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Review Article

Integrating Sustainable Bamboo Flooring into Interior Design Strategies

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Abstract *- The growing global trend of using sustainable materials in construction is not solely due to the advancement of technology and material exploration, but rather it comes from alarming environmental concerns. The construction industry is witnessing a constant depletion of natural resources and an increase in construction waste. There is a greater need to practice sustainability for balancing the rising demand for construction and mitigating environmental challenges. Engineered bamboo boards are fast emerging as the preferred choice for flooring in interior spaces. Bamboo's rapid renewability, durability, aesthetic variety, and versatility make it a promising material. A study comprising bamboo's environmental advantages, the perspective of interior designers, its assessment of performance in a variety of spaces, and integration in circular design strategies is still unexplored. Bamboo boards have the potential to heavily influence the eco-friendly interiors and spaces. This study is about understanding and evaluating characteristics of engineered bamboo flooring compared to its closest resemblance to wood, focusing on construction and demolition aspects in interior design practice. The methodology involves enumerating bamboo's performance via strength, durability, and environmental metrics through life cycle assessment from cradle to grave. The finding validates that bamboo scrimber and laminated bamboo have high strength and durability for viable flooring solutions. During in-use and at the end-of-life cycle, it also reduces embodied carbon and demolition waste. Its potential for reuse and repurposing translates into a reduction in landfill. Based on the findings, a decision-making framework is developed to select specific bamboo types for flooring in various projects. The framework serves as a tool to make informed choices aligning with practicality and sustainability. The study concludes that high-density bamboo scrimber is appropriate for high-traffic commercial spaces, while horizontal-grain carbonized bamboo boards are ideal for residential spaces, focusing on aesthetics. Bamboo flooring is a strategic material choice that effectively balances functionality, aesthetics, and environmental responsibility.*

Keywords *- Bamboo Boards, Carbon Footprint, Durability, Eco-friendly Interiors, Life Cycle, Versatility.*

1. Introduction

The construction industry is a noteworthy contributor to environmental deterioration [1, 2] by producing a huge amount of waste and endlessly consuming natural resources globally. The exploding population and the trend of high consumption of resources have caused an imbalance - an increase in demand and a decrease in raw material supply. Massive use of natural resources has a negative effect on the environment [3].

All construction activities, such as building new space, renovation, refurbishment, or demolition, use excessive amounts of natural resources and generate large volumes of contaminants and construction waste [4]. The cycle of manufacturing concrete and steel, acquiring timber, and discarding them at the end of the life cycle is constant in the construction industry, which clearly creates a burden on landfill capacities [5].

The construction industry has a rising need to adopt sustainable materials that can deliver environmental benefits and also have broad applicability and versatility [6]. From an Interior design perspective, lifestyle changes in urban cities have triggered the re-functioning and renovation of spaces in a short time span, where product use and life are shortened, resulting in consuming more material and generating more demolition waste. This has prompted a paradigm shift toward sustainable interior design, emphasizing the use of materials with low environmental impact. This concept crafts interior spaces by using core principles of functionality, accessibility, and aesthetics, simultaneously extending the scope to incorporate environmental factors [7]. Materials that reduce energy consumption, waste, and pollution during their life cycle are given priority. Conventional flooring materials like hardwoods from slow-growing forests and synthetic choices with high embodied energy are gradually seen as unsustainable [8]. Engineered bamboo is a promising substitute that combines environmental advantages with a wide range of applications. Bamboo boards have the potential to significantly influence the development of eco-conscious interiors [9, 10].

This paper discusses that bamboo flooring is an imperative choice for sustainable interior design due to its proven strength properties, environmental benefits, and design application. Engineered bamboo's mechanical properties of hardness and high strength-to-weight ratio are similar to or even superior to many conventional hardwoods [11] and wood composites [6, 12], making it a desirable choice for flooring. Furthermore, Life Cycle Assessment (LCA) studies reiterate that bamboo products typically have a lower environmental impact than conventional materials such as ceramic, steel, and wood in terms of natural resource depletion and global warming potential [13]. Its conformance to important green building standards, such as LEED (Leadership in Energy and Environmental Design), which allows it to earn credits for low-emitting products and quickly renewable materials, further increases its appropriateness (USGBC, 2023). By providing strength and stability for long-term performance, engineered bamboo extends functionality, blended with a wide range of aesthetic choices [14]. Even though challenges are associated with its life cycle - mainly manufacturing, processing, and transportation costs- bamboo remains a promising sustainable option that can replace conventional flooring materials in residential and commercial spaces.

Bamboo material is traditionally used for construction purposes and has excelled in regional markets where cultivation is favorable, predominantly in tropical and subtropical climate regions of Asia, Africa, and South America. The Asia-Pacific region accounts for approximately 67% of bamboo forests, followed by 30% in South America and 3% in Africa [15]. Bamboo is a naturally occurring resource – a rapidly renewable grass that grows in abundance in the short span of 5 to 7 years. Because of its strength, flexibility, and renewability, it has long been used in a wide variety of applications ranging from construction, structural components, Indoor and outdoor furniture, textiles, energy, medicine, paper, tools, culinary, and craft-based household accessories across the bamboo-growing countries like China, India, Philippines, and Indonesia. After China, India is the second key bamboo-producing country, having 125 species across 23 genera, presenting a substantial segment of bamboo diversity [16]. Bamboo covers 22.5 % of India's entire forest area, 16MHa [17]. Bamboo cultivation is present in almost all parts of India except in one state, whereas four states combined cover 40% total coverage area. Also, most of the species are suitable for construction. The characteristics of all bamboo species differ due to the culm and differences in fiber percentage. The anatomical properties of bamboo have a significant impact on mechanical properties, the absorption of preservatives and adhesives, and the final product quality [18]. China, India and Brazil have more diversity of bamboo species, making it possible to produce a wide variety of products. For example, the species Bambusa rigida is widely available in Southwest China, used for making agricultural tools and handicrafts. This species is also considered suitable for making Bamboo scrimber.

