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A critical review of bamboo construction materials for sustainability

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ABSTRACT

Bamboo construction materials are increasingly recognized in the construction industry as a promising path toward sustainable development, generating substantial interdisciplinary interest. However, previous research has often supported or criticized its sustainability in specific aspects through fragmented analysis. Comprehensive assessments that reveal the full scope of bamboo's sustainability remain scarce. To address this gap, this research aims to: (1) conduct an in-depth and systematic review of research on bamboo construction materials and sustainability; (2) elucidate the contributions of bamboo construction materials to sustainable development; and (3) identify research gaps and propose future research directions. This study employs a systematic literature review methodology, examining 742 relevant articles published between 2000 and 2023. Specifically, this research evaluates the sustainability performance of bamboo construction materials from three thematic perspectives: social sustainability, economic sustainability, and environmental sustainability. It summarizes the current state of research and identifies research gaps. Ultimately, four future research directions are proposed, including the relationship between bamboo materials and health and well-being, genomic sequencing and editing technologies, policies and regulations, and life cycle assessment. Unlike previous studies, this research uniquely depicts a comprehensive landscape of sustainability research on bamboo construction materials. The results of this research contribute to revealing the relationship between bamboo construction materials and sustainability, examining knowledge gaps in the field, avoiding repetitive imitative research, and promoting the sustainable development of bamboo construction materials.

1. Introduction

Construction activities, whether for new building, refurbishment, remanufacturing, or dismantling, are characterized by prodigious consumption of natural resources (such as mineral resources, fossil fuels and water). Simultaneously, these activities generate vast amounts of waste and pollutants that pose grave threats to the ecological equilibrium of our planet [1,2]. It is evident that the construction sector accounts for approximately 34 % of global energy consumption [3] and exerts a substantial demand of 12 % on the world's freshwater resources [4]. This high resource consumption brings considerable environmental repercussions, including the production of 100 billion tons of construction waste, accounting for 37 % of global greenhouse gas emissions, along with various other pollutants [3]. As global resources dwindle and environmental degradation intensifies, the industry's current practices - focused on rapid expansion at the expense of finite resources - are increasingly recognized as unsustainable. Furthermore, rising population levels continue to drive a growing demand for housing and infrastructure [5]. In the foreseeable future, the construction industry is confronted with an imminent difficulty, one that juxtaposes burgeoning construction requisites with the environmental degradation, unless a comprehensive sustainability agenda is promptly adopted. The primary concern of the construction industry is on finding viable strategies to address resource scarcity and ecological harm, while still meeting construction demands and supporting sustainable economic growth [6,7].

Recognizing this profound impact on the planet, construction industry professionals are actively exploring various sustainability strategies. Among these, material selection is widely acknowledged as a key determinant in achieving both optimal building performance and environmental goals [8,9]. Traditional construction materials such as cement and concrete products, which have served as stable building components for the past century, are now closely linked to significant energy consumption and pollutant emissions [10,11]. Consequently, the construction industry has sought innovative solutions to mitigate these environmental challenges. These initiatives have shown promising progress, but the pertinent question arises: Can the construction industry's historically gradual adoption of advanced production technologies

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Abbreviations

LBL	Laminated Bamboo Lumber
LCA	Life Cycle Assessment
SDG	Sustainable Development Goal
SLR	Systematic Literature Review

effectively address the rapidly deteriorating ecological landscape? Moreover, can non-renewable and finite resources, exemplified by the global sand crisis [12], adequately bridge the increased gap between supply and demand in the face of rapid urbanization and intense building demand? It is evident that people must eventually embrace a paradigm shift towards sustainable construction materials to enable future generations to construct habitable dwellings rather than being confined to a landscape marred by non-recyclable concrete structures or forced into natural caves. This forward-thinking concern inspired engineers to rediscover a traditional yet green and highly sustainable natural resource, bamboo [13,14], particularly during periods of timber scarcity in the timber industry [15].

Bamboo, characterized by its rapid growth and high renewability [16], is a non-timber forest resource with tremendous potential [17]. It stands out as one of the fastest-growing plants on Earth, typically maturing in a remarkably short span of four to six years, after which it can be harvested annually in a sustainable manner [18]. The yield of bamboo per hectare is impressive, reaching 78.3 tons, which is approximately 4.47 times higher than the average timber [19]. Consequently, bamboo emerges as a compelling candidate to replace or supplement steel and wood resources [20,21]. In stark contrast to the slow regeneration of deforested areas that can take up to 35 years or more for timber resources to replenish, bamboo offers a highly renewable alternative [22]. Furthermore, it is imperative to address the excessive deforestation occurring in many regions [23]. In addition to its rapid growth and high renewability, bamboo can efficiently store atmospheric CO_2, reduce energy waste, and alleviate other environmental threats [14,24]. Moreover, the high yield of bamboo provides sufficient raw materials for the continuously increasing housing demand. Bamboo construction materials can also be recycled, which will generate less construction waste. Most importantly, noteworthy advancements have emerged since the early 2000s. China, in particular, has spearheaded pioneering innovations, which effectively address some limitations of traditional raw bamboo: thin and hollow structure, susceptibility to cracking, and challenges in achieving reliable connections [25]. The mechanical properties of bamboo construction materials have surpassed those of timber and meet the requirements of modern construction [26–28]. Consequently, bamboo-based products have garnered acclaim as one of the most sought-after bio-based construction materials, receiving endorsements from experts in the field [29].

Meanwhile, research and reports on bamboo construction materials are emerging, covering aspects from mechanical properties [30,31] to social value [32], gradually becoming a new focal point in academic circles [33]. In the past decade alone, research on bamboo buildings has doubled in the Web of Science database. Nevertheless, research has shown a greater dedication to analyzing the physical performance [34], thermal conductivity [35], environmental benefits [14] of bamboo construction materials rather than directly elucidating their practical applications for sustainability. That is probably due to the fact that sustainability is not a "point" of performance, but a "chain" of concepts that may encompasses multiple dimensions including social, economic and environmental [36]. Therefore, many studies refrain from interpreting bamboo construction materials directly through the lens of sustainability. Instead, they rely on scattered knowledge to either support or criticize the materials' sustainability. Most importantly, few research has retrospectively examined and expounded upon the expertise of bamboo construction materials, providing convincing logical evidence regarding their sustainability. Academia has yet to systematically engage in discussions that intricately connect bamboo construction materials with sustainability. Therefore, further investigation is required to comprehensively explore the potential of bamboo as a sustainable construction material. This research contends that it is time to establish connections between these "points" and unravel the nature of the resulting "chain".

This review research aims to achieve the following four research objectives.

(1) To systematically summarize and review the studies between bamboo construction materials and sustainability;
(2) To analyze the potential contributions of bamboo construction materials in achieving the sustainable development goals (SDGs); and
(3) To explore the potential future directions concerning the sustainability of bamboo construction materials.

This research differs from previous ones because it systematically reviews and assembles a "knowledge map" on the sustainability of bamboo construction materials, provides logical evidence for assessing the sustainability of bamboo construction materials, and offers guidance for shaping the trajectory of future research in this field. The results of this research can fill the gaps and explore promising future directions in bamboo research. In addition, it can help the bamboo industry and policy makers to consider the implementation and management of SDGs (social, economic and environmental). The remainder of this research is organized into six sections. Section 2 following this introductory section, elaborates on the research framework and the methods. Section 3, Section 4 and Section 5 compile research trends, contributions and vacancies in the society, economy and biosphere sustainability of bamboo construction materials, respectively. Section 6 depicts possible research directions. Finally, Section 7 provides conclusions.

2. Research framework and methods

2.1. Research framework

Sustainable development has emerged as a focal debate area for governments and practitioners, and the academic community alike [37,38]. Sustainability is defined as meeting the needs of the present generation without compromising the resources and environment upon which future generations depend for their survival. In early 2015, members states of the United Nations endorsed the *2030 Agenda for Sustainable Development*, which established 17 interconnected goals, 169 targets, and various country-specific programs [39]. The aim was to foster an inclusive and sustainable future for all of society from 2015 to 2030 [40,41]. Specifically, sustainable development emphasizes the creation of a new paradigm to address hunger, eradicate poverty, and achieve ecological harmony - considered as the three principal pillars of the SDGs that studies have called for to be fully taken into account, namely "Society", "Economy", and "Biosphere" [40].

For the effective implementation of SDGs to be, they must be substantiated by tangible products or activities; otherwise, these goals remain theoretical. Within the construction industry, green buildings (or sustainable buildings) have been identified as a promising means to achieve the SDGs [42,43]. Construction materials, being among the most promising carriers of sustainability, offer various tangible and intangible contributions to the SDGs [42]. The United Nations is also emphasizing in the SDGs to try sustainable materials such as bamboo in construction activities [44]. Consequently, focusing on green construction materials is crucial when addressing the sustainability of construction [45]. The official WGBC website outlines at least nine SDGs where construction products may contribute, including SDG3 (Good Health and Well-being), SDG7 (Affordable and Clean Energy), SDG8

(Decent Work and Economic Growth), SDG9 (Industry, Innovation and Infrastructure), SDG11 (Sustainable Cities and Communities), SDG12 (Responsible Consumption and Production), SDG13 (Climate Action), SDG15 (Life on Land) and SDG17 (Partnership for the Goals) [42,46]. Numerous studies highlight the feasibility and importance of achieving SDGs within the construction industry [36]. However, due to the limited integration of bamboo into construction practices, research in this area may lack a comprehensive foundation to fully address all SDGs. To bridge this gap, this study presents a framework in Fig. 1 to illustrate the potential sustainability benefits that bamboo could offer to the construction industry. It is important to clarify that the building clusters depicted in Fig. 1 represent a broad spectrum of construction materials (not limited to those shown in the figure) and do not specifically compare the sustainability of bamboo with other materials. The SDGs framework provided here is intended not only for evaluating bamboo's sustainability as a construction material but also as a universal framework for assessing the sustainability of other materials in construction. Additionally, the term "bamboo construction materials" in this study refers to both natural bamboo resources (bamboo culm) used in structural applications and processed bamboo-based products (engineered bamboo materials).

(1) Society.

For SDG3 (Good Health and Well-being), endeavors are directed towards improving people's health and well-being. Furthermore, in alignment with SDG11 (Sustainable Cities and Communities), the emphasis is on building inclusive, safe, disaster-resilient, and sustainable cities and communities.

(2) Economy.

SDG8 (Decent Work and Economic Growth) aims to promote productive employment, create decent jobs and stimulate economic growth. Furthermore, in accordance with SDG12 (Responsible Consumption and Production), efforts are advocated to minimize resource wastage.

(3) Biosphere.

