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Bamboo in sustainable construction: effects on productivity and safety

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Abstract

Purpose – A significant amount of ozone-depleting chlorofluorocarbons is emitted during the production of building materials. With the world population expected to increase by 21.3% from 2030 to 2050, the demand for construction materials is set to rise, necessitating a shift toward eco-friendly options to preserve the ecosystem. Bamboo emerges as a promising solution to meet sustainable construction goals. This study aims to investigate bamboo's potential as a sustainable construction material, evaluating its impact on construction productivity and safety.

Design/methodology/approach – A systematic literature review was conducted, using relevant keywords to retrieve journal articles from the Scopus, Web of Science and Google Scholar databases. Articles were screened, and only those meeting the inclusion criteria were reviewed.

Findings – Bamboo offers numerous advantages as a construction material, including cost-effectiveness, abundance and strength, making it a viable alternative to traditional building materials with a reduced environmental impact. However, its widespread acceptance encounters significant challenges. The use of bamboo in construction can both positively and negatively affect productivity and safety in construction organizations.

Practical implications – This study proposes a framework for improvement that construction stakeholders can adopt to enhance bamboo's utilization in construction while maintaining high productivity and safety standards.

Originality/value – While previous studies have advocated for increased bamboo utilization in construction, this study goes further to explore the implications for productivity and safety in construction.

Keywords Construction materials, Ecosystem, Greenhouse gasses, Productivity, Safety, Sustainability

Paper type Literature review

1. Introduction

The emission of heat-trapping greenhouse gases (GHGs) stands as one of the most critical concerns of the millennium. Buildings are primary sources of CO_2 emissions, accounting for approximately 25% of all ozone-depleting chlorofluorocarbons (Sahlol *et al.*, 2021). The building industry is the largest energy-consuming sector globally (IEA, 2013), responsible for over 40% of global energy consumption (Mehrzad *et al.*, 2022). The sector contributes to about 45% of GHG emissions, with 11% linked to building materials (Singh *et al.*, 2023). Some GHGs, particularly carbon dioxide (CO_2), are abundant and can persist in the atmosphere for thousands of years (Ahmed Ali *et al.*, 2020). The construction industry has seen a surge in the use of eco-friendly building materials to mitigate the negative environmental impacts of building operations (Sahlol *et al.*, 2021) and enhance sustainability within the sector (Boity *et al.*, 2022). Building materials play a significant role in embodied energy (Mehrzad *et al.*, 2022; Al-Rukaibawi *et al.*, 2021). To improve sustainability in construction, there is a pressing need to increase the use of eco-friendly materials (Singh *et al.*, 2023; Boity *et al.*, 2022). Research into alternative building materials has been extensive to promote sustainable construction (Suksiripattanapong *et al.*, 2015) and reduce GHG emissions (Unni and Anjali,

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2022). Studies have explored phase change materials (Agarwal *et al*., 2023; Li *et al*., 2013), cementitious materials (He *et al*., 2020), bamboo (Boity *et al*., 2022; Chaowana *et al*., 2021), sugarcane bagasse waste (Mehrzad *et al*., 2022), alternative aggregates (Vijayakumar *et al*., 2019), among others.

Bamboo has recently garnered significant attention as a sustainable building material. It shares properties with structural wood and is recognized as an effective CO_2 absorber (Al-Rukaibawi *et al*., 2021). Bamboo-based construction not only emits lower levels of CO_2 but also has the potential to offset emissions from other conventional construction materials (Escamilla *et al*., 2018). The demand for bamboo is on the rise due to the dwindling supply of timber (Akwada and Akinlabi, 2018). However, despite its sustainable advantages, bamboo remains underutilized in construction. Its impressive tensile strength, reportedly higher than that of steel, positions it as one of the most versatile renewable materials (BambooLogic, 2023). Factors contributing to its limited acceptance include its shorter lifespan, lack of comprehensive standards and codes, inadequate understanding, poor government policies, and cultural associations with poverty. Bamboo construction is often linked with rural and urban poverty, leading to its label as "the poor man's timber." While bamboo's affordability is an advantage, its slow adoption by middle and high-income populations has hindered its mainstream acceptance (Witte, 2019). The construction industry consumes 25% of forest timber (Sharma and Sharma, 2022), and the increasing demand for construction projects, driven by population growth, is likely to escalate timber consumption and natural resource depletion (Boity *et al*., 2022). Bamboo has come to stay as an innovative and sustainable building material, due to a viable alternative to timber it offers (Mahdavi *et al*., 2012), with a sustainability profile reportedly 20 times that of wood (Xu *et al*., 2022a, b).

Among the leading factors that have bedeviled construction organizations in recent years are poor construction productivity (Adebowale and Agumba, 2024) and safety standards (Ibrahim *et al*., 2024), which both contribute to poor construction business performance (Gharbia *et al*., 2020). Although the call for increased utilization of bamboo as a sustainable construction material is legitimate and beneficial to the ecosystem, the effect of bamboo utilization on construction productivity and safety must be assessed. While previous studies have advocated for bamboo as a sustainable construction material (Boity *et al*., 2022; Fahim *et al*., 2022; Hailemariam *et al*., 2023), this study takes a unique approach by examining the potential of bamboo as a sustainable construction material and evaluating its impact on construction productivity and safety. This dual focus addresses a significant knowledge gap in the literature, as previous research has largely overlooked the effects of bamboo utilization on construction productivity and safety. Therefore, the study not only promotes bamboo for its sustainable benefits but also investigates its potential effects on construction productivity and safety. To understand the factors influencing increased bamboo utilization in construction, this study focuses on four key areas most relevant to productivity and safety. These factors include availability (Boity *et al*., 2022), cost performance (Sanni-Anibire *et al*., 2022a), quality concerns (Fahim *et al*., 2022), and acceptance by stakeholders (Xu *et al*., 2022a, b). Consequently, this study examined the effects of bamboo utilization on construction productivity and safety. This was done by considering bamboo availability, cost, and quality performance, as well as stakeholder acceptability. These findings would promote the utilization of bamboo in construction while simultaneously addressing concerns about productivity and safety. The study's findings offer valuable insights for construction professionals and stakeholders by demonstrating the potential of bamboo as a sustainable and safe construction material, which can enhance productivity and safety on construction sites. A great number of people are engaged in bamboo work to support their livelihoods. It was estimated that over 1.2 billion USD can be generated every year if the country's bamboo resource base is properly utilized (Mekonnen *et al*., 2014). This study enriches the existing literature by providing empirical evidence on the benefits of bamboo utilization in construction, thereby bridging the gap between theory and practice. By highlighting the impact of bamboo usage on construction productivity and safety, the research advances the understanding of sustainable and safe construction practices and lays the groundwork for future studies and policy-making initiatives. In the following sections, the study presents a review of the literature on bamboo utilization in construction concerning the study objectives. The study further presents the research methodology, discusses the research findings, introduces a performance framework, and concludes with the implications of the research.