More than just a plant, bamboo is an integral part of cultural heritage, identity, and livelihood for many communities, offering significant social, economic, and environmental benefits. For generations, local communities have possessed the traditional knowledge of growing bamboo, its cultivation, and utilizing it as a multifunctional resource. Bamboo community lives within the vicinity of the plantation and usually depends on bamboo for their sustenance [9]. For the Mao-Naga community in India, bamboo is an essential part of food, shelter, handicrafts, and livelihood. With the use of traditional knowledge, they have excelled in understanding when to farm, how to preserve soil and harvest the crop, sustaining communities' agricultural and environmental practices. [19]. Bamboo has shaped the community's engagement and enhanced their livelihood. Combining knowledge with the advancement of technology, knock-down design of temporary houses and furniture were proposed in remote areas of Indonesia, to improve the life quality of locals in disaster-prone areas [20].

Bamboo sourcing has the potential to boost the rural economy. Demand for Commercial products has given rise to bamboo plantations. The global market for bamboo was estimated to be priced at USD 71.6 billion in 2024 and is projected to grow at a 4.0% CAGR and reach USD 90.6 billion by 2030 [21]. The steady growth projection signifies the bamboo's expanding role in the economy and increased share in construction, furniture, food, and textile sectors as a sustainable and environmentally friendly material. Rapid renewability and environmental characteristics alone make the rising demand for bamboo products, which in turn makes bamboo plantation a beneficial business for farmers and industries [22]. All stages of producing bamboo from raw material to processing it for final usage give ample opportunities for income generation. This also gives rise to a conflict of interest when institutions prioritize profits over the economic growth of local communities. The expanding role of private players, limited access to farmers and communities in decision-making, and wealth concentration due to policies greatly impact the development strategies [23]. For enhancing the value-chain, contextual, cross-sectional, and participative strategies [24] are a must. For poor households, the bamboo plantation in Tripura generated a sizable revenue of 57.79% of their annual income, which included the personal consumption and sale of bamboo [25]. Another study from Ethiopia records more than 50% of annual income from bamboo crops and making and selling furniture to tourist trade enterprises [26]. INBAR member states funded by IFAD have directly or indirectly impacted 2.5 billion people worldwide by creating jobs [27].

Over 100 species of bamboo appropriately serve commercial applications, which can generate income from primary or secondary processes, with lower capital investment [18]. A sizable share of 24% of all bamboo products is attained by two industrialized products, which are bamboo flooring and bamboo panels, absorbing the international trade value of 362 million USD. Characteristically, countries around the world are heavily investing in making these products. Countries like India can benefit from international demand for bamboo products.

With technological innovation [22], bamboo's application is shifting from traditional to advanced, unlocking new possibilities across various sectors, predominantly food, textile, structural applications, and the environment. Industrial products like bamboo scaffolding, paper making, textile, food, and engineered bamboo products are the major compositions that claim 90% the total bamboo mass [16]. Bamboo is emerging as a bioenergy material where researchers are systematically evaluating its feasibility, economic viability, and environmental impact. Advancements in studies on bamboo fiber, high cellulose content, and water retention capacity across the bamboo species are explored to make it appropriate for biomass. The rapid regenerative quality and abundance of bamboo can be converted to make biomass with less environmental burden. To meet the energy requirement of northeast India, a bamboo-fueled power plant is being constructed in Mizoram. Bioethanol production is another sustainable energy source explored by researchers [18].

Despite so many benefits, bamboo faces ample challenges that hinder its widespread adoption. Absence of standardization in production processes and quality is the major barrier to completion for the global market. Diversity of plantations in bamboo species needs to be addressed for the full utilization of bamboo crops. Since Bamboo's renewability is high, knowledge and proper management of large-scale bamboo cultivation are necessary to prevent soil depletion. In the construction industry, bamboo's durability and long-term performance are still gauged with outdated perception rather than a reality check.

Technologies need improvement for high yield, fast production, and enhanced quality, less labor-intensive, and less costly. Access to market and advanced knowledge [26] can drastically change the economics of rural bamboo producers. Policy support, Weak infrastructure, and inadequate investment are key barriers that hamper a robust supply chain. For start-up companies, a huge market in the bamboo industry is awaiting. Partnership activities aimed to promote learning by conserving traditional knowledge, balancing with technological advancement, will be beneficial.

Within interior design practice and for renovation purposes, especially in commercial spaces where visual appeal, durability, and sustainability are paramount, bamboo flooring (either full flooring or surface applications) emerges as a convincing choice, aligning with eco-friendly design trends. Bamboo's resemblance to wood texture and ease of execution suits the needs of consumers. Despite its promise, challenges remain: variability in laminated products due to adhesive and manufacturing processes, moisture sensitivity, adhesive VOC emissions, insufficient data on long-term durability, and lack of standardized codes continue to hinder broader adoption and confidence in bamboo as a mainstream flooring material [28].

Numerous researchers have conducted studies to reflect bamboo as a sustainable construction material, analyzed its strength properties, and performed life cycle assessments. Research on bamboo's environmental science and application has taken center stage [18], emphasizing sustainability, mainly discussing carbon sequestration and ecosystem restoration. Research is often fragmented, and discussions are limited to focal aspects like carbon footprint or strength properties, separately. A gap exists as previous research lacks an assessment assimilating environment metric, strength, performance and circular economy aspects of bamboo flooring integrated from the perspective of interior designer and further comparing it with wood. In absence of evidence-based guidance, interior designers are clueless for practical implementation of bamboo boards for flooring.