In alignment with SDG13 (Climate Action), initiatives strive to reduce emissions to combat climate change. Regarding SDG15 (Life on Land), efforts are directed towards enhancing biodiversity, conserving nonrenewable resources and protect forests.

2.2. Research methods and process

This research employed the scientific method of a systematic literature review (SLR) to conduct a structured topic-based review aimed at providing an integrated overview of the current state of knowledge. The primary rationale for opting for the SLR method, in contrast to narrative reviews or meta-analyses, stems from its recognition as one of the most scientifically rigorous review methods [47]. The SLR is derived from the basic research searching method, it adheres to a transparent and objective working procedure, thereby circumventing the search bias commonly associated with traditional reviews caused by the personal judgment [47,48]. The SLR has become a mature and systematic literature review searching and screening method. Subsequently, this review designs a process for searching and screening the research to accomplish the goals of (1) avoiding replicative studies without substantially advance knowledge; (2) reasoning about objective results for this review to guide the decisions of new research; and (3) supporting claims of novelty. Fig. 2 employs a "catching the ball" metaphor (the ball represents the study, and the act of catching the ball refers to screening the study) to illustrate the steps of SLR, including conducting the database search, screening - excluded studies, and identifying suitable studies and thematic analysis.

This research followed the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" [47] and established a standardized procedure for conducting the SLR, detailed in Steps 1 through 3:

Step 1: Conducting the database search.

The studies for this review were identified and collected using the Web of Science database, a globally recognized and authoritative source for scientific research and the world's leading citation search engine [49,50]. Scientific citation searches are primarily conducted by utilizing combinations of Boolean operations. It is noteworthy that despite the acceleration in knowledge production in the field of bamboo construction, research has not directly interpreted bamboo construction materials within the framework of sustainability. In other words, the connection between the two is often established through extensive and scattered themes. Therefore, defining the search scope of this review research based on specific subject terms may inadvertently exclude important articles, even if they fall within a niche. To overcome this challenge, this research intentionally broadened the scope of the literature review search. The search query used was TS = ("bamboo" and

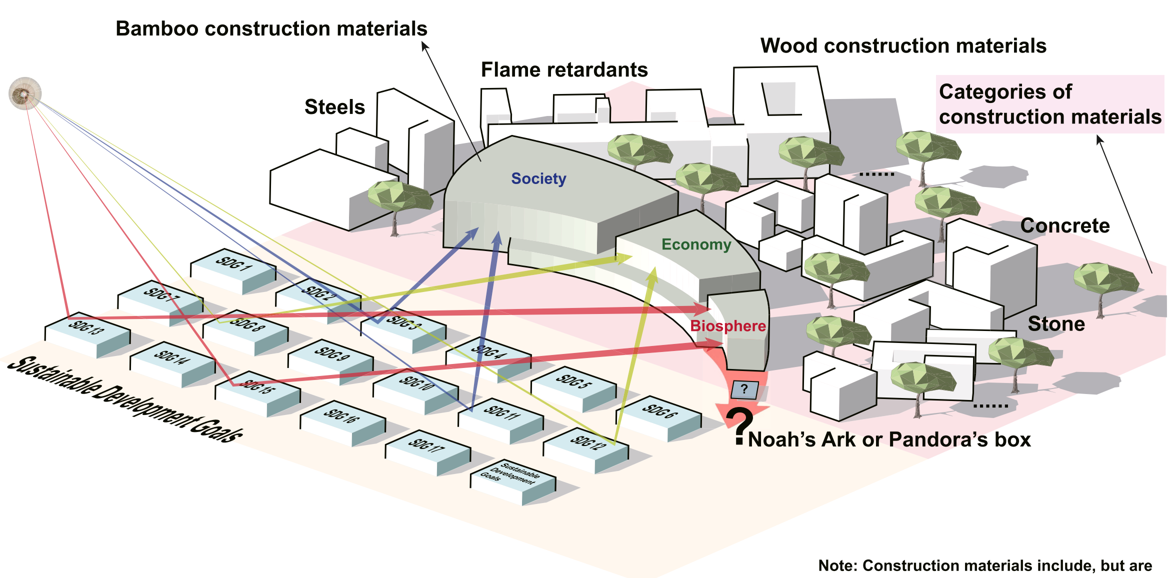

Fig. 1. Framework for evaluating the sustainability of bamboo construction materials.

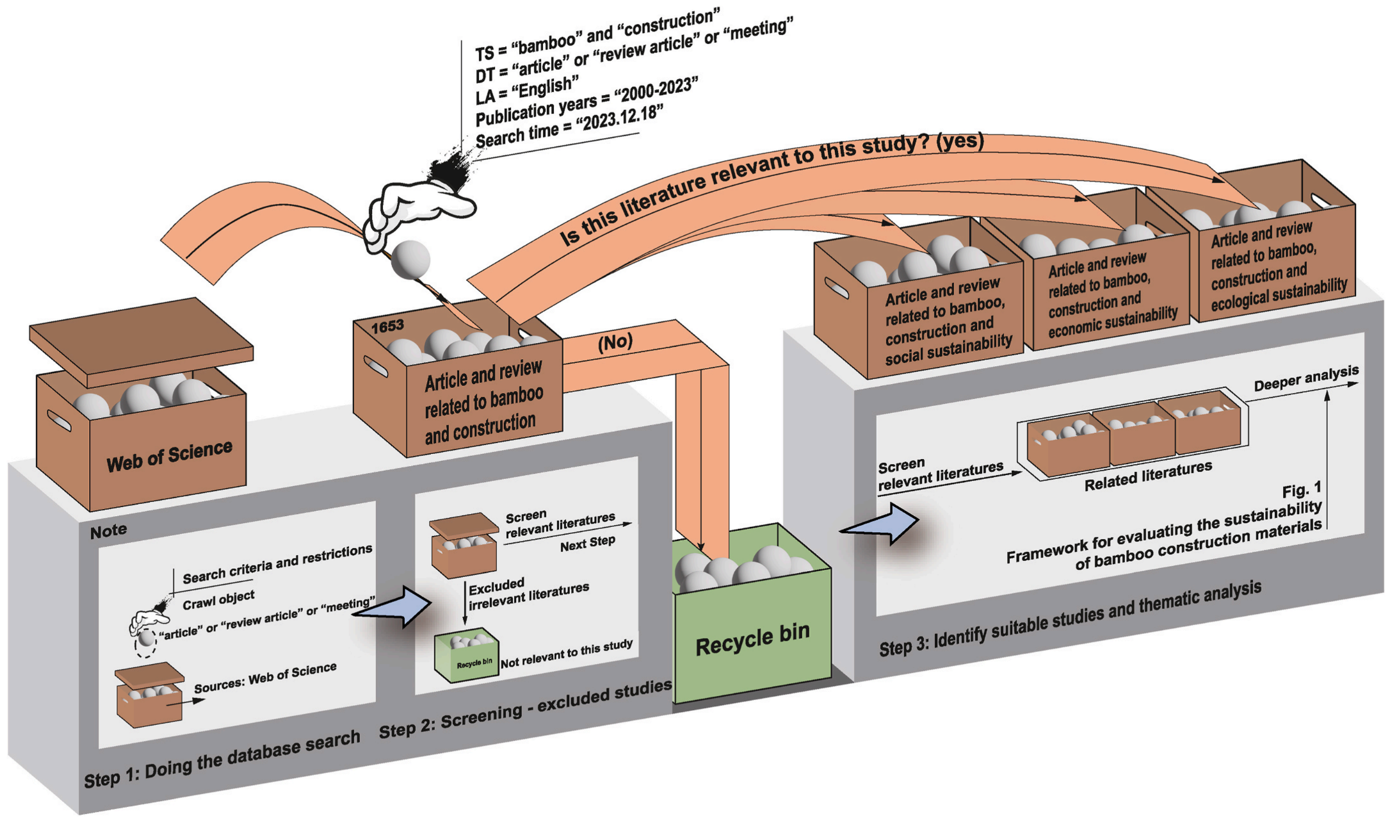

Fig. 2. Process of searching and selecting studies using the SLR method.

"construction"), publication years = "2000–2023", languages = "English", DT = "article" or "reviews" or "meeting". This search, conducted as of December 18, 2023, resulted in a total of 1653 records.

Step 2: Screening - excluded studies.

In this step, the records of 1653 studies were imported into EndNote software, and a meticulous examination of keywords, abstracts, and content was conducted to identify "articles", "reviews", and "conference papers" pertinent to the research question. Following a comprehensive review, a total of 911 studies were excluded.

Among the studies examined, 108 contained no information related to "bamboo." A further 97 studies primarily focused on animals or insects in bamboo forests, examining behaviors such as feeding and nesting. A total of 13 studies were missing titles, abstracts, and detailed content. One study had been retracted. A total of 18 studies were excluded due to their focus on bamboo-inspired biomimetics. Additionally, 87 studies had bamboo as their subject matter but did not address it as a material. Instead, these studies were oriented towards biotechnology (for example, genetics of ornamental bamboo), marine sciences, arts, or education. While 278 studies discussed bamboo materials, they were not within the scope of construction. Rather, they pertained to chemical materials (such as batteries and catalysts), textile materials, aerospace materials, and energy materials. Furthermore, 309 studies primarily analyzed the use of small quantities of bamboo leaf ash, bamboo particles, or bamboo fibers as admixtures in concrete or other materials. Although these studies involved bamboo materials and were related to the construction field, they did not align with the core concept of bamboo as a primary construction material.

Step 3: Identifying suitable studies and thematic analysis.

The screening - excluded studies phase retained 742 relevant studies for this review research. Subsequently, this research thoroughly investigated the available studies. It is worth reiterating that these studies were retained due to their focus on the application of bamboo as a construction material in relation to various SDGs. This refers mainly to SDG3 (health and well-being of the people), SDG11 (raw material inventories and market demand, characteristics of bamboo construction materials, and connection of construction elements), SDG8 (employment and income), SDG12 (production and consumption), SDG13 (climate change) and SDG15 (land ecology). Specifically, this research offers an overview of the three pillars of sustainability - social, economic, and environmental (Fig. 1) - in connection with bamboo building materials. The effort involves summarizing the themes identified in the literature review, encompassing socially sustainable 664 records, economically sustainable 106 records and environmentally sustainable 56 records. Notably, 54 records were double-counted as they addressed elements of two sustainability framework themes, and an additional 15 records discussed all three themes.

