reinforcement in concrete beams have been explored for performance in flexural elements like beams. It was found that bamboo offered high resistance to slippage, particularly corrugated bamboo strips, while wired bamboo also provided enhanced resistance compared to plain strips [77]. The testing of various bamboo samples revealed significant variation in mechanical properties, like elastic modulus and tensile strength, affecting bamboo's behavior in reinforced concrete beams [70]. The study highlighted the importance of elastic modulus and tensile strength in bamboo's behavior. Lower modulus of elasticity led to large deflections and wider cracks in BRC beams [70]. The research also emphasized the need for further studies on LRFD-based design in BRC beams, including Monte Carlo simulations for predicting deflection and serviceability limits [59]. Bamboo, being a fibrous material, tends to absorb water and is susceptible to fungal attacks, which can lead to strength failure [78].

#### 5.2.4 Column

Mishra et al. [79] have investigated use of bamboo is a potential material that can be replaced with steel in beam-column joints as well. It has been observed that, bond strength of bamboo with concrete shows higher while coated with Sikadur Gel 32 rather than uncoated specimen in beam -column joint, whereas BRC joints failed at the ultimate load they were reached. Resan et al. [80] investigated that knotted BRC columns offer a promising solution to enhance strength and stiffness in slender columns where the knots act as internal constraints, thereby delaying buckling and improving load capacity by up to 33% compared to non-knotted columns. However, reinforcement distribution must balance ductility and strength.

Existing studies demonstrate improvements in compressive strength, flexibility, and energy absorption, yet moisture susceptibility, degradation, and inconsistent mechanical properties remain critical concerns. Although prefabricated bamboo-based wall systems and slabs have shown structural viability, long-term durability, standardized treatment methods, and hybrid reinforcement strategies are still underexplored. Additionally, BRC beams and columns require further parametric studies to optimize load-bearing performance and reduce deflections. The absence of standardized IS codes for bamboo reinforcement further limits its practical implementation. Future research should focus on developing

advanced preservation techniques, computational modeling for structural optimization, and experimental validation under diverse environmental conditions to establish BRC as a mainstream material in sustainable construction.

### 5.3 Bamboo treatment

Bamboo's high starch and sugar content makes it highly susceptible to termite and fungal attacks, which can compromise the structural performance of BRC [45]. Therefore, for bamboo to be effectively utilized as a structural material, a comprehensive understanding of its selection, preservation, and maintenance is crucial. Prior to undergoing chemical treatment, bamboo should first be subjected to traditional and natural preservation methods, which include non-chemical techniques such as water immersion, smoking, and coating with diesel, engine oil, or phenol formaldehyde (PF) resin. For enhanced durability, chemical preservation techniques such as borax-boric acid treatment, vertical soak diffusion (VSD), and pressurized tank preservation should be explored [81]. Implementing optimized preservation strategies will ensure the long-term structural performance and durability of bamboo in construction applications [82]. The experimental results presented in research, demonstrated that bamboo splints immersed in different solutions exhibited significant loss of ultimate tensile strength, with samples in plain water, $Ca(OH)_2$ and NaCl solutions experience the greatest loss up to 29.61%, 29.14% and 25.14% respectively due to rotting and fiber disintegration [83]. Among the three solutions tested, NaCl solution treated samples showed no fungal attack on bamboo splints at nodes or inner surfaces, making it an appropriate treatment for coastal environments (Table 3). Treating bamboo splints with bitumen and sand mixture substantially improved the load-carrying capacity and ductility of cement-concrete beams, reducing the risk of sudden brittle failure. To enhance bamboo's performance and durability as concrete reinforcement the importance of applying waterproof coatings and treatments, such as Bitumen is also recommended [83–85], along with Sikadur Gel (both 32 gel and 52 gel) [70, 79, 86–88], Boric and Borax acid [59, 64, 89], Bond Tite adhesive [59, 64], Coal Tar Creosote, and Polyester Resin [78], to bamboo before using it as reinforcement in concrete. To increase the bond stress between bamboo and concrete, along with the above-mentioned treatment, screws were added used between successive nodes [90], along with installation of hose clamp which serves as shear connector [65, 87, 88], whereas over-tightening is also found to reduce the ductility of BRC beams [87]. Also, Sikadur gel- 32 LP is used to enhance the bond stress between bamboo and concrete [35, 79].

### 5.4 Bond strength of bamboo and concrete

Mr. H. K. Chow in the year 1914 and Prof. K. Ghavami in the year 1995 started testing bamboo as reinforcing material in concrete and its mechanical properties [91]. It was noticed that the inclusion of bamboo considerably enhanced the composite's load-bearing capacity. However, they also noted that the bond strength between bamboo and concrete was relatively inferior when compared to that of steel and concrete [79]. partial replacement of cement with like fly ash, GGBS [60, 92] along with use of M-sand, benefited pozzolans to the concrete mixture with *Bambusa vulgaris* as reinforcement enhances the compressive strength and enhanced split tensile strength whereas it performed worse under flexural loading compared to controlled BRC component. 3-point flexural testing was adopted for the study. To comprehend the bonding properties of bamboo and concrete, researchers [61] have adopted a series of pullout test, 3-dimensional nonlinear FE model simulating test as developed by using commercial FE software ABAQUS version 6.14. It was concluded that the bamboo bond strength with concrete is lower than steel, whereas the presence of bamboo nodes helps to increase bond strength. Also, [62] the corrugated bamboo samples performed better due to their improved mechanical interlock and geometry, exhibiting higher bond strength compared to plain bamboo samples, outperforming even epoxy-coated samples. Their tests were conducted on *Bambusa balcoa* species using a 60-ton Tinius Olsen UTM.