Based on this background study, it aims to evaluate engineered bamboo flooring's performance via strength, durability, and sustainability through life-cycle assessment. Combining existing data to make a comprehensive analysis of bamboo flooring's multi-dimensional advantage delivers a new perspective by creating a decision-making framework that enables designers to make tailored choices. Depending upon the project priority, the bamboo board selection framework will optimize functionality, sustainability, and foster waste reduction for eco-conscious design practices. The literature review throws light on various studies done so far for understanding bamboo as a material and exploring its potential across the sections. Further chapters compile the characteristics of engineered bamboo lumber and boards – mainly scrimber and laminated- and focus on design and execution aspects in interior design practice.

2. Literature Review

The author intended to do a literature review collection about bamboo, its products, and its characteristics and utilization. The author further studied all aspects of bamboo, including social, economic, and environmental. Based on the literature, the following four categories of studies have been determined.

1. Bamboo as a construction material
2. The strength properties of Bamboo

3. Applications of Bamboo
4. Environment feasibility study

2.1. Bamboo as Construction Material

Yadav & Mathur [9] investigate bamboo as a sustainable substitute for traditional building materials like steel and wood, in response to environmental degradation and the depletion of wood resources, in the Indian context. The authors assess bamboo's potential as a productive, affordable, and quickly renewable material for the building sector using a literature-based investigation. According to their research, bamboo, especially when used as a composite material, has great potential for a variety of uses, from flyovers and foundations to homes, multistory buildings, and large-span structures. It can also be used in interior spaces such as airports and recreational facilities, making it a wise choice for sustainable development.

The study by Thi Bich Van [7] positions bamboo as the most suited construction material for eco-friendly architecture in Vietnam. Study examines issues related to the adoption and application of bamboo in interior design and architecture practices. Study supports bamboo's potential to deliver a balance of strength and spatial design when used for structural shell, flooring, and furniture. Findings demonstrate that an architect's decision of material selection and innovative design of bamboo joints can reduce the environmental impact and add value to sustainable commercial interior design practices. Bamboo's environmental advantage and versatility can replace hardwood.

Vengala [29] emphasizes bamboo's potential as a sustainable material choice for cost-effective housing. He studied and reviewed traditional bamboo constructed houses of the North-east, southern part of India, and the housing system made by composite bamboo products developed by the Forest Research Institute, India. It highlighted the difference between conventional bamboo construction practices. Studies established bamboo as a viable, sustainable material for the substitution of other construction materials like wood, steel, and concrete. The findings concluded that underutilization of bamboo is due to many reasons, with a few primary ones: a lack of technical know-how, authentic design data, procurement and preservation techniques, and also durability concerns. Addressing such issues will help bamboo fully incorporate into mainstream building practices in the region of India near bamboo forests.

2.2. The Strength Properties of Bamboo

Boity et al. [30] measured strength tests – mainly compressive and tensile of treated and untreated bamboo using a Universal Testing Machine. The strength properties were found to be at par with commonly used building materials like steel and concrete, and versatile compared to timber. The results recommended exploring the untapped potential of bamboo. Bamboo can be hugely used as a green building material to lower carbon footprint and reduce embodied energy. Easy replenishment and abundance of bamboo production were one of the favorable factors for making bamboo a popular choice for small- and large-scale construction.

Adier et al. [10] systematically reviewed 57 articles to study the mechanical properties of different species, treatment methods, and standards and applications of bamboo to assess the materials perspective as a sustainable building material. Chemical and natural treatment enhanced bamboo's strength and durability; on the other hand, it reported a few disadvantages in terms of high temperatures. The gaps and concerns were listed after extensive assessment. Major gaps in terms of physical and mechanical properties included – standardization of preparation and processing techniques, finding alternative reinforcement filling material, and viability of structural application, including factors for wind, vibration, and earthquake. Concerns were listed for the lack of treatment codes and standards. Further studies to fill this gap will promote bamboo as a sustainable construction material and help in quick adoption.

Ming et al. [31] investigated previous research on the mechanical properties of bamboo and its composites. The compiled data of tensile and compressive strength, fracture toughness, and impact resistance were examined for several selected bamboo species, all under different conditions in the past. Findings highlighted that age, species, and environmental exposure are influencing factors for bamboo's performance. Among these, the moisture content had a drastic impact on the mechanical properties of bamboo. Bamboo, when used for real-life applications outdoors, will need precautionary and safety measures.

L.M. do Amaral et al. [32] examined the influence of traditional water leaching treatment on the physical, mechanical, and chemical properties of bamboo. This treatment comprises removing carbohydrates and starch by soaking bamboo poles in running water for 30 days. The results of density analysis, three point bending test, FT-IR spectroscopy revealed 23% reduction in density, significant 15% increase in modulus of rupture and 20% increase in elasticity. Research concluded that water leaching improves few mechanical properties, however it should not be used as a single treatment technique for structural purposes.

Khajouei-Nezhad et al. [11] revisited the development of engineered bamboo composites and analyzed the density-strength relationship, Modulus Of Rupture (MOR), and Modulus Of Elasticity (MOE), and further compared it with wood composites like Laminate Veneer Lumber (LVL) and PSL. Manufacturing processes were classified into three categories, namely minimally modified laminate, random strand mats, and controlled laminated mats, based on the way in which bamboo culms were used: full, split, and strands. Structural classification and surface area to resin consumption analysis revealed that strand strips require 6 to 10 times more resin than laminated bamboo. Findings revealed that high-density engineered bamboo is twice as strong as engineered wood and is suitable for various applications for construction, flooring, and decks. The raised cost of making high-density bamboo can be offset by innovations.

2.3. Application of Bamboo

Engineered bamboo boards allow varied applications ranging from construction, structural material, furniture, and household accessories to packaging, revealing a spectrum of possibilities. Bamboo fiber, its components, and other forms of bamboo have emerged as the most suitable material for a wide range of applications, including energy solutions, biomedical, food and pharmacy, and advanced materials for future technologies.