2. Literature

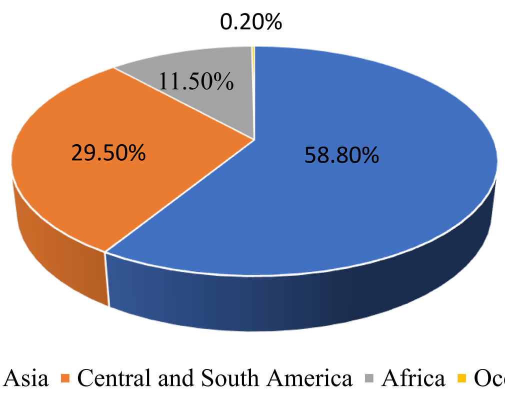
2.1 Availability

The global bamboo forest area has increased at an annual rate of 3%, producing 15–20 million tons of products annually—4.47 times that of wood (Xu *et al*., 2022a, b; Emamverdian *et al*., 2020). Bamboo forests are mainly distributed in tropical and subtropical climate zones across Asia, Central and South America, Africa, and Oceania (Emamverdian *et al*., 2020; Du *et al*., 2018). The bamboo forest covers approximately 36 million hectares globally, which is nearly 0.92% of the world's total forest area (Sawarkar *et al*., 2020; Du *et al*., 2018). A significant number of bamboo species are found in Asia, specifically in China and India (Du *et al*., 2018). The distribution of bamboo in Taiwan can be both natural and planted (Lin *et al*., 2011). India hosts approximately 148 species (both natural and planted), predominantly found in the deciduous and semi-evergreen regions of northeast India, as well as the tropical deciduous forests in northern and southern India (Boity *et al*., 2022). The northeastern hilly states of India cultivate nearly 90 species (Emamverdian *et al*., 2020). Globally, India is the second-largest producer country, with 160 species, following China, which has the highest number of 800 species (Sawarkar *et al*., 2020). China and India account for 36.18 and 32.19% of the total bamboo forest area in Asia, respectively, while Asia accounts for about 58.80% of the global forest area (Du *et al*., 2018). The bamboo forest area in Central and South America accounted for 29.5% of the global bamboo forest area, with Brazil possessing the richest bamboo forest resources in the world, accounting for 23.41% of the global bamboo forest area (Du *et al*., 2018).

There are approximately 4.56 million hectares of bamboo forest and 115 bamboo species across 48 African countries (Bahru and Ding, 2021), and Taiwan shares over 175,638 hectares (Lin *et al*., 2011). Bamboo forest areas in Africa account for 11.5% of the global bamboo forest, with Nigeria, Ethiopia, and Senegal being the three countries with the largest bamboo forest areas. They account for 38.07%, 32.30%, and 18.93% of the African bamboo forest area, respectively, and 4.24%, 3.60%, and 2.11% of the global bamboo forest area, respectively (Du *et al*., 2018). Mekonne *et al*. (2014) estimated that Ethiopia has an estimated one million hectares of natural bamboo forest. To increase bamboo cultivation in Africa, African nations need to allocate sufficient land and adopt advanced bamboo farming technologies (Okokpujie *et al*., 2020). Bamboo forests in Oceania are primarily distributed in Papua New Guinea, accounting for 0.2% of the global bamboo forest area (Du *et al*., 2018). Although bamboo is not native to Europe, European countries are the largest market for Asian bamboo species (Al-Rukaibawi *et al*., 2021). A European bamboo plantation program named BambooLogic has been established in several European countries; the first phase is already set up in Portugal, to be followed by Spain, Italy, and Greece (BambooLogic, 2023). Abundant bamboo resources account for 7.2% of the total forest area in Taiwan (Lin *et al*., 2011). With over 1,575 species from 111 genera, bamboo significantly differs from regular grass in terms of its height, width, size, and branches at internodes (Sawarkar *et al*., 2020). Despite the numerous bamboo species in some parts of the world, there are 6 main commercial bamboo species in Taiwan (Lin *et al*., 2011). Although bamboo grows widely, its distribution and concentration vary with climatic and edaphic conditions (Sawarkar *et al*., 2020). Its growth is uneven and varies with changing climatic factors, such as precipitation, temperature, altitude, and soil conditions (FSI, 2019). Moreover, more than 1,200 bamboo species in natural forests worldwide remain inadequately studied (Boity *et al*., 2022). The use of bamboo in construction is gaining momentum due to its availability in Africa, Asia, and South and Latin America, offering a sustainable alternative to traditional materials (Sanni-Anibire *et al*., 2022a). Bamboo can enhance productivity by providing a readily available and renewable resource, potentially reducing construction timelines (Manandhar *et al.*, 2019). However, its variability in size and quality can also introduce inconsistencies, posing challenges to construction safety (Goh *et al.*, 2020a, b). To realize bamboo's potential benefits while mitigating risks, proper training and quality control measures are essential to maintain or improve productivity and safety standards (Hailemariam *et al.*, 2023). To obtain a more skillful workforce and promote bamboo processing technologies, the government of Taiwan carried out training programs in collaboration with educational institutions and processing factories (Lin *et al.*, 2011). Figure 1 presents the global distribution of bamboo forests. Asia has the largest bamboo plantation, representing 58.8%, followed by Central and South America, which represent 29.5% of the global bamboo plantation. The figure indicates that Africa accounts for 11.5% of the global bamboo plantation, while Oceania has the smallest share at just 0.2%. The significant presence of bamboo plantations in Asia and Central and South America suggests a strong potential for these regions to lead in bamboo-based construction and sustainable building practices. Conversely, the low representation of bamboo plantations in Africa and Oceania highlights an opportunity for these regions to invest in and expand bamboo cultivation, potentially promoting sustainable construction and economic growth.