### 5.5 Mechanical properties

The selection approach was very complicated due to the wide variety of bamboo species available worldwide. To understand the mechanical property of bamboo, researchers have conducted a series of laboratory tests with different species (Sect. 5.1) and treated (Sect. 5.3) for various structural elements. Most of the bamboo species chosen were aged between 3 and 5 years, as the species shows the best mechanical properties during this period. The experimental study was performed to verify the physical and mechanical properties, like tensile strength, compressive strength and modulus of elasticity. Most researchers have considered split bamboo as potential reinforcement material hence the sample size was taken as 15 × 12 mm, 10 × 10 mm for the species called *Bambusa vulgaris* [60, 85, 92] and the average tensile

**Table 3** Influence of different bamboo treatment methods on performance metrics

| Treatment method | Impact on tensile strength | Impact on bond strength | Durability enhancements | Suitability |
|---|---|---|---|---|
| Water immersion | Up to 29.61% loss due to rotting and fiber disintegration [77] | No significant improvement | Increases susceptibility to fungal attack | Not recommended for structural use |
| $Ca(OH)_2$ solution | Up to 29.14% loss [77] | No significant improvement | Limited protection; prone to degradation | Not suitable for structural applications |
| NaCl solution | 25.14% loss but prevents fungal attack [77] | No major impact on bond strength | Effective in coastal environments | Suitable for humid and coastal regions |
| Bitumen coating | No major impact | Improves bond stress and reduces risk of brittle failure [77–79] | Waterproofing effect enhances durability | Effective for concrete reinforcement |
| Sikadur gel (32, 52 LP) | No major impact | Enhances bond strength between bamboo and concrete [45, 64, 73, 80, 81] | Provides additional protection against moisture | Highly suitable for improving bond efficiency |
| Boric acid & borax | No major impact | Minimal impact on bond | Protects against termite and fungal attack [53, 58, 82] | Suitable for general preservation |
| Bond tite adhesive | No major impact | Improves adhesion in BRC [53, 58] | Limited effect on long-term durability | Useful for strengthening bond |
| Coal tar creosote | No major impact | No major impact | Effective against moisture but toxic | Not environmentally preferred |
| Polyester resin | No major impact | No major impact | Provides waterproofing but brittle | Not widely used |
| Mechanical enhancements (screws, hose clamps, etc.) | No impact on strength | Increases bond stress between bamboo and concrete [45, 59, 81] | Can reduce ductility if over-tightened [45] | Effective for improving shear resistance |

strength as 126.72 MPa and modulus of elasticity as 16.72 GPa was recoded whereas *Bambusa balcoa* sample size taken as 18–24 mm × 7–15 mm × 650 mm, 18–24 mm × 4–9 mm × 760 mm [61, 62] and ultimate tensile strength and modulus of elasticity was recoded as 114 MPa and 18.02 GPa respectively. Tazowar et al. has recorded the received compression strength for *Bambusa balcoa* as 35.2 MPa. *Bambusa arundenacea* with sample size 20 mm × 10 mm has recorded the average tensile strength as 90.42 MPa, modulus of elasticity as 7.65 GPa and compressive strength as 65.1 MPa [75] whereas *Petung bamboo or Dendrocalamus asper* recorded as 126.75 MPa as average tensile strength and 17.236 GPa as modulus of elasticity with specimen size of 12 mm × 12 mm [67]. Many other results were found on the mechanical properties where species were not mentioned.

## 6 Discussion

The data presented herewith, compares various structural elements and materials, highlighting their performance characteristics with respect to load capacity, ductility, and sustainability. For instance, the key factors affecting masonry wall performance like openings, reduce load capacity, while thicker walls and grouting enhance it [47]. Reinforcement, particularly steel mesh, enhances deformability and load capacity [72].

The developed bamboo-reinforced prefabricated panels demonstrate significant potential as a sustainable alternative to conventional brick walls, offering a 40% cost reduction and 56% weight savings. Their compressive strength (17.6 MPa) aligns with high-strength masonry materials, making them structurally viable for partition walls. However, the observed debonding failure under flexural loads underscores the need to balance fly ash content with bonding efficacy. While the environmental benefits of bamboo (e.g., $CO_2$ sequestration) and fly ash utilization are clear, scalability remains contingent on addressing gaps such as fire resistance, seismic performance, and standardized codes. Future work should focus on validating cheaper bamboo treatments and conducting long-term field studies to ensure durability in diverse climatic conditions (Table 7).