Jafarnia & Mofidi [28] systematically reviewed 51 articles published in top journals and analyzed the mechanical properties and processing techniques of engineered bamboo. With a focus on only bamboo scrimber and laminated bamboo, the findings are more relevant in the field of engineered bamboo. Investigation showed that bamboo scrimber has higher compressive, tensile, and bending strength, where laminated bamboo has more variability primarily caused by adhesive type, orientation, and adhesion quality. Testing of manufacturing processes like pre-treatment and pressing conditions pointed out disparities in reporting practices, testing standards, and long-term durability evaluations. Findings helped to understand the determining factors for the performance of engineered bamboo. A need for more comprehensive durability studies for real-world exposure conditions was advised for future studies.

Hosseini et al. [33] conducted a study of the physical and mechanical properties of engineered bamboo to gauge their potential as a sustainable building material. Their result confirmed that these materials indeed have the potential to be used as structural frameworks imbuing environmental benefits and surpassing wood, but a lack of familiarity among design practitioners is hindering their application. Bamboo's environmental advantages must translate into widespread adoption. The inconsistencies and absence of comprehensive international standards have added to ambiguity. Conclusion advised to have consistent terminology for components, production stage, and final products of engineered bamboo.

Sharma et al. [6] examined the mechanical properties of two commercial products – bamboo scrimber and laminated bamboo sheets, and performance was compared to timber and engineered timber products. The results indicate both products show similar behavior in compression, tension, and shear when parallel to their fiber direction. This also remains true for perpendicular fiber direction, apart from only one exception where bamboo scrimber's compressive strength is double that of laminated bamboo. Summary suggested to have more research on the influence of heat treatment and moisture on density, to further determine design characteristics of engineered bamboo for structural applications.

Nghia [34] conducted elaborate research on large-scale architectural structures with the aim of examining bamboo's position as a sustainable construction material in Vietnam. With the practice-based method, the journal analyzed the modular frame and joint system developed to create eco-friendly architecture. Structural design, Spatial design, and environmental strategy of 6 classified structural systems – arches, domes, grids, HP Shell, inverse cones, and hybrid systems were studied. Results revealed efficient construction of complex, diverse, and impressive spaces. Bamboo expressed its potential as the most favored material for creating experiential spaces and strong structures.

The purpose of Sofiana et al. [20] study was to change the perception of bamboo, which was limited to simple and traditional designs, increase the value, and develop a modular furniture system and solution that can be used in remote areas of Indonesia, to improve life quality. To discover the most suitable bamboo for furniture production, researchers used various techniques like surveys, interviews, literature review, and training. Furniture prototypes were made to get feedback. Finding suggests that, beyond its traditional purpose, bamboo has high potential as a sustainable material, which can be further explored in modern design practice to create higher-value products and increase the quality of life.

Irawan et al. [18] aimed to explore the utilization of bamboo in numerous fields, particularly from its components. It systematically examined articles published between 1990 and 2024, focusing on bamboo's anatomy of high cellulose content, chemical compositions, and processing. The review also acknowledged bamboo's socio-economic value and cultural bonds with indigenous people. Investigations revealed the importance of chemical composition, which is pivotal for selecting species for biomass, bioenergy, and environmental remediation, and for making modified bamboo composite and engineered products, such as laminated bamboo lumber and cross-laminated bamboo for the construction sector. Research also unveiled many more advantages and uses of rich cellulose bamboo fibers for application in the food and pharmaceutical industry and in advanced materials as well. Key findings demonstrated bamboo's fiber structure and versatility as a unique property for applications across industries. It also advocated tapping the potential of bamboo with research and innovation at the intersection of material science, biotech, and environmental sustainability.

Research by Kaur et al. [35] endorses bamboo fiber reinforced polymers (BFRP) as eco-friendly and economical alternatives to oil-based synthetic composites like GFRP and CFRP. It examines the fabrication of resin-impregnated woven bamboo fibers and gauges their thermal and strength properties for lightweight applications, such as in aerospace. Finding confirms BFRP's superiority through application in construction (hybrid reinforcement, eco-roofs), Interiors (paneling and laminated roof), Furniture (bend bamboo), and in automotive (recycled frame) industries.

2.4. Environment Feasibility Study of Bamboo

According to ISO 14040 (ISO 14040, 2006), Life Cycle Assessment (LCA) is a modeling technique that evaluates the inputs, outputs, and the potential environmental impacts of a product system through its entire life cycle.

Gan et al. [36] evaluated the environmental performance of various bamboo products through a Life Cycle Assessment (LCA) model. The Global Warming Potential (GWP) of bamboo products was compared to benchmarked construction materials like concrete, steel, and plastics. Findings indicate a lower GWP of bamboo, and variation in GWP can be attributed to differences in cultivation, manufacturing process, and energy sources.

In the entire LCA, electricity use was a prominent source of emissions. It also uncovered that bamboo is a superior material choice for mitigating climate change impacts, while laying emphasis on more transparent and consistent LCA research in the future to improve the study of bamboo.

In his report, Vogtlander [37] conducted a Life Cycle Assessment (LCA) of Moso International's bamboo product portfolio with the aim of further improving sustainability and communicating bamboo's relative position of zero CO_2 emission in the entire life cycle. The study followed ISO 14040/14044 standards.

Both Cradle-to-Gate and end-of-life stages were included to clarify how carbon storage should be calculated within LCA. This resolved existing confusion and provided a clear explanation. Findings presented that all MOSO bamboo products are CO_2 neutral, attaining an overall negative carbon footprint across the complete life cycle.