2.2 Cost performance

There have been efforts by researchers to find an eco-friendly and local alternative to conventional building materials to reduce construction costs, particularly for low-income earners in developing countries (Ameh and Shittu, 2021). The majority of those who construct bamboo houses opt for it due to poor economic conditions (Vijayalaxmi and Singha, 2021). Bamboo offers economic benefits compared to other building materials (Al-Rukaibawi *et al.*, 2021). Bamboo is significantly less expensive than timber and has proven to be a viable alternative (Van der Lugt *et al.*, 2006). The cost-effectiveness of bamboo can encourage clients to consider bamboo over other conventional materials, potentially improving productivity in bamboo application (Goh *et al.*, 2020a, b). However, the unfamiliarity of construction workers with bamboo as a building material may lead to errors and safety hazards if proper training and guidelines are not in place (Xu *et al.*, 2022a, b), necessitating proper training and quality control measures to maintain or improve productivity and safety standards (Boity *et al.*, 2022). One of the most common pieces of equipment used for work at height is bamboo scaffolding, owing to its abundance and affordability (Sanni-Anibire *et al.*, 2022a). Despite its load-bearing capacity being comparable to that of steel, the cost of bamboo is only six percent of the cost of steel



Source(s): Researcher

Figure 1. Global distribution of bamboo forests

(Sawarkar *et al.*, 2020). A developed prefabricated bamboo-reinforced wall showed a 40% reduction in cost compared to traditional brick walls (Huang and Sun, 2021). The cost of constructing a typical 10-foot bamboo wall is 2.5 times less than that of a 10-foot brick wall (Prajapati and Dua, 2022). The city of Hong Kong is a global leader in the use of bamboo scaffolding, and as a result, various publicly available practice documents have been obtained (Sanni-Anibire *et al.*, 2022a). Similarly, in India, most scaffolding is made using bamboo due to its affordability (Bambhava *et al.*, 2013). The lightweight nature of bamboo makes transportation easier (Akinlabi *et al.*, 2017). The local application of bamboo in areas where it is grown and produced has the benefit of reducing transportation costs and carbon footprint (Mofidi *et al.*, 2020). However, in most cases, bamboo forests are located in difficult terrains, posing a challenge to bamboo transportation (Xu *et al.*, 2022a, b), which may significantly increase the environmental costs (Huang and Sun, 2021). Table 1 presents key cost and environmental considerations for using bamboo in construction. The table presents a comprehensive overview of the cost-effectiveness of bamboo in construction. Several studies, including those by Sanni-Anibire *et al.* (2022a, b), Al-Rukaibawi *et al.* (2021), and Huang and Sun (2021), highlight bamboo's cost-effectiveness as a construction material. Bamboo's low weight and favorable topography contribute to its low transportation costs, as indicated by studies from Mofidi *et al.* (2020) and Akinlabi *et al.* (2017). However, challenges arise in areas with poor topography, leading to increased transportation and eco-costs, as pointed out by Huang and Sun (2021). This suggests that while bamboo offers cost advantages in suitable conditions, careful consideration of the geographical context is essential for maximizing its cost performance in construction.

2.3 Quality performance

Bamboo exhibits mechanical properties similar to those of structural wood products (Al-Rukaibawi *et al.*, 2021). Due to fungal deterioration in the sclerenchymatous fibers, the functional quality of bamboo deteriorates rapidly, potentially affecting construction productivity and safety (Mohan *et al.*, 2022). Witte (2019) attributes the impermanence of bamboo in construction to improper use by low-income communities. However, when properly treated and industrially processed, bamboo elements can have a durable life of 30–40 years, contributing positively to construction safety (Goh *et al.*, 2020a, b). Research and development in technological processes and equipment for bamboo production and utilization can enhance the quality of bamboo materials, consequently improving safety in construction (Prajapati and Dua, 2022). Bamboo construction materials are high-strength assembled building components obtained through deep processing using modern technology (Xu *et al.*, 2022a, b). The tensile strength of treated and untreated bamboo can replace some commonly used building materials, potentially enhancing construction safety (Boity *et al.*, 2022). Hailemariam *et al.* (2023) identify a lack of understanding of bamboo treatment technology as the main contributory factor to the low quality of bamboo. Bamboo is often referred to as "green steel" due to its

Table 1. Cost consideration

Factor	Source
Cost-effective	Van der Lugt *et al.* (2006), Bambhava *et al.* (2013), Agyekum *et al.* (2017), Mofidi *et al.* (2020), Sawarkar *et al.* (2020), Al-Rukaibawi *et al.* (2021), Huang and Sun (2021), Prajapati and Dua (2022), Sanni-Anibire *et al.* (2022a, b)
Low transportation cost due to weight and good topography	Akinlabi *et al.* (2017), Mofidi *et al.* (2020)
High transportation and eco-costs in poor topography	Huang and Sun (2021)

Source(s): Researchers

superior mechanical properties compared to steel in certain aspects, such as surface tensile strength (Sanni-Anibire *et al.*, 2022a). The tensile strength of bamboo (28,000 pounds per square inch) exceeds that of steel (23,000 pounds per square inch) (Kaur, 2018). Globally, one billion people live in bamboo houses, and bamboo housing in Costa Rica, and other Latin American countries (Mekonnen *et al.*, 2014). Research indicates that bamboo can serve as a steel reinforcing alternative in low-cost housing projects with limited weight-carrying capacity, potentially increasing its application and ultimately construction productivity (Mohan *et al.*, 2022). It holds promising potential as an alternative material for concrete reinforcement in the low-cost housing industry (Rahim *et al.*, 2020). Bamboo occasionally exhibits optimum strength and is suitable for heavy-duty applications (Awalluddin *et al.*, 2017). The use of steel as a reinforcing material should be minimized due to air pollution during its manufacturing process (Rahim *et al.*, 2020). Bamboo's characteristics include high water absorption and low bonding strength with concrete (Rahim *et al.*, 2020). With a high moisture content of about 15% (Awalluddin *et al.*, 2017), bamboo shrinks upon drying (Fahim *et al.*, 2022). Interventions such as waterproofing agents can minimize water absorption and increase bonding strength, thereby enhancing construction safety.