In slab (Table 6), the data highlights the most common bamboo species used as *B. arundinacea* and *Bambusa vulgaris*-yellow strips as reinforcement with concrete. For instance, PCC slabs exhibited limited load capacity compared to RCC, UTBRC, PTBRC, and GTBRC slabs. The enhancements in load capacity and energy absorption in PTBRC and GTBRC slabs underscore the effectiveness of surface treatment and groove-concrete interlocking [63]. Ferro cement panels outperformed bamboo-cement panels in load-carrying capacity and flexural strength. These ferro cement precast panels are comparably lighter in weight, erecting time, low in costing about 36.78% less than conventional RCC panel for a given size and form [75]. The affordability of the proposed roofing system compared to conventional RCC roofing is noteworthy. Additionally, bamboo splints which are treated with coal tar creosote exhibited improved tensile strength. Concrete quality assessments via PUNDIT testing (a nondestructive testing) and compression tests provided insights into concrete (M25 mix ratio) quality and strength variations among different slabs [44]. Sophia et al. investigated that *Bambusa vulgaris* family can successfully be replaced with steel for reinforcement purposes by treating the bamboo strips with coal tar creosote. Applying coal tar creosote increases the strength of the bamboo strips and reduces the fungal attack to the bamboo strips. Asamoah et al. [76] also have experimented with one way slab by applying 3rd point line load monotonically using the same bamboo species "*Bambusa vulgaris*". They have investigated around 12 bamboo-reinforced slabs made using SCC (self-compacting concrete) and NC (normal concrete) mixes in the context of monotonic loading. Restrictions on the amount of coarse aggregate in SCC slabs resulted in lower post-cracking stiffness but better crack control. The load capacity increased by 83–91% with added bamboo reinforcement (1–3%). The results emphasize the importance of bamboo as an eco-friendly construction material for rehabilitation works and recommend using a conservative safety factor or 4.0 in rural construction practices. Ikponmwosa et al. [74] concluded that by partial replacement of PW (Polyvinyl Waste) content with sand helps to improve the compressive strength of the slab specimen as well as improved the bending performance. Ultimately, the study underscores the importance of material selection, reinforcement, and surface treatment in enhancing the performance and affordability of concrete structures. None of the studies comprehensively address the long-term performance of bamboo-reinforced concrete (BRC) under environmental stressors (e.g., humidity, temperature fluctuations, alkaline degradation) whereas Mali and Datta [63] discussed on durability as a concern but lacks extended experimental data. The existing literature focuses on short-term mechanical performance and cost reduction but neglects holistic evaluations of durability, environmental impact, and real-world applicability. No investigation into the fire resistance of BRC slabs or the effects of high temperatures on bamboo-concrete bond strength. Limited data on long-term moisture absorption by bamboo in concrete, which could lead to swelling, cracking, or bond degradation.

Tables 4 and 5 study shows the experimental data highlights the exceptional performance of BRC beams and columns, showcasing their sequential enhancement in load capacity and ductility, particularly evident in treated grooved beams whereas novel approaches such as bio-based resins, hybrid composites, or nanotechnology-enhanced interfaces are yet to be explored (Tables 6, 7). Mondal et al. stated that Mechanical properties of *Bambusa balcoa*, crucial for LRFD (Load Resistance Factor Design) based design in flexural BRC members, reveal variations across culm height and nodal regions as well as show larger deflections and wider cracks due to low bond of bamboo in concrete [59, 70]. They have concluded to perform Monto Carlo simulation to obtain LRFD factors. Despite challenges like inadequate bonding and lower tensile modules, further research is needed to optimize BRC beam performance under varying loads and serviceability checks. Overall, the study highlights bamboo's potential as a sustainable and effective concrete reinforcement material, offering significant enhancements in structural strength and resilience. Most of the researchers have used M20 and M25 concrete mix for BRC structural members with river sand and OPC where Coarse Aggregates are 20 mm in size (Table 8).

Haryanto et al. have discussed experimental and finite element analysis (FEA) results confirm the performance of Near-Surface Mounted (NSM) bamboo reinforcement in enhancing the flexural strength of reinforced concrete (RC) beams. The findings of this study correspond with earlier studies in that NSM strengthening has the capacity to increase the ultimate load capacity. The experimental results revealed an ultimate load increase ranging from 12.46 to 41.74% for the NSM enhanced beams, while FEA results showed much more revealing figures of 75.46–86.39% for two samples like NSM1 and NSM2 [96]. This emphasizes the scalability and the viability of the method. Flexural capacity improvement in both studies has been characterized as being influenced by geometry of bamboo strips, concrete compressive strength, and percentage ratio of reinforcement. Experimental results showed the ability to carry load increased by as much as 101.44% as the concrete compressive strength increased, and FEA results depicted 15.65–23.90% reductions in the deflection ductility indices respectively [97]. Both studies confirm that NSM bamboo reinforcement is a viable and efficient method for enhancing the flexural capacity of RC beams.Researchers like Musab et al. and Mayank et al. have also discussed strengthening the load carrying capacity by introducing knotted confinement and peg configurations on beam tests. Knotted specimens generally have higher strength, enhancing load capacity and reducing lateral deformation. However, extreme reinforcement variation can reduce strength [79, 80]. The relative contributions of mechanical interlock (pegs) vs. frictional resistance (surface treatments) to bond strength remain unclear. Need for microstructural analysis of bamboo-concrete interfaces.

IS code 15914: 2018 (Structural Design Using Bamboo Code of Practice- 1st revision) and NBC 2016 recommend that about 16 species (Table 2) are suitable for structural use in round form, while 5 species named *Bambusa balcoa*, *B. glancescens*, *B. pallida*, *B. ventricosa*, *B. vulgaris* and *Oxytenanthera abyssinicia* in split form have been specified to use as reinforcement in concrete along with its strength properties (Table 9). These properties are taken during their green condition whereas it is important to discuss the strength properties after the chemical treatment as mentioned in IS code 15914: 2018-point no. 9.3 [43].