Gu et al. [38] investigated production processes of bamboo scrimber flooring for outdoor purposes. The study assessed CO_2 emission and carbon transfer ratio across the production process, starting from transporting bamboo culms to the fabrication and packing of products.

Results proved that bamboo scrimber flooring is a negative carbon-emission product that sequesters carbon for at least 20 years. Findings also emphasized the need to track the environmental impact of carbon at the production level to ease the burden of carbon footprints. Net carbon footprint for manufacturing 1 m^3 bamboo scrimber was -14.89 kg CO_2 eq. Reduction of carbon emissions during the production process was advised to help bamboo become a solution to the climate change problem and maintain the environmental edge.

Yu et al. [8] measured laminated bamboo and scrimber flooring's Life Cycle Assessment (LCA) to evaluate and compare the environmental impacts of these two types of bamboo flooring. Using SimaPro software, the study carefully analyzed material and energy, inputs and outputs across each product's complete life cycle, with the aim of identifying more environmentally friendly flooring among the two.

Results measured that the process of bamboo strip production accounted for 59.3% of the environmental burden in the case of laminated bamboo flooring, and the process of panel processing accounted for 56.9% in the case of bamboo scrimber flooring. The experiment concluded that laminated bamboo flooring is a more sustainable choice compared to scrimber flooring, which had nearly 1.6 times more environmental load.

Choudhary et al. [39] calculated the environmental impacts of Marble-stone and Kota-stone flooring used in India. The study followed the Life Cycle Assessment (LCA) framework based on ISO 14040 guidelines. Environmental impacts were measured by gathering primary data from construction sites and secondary data from the Ecoinvent 3.0 database for three major phases: Raw material, polishing, and disposal. Result comparison shows marble flooring generates significantly higher environmental impact than Kota stone flooring.

Study found that metal depletion, resource damage, and agricultural land use during the raw material extraction phase affect climate change. The study highlights bamboo's potential as a carbon sink that can compensate for carbon emissions. It also establishes bamboo as a benchmarking material for architects, designers, and policymakers to help enable sustainability practices.

Bowyer [40] carried out a study to examine the effects of different flooring materials on the environment, which will help designers and builders make sustainable building solutions. Bamboo products and composite bamboo floors are excluded from this research. After systematic assessment, findings reflected that no flooring alternative outperforms all others in every impact category. It also revealed that plant-based flooring, such as wood and cork, is associated with the lowest impacts, since they absorb carbon and consume less energy for production. Ceramic, terrazzo, marble, and composite floor coverings have a greater environmental impact due to various factors. The study recommends using materials that can be recycled to have a significant reduction in carbon footprint.

Table 1. Key findings of existing literature on various aspects of bamboo

Category	Inferences of Key Finding	Author
Bamboo as Construction Material	Bamboo and its composites have great potential for a variety of uses, from flyover and foundation to homes, multistory buildings, and large-span structures.	[9]
	An architect's choice of material, procurement practices, and innovative construction techniques can transform bamboo into a sustainable material for major structures in Vietnam.	[7]
	Bamboo is a viable substitute for wood and other materials in housing and infrastructure in the Indian context.	[29]
Strength Properties of Bamboo	Tensile and Compressive strength of bamboo were compared with Concrete and steel. Bamboo has significant potential as an environmentally friendly building material for small and large-scale construction.	[30]
	Species, age, location, and variety of treatment methods influence the mechanical performance of bamboo. Standardization for treatment and codes is the major gap.	[10, 31]
	Water leaching treatment of bamboo has an impact on the Physical, mechanical, chemical, and durability of bamboo.	[32]
	Engineered bamboo composite, like laminate, mats, and scrimber, excels in MOR due to high resin consumption per surface area, but is weak in MOE due to bonding issues. Bamboo composites excel in strength properties compared to wood composites.	[11]
Application of Bamboo	Inconsistencies in testing standards, long-term durability evaluations, and reporting practices need to be addressed to enhance the reliability and application of engineered bamboo.	[28]
	Engineered Bamboo's unexplored structural potential and lack of familiarity among modern practitioners are the reasons for not using bamboo in sustainable building practices.	[33]
	Mechanical properties of engineered bamboo match or even outperform timber and timber-based products.	[6]
	Environment-friendly interior design practices have not received much attention in selecting bamboo boards as a material choice for furniture design in Vietnam.	[34]
	Bamboo, when utilized beyond its traditional purpose, offers potential for innovative and practical furniture design in Indonesia.	[20]
	Bamboo's versatility is reflected in wide range of application as engineered lumber (e.g., LBL, CLB) for construction, bamboo ash as cement supplementary material, phenolic-rich leaves/shoots as antioxidants and antimicrobials in food/pharma, eco-friendly fibers for remediation and textiles, cellulose for bioethanol/biomass energy and wind turbine blades, and nano cellulose composites for advanced materials like electrodes and biodegradable plastics.	[18]
	Bamboo Fiber Reinforced Polymers (BFRP) are eco-friendly composites having superior strength qualities, which enable their application in construction, interior, furniture, and automotive.	[35]
Environmental Impact of Bamboo	Bamboo has a lower Global Warming Potential (GWP). It promises to be a low-carbon material while stressing the need for more consistent and transparent Life cycle assessment (LCA) research.	[36]
	Carbon storage should be calculated within LCA. All MOSO bamboo products are CO2 neutral, with an overall negative carbon footprint across the full life cycle.	[37]
	Bamboo scrimber flooring functions as a negative carbon-emission product.	[37, 38]
	While both flooring types - laminated and scrimber are better performing than other wood flooring, laminated bamboo is more sustainable between the two due to its material and energy inputs and outputs across the product's full life cycle.	[8]
	Marble flooring imposes a higher environmental burden than Kota-stone in LCA. Bamboo is the potential material choice for carbon-neutral buildings for architects, builders, and policymakers.	[39]

2.5. Summary of Literature Review

Along with eco-friendly alternatives, bamboo is a high-performance structural material capable of replacing wood and steel in diverse structures. The path to its widespread adoption lies in transitioning from a craft-based material to an engineered one through standardized testing, codification, and the industrial production of reliable bamboo-based components like composites and prefabricated joints.