3. Social sustainability of bamboo construction materials (SDG3 and SDG11)

3.1. Can bamboo construction materials provide sustainable health and well-being to society?

The SDG3 (Good Health and Well-being) envisions the promotion of healthy lifestyles and well-being for citizens of society [51]. However, health concerns of building occupants have continued to rise [52]. In contemporary society, individuals spend more than 90 % of their time in enclosed spaces, and approximately 90 % of the pollutants to which they are exposed originate from the indoor environment [42]. Consequently, indoor pollutants may cause more significant harm to human health than the outdoor environment [53], and are potential cause of building-related illnesses [54,55]. Over the past decades, there has been an increasing trend in the concentration of pollutants associated with construction materials [56]. Generally, construction materials and the pollutants they release can damage the mental health of occupants and lead to respiratory diseases, sick building syndrome, and even cancer

[57–59]. However, if selected appropriately, healthy construction materials can directly contribute to the construction of healthier indoor spaces [42,60].

3.1.1. Physical health

Harmful substances have been found in several construction materials, such as brominated flame retardants [61], asbestos and heavy metals [62]. Asbestos exposure can lead to asbestosis and various types of cancer [63,64]. Stone materials emit radioactive radon [56]. In contrast, natural bamboo does not appear to be harmful to human health. This is because bamboo is also the raw material for textiles [65], bamboo bicycle frames [66] and bamboo furniture [67], all of which come into direct contact with the human body. Bamboo shoots are even consumed as food [68,69]. However, during the manufacturing process of engineered bamboo, the addition of chemicals may result in the leaching [70] or the emission of unpleasant odors [71], causing concerns among both workers and occupants. Despite these concerns, several studies have demonstrated that bamboo materials can adsorb indoor formaldehyde [72], release fewer toxic elements, and pose a low health risk to humans [14]. In addition, bamboo materials absorb heat and allow natural ventilation, providing decent indoor air quality, and thus preventing health problems for occupants [73]. Undeniably, the relationship between “bamboo materials” and “health” is less discussed in SLR’s survey. It remains uncertain whether bamboo can contribute to the construction of healthy buildings. The few studies available focus on sub-Saharan Africa, where malaria is a significant health problem [74]. Among various housing design options, a two-story bamboo building has been shown to reduce indoor mosquito density, thereby decreasing the risk of mosquito-borne diseases such as malaria [74]. However, some respondents expressed concerns: bamboo walls can be vulnerable to insects and ants, producing irritating dust that may affect occupants’ respiratory health [74]. Beyond these points, research on such issues remains limited. Notably, in addition to the bamboo construction material itself, attributes related to visual stimulation [75], odor emissions [76], and biophilic design [77] also have the potential to impact the physical and mental health of occupants. Research directly examining the correlation between bamboo construction materials and occupant health is generally scarce and remains in its early stages. For instance, limited exploration exists on how bamboo materials influence human health through factors like indoor air quality and building layout. The few studies that do address the relationship between bamboo materials and health are often superficial and narrow in scope.

3.1.2. Psychological health

Health and well-being are not only the absence of disease, but also the absence of mental problems, including anxiety and depression [42,60]. Previous studies have suggested that bamboo forests are beneficial for restoring human concentration and relieving stress, thereby stabilizing the physiological health of individuals in sub-healthy state [78]. Similar studies have also experimentally demonstrated that young people can reduce anxiety by walking in a bamboo forest for 15 min [79]. Bamboo therapy has become a popular method for naturally promoting health and enhancing well-being [80]. However, it remains inconclusive whether bamboo-enclosed buildings can also evoke more positive emotions (comfort and naturalness) in people. While studies have confirmed that wooden furniture and interiors can reduce blood pressure and stress levels in users [77], any similar effects of bamboo materials can only be inferred at this stage, not conclusively demonstrated. Fortunately, there are glimpses of potential directions for future research. For instance, the relationship between bamboo-based buildings and human health, the biophilic design of bamboo materials, and the connections between bamboo building and bamboo therapy are scarce yet intriguing topics worthy of further exploration.

3.2. Can bamboo construction materials build sustainable cities and communities?

The agenda of SDG11 (Sustainable Cities and Communities) underscores the imperative to ensure that all individuals have access to housing that is adequate, safe, and affordable, as well as basic services. This goal also stresses the importance of universal access to public spaces that are safe, inclusive, accessible, and environmentally friendly, along with the need for buildings that are sustainable and resilient to disasters [51]. Undoubtedly, buildings are fundamental to the development of cities or communities [42]. To construct a sustainable building, the requirements for materials lie in the ability to produce safe (mechanical property, creep, seismic defenses and fire resistant), adequate (moisture and heat performance, air ventilation, and sound insulation), and durable (mold resistance and termite-proof) building components or assemblies, which can be stably connected, with long-term (sufficient raw material inventory and potential market demand) production. Fig. 3 presents a conceptual diagram of a sustainable bamboo-based city. The building names indicate types of structures that have already been constructed using bamboo materials. The detailed schematic highlights five key considerations essential for developing sustainable cities and communities.

3.2.1. Raw material inventories and market demand

(1) Raw material inventories. Bamboo is a non-timber forest product widely distributed in tropical, subtropical and temperate regions from about 47° south to 46° north latitude in countries in Asia, Latin America, Oceania and Africa [81]. According to the *Global Forest Resources Assessment 2020* reported by the Food and Agriculture Organization of the United Nations, bamboo forests cover about 35.04 million hm^2 of land globally, making an increase of nearly 50 % over the global bamboo forest area in 1990 [82]. Furthermore, despite the ongoing decline in global forest areas since the 1990s, bamboo forests have maintained an annual growth rate of approximately 3 % [83]. Bamboo’s sustainability metrics - such as growth cycle, yield, and regeneration capacity - surpass those of traditional construction materials like timber, steel, and concrete, making it over twenty times more sustainable [19]. According to current estimates, there are over 1200 species of bamboo plants worldwide, of which approximately 60 species are considered suitable raw materials for construction purposes [84,85]. These 60 or so bamboo species account for more than 74 % of the total global area under bamboo cultivation [86,87]. Among them, Moso bamboo (*Phyllostachys edulis*) stands out as the most prevalent species globally, extensively developed and researched for its significant economic value [88]. Other notable bamboo species used in construction also include *Dendrocalamus sinicus* [89], *Guadua angustifolia Kunth* [90], *Neosinocalamus affinis* [91], and some clumping bamboo species such as *Thyrsostachys oliveri* [92].

From a regional perspective, approximately 80 % of the world’s bamboo resources are located in the Asia-Pacific region, with China - the “Land of Bamboo Civilization” - being the country with the largest bamboo resources (accounting for approximately 33.9 % of the world’s bamboo forests) and the largest area of Moso bamboo [82]. According to the *China Forest and Grassland Ecological Comprehensive Monitoring and Evaluation Report 2021*, China’s bamboo forest area reached 7.5627 million hm^2, and the bamboo timber output reached 3.256 billion culms, an increase of 1.1511 million hm^2 (17.95 % increase) compared to the 9th National Forest Resources Survey [93,94]. Among them, Moso bamboo forests constitute 5.2776 million hm^2 (accounting for 69.78 % of the bamboo forest area), with an output of 1.927 billion culms, marking a 12.82 % year-on-year increase [93,94]. China, the Asia-Pacific region, and indeed the world possess abundant and sustainable bamboo reserves. Almost all bamboo products use Moso bamboo as a primary raw material [95]. However, many high-quality bamboo resources remain undeveloped and underutilized, with certain clumping bamboo species, common in Southeast Asia and South Asia,

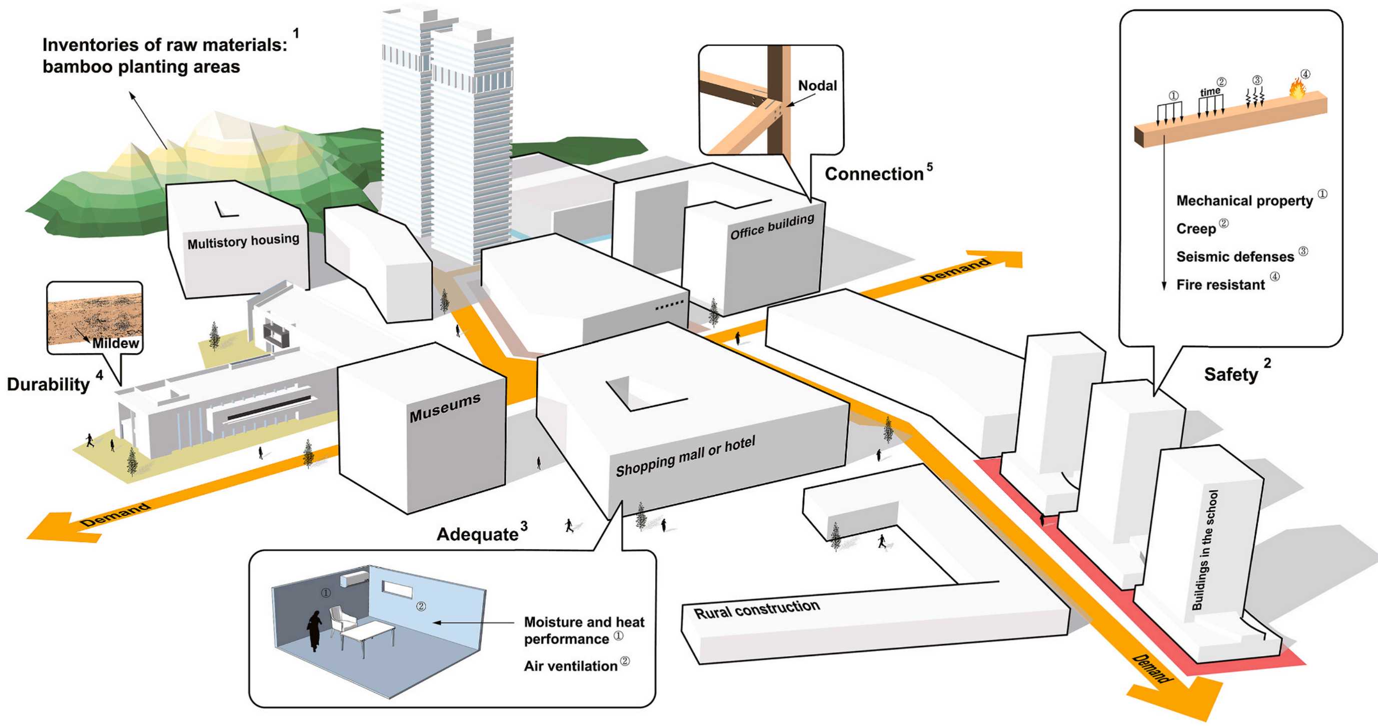

Fig. 3. Research on sustainable bamboo building materials.

largely overlooked [96]. Another notable challenge is the limited genetic diversity among bamboo species [87,97]. Bamboo reproduces primarily through asexual means [87], making it vulnerable to diseases and pests and restricting opportunities to cultivate improved varieties [17,97].