## 7 Conclusion

This systematic literature review provides an overview of the potential of bamboo as a sustainable and viable alternative to steel reinforcement in concrete structures. The main conclusions can be summarized as:

- Implementing targeted treatment strategies, such as borax-boric acid solutions, vertical soak diffusion, and pressurized tank preservation, significantly enhances bamboo's resistance to insect attacks.
- To improve the durability and bond strength of bamboo for structural applications in beams and columns, it is imperative to implement advanced treatment methodologies. Effective waterproof coatings, including bitumen, Sikadur Gel, boric-borax acid, and polyester resin, enhance bamboo's resistance to degradation. Furthermore, the incorporation of mechanical reinforcements, such as screws between nodes and hose clamps as shear connectors, significantly improves bond stress, thereby ensuring the structural integrity and load-bearing capacity of bamboo-reinforced concrete (BRC) elements.
- Bamboo-reinforced prefabricated panels demonstrate a 40% cost reduction, and 56% weight savings compared to conventional brick walls, while maintaining compressive strength (17.6 MPa) comparable to high-strength masonry materials. However, debonding failure under flexural loads necessitates optimization of bonding efficacy.
- The study underscores the structural viability of bamboo species such as *Bambusa Balcoa*, *Bambusa vulgaris*, *Dendrocalamus asper* (*Petung bamboo*), *Bambusa bamboo*, and *Bambusa arundinacea*, which exhibit high tensile strength and

**Table 4** Summary of research on BRC beam

| Author | Research focuses | Bamboo species | Treatment | Beam details | Types of tests | Key finding |
|---|---|---|---|---|---|---|
| [64] | Experimental evaluation on BRC beam—flexural strength, bond strength | *Bambusa arundinacea* | Treated with 6% boric acid solution & surface treatment with bond tite chemical adhesive | Beam size: 140 mm × 150 mm × 1100 mm<br>Bamboo strips size: 20 mm × 10 mm | Four-point bending test (pre-bending)- 100 KN capacity flexural testing machine (FTM) | BRC beams show the highest shear strength as well as flexural strength |
| [83] | Mechanical property (tensile strength) & durability evaluation | Not mentioned | Surface treatment: bitumen & sand mixture | Beam size: 500 mm × 100 mm × 100 mm<br>Bamboo splint size: 71–76 mm (L), 1.6–2.6 mm (W), 0.6–1.2 mm (thickness) | Durability testing, three-point flexural test | Bamboo splints used as reinforcement where Sufficient number of deflections were observed before ultimate load in costal environment. Shear reinforcement design required |
| [59] | Designing flexural bamboo reinforced concrete (BRC) members | *Bambusa balcoa* (*Bhalki*) | Treated with 5% concentration solution of borax and boric acid for 2 weeks | 300 mm × 230 mm and is 2600 mm long | Tensile testing by UTM & FEM by ABAQUS software | It shows variations in bamboo's mechanical properties due to different volume fractions of fiber and nodal presence |
| [93] | On evaluating the impact of different bamboo stirrup arrangements on the shear and flexural performance of the BRC beams | Not mentioned | Surface treatment with bond tite chemical adhesive | Bamboo strip size: 20 mm × 10 mm with groove size 10 mm × 5 mm with 20 mm c/c<br>Beam size: 140 mm × 150 mm | Pure bending test using FTM with a capacity of 100 KN & four-point bending test | BRC beams outperform PCC beams in first crack load, ultimate load, deformation, and energy absorption, with performance further enhanced by using treated grooved bamboo strips |
| [19] | Assessment of bamboo's effectiveness as reinforcement in concrete | Not mentioned | Not mentioned | Beam size: 150 mm × 150 mm × 750 mm<br>Bamboo strip size: 20 mm (W) | Tensile strength test & flexural strength test | Bamboo can be a potential reinforcement in concrete as this type of beam has higher load carrying capacity |
| [70] | Developing load and resistance factor (LRFD) design for BRC beams investigating the behavior of BRC beams through experiments and numerical simulations | *Bambusa balcoa* (*Bhalki*) | Sikadur 32-LP gel coating is applied to bamboo strips with medium sand is sprayed | Beam size: 200 mm × 250 mm × 2700 mm | Real-life experiments and finite element (FE) based numerical experiments | RC beams exhibit greater deflection and more extensive cracks in comparison to SRC beams<br>Enhancing bond capacity can prevent larger deflection and wider cracks |
| [89] | Optimizing materials and reducing costs in construction, coupled with the study of flexural behavior of concrete beams reinforced with bamboo bars | *Bambusa tulda* | Not mentioned | Beam size: 150 mm × 200 mm × 1200 mm<br>Bamboo bar size: 12 mm Φ & 16 mm Φ with length 1000 mm | Evaluating tensile strength using a UTM and obtaining load deflection response from an electronic control system | The load capacity of FRS-BRC beams is comparable to that of RCC control beams. Moreover, FRS-BRC beams exhibit less deflection than RCC control beams |
| [78] | Bamboo behavior as reinforcement in concrete and comparison of analytical and experimental results | Not mentioned | Coated with coal tar creosote and polyester resin | Beam size: 230 mm × 300 mm × 2000 mm<br>Bamboo strips with 8 mm & 10 mm | Water absorption testing for bamboo. Compression testing for bamboo specimens | Bamboo without knots has higher compressive strength. Bamboo reinforcement boosts beam capacity but causes shear failure due to lower Young's modulus |