Bamboo demonstrates significant and competitive mechanical properties, including high tensile strength, compressive strength, impact resistance, and fracture toughness, providing a technical basis for its use as a structural, low-carbon material. However, mechanical performance is not intrinsic but is heavily influenced by treatment methods and species used. For example, traditional treatment of water leaching paradoxically increases strength by 15% and stiffness by 20% despite reducing density. All engineered bamboo products demonstrate superior mechanical properties, often matching or exceeding the performance of timber and engineered wood. Bamboo scrimber possesses excellent compressive, tensile, and bending strengths, while for laminated bamboo products, strength can vary significantly based on fiber orientation, manufacturing processes (pre-treatment, pressing), and adhesive types.

LCA studies firmly establish bamboo and its engineered forms as a low-carbon and often carbon-negative material when compared to conventional alternatives. A key driver for bamboo's carbon-negative status is the long-term storage of biogenic carbon within the final product. Manufacturing processes play a significant role in determining the environmental impacts of the end-product, as energy consumption (electricity for processing) and the use of additives or adhesives can offset the carbon benefits. Table 1 summarizes the key findings of existing literature on various aspects of bamboo.

2.5.1. Research Gap

The literature clearly substantiates bamboo's strength properties and its capacity to store carbon in various stages of its life cycle. As most studies only emphasize the cradle-to-gate stage, significant shortcomings are identified for conducting cradle-to-grave assessments applicable to interior design practice.

Bamboo flooring is extensively marketed and claimed as sustainable; however, bamboo flooring installation, real-world performance, and the designer's perspective are underexplored. The current knowledge on the use of engineered bamboo is fragmented, and often leaves designers without any comprehensive, multi-dimensional framework that can justify the appropriateness of choosing bamboo flooring, optimizing choices over its primary alternative, composite wood.

2.5.2 Research Objectives

To address the gap, this study investigates strength properties that impact performance aspects, life cycle assessment till the end, and interior design practices. The aim is to develop a reliable decision-making framework that logically evaluates technical, environmental, and socio-economic factors. The framework will help to choose bamboo flooring types across various selection criteria, which currently has only one focus. To achieve a comprehensive and verified checklist for flooring selection, the following research objectives have been formulated:

RO1. To analyze strength properties and In-use performance of engineered bamboo for flooring, identifying key influencing factors for applications in different spaces.

RO2. To determine the cradle-to-grave environmental impact of engineered bamboo and examine the socio-economic dimensions of bamboo flooring against composite wood flooring.

RO3. To integrate the findings in a logical and theoretical manner, for creating a multi-criteria decision-making framework/flowchart for interior designers.

3. Bamboo Flooring: An Overview

Bamboo flooring is progressively recognized as a prominent sustainable material in the construction and interior design industry globally. It is marketed and promoted as a feasible alternative to its closest competitor, conventional hardwoods, and composite wood products [12]. Table 2 constitutes comparative environmental properties of bamboo and other conventional materials. Bamboo's worth is rooted in its rapid renewability, mechanical proficiency, and potential for carbon capture and storage. Unlike traditional timber species that require decades to mature, bamboo - an everlasting grass reaches harvestable maturity in just 5 to 7 years, facilitating a rapid cycle of resource regeneration [41, 42].

The method and process of transmuting raw bamboo culms into engineered flooring products is fundamental to its performance. The primary types of manufactured bamboo end products are made of horizontal and vertical laminates-laminated bamboo and strand-woven bamboo or bamboo scrimber. For strand-woven, the process involves shredding bamboo fibers, impregnating them with thermosetting resins, and compressing them under high pressure and heat, with significantly enhanced material properties. This engineered composite demonstrates superior mechanical strength and better performance, often surpassing many traditional hardwoods and their composites. Findings of various studies have confirmed its high compressive and tensile strength, exceptional hardness, and excellent strength-to-weight ratio, making it a preferred material choice for both residential and commercial applications, owing to high traffic loads [6]. Figure 1 shows the use of bamboo flooring in a residential setup. [50]

Table 2. Comparative environmental properties of bamboo and other conventional materials [43]

Property	Bamboo	Wood	Steel	Plastic	Concrete	References
Carbon Sequestration (Above ground)	7.17 Mg C ha^{-1} yr^{-1}	3 Mg C ha^{-1} yr^{-1}	None	None	None	[44]
Renewability	Rapid (3-5 years)	Slow (10-30 years)	Non-renewable	Non-renewable	Non-renewable	[45]
Carbon footprint over life cycle (kg CO_2 eq/m^3)	-141 to -613	-334	14429	2904	554	[37]
Biodegradability	Biodegradable (Untreated)	Biodegradable	Non-Biodegradable	Non-Biodegradable	Non-Biodegradable	[46]
Recyclability	Emerging (Composite, Charcoal)	Limited	High	Limited (for certain plastic types)	Low	[47, 48]
Flammability	High (Untreated), Moderate (Composite- Subject to adhesive types)	Moderate (Subject to moisture content)	Non-Flammable	High-Flammable	Non-Flammable	[49]

In terms of environmental aspects, bamboo has various advantages. The bamboo plant acts as an effective carbon sink, and this stored carbon remains within bamboo products throughout their service life, contributing to a negative carbon footprint at the end of life [37, 51].

Life Cycle Assessment (LCA) studies have quantified this benefit, with research on bamboo scrimber flooring demonstrating a net negative carbon emission at the end, when in calculation biogenic carbon storage is accounted for, despite considerable energy consumption and emissions from processing and transportation [38].