The lightweight and strength of bamboo are common advantages for using it in buildings (Xu *et al.*, 2022a, b). A bamboo-reinforced wall showed a 56% reduction in weight compared to traditional brick walls (Huang and Sun, 2021). Bamboo's lightweight nature facilitates easier construction (Wang *et al.*, 2018). Besides its high tensile strength, the compressive strength of bamboo is comparable to the commonly used grade of concrete in residential buildings (Boity *et al.*, 2022). Bamboo possesses greater compressive strength than brick, concrete, and wood (Yadav and Mathur, 2021). Its shear strength ranges from 4.09 to 5.86 N/mm^2, which is very close to concrete and can be improved with suitable treatment methods (Boity *et al.*, 2022). Bamboo also boasts a high strength-to-weight ratio, high stiffness-to-weight ratio, and moderate density (Qiu *et al.*, 2021). In areas prone to earthquakes, typhoons, and hurricanes, bamboo is suitable due to its elasticity and lightweight, enhancing construction safety (Boity *et al.*, 2022). The elasticity of bamboo enhances the structure's earthquake resistance with fewer chances of collapse, and if it does collapse, it causes comparatively less damage to property and life (Yadav and Mathur, 2021). Seasonal variations affect bamboo quality; during dry seasons, the vulnerability to fungal attacks increases due to higher starch content. Therefore, the best time to harvest is within or after the rainy season (Mohan *et al.*, 2022).

Table 2 presents quality-related factors associated with bamboo in construction. Bamboo, with properties similar to wood, can last 30–40 years when properly treated (Goh *et al.*, 2020a, b;

Table 2. Quality consideration

Factor	Source
Mechanical properties similar to wood products	Al-Rukaibawi *et al.* (2021)
Rapidly deteriorate due to fungi attack	Mohan *et al.* (2022)
Elements can last for 30–40 years with appropriate treatment and processing	Goh *et al.* (2020a, b)
High tensile strength	Kaur (2018), Boity *et al.* (2022), Sanni-Anibire *et al.* (2022a, b)
High water absorption	Rahim *et al.* (2020)
Low bonding strength with concrete	Rahim *et al.* (2020)
Shrinks rapidly	Fahim *et al.* (2022)
Lightweight favours brick wall construction	Huang and Sun (2021)
High compressive strength	Yadav and Mathur (2021), Boity *et al.* (2022)
Shear strength close to concrete	Boity *et al.* (2022)
Suitable for construction in places prone to natural disaster	Boity *et al.* (2022)
High fungi attack in dry seasons	Mohan *et al.* (2022)

Source(s): Researchers

Al-Rukaibawi *et al*., 2021). According to the table, challenges like rapid fungal deterioration and high water absorption can compromise safety (Rahim *et al*., 2020; Mohan *et al*., 2022). Its high tensile and compressive strength enhance productivity and safety, especially in disaster-prone areas (Kaur, 2018; Huang and Sun, 2021; Yadav and Mathur, 2021; Boity *et al*., 2022). This raises the cautiousness of the need to develop eco-friendly preservatives to improve bamboo's shelf life, making it an attractive material for the housing and building industry (Kaur, 2018). As a preservation method, bamboo is commonly soaked in water for 3–4 weeks to remove the starch content from its culms (Fahim *et al*., 2022). A lower starch content makes bamboo more resistant to fungal and termite attacks, thereby enhancing construction safety. Bamboo can also be preserved against microorganism attacks by heating it to about 150 °C. This treatment reduces its mechanical strength and elasticity but provides better resistance against termites and fungi due to the evaporation of water during heating. Chemicals such as NaCO3 can also be used for bamboo treatment; however, chemical treatments come with environmental and safety concerns (Fahim *et al*., 2022).

2.4 Stakeholders acceptability

The primary challenge facing the bamboo industry is overcoming its negative public image (Witte, 2019). Acceptance by stakeholders is a significant concern for bamboo utilization in construction (Awalluddin *et al*., 2017; Opoku *et al*., 2016). Due to a lack of understanding among key stakeholders, bamboo has often been labeled as "poor man's timber," hindering its acceptance in modern architecture (Vijayalaxmi and Singha, 2021). This lack of knowledge about bamboo's qualities and potential undermines its application in construction (Hailemariam *et al*., 2023). Inadequate knowledge about bamboo materials and methods leads to lower demand for bamboo compared to other construction materials (Witte, 2019). Opoku *et al*. (2016) describe this as a lack of expertise in bamboo construction. Only a few designers practicing sustainable architecture are familiar with bamboo's construction and preservation techniques, limiting the efficiency and safety of bamboo-based constructions (Mohan *et al*., 2022). There is a shortage of architects, engineers, and contractors who understand how to properly design or build with bamboo (Witte, 2019). Consequently, bamboo is mainly used for scaffolding, as most practitioners are unaware of its broader applications, which can impact construction productivity and safety (Mohan *et al*., 2022). Hailemariam *et al*. (2023) identify low awareness of bamboo material and lack of innovation and institutional support as barriers to bamboo's acceptance in construction. Studies have reported a lack of knowledge about bamboo connections and detailing; the absence of governmental policy on bamboo as an alternative construction material; the absence of design standards for bamboo products; and poor public perception of the use of bamboo in building construction as major barriers to the acceptability and use of bamboo for construction (Okokpujie *et al*., 2020; Ameh *et al*., 2019; Opoku *et al*., 2016). Some researchers suggest that the main barriers affecting bamboo's application are technological, such as fire resistance (Desalegn and Tadesse, 2014), inadequate research funding (Xiao and Lee, 2015), and concerns about its durability (Li *et al*., 2022). Li *et al*. (2022) further identify bamboo's small diameter, hollow structure with thin walls, sharp taper, uneven material distribution, and anisotropic properties as factors that limit its applications in engineering structures.