**Table 4** (continued)

| Author | Research focuses | Bamboo species | Treatment | Beam details | Types of tests | Key finding |
|---|---|---|---|---|---|---|
| [94] | Experimental and numerical analysis of BRC beams is having crushed sand<br>Flexural behavior and performance of the beams | Not mentioned | Bamboo strips were treated with adhesives to ensure the bond strength of the composite | Beam size: 150 × 150 × 700 mm<br>150 × 200 × 1200 mm<br>150 × 150 × 2000 mm<br>Bamboo strips was 10 mm | Tensile strength testing using UTM<br>Non-destructive testing using ultrasonic pulse velocity (UPV) method | Bamboo beams matched steel in performance, increased curing boosted strength. Bamboo-reinforced beams exhibited higher mid-span deflection and lower stiffness after cracking |
| [17] | Research investigates the durability of BRC in adverse operational environmental conditions like acidic, high-temperature, and saline environments | *Brachystachyum densiflorum* species | Bamboo strips were treated with adhesive and Acid Hydrochloric acid (HCl) was used to check the concrete's durability | Beam size: 150 × 150 × 550 mm<br>Bamboo strips size: 10 × 10 × 520 mm | Compressive tests<br>High-temperature test was performed on the bamboo-reinforced concrete (BRC) samples<br>Acid attack and chloride attack tests were performed on BRC samples | BRC prism performed better than SRC prism under harsh conditions. With less water absorption using coatings, BRC showed better durability in acidic solutions and high temperatures, suggesting suitability for lightweight construction |
| [95] | The research focused on exploring the performance of BRC beams with the addition of bamboo pegs on the reinforcements | Not mentioned | Not mentioned | Beam size: 180 × 280 × 1600 mm<br>Bamboo strips: 10 × 10 mm<br>And 8 × 8 mm<br>Peg spacing: 60 mm & 120 mm | Pull out test, concrete test | It is found that adding peg (recommended spacing 100–120 mm) enhances bamboo reinforcement bonding in concrete beams which increases in flexural capacity by 27–35% |
| [87] | To enhance the bond strength between the bamboo reinforcement and the concrete matrix, and to assess the flexural performance of the beams after concrete cracking occurs | Not mentioned | Coated with water-based paints or bitumen, surface treatment with coarse aggregate, Sikadur 32 Gel adhesive coating | Beam size: 180 × 280 × 1600 mm<br>Peg distance: 60–100 mm | Load deflection testing, crack pattern analysis, bond strength testing, concrete stress analysis | The research demonstrated the effectiveness of using additional pegs to enhance the bond strength and flexural performance of BRC |
| [65] | Focuses on BRC beam with the use of hose-clamps as shear connectors | Bamboo petung (*Dendrocalamus asper*) | Sikadur®-752 gel coating, sprinkling the dry sand on bamboo | Beam size: 75 × 150 × 1100 mm<br>Bamboo strips: 7 mm × 10 mm<br>10 mm × 10 mm<br>15 mm × 15 mm | Material testing: UTM, pull-out testing, cyclic load testing, flexural beam testing, FEM analysis | Hose-clamps act as a shear connector & enhance bond-stress, BRC beam shows lower stiffness |

**Table 4** (continued)

| Author | Research focuses | Bamboo species | Treatment | Beam details | Types of tests | Key finding |
|---|---|---|---|---|---|---|
| [69] | On determining the optimal cutting shape for bamboo strips in tensile tests, the study examines the impact of bamboo species, bark and nodes presence, and moisture content on the tensile strength of the bamboo strips | *Bambusa vulgaris* Vittata (BV), *Bambusa heterostachya* (BH), *Schizostachyum brachycladum* Yellow (SB) | Chemical treatment | Beam size: 100 mm × 150 mmx 1000 mm long | Tensile test for different cutting shapes for bamboo strips, pull-out test, 3- point bending test, comparison of theoretical calculation and experimental result | The study found that SS-shaped bamboo strips with bark showed the highest tensile strength. Bark presence and low moisture content enhanced strength. Also found that bamboo is suitable as reinforcement in concrete |
| [90] | The focus area of the research is to investigate the usage of screws to increase the bond between Iraqi bamboo and concrete in concrete beams | Iraqi bamboo | No treatment done to the species | Beam size: 100 × 200 × 1200 mm<br>Bamboo stick: 8 mm Φ with 1200 mm long | Four-point load testing, compressive strength testing, yielding strength testing, sieve analysis testing, auditory perception testing, crack pattern analysis | Bamboo-reinforced beams carry 80% less load than steel ones. More sticks increase deflection. Hollow bamboo crushing causes cracks. Bond improves with screws |
| [88] | The research focuses on studying the flexural behavior pattern of BRC beams and evaluating the experimental performance of BRC beams | Petung (*Dendrocalamus asper*) | Treated with Sikadur- 752 for waterproof coating | Beam size:<br>120 mm × 200 mm × 2100 mm<br>Bamboo strips: 15 mm × 15 mm | Test and characterization of tensile strength, bamboo concrete bond strength, flexural behavior model | Bamboo reinforcement with hose-clamp & water proofing coating can increase bond strength. Hose clamp installation helps bond stress & stiffness. Too tight hose clamp can reduce the ductility of BRC beam |
| [66] | The research focuses on the stiffness and cracked pattern of BRC beams using a hose clamp | Petung (*Dendrocalamus asper*) | Treated with waterproof coating, sand coating, hose clamp installation | Beam size:<br>75 mm × 150 mm × 1100 mm<br>Bamboo strips: 7 × 10 mm, 10 × 10 mm, 15 × 15 mm | Pull-out test, flexural beam test | Using stainless steel hose-clamps on BRC beams increased ultimate load by 90%. Hose-clamps enhanced crack distribution & BRC beams had lower stiffness than SRC beams |
| [84] | The focus of this research is on the behavior of bamboo reinforced self-compacting concrete (SCC) beams without stirrups | Not mentioned | bamboo strips were treated with a bituminous material with a sand coating of thickness about 3–5 mm | Beam size:<br>150 mm × 250 mm × 2750 mm<br>Bamboo strips: 15 mm × 10 mm | Flexural testing, crack width and height testing, compressive strength testing | Bamboo-reinforced SCC beams have higher deformation capacity<br>Beam depth impacts shear resistance significantly |