The sustainability statement is not without its complexities. The environmental benefit of bamboo flooring is deeply influenced by manufacturing processes, particularly the higher energy consumption during some of the manufacturing stages and the type of adhesives used for binding under different treatments.

Formaldehyde-based resins in some laminated bamboo can raise concerns about indoor air quality, while the carbon mitigation potential also offsets these benefits since it includes long-distance transportation from primary manufacturing hubs in Asia [8, 37]. Moreover, a comprehensive cradle-to-grave assessment, including in-use and end-of-life scenarios, is often lacking in the current literature, leaving disparities in assessing its full environmental potential.

Fig. 1 Bamboo flooring used in residential
Source: IndiaMART (https://url-shortener.me/89KS)

3.1. Manufacturing of Engineered Bamboo

The making of bamboo flooring is fundamentally an engineering process that transforms a natural, hollow culm into a high-performance, isotropic composite. Bamboo flooring is not a single product and can be categorized into two primary types – bamboo scrimber and laminated bamboo, each with a distinct manufacturing process, properties, and forms.

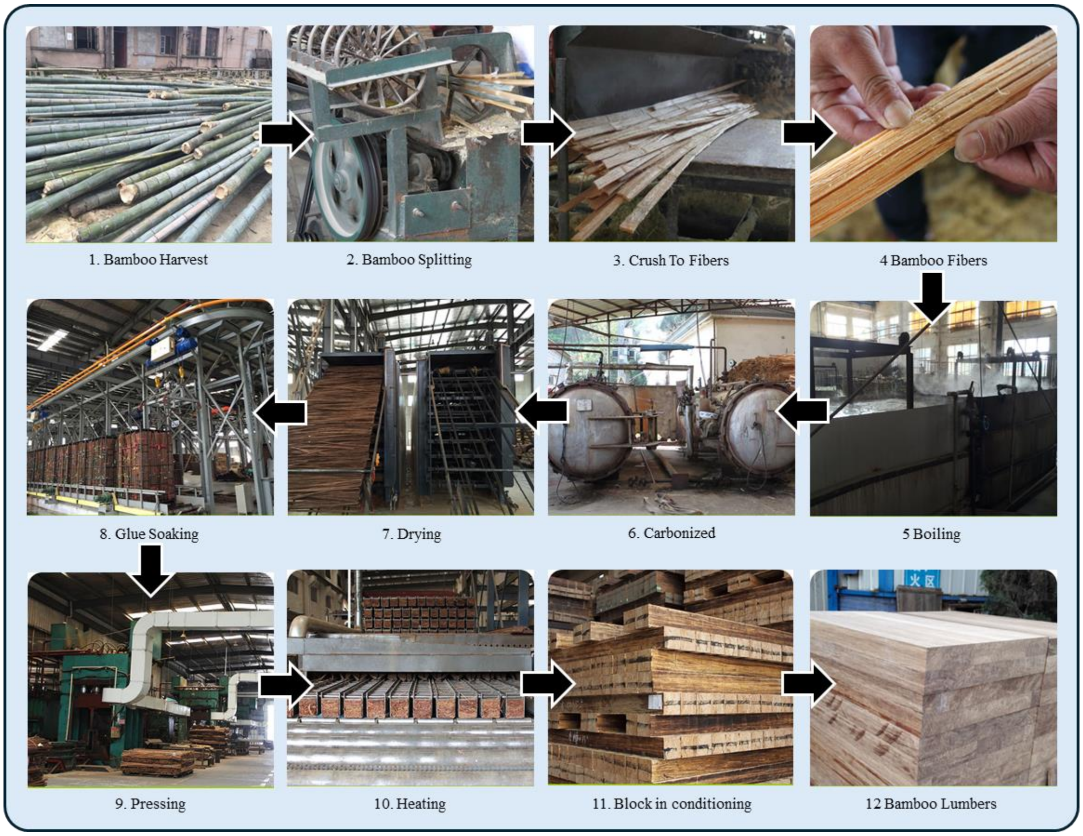

Fig. 2 Manufacturing process of bamboo scrimber

Source: www.bambooindustry.com/blog/how-is-strand-woven-bamboo-flooring-made

Fig. 3 Manufacturing process of laminated bamboo board

Source: www.magicbambu.com/production-process/

Bamboo scrimber is made by crushing bamboo culms into fiber bundles, mixed with high-performance resins, and compressing them into dense blocks, also known as parallel strand or strand woven bamboo. Crushing bamboo completely destroys the natural vascular structure and reorients the fibers randomly, creating a homogeneous composite with enhanced properties.

Due to this, the bamboo nodes are hardly visible. Figure 2 shows the manufacturing process of Bamboo Scrimber. Also, the process is highly efficient as it utilizes approximately 80% of raw material while maintaining the longitudinal fiber direction [6]. After defibering and drying at 12–15% moisture content, resin-impregnated bamboo bundles can be either cold-pressed or hot-pressed, resulting in 2 different forms of bamboo scrimber.

High pressure (70-80 MPa), cold-pressing is mostly used to manufacture square-edged bamboo scrimber with thicknesses ranging from 15 to 18 cm. Square stock is typically measured as 193×10.5×15.0 cm or 200×14.5×15.0 cm (length, breadth, and thickness), while low-pressure (4-6 MPa) hot pressing is used to manufacture slab-bamboo scrimber board typically measuring 244×122×1.5–4.0 cm (length, breadth, and thickness) [12]. MOSO bamboo products developed three main production techniques: lamination of strips, compression of rough strips/fibers, and flattened bamboo [37]. Due to its superior hardness, bamboo scrimber is more appropriate for decking.