The industrialization of bamboo for construction materials is not yet complete, and bamboo is not widely accepted by society as a building material (Xu *et al*., 2022a, b). Bamboo construction is not yet a recognized form of building in many countries (Ross and Alexander, 2022). Considerable local and practical research is needed if bamboo construction were to become an accepted and standard construction technology, which could enhance construction productivity and safety (Ross and Alexander, 2022). Bamboo-based research must increase stakeholders' awareness to better understand the application of bamboo as a green building material and develop effective measures for applying the materials in practice (Shen *et al*., 2019). Witte (2019) suggested hybrid building systems that integrate bamboo with metal and/or wood to improve the ease and acceptance of bamboo construction. Okokpujie *et al.* (2020) emphasize the need for the government and other stakeholders to invest in the right technology and strategic awareness to promote bamboo as a construction material. Construction stakeholders need to rethink, accept, and utilize high-quality bamboo species with proven processing equipment and technology, which would positively impact productivity and safety (Goh *et al.*, 2020a, b). The promotion of bamboo usage in building construction should receive the attention and awareness it deserves (Opoku *et al.*, 2016). Despite its potential, bamboo's application has been largely limited to temporary works such as props, sheds, scaffolding, and ladders, especially in countries like India where it's recently gaining recognition as a mainstream construction material by the Public Work Department (Vijayalaxmi and Singha, 2021). Amede *et al.* (2021) attribute the limited use of bamboo in construction to the lack of universally applicable standards and codes for structural element design. The absence of standards and specifications undermines confidence in using bamboo among construction practitioners (Prajapati and Dua, 2022). Many countries currently lack design codes for bamboo structures (Ross and Alexander, 2022). Bamboo as an engineering material has largely depended on established traditions, ancestral intuitions, and engineering experience (Amede *et al.*, 2021). Tenorio and da Costa Junior (2020) argue that government legislation and regulatory frameworks should promote the acceptance of bamboo as a modern building material. As the case in Taiwan, as far back as 2011, regulations for construction stipulate that the percentage of green building materials should reach a 30% minimum to reduce carbon emissions (Lin *et al.*, 2011). This can help promote bamboo utilization among construction stakeholders. Despite its potential, its application has been largely limited to temporary works, highlighting construction stakeholders' reservations about its suitability for permanent construction. Table 3 highlights factors impacting the social acceptability of bamboo in construction. As presented in the table, negative public perception, the "poor man's timber" label, and low industrialization and social acceptance significantly impede the adoption of bamboo in construction (Ameh *et al.*, 2019; Witte, 2019; Vijayalaxmi and Singha, 2021). Limited application and the absence of universally applicable standards and codes also contribute to skepticism among construction practitioners (Opoku *et al.*, 2016; Ameh *et al.*, 2019; Amede *et al.*, 2021; Boity *et al.*, 2022). Additionally, the lack of professional knowledge

Table 3. Social acceptability

Factor	Source
Negative public perception	Ameh *et al.* (2019), Witte (2019)
"Poor man's timber" appellation hinders acceptance	Vijayalaxmi and Singha (2021)
Low industrialization and social acceptance	Xu *et al.* (2022a, b)
Limited application in construction	Boity *et al.* (2022)
Limited standards and codes for designs	Opoku *et al.* (2016), Ameh *et al.* (2019), Amede *et al.* (2021)
High ignorance of construction techniques and preservation methods among construction practitioners	Mohan *et al.* (2022)
Bamboo integration with other acceptable materials	Witte (2019)
Lack of professional knowledge and expertise	Opoku *et al.* (2016), Ameh *et al.* (2019), Witte (2019)
Low awareness	Hailemariam *et al.* (2023)
Problem of innovation	Hailemariam *et al.* (2023)
Poor government policy	Ameh *et al.* (2019), Okokpujie *et al.* (2020)
Research and publicity	Xiao and Lee (2015), Opoku *et al.* (2016), Ross and Alexander (2022)
Poor fire resistance	Desalegn and Tadesse (2014)
Durability	Li *et al.* (2022)

Source(s): Researchers

and expertise, low awareness, and poor government policy hinder the proper application of bamboo, leading to suboptimal construction practices (Opoku *et al.*, 2016; Ameh *et al.*, 2019; Okokpujie *et al.*, 2020; Amede *et al.*, 2021; Hailemariam *et al.*, 2023). These factors collectively reduce the confidence and willingness of professionals to integrate bamboo into construction projects, affecting the possibility of leveraging bamboo to promote high productivity and safety standards. This necessitates a need for increased research, publicity, and innovation in bamboo construction techniques and materials.