**Table 4** (continued)

| Author | Research focuses | Bamboo species | Treatment | Beam details | Types of tests | Key finding |
|---|---|---|---|---|---|---|
| [85] | The study focuses on evaluating the load–deflection curves, serviceability and ultimate failure characteristics, cracking behavior, and ductility measures of the tested beams | *Bambusa vulagis* | Treated with Bituminous material for water absorption | Beam size: 110 mm × 275 mm × 1800 mm Bamboo strips with 15 mm × 12 mm | 4-point bending test until ultimate failure | Study found SCC beams with bamboo reinforcement exhibit enhanced flexural capacity, influenced by shear span-to-depth ratio and longitudinal reinforcement level, necessitating further research on bamboo's applicability in SCC structures |
| [77] | Research aims to assess bamboo as steel replacement in concrete beams, analyzing its mechanical properties and feasibility under bending | Not mentioned | Not mentioned | Beam size: 230 mm × 230 mm × 1880 mm Bamboo strips with | Tensile tests, water absorption tests, pull-out tests, beam testing | Different techniques, such as using wired or corrugated bamboo strips, improved the bond strength significantly |
| [68] | The study aims to evaluate the structural behavior of reinforced concrete beams | *Bambusa vulgaris* | Bamboo splints coated with rubber latex, made from *Bambusa vulgaris* stems | Bamboo splint: 70 × 2 × 0.5 cm | Pull out test, compression test, bending test | Pullout tests showed a 28% increase in tension at bamboo node reinforcement. Bending tests increased beam strength by 58% |
| [96] | The research focused on enhancing the flexural strength of reinforced concrete (RC) beams using the Near Surface Mounted (NSM) technique with bamboo reinforcements | Not mentioned | Not mentioned | Beam size: 100 mm × 150 mm × 1000 mm | Finite element analysis (FEA) | Result from both experimental & FEA for NSM strengthened beams was similar and it was a flexural failure |
| [86] | The study aims to analyze the deflection at the beam's central span, where the maximum bending moment, deflections, and strains are observed | Muli bamboo | Treated with Sikadur 32 gel | Beam size: 75 mm × 150 mm × 1000 mm | Tensile testing using UTM & two-point bending testing. Also used ANN software for satisfactory performance in predicting the deflection behavior | The BRC Beam exhibited a 30% increase in load-carrying capacity compared to a plain reinforced concrete beam with 1.5% reinforcement. Additionally, with 1.1% steel reinforcement, the BRC Beam demonstrated an 8% increase in load-carrying capacity |

**Table 4** (continued)

| Author | Research focuses | Bamboo species | Treatment | Beam details | Types of tests | Key finding |
|---|---|---|---|---|---|---|
| [18] | The study focuses on the utilization of cassava peel ash as a supplementary cementitious material and bamboo as reinforcement in the concrete beams | Not mentioned | Sun dried for 15 days. Water absorption treatment "bitumen coating" done to bamboo species | Beam size: 100 mm × 150 mm, 100 mm × 150 mm, 100 mm × 250 mm<br>Bamboo culm used as reinforcement here & size 12 mm Φ, 14 mm Φ, 6 mm Φ | Flexural strength testing, flexural strain testing<br>RMS (response surface methodology) used to generate 3D plots for all factors | BRC containing 3% of Cassava Peels Ash (CPA), helps to achieve flexural strength of 11.85 N/mm$^2$, 14.34 N/mm$^2$, 14.95 N/mm$^2$ for different beam sizes. Also, resulted that beam high L/D ratio increases the flexural strength and reduced L/D ratio increases flexural strain |
| [97] | This study aimed to extend Haryanto et al.'s work by modeling reinforced concrete beams strengthened with non-metallic bamboo to better understand their response and behavior, considering bamboo diameter, concrete compressive strength, and steel reinforcement ratio | Not mentioned | Not mentioned | Beam size: 150 mm × 100 mm × 1000 mm<br>Bamboo strip size: 6 mm dia | 4-Point bending test, UTM, NSM (near surface mounted) technique | Flexural capacity of RC beams can be improved by strengthening the beams with bamboo strips using the NSM technique |

**Table 5** Summary of research on BRC column

| Author | Research focuses | Bamboo species | Treatment | Column details | Types of tests | Key finding |
|---|---|---|---|---|---|---|
| [79] | The study focuses on replacing bamboo as a reinforcing material in beam-column joints rather than steel as reinforcement material | Not mentioned | Testing done with Sikadur 32 gel coating on bamboo strips | Beam size: 400 × 150 × 150 mm<br>Bamboo strips for beam: 12 × 6 mm<br>Column size: 1000 × 150 × 150 mm<br>Bamboo strips for column: 13 × 6 mm | Pullout tests, beam-column joint tests | Experimental study says bamboo coated with Shikadur 32 gel helps to increase the bond stress hence bamboo can be used as a replacement to steel to concrete. Further study required for different treatment processes for bond strength, water repellent behaviour & durability of bamboo reinforcement |
| [80] | Focuses on using the philosophy of biomimicry to adapt bamboo culm structure in designing slender reinforced concrete columns under eccentric load | Not mentioned | Not mentioned | Column size: 120 × 80 mm | Flexural strength test, compression test, splitting test | Slender concrete columns with enhanced reinforcement and knots showed improved strength, stiffness, and delayed buckling. This approach offers new structural design options |