(2) Market demand. Bamboo possesses significant potential and prospects in the global forest products marketplace [98]. In fact, the application of bamboo in construction is not new, as archaeological evidence suggests that humans may have utilized bamboo materials to construct buildings as early as the Sanxingdui civilization [99]. Over millennia, bamboo has evolved to meet the demands of modern architecture, transitioning from natural bamboo culms to engineered bamboo products such as laminated bamboo lumber (LBL) [24,100,101], glubam [102,103], bamboo scrimber [104,105], parallel strand bamboo [106,107] and bamboo mat board [85]. Modern bamboo construction materials are no longer limited to the construction of stilted houses and single-story dwellings. They are now prevalent in high-rise residential buildings [108], office buildings (for example, the bamboo office building of Sentai Bamboo Co. Ltd. located in Jiangxi Province, China.) [109], school buildings [110], tourism landscape architecture [111], shopping malls, airports, museums [84], and landmark buildings in villages [111]. Specifically, bamboo is utilized for scaffolding [112], structural components (such as columns [113], beams [114], trusses [115], floors [116], partition walls [117] and roofs [118]), architectural surface [119] and alternatives to steel reinforcement [120], bamboo piles [121] and bridge engineering (portable bridges [122], pedestrian bridges [115], and truck road bridges [123]).

From the perspective of global trade, the bamboo product sector demonstrated substantial growth, with the global export trade in bamboo products totaling approximately $3.599 billion in 2021. Within this sector, bamboo panels and bamboo-based construction materials comprised 12.20 % of the trade volume [124]. China, as the world's largest exporter of engineered bamboo, engages in trade with 195 countries [125,126]. In 2021, the revenue from China's bamboo material sales reached 23.61 billion yuan, accompanied by the production of 180.607 million m^3 of bamboo plywood and 703.061 million m^2 of bamboo flooring [93]. The global market is experiencing a surge in demand for bamboo products. This is evidenced by initiatives such as China's action plan to promote the use of "bamboo as a substitute for plastic" [127,128], Vietnam's "bamboo diplomacy" [129], and the strategic bamboo resource management in countries like Kenya and Ethiopia [130]. These developments indicate a continuing and robust growth in the demand for bamboo building materials globally.

3.2.2. Safety

In building design, the foremost criterion for selecting a construction material hinges on its safety and reliability. Essentially, the safety of a building is inextricably linked to the lives and property of its occupants. A material must first be verified as capable of safely being used in the construction of permanent structures before further considerations regarding its suitability or sustainability can be addressed. The safety of a structural design fundamentally depends on several key properties of the materials used: mechanical strength, creep resistance, seismic defenses, and resistance to fire and smoke.

(1) Short-term mechanical properties. The evaluation of building components often begins with assessing their mechanical properties. Classical mechanical theory suggests that the hollow cylindrical structure of natural bamboo provides exceptional mechanical properties. Specifically, the strength-to-mass ratio and stiffness of bamboo culms exceed those of traditional timber, with bamboo fibers demonstrating strength surpassing even that of steel [26–28]. For instance, timber's modulus of rupture is approximately 84.27 MPa, with a ductility factor around 2.12 [131]. At comparable densities, Moso bamboo's modulus of rupture is approximately 1.72 times that of conventional timber, and its ductility factor is 3.06 times greater [131]. However, bamboo is an anisotropic material, with longitudinal splitting primarily governing the failure of bamboo culms, while its transverse behavior is complex [132]. The shear strength of bamboo ranges from 8.65 to 18.06 MPa, representing only about 9 % of its tensile strength [133]. Nevertheless, most timber materials - spruce, larch, and paulownia timber - are still more susceptible to shear failure than bamboo, with maximum shear strengths of approximately 7.7 MPa, 11 MPa [134], and 6.7 MPa [135], respectively. It is worth noting that the mechanical experiment results of bamboo may exhibit deviations, as its performance depends on various factors about bamboo species and characteristics, including moisture content [136], density [85], and the volume fraction and distribution of fiber bundles [85,132]. Among these, density is one of the best indicating properties determining the strength of bamboo materials [137]. The denser the bamboo fibers, the higher the strength typically [138]. Densification is also one of the driving forces that dominate the development of natural bamboo into engineered bamboo materials. Compared with natural bamboo culms and engineered timber, the mechanical performance of engineered bamboo is more satisfactory [85]. Bamboo materials are nearly nine times lighter than steel, with a tensile strength-to-weight ratio approximately six times higher than that of steel [85,139]. Remarkably, densified bamboo exhibits record-breaking mechanical properties, including a tensile strength of 1 GPa, flexural strength of 400 MPa, and toughness of 9.74 MJ/m^3, outperforming traditional timber, engineering steel, and even some high-strength metallic alloys [140]. Similarly, the performance of engineered bamboo materials is also influenced by various processing parameters, such as bamboo fiber orientation and distribution [141], temperature, pressure, and duration of pressing [85], adhesive concentration and spread rate [85]. Although research has yet to fully clarify all bamboo processing parameters, substantial information is available on the short-term mechanical properties of bamboo. The mechanical characteristics of several established types of bamboo construction materials are well-documented. From laboratory test results to engineering applications, one clear finding is that bamboo products manufactured with suitable additives and advanced processing techniques are mechanically robust, positioning them as viable alternatives to concrete and steel. Table 1 provides mechanical property indices for commonly used bamboo materials in construction.

(2) Long-term creep behavior. In addition to the short-term mechanical properties, another crucial reliability constraint that requires in-depth consideration is the creep behavior of bamboo. Creep refers to the inevitable progressive permanent deformation of a material over time under continuous loading conditions [143]. Previous studies have provided preliminary insights into the creep behavior of bamboo materials. Bamboo has a low elastic modulus, and the atomic or molecular bonds are easily disturbed, making it more susceptible to creeping under load [143]. Specifically, as the applied stress level continuously increases, the microscopic particles in bamboo will undergo dislocation and slip, leading to an increase in creep residual deformation and an accelerated decrease in creep recovery [144]. Based on the specific creep test results, the creep performance of bamboo appears to be reasonably good [144]. Under a compressive stress level of 40 % of the ultimate strength, the surface of bamboo specimens shows almost no signs of deterioration in the short term (at least 6 h) [144,145]. Notably, at this loading level, studies predict that the strain of a bamboo specimen may reach 2 % over approximately 40 years [145]. In a separate long-term study monitoring the deflection of a truck-transported bamboo bridge over 1350 days, the beam's average creep was found to be only 7.89 mm [146]. However, within these limited test results, it is undeniable that information on the long-term creep behavior of bamboo materials is scarce. The first challenge in creep testing is the time factor [147]. Direct testing of material creep behavior may require five years or even longer [145]. Therefore, accelerated creep testing provides a novel alternative approach. It primarily involves accelerating the creep of bamboo by increasing temperature [148] or stress [149], and then using mathematical models (such as the Burgers model and Findley model [150]) to predict the master curves of creep response over a longer time range. Examples include the stepped isothermal method [145] and the short-term stepped isostress method [151]. However, the research progress on accelerated creep testing is still in its early stages. Another challenge is the difficulty in comprehensively analyzing the factors influencing bamboo creep within the limited creep tests. Unlike short-term mechanical performance, the factors affecting long-term creep are different. For instance, a study has shown that density is a key factor affecting the initial deflection of bamboo, but not the long-term creep [152]. Based on the limited research, factors such as loading level [153], loading duration [154], moisture content, temperature, and humidity [154,155] may influence the creep of bamboo materials. However, the mechanisms and the coupled effects of these multiple factors have not yet been discussed [144].

(3) Seismic defenses to withstand disasters. Bamboo buildings are also a stable form of construction that can effectively resist the inertial forces of storms or earthquakes [156]. A typical building example is the earthquake-resistant demonstration bamboo building located at Nanjing Forestry University. This is because the precise fiber bundles and thin-walled cellular organization of bamboo [157], along with its light, viscoelastic, high toughness, malleable, and high strength-to-mass ratio [158], give bamboo natural vibration-damping capabilities. For example, bamboo columns can recover at least 80 % of their deformation after unloading (vibration loads) [159]. In professional seismic tests, bamboo structures have resisted dynamic forces of moderate to strong earthquakes with minimal damage levels [160]. The multi-story bamboo frame structure exhibited a maximum inter-story drift ratio of 0.74 % under a mild earthquake (peak ground acceleration of 0.07g), and a maximum inter-story drift ratio of 2.57 % under a strong earthquake (peak ground acceleration of 0.4g) [161]. Bamboo buildings not only respond well to conventional vibration behavior but also hold promise in earthquake prone areas [162]. The most compelling evidence is that bamboo buildings are often among the rare survivors in the aftermath of global earthquake disasters (such as the heartbreaking earthquakes in Nepal), with some even being repurposed as shelters [163]. Without a doubt, engineers can fully trust the disaster-resistant capabilities of bamboo construction.

(4) Challenging flame retardant and smoke suppressant properties. The fire resistance of bamboo materials has long been questioned by the public. Bamboo, being a naturally combustible material, is highly susceptible to ignition and rapid flame propagation when exposed to fire [90]. Under high-temperature fire conditions, the hemicellulose and lignin components of bamboo undergo progressive pyrolysis, resulting in continuous mass loss [90,164,165]. This process leads to structural cracking and eventual failure, with bamboo's mechanical strength

Table 1
Mechanical property indexes of common bamboo materials for construction.

Raw bamboo or bamboo materials	Tensile Strength (MPa)	Compressive Strength (MPa)	Bending strength (MPa)	Shear Strength (MPa)	Flexural Modulus of Elasticity (MPa)	Density (g/cm^3)	moisture content (%)	Data sources
Phyllostachys edulis	–	67.0	180.9	18.17	10850	0.64	–	[142]
Neosinocalamus affinis	273.3	55.6	255.7	11.7	–	–	–	
Dendrocalamus sinicus	177	70	193	10.6	16373	0.74	8.0	[84]
Bambusa blumeana	279.2	62.6	117.2	10.1	–	–	–	
LBL	84.5	71.6	92.6	13.85	7999	0.6–1.0	8.0	[142]
Bamboo scrimber	151.6	98.8	144.3	26.7	9919	>1.0	–	
Glubam	83	35–81	99	16	9407	0.8–0.9	–	[84]
Laminated bamboo sliver curtain lumber	137	85.5	160.9	22.7	12200	0.96	–	

deteriorating rapidly as it burns [164,165]. However, bamboo and timber materials are also noted for certain fire safety advantages. During combustion, bamboo undergoes a “carbonization” process that can help prevent flames from penetrating the material’s interior, thereby slowing down heating, softening, and structural collapse [90,166]. This property can help maintain the structural integrity and provide longer safe evacuation times for occupants. Additionally, the critical heat flux required to ignite bamboo is significantly higher than that of many common tree species [90]. Nevertheless, the charring characteristics of bamboo alone may not be sufficient to meet the stringent fire-resistance requirements of modern buildings. Consequently, research has focused on enhancing the flame-retardant properties of bamboo [167]. The most effective fire-retardant treatments involve the addition of substances that directly interfere with the combustion process [168], such as organic materials, inorganic salts, metal ions, and boric acid [169,170]. The most common ways of adding these fire-retardant additives are surface coating and impregnation [168,171]. The flame retardancy of bamboo construction materials has been a topic of long-standing discussion. While fire-retardant treatments have somewhat improved bamboo’s resistance to fire, they do not eliminate the risk entirely. Further research is needed to deepen our understanding of bamboo’s behavior under fire conditions.