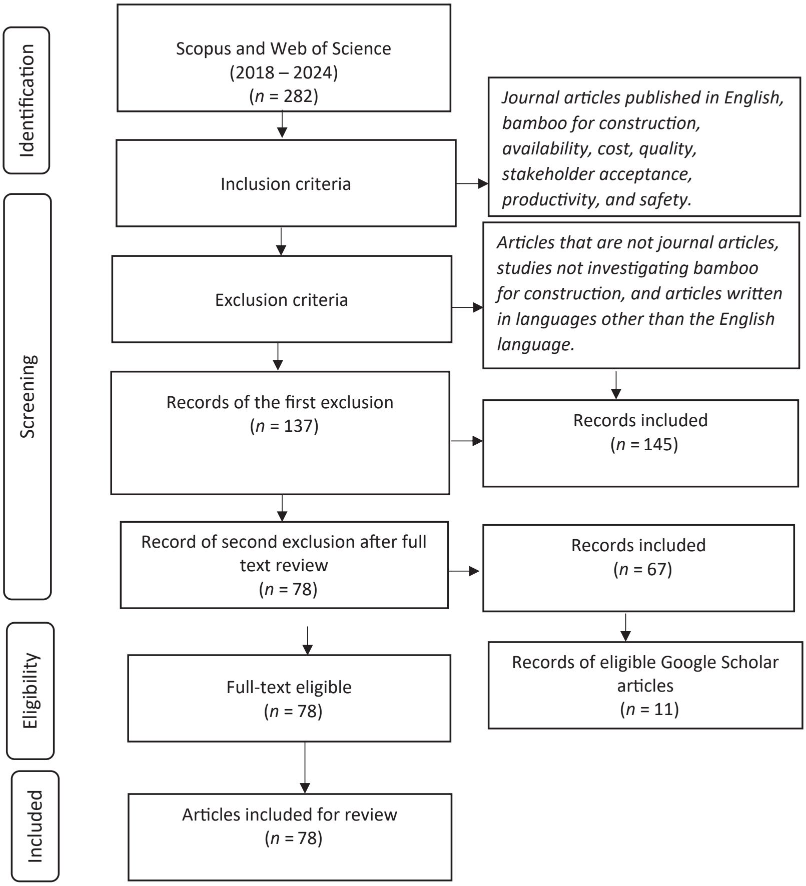
3. Methodology

3.1 Article search and selection

This systematic review adhered to the methodological standards of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis guidelines for systematic review and meta-analysis (Ang *et al.*, 2019). Systematic reviews have been widely utilized by researchers in various areas of construction, such as lean construction (Babalola *et al.*, 2019), robotic technologies (Gharbia *et al.*, 2020), augmented reality (Adebowale and Agumba, 2024), and sustainable construction management (Goh *et al.*, 2020a, b), among others, contributing significantly to their respective fields. The systematic literature search was conducted on Scopus (www.scopus.com) and Web of Science (WoS) (www.webofscience.com) databases from March 8, 2024, to March 10, 2024, to obtain studies on bamboo in construction. Scopus and WoS are multidisciplinary databases that cover a wide range of research areas. They include scholarly articles, conference proceedings, and citation data, making them valuable resources for finding articles in the field of sustainable construction materials (Babalola *et al.*, 2019; Abioye *et al.*, 2021). A comprehensive search strategy was employed using keywords including “bamboo,” “construction materials,” “building materials”, “productivity,” “safety,” “availability”, “cost”, “quality”, and “stakeholders acceptance” within Scopus and Web of Science. These search queries were chosen due to their relevance to the research objectives. The search was conducted within the titles of articles and limited to articles published within the last seven years (2018–2024) to obtain the most recent article in the subject area. The search yielded a variety of document types, including journal articles, conference papers, book chapters, reviews, errata, and editorials, totaling 283 documents. Figure 2 presents the PRISMA flow diagram of the literature search, outlining the research process employed in the study.

3.2 Article screening and quality assessment

The screening for article eligibility and quality assessment was conducted between March 15, 2024, and March 29, 2024. Rayyan software facilitated the screening process of the articles. Articles obtained from the two databases were imported into Rayyan software in RIS format. The initial screening involved requesting Rayyan to identify duplicate articles within the pool acquired from the two databases. The duplicates identified (86 articles), were removed, retaining one copy of each article. The subsequent screening involved utilizing Rayyan to screen articles using inclusion and exclusion criteria. The inclusion criteria included peer-reviewed journal articles published in English. The inclusion criteria also included studies that focused on bamboo for construction containing the key study variables, including availability, cost, quality, stakeholder acceptance, productivity, and safety. Exclusion criteria comprised conference papers, book chapters, reviews, errata, and editorials. Exclusion criteria also included studies not specifically investigating bamboo for construction or not considering the key study parameters. Finally, exclusion criteria comprised articles written in Chinese, Japanese, and Spanish. These criteria were defined in Rayyan resulting in highlighting inclusion variables in green and exclusion variables in red, serving as a guide for article selection. The lead author, via Rayyan software, invited the research collaborator online through email to participate in assessing the quality of the research articles and deciding on



Source(s): Researcher

Figure 2. PRISMA flow diagram of literature search

inclusions and exclusions based on the predetermined criteria. The assessments were independently carried out by the authors. In cases of conflicting opinions on articles, the lead author made the final decision. After eliminating 86 duplicates and screening articles using the set inclusion and exclusion criteria, another 139 articles were excluded, making the total excluded articles 137. A new review was created in Rayyan for the full-text review, where the full text of the 145 articles was scrutinized in line with the study's objectives. The evaluation considered the relevance of the research to the study objectives, the quality of the articles in terms of research design rigor, and articles published in the last seven years. After this screening, 78 of the remaining 145 articles that did not meet these criteria were excluded from consideration, while the remaining 67 articles were deemed eligible and included in the study for review. To supplement these articles, Google Scholar was searched to obtain articles that comply with inclusion criteria. Only 11 new articles were obtained from Google Scholar as most of the articles published in Scholar have been obtained from either Scopus or Web of Science. The content of the remaining 67 articles obtained from Scopus and Web of Science and 11 articles obtained from Google Scholar, totaling 78 articles was reviewed to assess bamboo utilization as a sustainable construction material and its effects on construction productivity and safety. The publication channels with a minimum of two articles are presented (Table 4). These research articles were distributed across thirteen countries, with India contributing the highest number of publications (31), representing 39% of the articles.

3.3 Data synthesis and analysis

Thematic analysis was utilized to identify relevant themes and sub-themes related to the effects of bamboo in construction on productivity and safety. Thematic analysis was employed as it is a flexible and widely used method for analyzing qualitative data, enabling the identification, interpretation, and reporting of patterns or themes within the data (Braun and Clarke, 2006). The analysis process involved familiarization with the data, generating initial codes, searching for themes, reviewing themes, defining and naming themes, and producing the report (Braun and Clarke, 2006). To ensure the reliability and validity of the thematic analysis, a systematic and iterative approach was adopted. Initially, the two researchers independently coded a subset of the data to identify initial themes, which were then compared and discussed to resolve discrepancies and refine the coding framework. This iterative process continued until consensus was reached on the final set of themes, enhancing the credibility and trustworthiness of the analysis (Nowell *et al.*, 2017). The interpretation of themes involved linking them to the research objectives and existing literature, providing a coherent and comprehensive understanding of bamboo in sustainable construction and its effects on construction productivity and safety.