**Table 6** Summary of research on BRC slab

| Author | Research focuses | Bamboo species | Treatment | Slab details | Types of tests | Key finding |
|---|---|---|---|---|---|---|
| [63] | Research focuses on feasibility & performance of slab panels using bamboo strips as the main reinforcement | *Bambusa arundinacea* (*katang*) | Treated with 6% boric acid solution with normal water for 72 h & air dried for 5 days<br>Chemical treatment: bond tite chemical, sand blasting | Salb thickness: 100 mm<br>Bamboo strip size: 20 mm × 10 mm | Pull out test, flexural testing machine (FTM) | Study showed that treated grooved bamboo strips in concrete slab enhance flexural strength, energy absorption capacity, and ductility |
| [75] | Research focuses on reducing the cost of Construction & Flexural Strength by introducing Bamboo cement precast infill panel | Not mentioned | Bamboo coated with bitumen, M-sand | Bamboo cement precast infill panel size: 0.65 m × 1.25 m with 40 mm thickness | Panels were tested under 2000 kN uniformly distributed load, reliability analysis- Monte Carlo simulation method, cost analysis | The proposed affordable roofing system reduced costs by 36.78% compared to conventional RCC slabs |
| [44] | The study focused on developing a BRC slab for low-cost housing, promoting sustainable growth and reducing global warming by decreasing fossil fuel demand while meeting housing needs | Bambusa vulgaris- Yellow | Soaked in air drier & in coal tar creosote for about 24 h | Slab size: 1500 × 500 × 75 mm | Non-destructive test- ultrasonic pulse velocity—PUNDIT device. Destructive tests- 1000 KN load to determine the strength | Bambusa vulgaris is an alternative to steel in low-cost construction<br>Coal tar creosote treatment improves strength and resists fungi. Bamboo panels show higher deflection, lower load capacity |
| [74] | The research focused on innovative structural and construction materials that can reduce the reliance on non-renewable materials like sand and cement | Not mentioned | Bamboo is dried & coated with bitumen | Slab size: 1300 × 500 × 100 mm<br>Bamboo splint size: 10 × 10 × 1200 mm | Density and compressive strength test, flexural test, structural configuration and bending moment analysis, deflection and failure load analysis | Replacing sand with polyvinyl waste in concrete slabs improved compressive strength and bending performance. Higher polyvinyl waste content increased strength and reduced deflection under load. Polyvinyl waste-replaced slabs exhibited shear bending failure, unlike diagonal shear in control slabs |
| [76] | The study aimed to evaluate the feasibility and performance of bamboo as tensile reinforcement in self-compacting concrete one-way slabs | *Bambusa vulgaris* | Treated with bituminous coating | Bamboo strip thickness: 2 mm | Compressive test, modulus of rupture (MoR) | Bamboo-reinforced SCC slabs showed lower post-cracking stiffness compared to NC slabs. Increasing bamboo reinforcement improved ultimate load and deformation capacities. Bamboo-reinforced SCC slabs performed better in crack control |

**Table 7** Summary of research on BRC wall

| Author | Research focuses | Bamboo species | Treatment | Wall details | Types of tests | Key Finding |
|---|---|---|---|---|---|---|
| [35] | Development of an alternative sustainable infrastructure component like prefabricated bamboo reinforced wall panels for low-cost housing | Bambusa Balcoa | Lime water treatment, Sun dried, Sikadur 32 L P Epoxy | Wall panel size: 2400 × 300 × 50 mm<br>Bamboo strips: 3–5 mm thickness | Compressive strength testing, flexural loading, behavior testing, rebound hammer test, cost and dead load analysis | Prefabricated bamboo-reinforced wall panel system resulted 40% cheaper, lighter & energy-efficient than traditional brick walls. It improves earthquake resilience, reduces carbon emissions and offers high strength & flexibility |
| [47] | Focused on the effect of opening on BRC wall panels & Aspect ratio (AR) & Thinness ratio (TR) on load carrying capacity of wall panel | Bambusa bamboo | Varnished & sandblast | Wall panel size: 2000 × 2000 × 80 mm<br>Bamboo strips: 20 mm | Testing under one-way in-plane action, lateral deflection testing (LVDT) | Ultimate load of wall panels with opening is 50% of solid wall panels<br>Lateral deflection of wall panels vary with aspect ratio |
| [72] | On flexural behavior of hollow compressed stabilized earthen interlocking block masonry walls. Impact of grouting, channel block, and reinforcement layout for the wall | Not mentioned | Not mentioned | – | Prism tests as per IS 1905, out-of-plane flexural test performed as per BS 5628 | Steel reinforcements outperformed bamboo, but bamboo could be a sustainable, cost-effective alternative particularly where steel is unaffordable for low-cost housing |
| [98] | The research focuses on bamboo's mechanical properties and potential as an affordable, sustainable alternative to traditional reinforcement materials, while emphasizing the importance of quality and durability | *Gigantochloa scortechinii* (Buluh Semantan in Malaysia) | Untreated bamboo, only air dried for 1 month | Panel size: 1500 × 500 × 125 mm<br>Bamboo size: used as culm with 45–60 mm Φ | Axial load test, flexural test | Bamboocrete technology offers an alternative for building constructions and other applications like wall panels, floors, pathways, and manhole covers which promotes sustainable construction |
| [73] | Focuses on finding alternative materials for safe housing in developing regions. The goal is to use locally available resources and labor to construct affordable and durable housing | *Arundinaria amabilis* | Coated with an inexpensive spar (marine) varnish to waterproof & dusted with sand | Panel size: 190 × 390 × 190 mm<br>Bamboo culm size: 25 mm Φ | Cyclic testing, quasi-static testing, bilinear idealization, comparison testing, unreinforced wall testing | Bamboo reinforcement in concrete block shear walls enhances shear capacity and ductility, performing similarly to steel. Proper waterproofing is essential to prevent moisture absorption and cracking |
| [67] | The research conducted focused on investigating the performance of BRC precast panels (BRCPP) under axial compressive loads | Bamboo petung (*Dendrocalamus asper*) | | Panel size: 1200 × 400 × 50 mm<br>Bamboo size: 12 × 12 mm with 150 mm spacing | Tensile strength testing and compressive strength testing | BRCPP Panel size & spacing meets the capacity of SRCPP. Failures occurred in zones of maximum stress, aligning with FEM simulations |