3.2.3. Adequate

Adequate is another dimension of building sustainability. A construction material can only be considered sustainable if it can provide a comfortable living environment for the occupants, enabling them to reside there for an extended period. Specifically, the living environment must maintain a comfortable temperature, relative humidity, and natural ventilation, while effectively insulating against annoying noise.

Thermal and humidity performance is a key indicator for evaluating the thermal comfort of buildings, and bamboo materials are no exception. The thermal conductivity of engineered bamboo products generally ranges from 0.20 to 0.35 W/(m K) [172], significantly lower than that of aerated concrete blocks, reinforced concrete, and cement mortar [173]. In the summer, a 28 mm bamboo plywood partition wall can insulate a maximum of 11.73 °C outside temperature [174]. In the winter or some extremely cold regions, bamboo buildings can also reduce indoor energy loss [175]. In addition, bamboo walls have a high resistance to outdoor temperature fluctuations [173]. Bamboo is a poor thermal conductor, with a thermal conductivity range comparable to that of certain insulation materials, such as expanded perlite and vermiculite [176]. This is largely due to the fact that in the low-density bamboo material, heat flow transfer occurs through the lower thermal conductivity of the air in the bamboo tissues and voids, resulting in an overall low thermal conductivity of the bamboo [176]. Bamboo buildings have satisfactory thermal comfort. However, the pore structure and abundant free hydroxyl groups in bamboo tissues make it highly hygroscopic [177,178], increasing indoor humidity. Studies have shown that humid environments can encourage mold growth, leading to discomfort and potentially causing allergies and other health issues for occupants [179]. This can result in occupants developing a negative perception of the humidity in bamboo buildings. The combination of bamboo’s thermal conductivity and hygroscopicity causes cyclic expansion and contraction, making bamboo products susceptible to deformation, warping, and cracking when exposed to sunlight or humid conditions [177,180]. Consequently, occupants may experience privacy issues due to visible cracks in the material [74]. Moreover, these cracks can also make it difficult to regulate air circulation, leading to an uncomfortable indoor space environment [74]. Natural ventilation is essential for maintaining occupant comfort, as even minor airflow restrictions can cause discomfort or intolerance in high-temperature or humid environments [74]. However, some studies suggest that bamboo buildings support natural ventilation [73] and maintain optimal indoor temperatures for sleeping [74]. In summary, while research has critically examined certain comfort-related aspects of bamboo buildings, these discussions remain limited in depth.

The hollow structure of bamboo can also absorb sound energy [181], and bamboo fibers can reduce the sound absorption coefficient of materials (at higher frequencies) [182]. Bamboo culm is a natural sound-absorbing material. The acoustic performance of engineered bamboo materials is well recognized. For instance, bamboo panels have been used to address noise issues around buildings [183]. Additionally, bamboo can be further processed and combined with other materials to enhance sound insulation. For example, a composite product can be created by using bamboo as face sheets with a balsa timber core [184]. The acoustic performance of such composites depends on various factors, including porosity, viscoelasticity, density, and moisture content [185,186]. For instance, higher-density bamboo particleboard shows increased sound transmission loss [187], while bamboo boards with high porosity and low density improve the noise reduction coefficient [188]. However, not all influencing factors have been thoroughly analyzed or discussed in the research. The combined effects of these factors on the acoustic performance of bamboo materials remain a complex issue requiring further investigation.

3.2.4. Durability

Bamboo tissues are rich in nutrients such as proteins, starches, and glycogens, which unfortunately attract fungi, bacteria, and termites. This susceptibility makes bamboo materials prone to mold, fungal decay, and insect infestation, significantly reducing their service life [189,190]. Additionally, ultraviolet radiation can degrade bamboo cellulose, accelerating its aging process [191,192]. These issues significantly shorten the service life of bamboo materials. In typical outdoor environments or damp soils, natural bamboo maintains its integrity for only one to three years [193]. Even under optimal storage conditions, its maximum lifespan is around 15 years [84]. Despite these natural limitations, ongoing research indicates that with appropriate treatments and industrial processing, bamboo components can achieve lifespans of 30–40 years or more [194]. The durability of improved bamboo materials can be achieved through chemical solution impregnation [195–197], heat treatment [196–198], and other techniques. Over the past period, chemical treatment has been recognized as one of the most effective methods for extending the service life of bio-based materials [193]. Common preservative chemicals include boric acid and borax [199], alkaline copper quaternary compounds [200], CuAz preservatives [201], or chromium-based reagents [202]. Unfortunately, most preservatives have been found to have relatively low penetration abilities, only providing limited protection for bamboo; moreover, leaching issues remain unresolved, potentially leading to environmental pollution and threats to human health and well-being [203]. For instance, creosote can extend the service life of bamboo to around 36 years, but its toxicity to organisms cannot be ignored [193]. In contrast, heat treatment is considered a more efficient and environmentally friendly modification method [177], as it enhances bamboo’s durability by dehydrating the material, inactivating nutrients, or directly killing microorganisms through high-temperature processing. Heat treatment technology has frequently appeared in the production practices of the bamboo industry [18]. However, some studies have critically pointed out that heat treatment may degrade the cellulose and hemicellulose of bamboo, thereby weakening its mechanical performance [204,205]. Additionally, in rural areas, the traditional methods of smoke treatment and carbonization are used to treat the surface of bamboo [14,206]. Interdisciplinary collaborators are also dedicated to inhibiting the decay and insect infestation of bamboo materials at the nano-technology and cell science levels. For example, the use of nano-copper impregnation can reduce termite attacking losses from 6.8 % to 0.2 % [205,207]. Zinc oxide can provide complete protection for bamboo after leaching [205].

3.2.5. Stable connection

The inherent characteristics of native bamboo, such as its propensity to split and its naturally round, thin-walled, hollow cross-sections, present significant challenges in designing reliable connection structures [208]. In traditional bamboo constructions, connections between culms typically rely on reinforcement methods such as rope lashing [209], mortise-tenon joints [210], bolted connections [211] and metal clamps and removable clip connection [212]. Connections, being critical points for load transfer and often the weakest links in a structure, are frequently the source of structural failures [213,214]. The vulnerability of these connection methods (reinforcement or embedding) in natural bamboo has inhibited its ability to meet all structural application requirements, leading to its gradual marginalization in modern construction. To address the construction challenges of natural bamboo efficiently and economically, engineers have developed engineered bamboo products [213]. These products emulate modern wooden building materials, utilizing dowel-type connections (such as screws, bolts, and nail) [208,215], glued-in joint [216], or tenon-mortise joints [217] for assembly in buildings. Taking the popular dowel-type connections as an example, previous research has tested and elucidated their embedment properties [218], cyclic response [214], and failure modes [219,220] under laboratory conditions. Specifically, nails may undergo bending deformation before resisting pullout [221]. The strength, position and arrangement of nail-type fasteners, as well as the thickness and specific gravity of components, directly influence the collapse threshold of connection load-bearing capacity [222]. Bolted connections are more stiffer and reliable than dowel connections [223]. Similarly, the diameter, end distance, anchorage depth, and load direction of screws strongly correlate with connection structure failure [213,224]. Additionally, teams are focusing on bonding techniques, such as the bond behavior between bamboo plate and concrete interface [225], and adhesive bonding between bamboo plywood and steel [226]. Finally, the tenon-mortise joint, one of China's oldest connection methods for bamboo and timber materials, is far from ineffective. On the contrary, it is a reliable structural system capable of securely connecting bamboo and timber materials for millennia (as evidenced by China's Forbidden City [227] and Yingxian Wooden Pagoda [228]). This method is not prioritized due to the labor-intensive nature of crafting tenons and mortises, and the prohibitively complexity of tenon-mortise joints [229,230]. Fortunately, with the advancement of computer numerically controlled manufacturing technology, tenon-mortise joint techniques are experiencing a revival [231]. In conclusion, connection technologies for bamboo materials are both reliable and evolving. They not only achieve dependable assembly between bamboo and timber materials but also accomplish stable connections across different materials (steel and concrete). This progress significantly enhances the potential for bamboo in modern construction applications.

4. Economic sustainability of bamboo construction materials (SDG8 and SDG12)

4.1. Who does bamboo construction material enable to get decent jobs and profits?

SDG8 (Decent Work and Economic Growth) aims at the creation of quality jobs for all while promoting inclusive and sustainable economic growth [51]. The bamboo industry, being labor-intensive, demands significant human resources throughout the material's life cycle, including bamboo planting, production, transportation, installation, and maintenance [42]. This need for labor is particularly pronounced in the planting and production phases [97]. Consequently, the bamboo industry holds the potential to generate numerous employment opportunities in rural areas and bamboo manufacturing facilities, thereby contributing to sustainable economic growth [16,97].

4.1.1. Farmers

In rural areas and bamboo farms, bamboo serves as a crucial economic resource [87]. In countries such as China [232], India [233] and several African nations [97,234], bamboo planting and production have emerged as effective tools for providing decent work to farmers and promoting rural development. For instance, in China, over 19 million farmers are engaged in the bamboo industry [235]. Similarly, India employs approximately 10 million people in bamboo cultivation [236]. Specifically, farmers have access to diverse employment opportunities, including bamboo forest maintenance [237], bamboo sales [234], and guiding tours in bamboo forests [238]. Furthermore, bamboo cultivation indirectly drives the development of rural infrastructure (such as roads), potentially creating additional employment opportunities [97]. Consequently, rural areas have experienced a significant increase in income levels. Farmers in India can earn an annual income of $800 per hectare from selling bamboo culms [236]. Bamboo cultivation has consistently provided farmers with rapid and stable income generation.