4. Discussion of the research findings

Bamboo forests have witnessed a global increase in their area, yielding a significant annual output of bamboo products. This widespread availability offers notable advantages, providing a readily accessible and renewable resource for construction projects. Proximity to construction sites minimizes delays, ensuring timely material supply and expeditious delivery of construction operations. The scarcity of some timber species reported in (Akwada and Akinlabi, 2018) could result in delays in the delivery of timber material, which could further affect the timeliness of delivering construction tasks. Increasing bamboo's availability and lightweight nature can mitigate such delays and reduce the risk of strain or injuries for workers, thus enhancing productivity and safety in construction. While bamboo is widespread, variations among bamboo species pose challenges in selecting the appropriate species for construction purposes. Differences in strength, durability, and other mechanical properties can

Table 4. Publication channels with a minimum of two articles

Source	Publication channels	No. of publications
Journal	Sustainability Switzerland	12
	Construction and Building Materials	9
	Bioresources	8
	Science of The Total Environment	8
	Bioresource Technology	6
	European Journal of Wood and Wood Products	4
	Forests	4
	International Journal of Food Properties	4
	Journal of Bamboo and Rattan	4
	Journal of Food Processing and Preservation	3
	Journal of Materials Research and Technology	3
	Materials Today	2
	Polymers	2

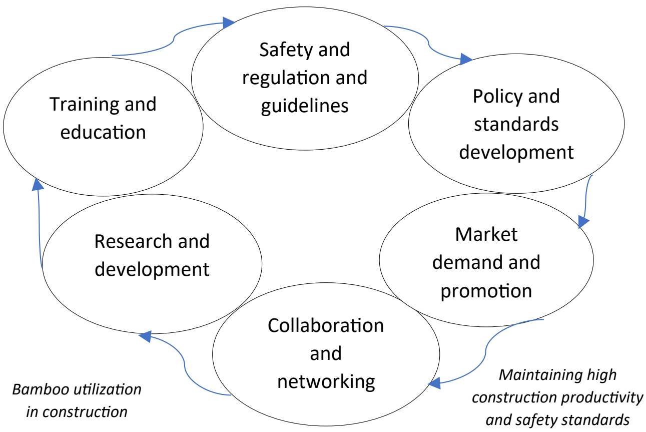
Source(s): Researchers

impact structure quality and performance, affecting contractor and client confidence in bamboo for future construction. This finding is consistent with Sanni-Anibire *et al*. (2022b) who advocated the need to understand variations in bamboo to ensure that sourced bamboo meets safety standards. While Sanni-Anibire *et al*. (2022b) advocated the need to understand variations in bamboo to ensure that sourced bamboo meets safety standards, other studies such as Ameh and Shittu (2021) and Bahru and Ding (2021) also emphasized the significance of developing standardized treatment methods and comprehensive training programs for construction workers handling bamboo materials not only to understand variations in bamboo but also bamboo structural-grading. Understanding structural grading holds promise in improving safety and resilience in housing markets. This can be leveraged for cost-effective housing. Bamboo affordability allows construction organizations, particularly in low-income settings, to reduce costs and allocate resources efficiently, enabling more projects within budget constraints. Its use in construction contributes to a healthier and safer work environment, with lower noise levels and reduced vibration transmission compared to heavier materials like steel. Although bamboo's lightweight nature could minimize transportation costs, logistical challenges in delivering bamboo to sites located in difficult terrain may lead to delays, impacting project timelines. Construction organizations must invest in comprehensive training programs to educate workers on the safe assembly and use of bamboo, ensuring adherence to safety protocols. Effective training minimizes the potential risks associated with working at heights, fostering a safer work environment and reducing the likelihood of accidents or injuries. One of the primary factors hindering the widespread adoption of bamboo in construction is its poor social acceptability. Long-standing perceptions of bamboo as a "poor man's timber" contribute to its negative public image, limiting its acceptance and utilization in the construction industry. Ignorance about bamboo does not only apply to lower management construction workers, (Witte, 2019) reported insufficient knowledge and expertise even among construction professionals, including architects and engineers. The selection of materials to use in construction is largely determined by these professionals, hence, their poor knowledge of bamboo utilization in construction can affect their preference for bamboo selection for construction. This finding is consistent with the perception of Mekonnen (2014) who reports that the customary and current bamboo use is far below its potential due to a lack of knowledge and skills in bamboo versatility across construction and non-professionals alike. Due to the safety benefits of using bamboo for scaffolding, bamboo is widely used scaffolding in construction (Awalluddin *et al*., 2017). Bamboo is primarily relegated to scaffolding use, while its potential applications in other construction areas remain largely untapped. Lack of awareness and poor expertise in bamboo applications was emphasized by (Emamverdian *et al*., 2020) as the major factor that undermines the wider application of bamboo in construction. The inadequate understanding of bamboo connections and detailing, coupled with the absence of governmental policies and design standards, affect its widespread adoption as a construction material. Addressing the lack of awareness can lead to increased utilization of bamboo in construction. Educating stakeholders about bamboo's properties and potential applications empowers them to make informed decisions, optimize designs, and streamline construction processes. Enhanced knowledge about bamboo connections and detailing is crucial for ensuring structural integrity and safety, reducing the risk of accidents or failures.

The quality performance of bamboo influences its impact on productivity and safety in construction. Bamboo's mechanical strength is a notable advantage, comparable to structural wood products and even surpassing steel in certain aspects (Boity *et al*., 2022). Its high tensile and surface strength enable it to withstand heavy loads, providing structural stability and enhancing safety on construction sites. However, bamboo's durability is a critical consideration. Vulnerability to fungal deterioration poses safety risks, particularly if not addressed through proper treatment and construction practices. Research and development efforts are necessary to improve bamboo's quality and lifespan. Fahim *et al*. (2022) advocated the need to implement standardized treatment methods, such as removing starch content and using eco-friendly preservatives, which can enhance resistance to fungal attacks and termite infestations. Industrial processing techniques can further improve durability and stability, although careful consideration of safety issues associated with chemical methods is required. Effective training programs are essential to educate construction workers on proper handling, treatment, and installation practices specific to bamboo. Additionally, developing national codes for bamboo construction can ensure compliance with safety standards and long-term durability. Countries can reference international design standards, such as ISO 22156, to formulate their national standards (Ross and Alexander, 2022), considering relevant safety factors and load considerations according to national standards (Amede *et al.*, 2021). However, the lack of innovation surrounding bamboo limits its potential and hampers productivity in construction organizations, as conventional practices may prevail without sufficient research and development. Research has to come up with various innovative bamboo uses and management technologies, which currently do not seem to exist, except very few at the upper-value chain (Mekonnen *et al.*, 2014). The absence of governmental policies, design standards, and codes specific to bamboo construction poses challenges to productivity and safety in construction. Without clear guidelines, uncertainties regarding compliance with safety regulations and best practices arise, potentially compromising safety measures and increasing the risk of accidents or structural failures. Concerns about bamboo's poor fire resistance, durability, and structural limitations which may deter its adoption, and limit its application must be addressed to promote improved utilization of bamboo in construction. Addressing these challenges through education, innovation, and policy development is essential to unlock the full potential of bamboo as a sustainable construction material and improve productivity and safety in construction projects.