**Table 8** Specification of concrete mix used for BRC by researchers

| References | Concrete mix | Types of cement used | Size of course aggregate (CA) used | Types of sand used | Water–cement ratio | Admixtures | Mix ratio (cement:sand:coarse aggregate) |
|---|---|---|---|---|---|---|---|
| [64] | M20 | – | 20 mm & 10 mm (70:30) | – | – | Not used | IS10262 & IS 456 |
| [83] | M20 | OPC | NA | – | 0.5 | – | 1:1.4:3.1 |
| [19] | – | OPC | 20 mm | River sand | 0.52 | | 1:1.5:2.8 |
| [89] | M20 | OPC grade 53 | 20 mm | River sand | 0.5 | | |
| [63] | M20 | OPC grade 53 | 20 mm & 10 mm (70:30) | – | – | – | IS 10262 and IS 456 |
| [75] | – | – | – | CD waste | 0.45 | Expanded polypropylene fibres & plasticizers | – |
| [44] | M25 | – | – | – | 0.5 | – | – |
| [35] | | | | | 0.25–0.5 | Fly ash | |
| [80] | – | – | 9.6 mm | – | – | Superplasticiser | – |
| [96] | – | – | 20 mm | River sand | 0.43 | – | – |
| [77] | – | OPC | 19 mm | – | 0.45 | – | 1:2.6:4.5 |
| [85] | – | | 10 mm & 14 mm | River sand | 0.5 | Rheobuild 561-ASTMC 494 type A | 1:1.82:1.27 |
| [84] | – | OPC grade 42.5 | 20 mm | River sand | – | – | 1:2.8:1.7 for SCC & 1:1.5:3 FOR VC & 1:4.5 |
| [90] | M25 | – | 12 mm | – | 0.46 | – | 1:2.67:2.16 |
| [65] | – | PCC | – | Malang sand | – | – | 1:1.8, 1:2.8, 2:0.52 |

**Table 9** Properties of Indian bamboo (in split form) [43]

| Sl. No. | Bamboo Species | Fibre Stress at Elastic Limit N/mm2 (kg/cm2) | Modulus of Rupture $N/mm^2$ | Modulus of Elasticity X $10^3$ $N/mm^2$ | Maximum Compression Strength (Parallel – without node) $N/mm^2$ | Maximum Compressive Strength $N/mm^2$ |
|---|---|---|---|---|---|---|
| 1 | Bambusa pallida | 37 | 59.3 | 3.2 | 58.3 | 9.6 |
| 2 | Bambusa vulgaris | 45.5 | 86.8 | 5.1 | 39.5 | 9.3 |
| 3 | Dendocalamus hamiltonii | 29.5 | 51.4 | 3.7 | 40.6 | 7.6 |
| 4 | Dendrocalamus giganteus | 46.3 | 83.2 | 5 | 35.3 | 8.7 |
| 5 | Oxytenanthera abyssinica | 44.1 | 81.5 | 3.3 | 37 | 11 |

Note: Strength for Bambusa pallida and Oxytenanthera abyssinica taken as average of bottom and middle portion only

modulus of elasticity. Experimental investigations reveal an average tensile strength of 118.578 MPa and a modulus of elasticity of 15.529 GPa across these species, with various chemical treatments enhancing their mechanical properties. Notably, immersion in NaCl solutions has demonstrated potential in improving durability by mitigating fungal degradation and moisture absorption. Despite their promising structural performance, these bamboo species are currently unrecognized in IS codes and NBC 2016, highlighting the need for further research and regulatory inclusion to facilitate their adoption in structural applications.

- Current design codes IS 15914:2018, NBC 2016 specify bamboo species suitable for structural use in green form, but comprehensive data on chemically treated bamboo's strength properties remain limited. Future research should focus on integrating treated bamboo into standardized design frameworks.
- Existing studies lack long-term assessments of bamboo-reinforced concrete (BRC) under environmental stressors such as humidity, temperature fluctuations, and alkaline degradation. Limited investigations exist on fire resistance, moisture absorption effects, and bamboo-concrete interface microstructures, which are critical for its widespread adoption.

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