(1) **Rapid income generation.** Bamboo's fast growth cycle [18,239] and higher biomass production compared to woody plants (in the same planted area) [97] enable quicker income generation from bamboo-based construction materials [239].
(2) **Stable income generation.** Bamboo plantations do not compete for land with other activities such as agriculture or forestry. Additionally, harvested bamboo can regenerate [239]. Moreover, the development of bamboo-based composite materials has gradually increased the utilization of small-diameter bamboo, further enhancing farmers' incomes [176].

4.1.2. Workers

Bamboo has also created numerous employment opportunities in factories and workshops dedicated to its production [234]. For example, China has over 10,000 factories manufacturing bamboo, collectively employing more than 29 million workers [235]. In the Philippines, a bamboo factory covering an area of 55,000 ha is projected to meet the employment needs of about 28,000 workers [239]. Another noteworthy aspect is that the production phase of bamboo can be decentralized and operated independently in multiple small workshops [239]. Consequently, bamboo materials are regarded as having significant job creation potential, even exceeding that of glue-laminated timber by twofold [239].

4.2. Are bamboo construction materials sustainably consumed and produced?

SDG 12 (Responsible Consumption and Production) aims to ensure sustainable consumption and production patterns [51]. Among its specific targets, governments, companies, and other stakeholders are urged to pursue the sustainable management of natural resources, as well as sustainable production and procurement of products [51].

4.2.1. Government

Local government actions, such as responsible governance, are closely intertwined with economic activities [240]. However, bamboo, despite its significant socio-economic potential, has not yet received sufficient attention [237,241]. Historically, bamboo has been viewed as a low-value product, often neglected or marginalized in governmental development blueprints and official forestry policies [237,242]. Additionally, there is a paucity of policy information regarding the sustainable development of bamboo resources [237,243]. Generally, governments have been largely absent in the sustainable management of bamboo resources over an extended period. The management of bamboo resources faces multiple challenges.

(1) **Ambiguous ownership and usage rights of bamboo forests.** Most government or collectively owned bamboo forests are, in practice, open-access resources [237,244].
(2) **Weak regulatory and enforcement mechanisms.** The use and management of bamboo forests lack stringent rules and constraints [237,245].

As a result, local people engage in unrestricted bamboo harvesting and arbitrary conversion of bamboo forests to agricultural land, leading to the degradation of numerous bamboo resources [237]. Nevertheless, some countries have begun to take action to promote sustainable management of bamboo resources. In Anji County, China, the government has introduced supportive policies for bamboo cultivation (subsidies and funding) and implemented a household responsibility system in production [240]. The Nepalese government has implemented encouraging policies such as developing bamboo nurseries, and establishing collection and processing centers for bamboo [246]. The Nigerian government has executed regulatory, distributive, and redistributive policies to constrain improper harvesting by citizens and promote investment [32]. However, managing bamboo resources presents challenges for many countries worldwide, necessitating the formulation of sustainable plans to address these issues. Few studies have investigated the role of the government in managing bamboo forests, promoting the scaling up of the bamboo industry and formulating related policies.

4.2.2. *People who manage bamboo forests*

Bamboo cultivation has created decent jobs for farmers, but their management of bamboo forests has been less than satisfactory. Farmers and foresters often rely on ancestral experience rather than professional training and technical knowledge to manage bamboo groves [237,247]. Early studies have identified a widespread lack of awareness regarding cultivation and silvicultural management among farmers, directly contributing to the gradual decline in bamboo's healthy productivity [246]. Furthermore, in the context of bamboo marketing, various factors including demographic characteristics, socio-economic conditions, and institutional and psychological aspects influence farmers' decisions regarding bamboo sales [234]. However, how to control these factors to enable farmers to manage bamboo marketing more sustainably remains unresolved. In other words, those involved lack the capability (due to insufficient data on bamboo resources, information, and cultivation and management techniques [234,237,245]) to properly manage bamboo forests. To overcome these challenges, practitioners require training and technical support.

4.2.3. *Factory for manufacturing bamboo*

Sustainable production aims to minimize resource consumption and waste generation while maintaining economic viability [248]. Specifically, sustainable products should conserve resources and energy, avoid waste, and be produced efficiently, all while balancing the tension between economic activities and environmental concerns.

(1) **Resource and energy consumption.** The depletion of resources and energy is undoubtedly one of the most pressing concerns in the contemporary construction industry. The demand for resource-efficient construction materials is more urgent than ever before. Bamboo emerges as one of the promising candidates. The energy consumption associated with cutting bamboo is approximately 1.32 MJ/t, which is only 20–30 % of required for timber [249]. Across its life cycle, bamboo-based structures also consume less energy compared to brick-concrete buildings [249], aluminum and steel [250], and concrete structures [14,175]. However, the use of bamboo is not without limitations, and there are potential issues regarding the use of certain resources. Traditional irrigation methods for bamboo plantations consume significant water resources [24,251]. Additionally, bamboo processing is criticized for the excessive use of adhesives and other additives [14]. These waste resources are, in principle, avoidable. Therefore, there remains room for improvement in resource and energy use within bamboo processing.

(2) **Avoiding waste.** Historically, bamboo exhibited rapid growth but was underutilized [240]. This was mainly due to the necessity of removing bamboo joints [29], and bamboo green and yellow surfaces [18,91] during processing. For example, LBL typically achieved a utilization rate of 65–70 %, resulting in substantial quantities of bamboo powder and waste materials [18,95]. Interestingly, these waste materials (off-cuts or chippings) were not discarded. Instead, they were recycled and continue to be processed into graphene-like materials [252], particleboard [253], and handicrafts [240]. In addition, advancements in bamboo flattening [232,254] and bamboo scrimber [255,256] have enabled the processing of a greater proportion of raw bamboo into structural components. It has been shown that more than 95 % of bamboo can be utilized [240]. Furthermore, bamboo components can be recycled, refurbished, and remanufactured. For example, bamboo laminated veneer lumber can achieve a recycling rate of 90–95 % [257]. Consequently, the quantity of waste generated during bamboo production is minimal.

(3) **Technological innovation.** Efficiency, intelligence, and lean production are key factors for companies to develop more competitive products. In response, professionals have conducted innovative research on efficiently and accurately handling bamboo raw materials, as well as automating and intelligently manufacturing bamboo components. This research has created opportunities for bamboo to compete with industrialized materials. In the bamboo handling phase, research has used 3D scanning [258], mathematical modeling [259], and robotics [260] to manage the non-uniform geometric characteristics of bamboo culms for more precise handling. Additionally, nanotechnology [205] and sand blasting [91] are employed to modify unfavorable bamboo characteristics. For example, sand blasting can destroy the wax and silicon on bamboo surfaces, increasing roughness and consequently enhancing the bonding strength between bamboo strips [91]. During the engineered bamboo material manufacturing phase, producers have designed digital workflows to automate bamboo processing [261,262] and assist unskilled labor in working more accurately [263]. They have also optimized manufacturing processes [264], as well as updated the technologies, including new high-temperature bending techniques [265], adhesive technologies (such as chemical and steam treatments [257], novel adhesives [266], and microwave-assisted bonding [267]), microwave heating [268], and automated mechanical devices. Finally, new bamboo materials have been developed, such as densified bundle-laminated veneer lumber [269] and transparent bamboo [270,271].

(4) **Economic activities and the environment.** The production of bamboo construction materials results in minimal environmental damage [18,29]. Regarding the negative externalities associated with environmental pollution, the societal costs incurred to mitigate the environmental impact of bamboo material production are significantly low [24]. Producers of bamboo materials operate in harmony with nature.

4.2.4. *Consumers*

In economic terms, affordability is typically the primary consideration when consumers consistently choose a material. Consumers generally do not worry about the price of natural bamboo culms, as they are highly affordable even in impoverished regions [16,85]. Bamboo is even referred to as "the poor man's timber [272,273]" However, as manufacturing techniques become more sophisticated, the cost of engineered bamboo materials gradually exceeds consumers' affordability threshold. For instance, the production and supply cost of 1 m^3 of LBL for manufacturers can reach approximately 12,169.37 RMB, with consumers expected to pay even more [95]. In addition, for non-local bamboo materials, the logistics cost alone is sufficient to discourage most consumers [95,238]. Research has also found that consumers may incur additional costs due to a lack of knowledge and experience in using bamboo [274]. Overall, the use of engineered bamboo materials is economically unattractive due to factors such as low industrialization levels, labor-intensive processes, high logistics costs, and poor management [95,236]. Fortunately, some professionals are working to change this situation. For example, by optimizing the use of resources, energy, and supply models for LBL, at least 35.31 % of unnecessary costs can be controlled [95]. New prefabricated wall panels made of bamboo and fly ash sold for around $42.05, which is 40 % cheaper than conventional single wall bricks [139]. Nevertheless, it is undeniable that consumers' willingness to purchase expensive bamboo construction materials remains low. This situation may lead to the stockpiling of bamboo and potentially bankrupt the bamboo industry supply chain.

5. Environmental sustainability of bamboo construction materials (SDG13 and SDG15)

5.1. Which climate change can bamboo construction materials cope with?

SDG 13 (Climate Action) occupies the central role [275] and stands as the most ranked goal among all SDGs [42]. It mandates urgent action from all nations to mitigate and adapt to climate change. A rapid and sustained reduction in greenhouse gas emissions is of paramount importance [51]. Although only 56 studies in the SLR directly addressed environmental sustainability, a significant 43.26 % (321 out of 1653) of the research employed terms such as "carbon storage" to describe bamboo materials. This widespread recognition highlights the potential of bamboo construction materials in addressing climate change issues.

5.1.1. Global warming

The potential of bamboo construction materials to mitigate global warming potential largely depends on the planting phase of bamboo. During growth, atmospheric CO_2 is stored in mature leaves through photosynthesis [276]. In bamboo plants, carbon is converted to organic matter and predominantly stored in the culm [277]. A review study found that the total carbon sequestration of a 1 hm^2 bamboo forest ranges from 94 to 392 Mg [278]. It is noteworthy that the carbon storage of bamboo forests is not fixed, as it varies with factors such as temperature, rainfall, forest density, and bamboo age [278]. Table 2 organizes the carbon stocks of ten major bamboo species. Although the exact carbon storage potential of bamboo forests remains uncertain, substantial evidence suggests that bamboo forests exhibit superior carbon fixation capabilities compared to tropical rainforests [278,279], Chinese fir [280,281], and *Pinus taeda* [276]. In addition, bamboo forests increase carbon occluded in phytolith, which can be sequestered in soil for thousands of years [282]. However, as bamboo plants age and die, the carbon they sequester may be rapidly released back into the atmosphere [278]. Nonetheless, if bamboo is processed into durable products (such as permanent construction materials), carbon can be sequestered for 20–50 years [168]. Over a period of 30 years, bamboo products would store 15,293,341 tC [283]. While it is challenging to predict the market share of bamboo materials as a substitute for conventional construction materials, it is clear that in the context of sustainable development, bamboo materials will see a significant rise in market share in the future [284]. This suggests that the carbon storage potential of bamboo materials is also likely to increase in the foreseeable future.