5. Framework for performance

Figure 3 presents a framework for enhancing bamboo utilization in construction while maintaining high productivity and safety standards. The figure highlights the importance of research and development initiatives that focus on enhancing understanding of bamboo through innovative construction techniques, treatment methods for improved durability, and the development of standardized testing protocols to evaluate its structural performance. The framework proposes training and education programs that would increase awareness and knowledge about bamboo construction construction stakeholders. Specialized courses, conferences, workshops, and certification programs would emphasize proper design,



Source(s): Researcher

Figure 3. Framework for improvement

construction, and maintenance of bamboo structures. It is essential to develop and implement comprehensive safety regulations and guidelines tailored specifically to bamboo construction. These should cover scaffolding practices, handling and transportation procedures, and fire safety measures, with regular inspections and enforcement to ensure compliance. The framework recommends collaboration and networking among construction stakeholders and bamboo suppliers to foster partnerships, facilitate knowledge-sharing, and promote best practices in bamboo construction. Policy and standards development, including governmental policies supporting bamboo utilization in construction and the inclusion of bamboo in national building codes and regulations, are crucial. National and regional standards for bamboo construction covering design, material specifications, and quality control must be developed. Market demand and promotion efforts would raise awareness about the benefits of bamboo construction, highlighting its cost-effectiveness, environmental sustainability, and aesthetic appeal (Figure 3). Showcasing successful projects and case studies would demonstrate bamboo's viability and quality, fostering market demand. By appropriately integrating the elements of this framework, bamboo can increasingly be utilized as a sustainable and eco-friendly building material without compromising productivity and safety in the construction sector.

6. Conclusion and implication of the research

This research investigated bamboo utilization in sustainable construction and the effects on productivity and safety. Bamboo's availability emerges as a key advantage due to its abundance and renewability compared to other building materials, presenting construction organizations with a cost-effective and sustainable resource. Bamboo's lightweight nature facilitates easier transportation, enhancing its availability for construction projects. However, challenges related to transporting bamboo in difficult topography may increase associated eco-costs (Huang and Sun, 2021), highlighting the need for careful logistical planning to prevent delays in construction projects. Cost and environmental performance are intertwined aspects that contribute to bamboo's viability in construction. Research demonstrates that bamboo is economically beneficial compared to traditional materials like timber and steel, offering a cost-effective alternative. Bamboo cost-effectiveness has been emphasized in previous research, including (Huang and Sun, 2021; Prajapati and Dua, 2022; Sanni-Anibire *et al.*, 2022a, b) – (Table 1). Using bamboo as a local climate-adaptive building material can reduce transportation costs and carbon footprint (Akinlabi *et al.*, 2017; Mofidi *et al.*, 2020), promoting sustainability and environmental well-being in construction projects. Bamboo's quality performance is crucial for its use as a construction material, with favorable characteristics such as flexibility and good load-bearing capacity making it reliable for scaffolding and other structural applications. Despite limitations in fire resistance, durability, and structural design, research and technological advancements can address these concerns and expand bamboo's potential applications. Establishing design standards and codes specific to bamboo structures would further enhance confidence in its usage and quality performance. The positive effects of bamboo on construction productivity and safety are evident, but its social acceptability remains a challenge. Factors such as lack of awareness, low innovation, and institutional support hinder widespread adoption in construction. Overcoming these barriers requires collaboration among stakeholders, including educational institutions, industry professionals, and government entities. By providing training and disseminating knowledge on bamboo's benefits, construction organizations can harness its potential to enhance productivity, improve safety, and contribute to sustainable construction practices.

The study has implications for practice and society. It underscores the potential of bamboo as a viable alternative construction material, challenging the prevalent misconception of bamboo as a "poor man's timber." The study demonstrates how the findings can inform construction practices, promoting the use of bamboo in various construction projects, while maintaining high productivity and safety standards. Its societal implication is emphasized by illustrating how dispelling the misconception of bamboo as a “poor man’s timber” can contribute to broader sustainability objectives through improved acceptance and utilization of bamboo, which would ultimately contribute to preserving the ecosystem through environmental preservation, aligning with sustainable development goals. The acceptance and widespread use of bamboo in construction would offer affordable housing options for low-income earners, especially in developing countries, addressing issues of housing affordability and social equity. Widespread bamboo utilization would also promote bamboo-related industries and significantly contribute to providing jobs and revenue to bamboo farmers, local communities, and the government. Consequently, there is a pressing need to implement awareness programs and capacity-building sessions for construction practitioners to empower professionals to recognize the viability of bamboo as a sustainable construction material and equip them with the necessary skills to utilize bamboo correctly in construction projects, without compromising productivity and safety. While this study provides valuable insights into the utilization of bamboo in construction, some limitations should be acknowledged. First, the study acknowledges the variations in mechanical properties among different bamboo species. However, a more comprehensive understanding of the specific properties of various bamboo species is needed to ensure consistent quality and safety in construction. Second, the study reviewed in this study primarily focuses on regions with widespread bamboo forests (Figure 1), potentially limiting the generalizability of the findings to other geographic areas where bamboo cultivation and construction practices may differ. Third, the study touches upon bamboo’s durability and vulnerability to fungal deterioration. However, there is a need for long-term studies to evaluate the maintenance requirements of bamboo structures. While the study emphasizes the importance of safety in bamboo construction, a detailed analysis of safety protocols, risk assessments, and accident rates specific to bamboo construction is lacking. Future research should aim to address these knowledge gaps by considering additional databases to access a broader range of research articles beyond those analyzed in this study (Figure 2). Collaborative research initiatives involving multidisciplinary teams can contribute significantly to advancing bamboo as a mainstream construction material.

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