Table 2
Mean annual carbon stocks of different bamboo species (unit: Mg C/ha).

Bamboo species	Vegetation C density	Ground layer C density	Soil organic C density	Ecosystem C density	Data sources
Phyllostachys edulis	30.790 ± 10.440	3.780 ± 1.260	109.030 ± 34.120	143.600 ± 35.750	[285]
Neosinocalamus affinis	–	–	–	135.950	[286]
Dendrocalamus strictus	49.810	–	–	–	[287]
Bamboos in India	61.050	2.400	57.300	120.750	[288]
Bambusa vulgaris	50.440	2.520	24.710	77.670	[289]
Dendrocalamus latiflorus	27.605 ± 8.654	1.279 ± 0.323	77.188 ± 21.736	106.073 ± 37.764	[277]
Dendrocalamus membranaceus	23.800 ± 7.265	2.153 ± 0.648	115.700 ± 25.397	141.662 ± 39.537	
Bambusa textilis	26.202 ± 8.347	1.322 ± 0.382	76.087 ± 23.487	103.611 ± 32.648	
Guadua angustifolia	69.900	7.500	79.000	156.400	[278]
Phyllostachys praecox	6.800	3.000	142.000	151.800	

The net carbon storage in bamboo products varies among different bamboo materials throughout their life cycles [29]. The environmental impact of bamboo pole is 41.34 mPt (in IMPACT 2002+ life cycle assessment (LCA) methodology, "mPt" represents the cumulative value with equal contribution of the normalized impact categories), which is around one-ninth of glued laminated bamboo [29]. Each cubic meter of LBL has an approximate 83.60 % probability of storing 249.92 kg of atmospheric CO_2 [18]. Generally, the more processed the bamboo product, the lower the likelihood of net carbon storage [29]. This is due to CO_2 emissions during the production, transportation, and use of bamboo materials [18,95,290]. Among these, the production phase is often the largest contributor to carbon emissions [18,291], while the transportation phase presents the most volatile threat [95,292]. In particular, electricity consumption during production is the most significant and sensitive factor affecting carbon emissions [29,239]. The non-standardized manufacturing process of bamboo products, including energy-intensive activities like "carbonization" and "drying", can also substantially contribute to CO_2 emissions [95,290]. During the transportation phase, the distance for supplying bamboo materials is often uncertain; excessive distances can increase carbon emissions, potentially offsetting the carbon reduction benefits [293]. Fortunately, efforts are being made to reduce carbon emissions in both production and transportation phases, including adjustments to the electricity mix [29], optimization of material and energy inputs [18,95], and modifications to supply patterns [18,95]. Overall, substituting carbon-intensive construction materials such as aluminum, steel [250,294], concrete [14,295], and brick-concrete structures [296] with bamboo construction materials can reduce the carbon emissions of buildings.

However, it is crucial to consider the entire life cycle of bamboo construction materials when assessing their carbon storage potential. Beyond the initial phases of planting, production, and transportation, the life cycle of bamboo construction materials also includes installation, use and maintenance, and demolition. Yet, these phases are often excluded from current system boundaries [18,276]. This exclusion is primarily the relatively short history of bamboo buildings construction and the limited number of examples [14,18]. Consequently, research encounters challenges in obtaining reliable measurements or predictions from these scarce samples. Furthermore, the variety of bamboo construction materials available for research is limited, typically comprising bamboo culms, glued bamboo, and LBL [14,18,29]. This restricted selection further hinders comprehensive assessment. Moreover, materials like bamboo scrimber and bamboo-timber composites have yet to be extensively studied for their carbon storage capacity.

5.1.2. Other climate change

In addition to balancing greenhouse gas emissions, bamboo materials mitigate the release of ozone-depleting substances and reduce ultraviolet radiation [32]. Furthermore, bamboo materials demonstrate positive feedback in addressing various climatic and environmental issues, including acidification, smog, particulate (PM2.5), eutrophication, and ecotoxicity [14,24,250]. However, it is undeniable that quantitative research on these climate impacts is notably scarce. Moreover, climate challenges are often assessed in isolation, despite their potential interconnectedness [14,297]. Therefore, research should prioritize a comprehensive approach to studying and mitigating the impacts of these interrelated climate changes, as any single change could lead to irreversible consequences.

5.2. How can bamboo construction materials protect land ecology?

SDG 15 (Life on Land) focuses on halting and reversing land degradation, combating desertification, protecting and restoring terrestrial ecosystems, and preserving biodiversity [51]. Between 2015 and 2019, an estimated 100 million hectares of healthy land were degraded annually [298]. Moreover, agricultural expansion has led to the deforestation of nearly 90 % of forests [298]. Maintaining bamboo forest ecosystems, which serve as the raw material for bamboo construction materials, is therefore essential.

5.2.1. Restore degraded land

Bamboo is widely recognized as a valuable natural ecological resource for mitigating and restoring degraded land [240,299,300]. This is attributed to bamboo's remarkable ability to rapidly grow and regenerate [301], providing continuous and long-term canopy cover [302], and its capacity to adapt to harsh survival environments [97,303] while conserving water and soil nutrients [97]. These characteristics make bamboo an excellent choice for restoring land degradation. Crucially, bamboo's dense root system enables it to thrive on degraded or marginal lands, binding and loosening compacted soils [246,304]. In addition, the dense foliage and thick bamboo litter help maintain soil moisture, further aiding in the restoration of degraded lands [246,300].

5.2.2. Soil and water conservation

Some studies have shown that bamboo forests and bamboo materials help reduce soil quality degradation [97,305]. According to the Food and Agriculture Organization of the United Nations, bamboo forests are estimated to conserve an average of approximately 27 tons of soil per hectare annually [306]. Specifically, bamboo enhances slope and land stability by retaining soil particles and anchoring the soil through its root system [246,307]. Bamboo products, such as bamboo grids, can also reinforce soil beds [308]. In addition, bamboo also contributes to soil and water conservation [240,309], reducing the risk of disasters such as floods and landslides [306]. However, some studies suggest that the role of bamboo in soil reinforcement is negligible. Specific soil erosion strengthening approaches or the cultivation of some tree species to conserve soil and water are more significant [310]. Overall, bamboo should not be the top priority when considering plant species for optimal soil and water conservation. Nevertheless, bamboo can contribute to soil and water conservation, although to a limited extent.

5.2.3. Increase soil fertility

Bamboo also serves as a soil amendment, enhancing soil fertility to promote healthier land [311]. For instance, integrating bamboo into agricultural fields has been shown to increase the content of organic matter, nitrogen, and phosphorus in the soil, ultimately leading to improved crop yields [312]. This is because of bamboo's ability to enhance the diversity of soil bacteria [313]. Furthermore, bamboo litter and dead culms can be used as fertilizers to enrich the soil's nutrient content [314]. Besides that, bamboo has the capacity to remediate soil polluted by heavy metals [315]. Specifically, bamboo can adsorb lead and cadmium from polluted soils [97]. Bamboo has been demonstrated to effectively remove other pollutants from soil and water, including polycyclic aromatic hydrocarbons and volatile organic compounds [97].

5.2.4. Habitat for wildlife

Bamboo plays a significant role in biodiversity conservation [97,316]. There is a positive correlation between bamboo coverage and species diversity [246,317]. Bamboo serves as a habitat and food source for numerous animals [97,318], plants [246], and insects [319]. Beyond the well-known panda, bamboo forests provide a home for elephants, several deer species, wild boars, and red pandas [320]. Consequently, the loss of bamboo habitats could potentially threaten the survival of many wildlife species [321]. Moreover, bamboo forests function as natural biological barriers, contributing to the mitigation of human-wildlife conflicts [322].

6. Research gaps and future research agenda

A curious "bandwagon effect" has been observed in previous research, with a tendency for studies to cluster around popular topics. Nevertheless, much of the work involves only minor modifications of previous studies, ultimately leading to the collapse of the field [323]. Bamboo as a sustainable construction material has become a prominent research focus. While more and more attention has been attracted to this field, few studies have made innovative breakthroughs or improvements. This review does not simply categorize studies. Instead, it seeks to reflect on how to avoid the repetitive studies.

Therefore, this research reviewed 742 publications and summarized four potential future research directions that transform the field into a vibrant, thriving area of research. Specifically, this research summarizes the thorough interpretations of the findings in Sections 3-5, organizes them into specific research gaps, and further suggests directions for future research. Fig. 4 visualizes four potential future research directions by organizing relevant studies on the three principal pillars (society, economy, and biosphere) of the SDGs. The "dotted lines" connecting the sections mean that the findings of these sections can be summarized into a unified research gap to be addressed. For example, the findings of sections 3.1.1 and 3.1.2 can be summarized in a specific research question (the relationship between bamboo construction materials and human health) and produce direction 1.

6.1. Bamboo construction materials and human health and well-being

This review has identified 664 publications on social sustainability, yet only eight focus specifically on bamboo construction materials and the health and well-being of occupants. Research on the relationship between bamboo materials and human health remains limited, largely because this is still an emerging field. Few studies have examined the impact of bamboo materials on indoor air quality - a topic of considerable interest - as bamboo has the ability to absorb formaldehyde and VOCs, thereby reducing indoor pollutants [14,72]. In addition, timber, which is similar to bamboo but has received earlier attention, has provided some relevant hot research that can be referenced, such as the relationship between bamboo construction materials and human physiological and psychological health, as well as the application of bamboo materials in biophilic design and bamboo forest therapy.

To address these research gaps, this research proposes a future research agenda. Firstly, subsequent studies could employ sensors to monitor indoor air quality in bamboo buildings and develop intelligent platforms for dynamic analysis of bamboo materials' impact on indoor air quality and human health. Secondly, research should explore the application of bamboo materials in biophilic design and bamboo forest therapy. These studies could use standardized questionnaires to assess the psychological effects on users and incorporate machine learning and transfer learning techniques to analyze multi-source heterogeneous data. During the research process, tools such as virtual reality and electroencephalogram can be introduced to help research comprehensively and objectively assess the impact of bamboo construction materials on human psychological health (e.g., emotions and stress).

6.2. Genome sequencing and compilation technology

This review highlights key unresolved issues in the use of raw bamboo materials. First, bamboo's asexual reproduction, limited genetic diversity, and small gene pool pose challenges for large-scale planting and breeding [87]. These limitations restrict the development of improved bamboo species and the potential for large-scale cultivation.

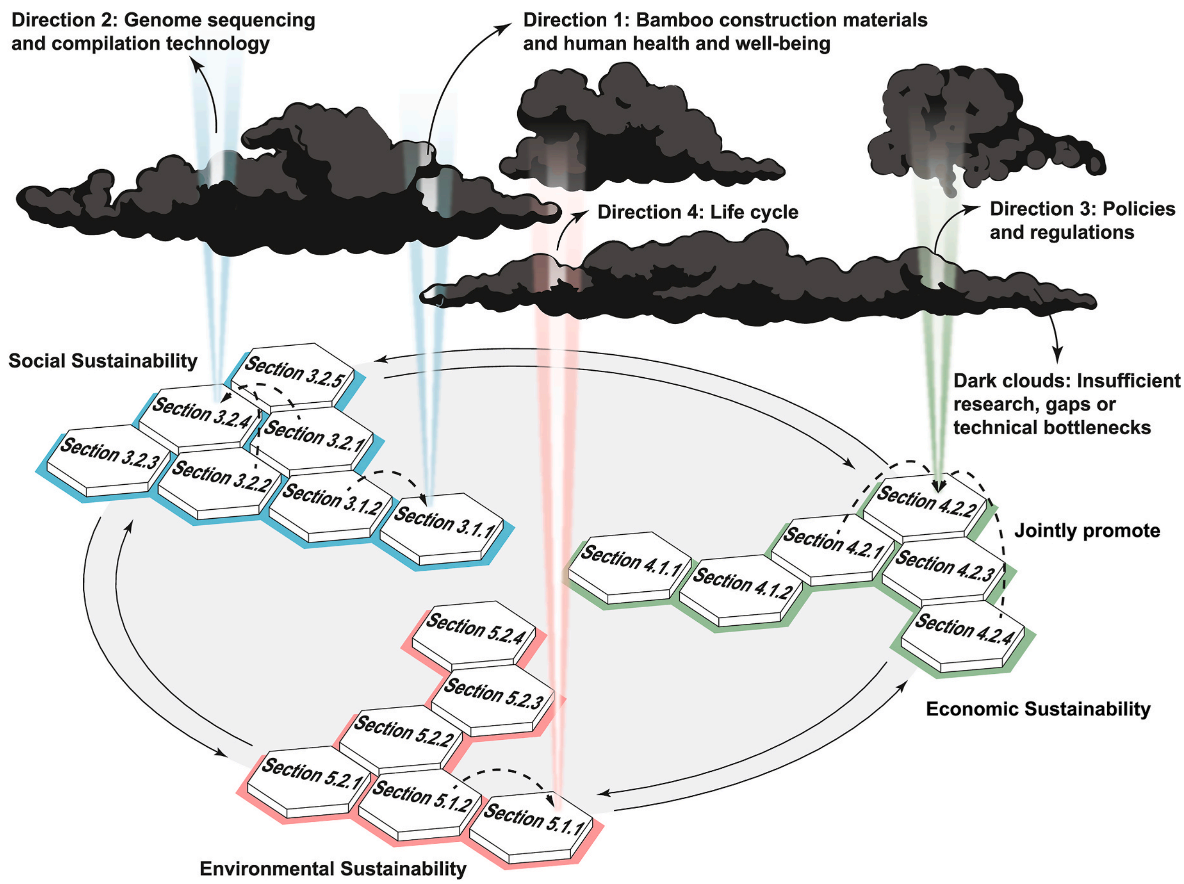

Fig. 4. Detailed points of future research agenda.

Consequently, whole-genome resequencing of bamboo species will likely be a critical focus for future research. Additionally, bamboo contains high levels of starch and protein, which attract fungi and pests, making it prone to mold, fungal decay, and insect infestation [204]. Relevant studies agree that natural bamboo is poor in durability. Although existing research has conducted analyses on inhibiting bamboo decay and mold growth, the benefits have been unsatisfactory. This limitation significantly hinders the use of bamboo materials in construction.

To address these issues, promising modification research includes nanotechnology and cell science [205]. Therefore, genetic engineering, which is closely related to these, holds significant potential [324,325]. This is because bamboo traits can be traced back to specific gene sequences. Research into gene editing could control the expression of starch and protein characteristics in bamboo, fundamentally solving the durability problems of bamboo materials. One potential approach is to precisely regulate the specific DNA sequences responsible for synthesizing sugars and proteins in bamboo, thereby reducing their content, making them less attractive, or interfering with the reproduction of fungi, bacteria, and termites. Meanwhile, editing DNA sequences can also alter the tissue structure of plants, which could be the key to overcoming the technical bottleneck in producing ultra-high-strength bamboo material. Therefore, it is highly recommended that research carry out innovative research oriented toward this issue.

6.3. Policies and regulations

Previous research has identified significant gaps in the sustainable management, production, and consumption of bamboo materials, largely attributed to insufficient government action, especially during the early stages of bamboo material development. Without government support, establishing policies and regulations for bamboo applications is challenging. Such policies are crucial for enabling large-scale bamboo use and reducing initial costs [245]. The absence of these policies has created considerable obstacles for producers in the production and promotion stages and has diminished consumer willingness to invest in higher-cost bamboo materials [245]. Specifically, there are two main deficiencies in policies related to bamboo construction materials. First, there is limited research on legal frameworks for bamboo, including unclear ownership rights for bamboo forests and weak regulatory mechanisms. Second, there is a lack of systematic training for workers and insufficient promotional efforts directed at potential users by the government.

Experts have pointed out that only changes in building codes can make timber competitive with steel and concrete (scale of use, cost, and so on) [326]. The same applies to bamboo. However, many countries still lack comprehensive policies and regulations. Future research could explore policies and incentive mechanisms for the development of the bamboo industry, such as subsidies for bamboo forest cultivation and tax incentives for bamboo manufacturing factory, and propose policy recommendations to promote the development of the bamboo material industry. In addition, studies could examine policies for promoting and applying bamboo materials, such as publicity and education initiatives, and suggest policy recommendations to facilitate the large-scale application of bamboo in construction. How to establish and implement relevant policies and regulations remains a focus for future research.

6.4. Life cycle assessment

The LCA for bamboo materials is valuable. However, the lack of analysis of full life cycle phases in the study of environmental sustainability of bamboo construction materials remains a significant limitation. Specifically, the LCA of bamboo construction materials is primarily limited to the pre-construction phase (i.e., cultivation, production, and transportation phases), neglecting the construction, operation, and demolition phases. Moreover, existing research on the LCA of bamboo construction materials remains scarce and lacks depth. Previous studies have simplified the LCA of the pre-construction phase, leading to less precise research findings. Secondly, few studies have considered comprehensive environmental impact assessments for bamboo construction materials throughout their full life cycle.

These limitations not only impede a thorough understanding of the environmental impacts of bamboo construction materials but may also lead to biased evaluations of their long-term sustainability. Therefore, addressing these gaps in the full life cycle of bamboo construction materials will become a key direction for future research. However, obtaining sufficient construction case studies and long-term data will require at least several decades. To address this practical gap, simulation modeling tools offer a viable alternative [175]. For example, linking realistic environmental factors (such as temperature, wind speed, and user behavior) and material characteristics (including thermal conductivity and air-tightness of the building) to simulation software can enable the modeling of energy consumption patterns for bamboo construction materials over extended periods of use and maintenance even full life cycle. For instance, the integration of SketchUp software, EnergyPlus software, and AnyLogic software. Based on this primary further research, subsequent studies can continue to deepen this field by updating the level of simulation of existing intelligences, and by developing different environmental impact modules. Therefore, future research efforts should be directed toward developing and refining these simulation approaches.

7. Conclusions

Bamboo construction materials have garnered widespread attention in the construction industry due to their sustainable characteristics, such as rapid growth, renewability, and carbon sequestration. This has also led to their emergence as a prominent topic in academic circles. However, the relationship between bamboo construction materials and sustainability has not been systematically validated. To comprehensively analyze this field, this research employs a systematic literature review method, structured around the three pillars of sustainable development goals - social sustainability, economic sustainability, and environmental sustainability. Through standardized and transparent search and screening processes, this research reviewed 742 “articles”, “reviews”, and “conference papers”. The findings reveal that in terms of social sustainability, research has paid less attention to the relationship between bamboo construction materials and human health and well-being (SDG 3). Analysis related to sustainable cities and communities (SDG 11) is notably systematic and mature, but there has been a lack of breakthrough progress on issues such as the genetic diversity of bamboo species and the durability of bamboo materials. Regarding economic sustainability, bamboo construction materials have provided decent work opportunities for farmers and workers (SDG 8). However, the lack of sound policies and regulations (SDG 12) has led to unresolved issues in the management, production, and cost applications of bamboo materials. Regarding environmental sustainability, bamboo construction materials have the potential to mitigate global warming and other climate change effects (SDG 13), but further efforts are needed to assess their full life cycle performance. Additionally, bamboo materials can contribute to the protection of land ecology (SDG 15). Based on this critical review, promising future research directions are proposed, including (1) bamboo construction materials and human health and well-being; (2) genome sequencing and compilation technology; (3) policies and regulations; and (4) life cycle assessment.

The results of this research have significant implications for comprehensively examining the sustainability performance of bamboo in the construction field. This research innovatively describes the “knowledge map” of sustainable bamboo construction materials, extracting fragmented knowledge from numerous studies to clarify the relevance of bamboo materials to sustainability, critically examining knowledge gaps in the field, and exploring promising research directions. Furthermore, this review promotes interaction between academic research and practice. It provides relevant knowledge for policymakers and managers to establish comprehensive policies and regulations. In addition, it helps producers understand technical bottlenecks and production issues, guiding their industrialization efforts and product and technology development.

Despite these advantages, this research has two limitations. First, the literature review search was confined to the Web of Science database, potentially omitting research outputs not included in this database. Future studies are recommended to consider other databases such as Google Scholar, Science Direct, and Wiley Library. Second, while this research strived for objectivity in thematic analysis, some subjective interpretations are inevitable. Future research could incorporate bibliometric analysis methods to enhance the objectivity of the review.

CRediT authorship contribution statement

Peiyu Xu: Investigation, Writing – original draft, Writing – review & editing, Conceptualization, Software. **Vivian W.Y. Tam:** Writing – review & editing, Conceptualization. **Haitao Li:** Writing – original draft, Conceptualization. **Jianjun Zhu:** Writing – review & editing. **Xiaoxiao Xu:** Investigation, Writing – original draft, Writing – review & editing, Conceptualization, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2024.115230.

Data availability

Data will be made available on request.

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