Laminated bamboo is produced by flattening culms or splitting culms [11], planing, and processing culms before laminating and pressing them into board form. Depending on strip orientation, it is classified as “plain pressed” (flat) or “side pressed” (vertical), while color variations are achieved through bleaching (natural), carbonization (caramel), or double carbonization (chocolate). Nodes are clearly visible in plain pressed style, while in side-pressed nodes are less visible. Figure 3 shows the manufacturing process of Laminated Bamboo Boards. Laminated bamboo preserves both the longitudinal and a section of the original culm matrix. However, this process is less material-efficient, utilizing only about 30% of the raw bamboo due to losses during planning [6].

Bleaching is the process that uses chemicals to lighten the bamboo’s color, while caramelization uses heat and steam for darkening the bamboo. The bleaching process of bamboo improves its surface properties for bonding than the caramelizing method, as it modifies the lignin [52]. Research by Shah et al. [53] endorses that preservative treatments like caramelization weaken adhesive bond strength by 15-75%. The bleaching process on bamboo achieves the opposite result, enhancing bond strength up to 130%. This remarkable performance is attributed to bleaching's unique capability to create ideal surface condition for glue penetration and adhesion, making it the most effective treatment for creating strong and long-lasting laminated bamboo products.

The properties of engineered bamboo are predominantly determined by the diversity of its manufacturing processes, which majorly include variations in resin type, bamboo species, and structural configuration [28]. The study by Sewer et al. [52] confirms that two manufacturing techniques - densification and heat treatment- directly boost the mechanical properties by increasing density and reducing moisture absorption capacity, respectively. Increased density through hot pressing improves bonding strength.

The selection of adhesives is a decisive factor that directly influences both mechanical performance and indoor air quality. A variety of adhesives are used depending upon how they serve the intended purpose of balancing strength, durability, and environmental concerns. As per popular industry practice, Urea-Formaldehyde (UF) resins are cost-effective but pose risks of formaldehyde emissions. Methylene Diphenyl Diisocyanate (MDI) or Polyurethane (PU) based binders are increasingly favored for their better moisture resistance quality and low Volatile Organic Compound (VOC) emissions, directly impacting the flooring's suitability for sensitive interior environments. Low-volatile substances evaporate fewer chemicals into the air, resulting in lower odor and better air quality in indoor spaces.

3.2. Strength Properties of Engineered Bamboo

As mentioned by Jafarnia & Mofidi [28], strength properties and durability of engineered bamboo heavily rely on the manufacturing process, which includes fiber volume [54] and orientation [55], adhesive, and testing standards. Density is a core distinction that has a significant impact on other attributes [55]. Bamboo scrimber displays much higher density, ranging from 950 kg/m³ to 1300 kg/m³, with one study recording an average of 1160 kg/m³. This is a result of its intensive densification process. Laminated bamboo has a lower and more variable density, generally ranging from 600 kg/m³ to 850 kg/m³, with one study recording an average of 686 kg/m³ [6]. Extensive research by other authors also supports the same range.

Mechanical strength is measured by compressive, tensile, and shear properties. These properties describe a material’s capability to withstand various types of forces, prior to permanent damage like breaking or deforming. Compressive, tensile, and shear properties measure push force, pull force, and force parallel to its surface, respectively. Bamboo scrimber holds strong mechanical properties compared to laminated bamboo in most cases, with a few exceptions. For compressive strength parallel to the grain, bamboo scrimber shows more consistent values ranging from 86 MPa to 96 MPa, and laminate bamboo shows 63 MPa to 77 MPa.

This characteristic is attributed to scrimber's denser, more oriented microstructure and extensive resin impregnation, which increases load transfer between fibers [6]. For tensile strength parallel to the grain, bamboo scrimber measures strength exceeding 110 MPa to 120 MPa and even 143.1 MPa. Laminated bamboo remains less than 90 MPa in this regard [6]. This is attributed to the type of processing technique used for making laminated bamboo. Research by Li et al. [54] uncovered that a laminate's structure and fiber volume considerably govern the mechanical properties of Bamboo Laminated Composites (BLCs). Their experiments showed that parallel lamination in bamboo composite has higher bending and tensile strength than cross lamination. This establishes that the direction of lamination has a direct impact on material performance. The structural integrity of a material can be determined by its response under shear force. Bamboo scrimber exhibits a higher median shear, approximately 23MPa, and laminated bamboo shows close to 13MPa. Due to strong internal bonding, bamboo scrimber fails through fiber pull-outs and resin fractures [28], while laminated bamboo is vulnerable at adhesive bond lines, resulting in chipping off. This characteristic demonstrates the crucial role of adhesive quality for the integrity of laminated products.

Table 3 is a compilation of key strength properties for engineered bamboo, raw bamboo, timber, and engineered wood products by various authors. Engineered bamboo displays superior tensile strength, compression (parallel to grain), and Modulus Of Elasticity (MOE) compared to engineered wood, raw wood, and raw bamboo, but differs in other properties. As per Dauletbek et al. [56], LBL shows tensile strength and MOE comparable to hardwood or softwood. Within the engineered wood category, wood scrimber outperforms in tension (parallel to grain) and Modulus Of Rupture (MOR). Cross-laminated timber from reclaimed wood exhibits low MOR. Results of a comprehensive test done by Namari et.al [57] show that Compressed Wood (CW) has better compressive (perpendicular to grain), tensile, and bending strength than normal wood. Wood recovered from a demolished building was found to have reduced density and moisture content, and also had lower peak strength and MOE/MOR due to aging and exposure to the environment [58].

Table 3. Key strength properties for natural bamboo, engineered bamboo products, and timber products from various studies by Sharma et al. [6], Jafarnia & Mofidi [28], Huang. Y et al. [12], Fernandez Llana et al. [59], Chen et al. [60]

		Density: kg/m³	**Compression: MPa**	**Tension: MPa**	**Shear: MPa**	**Flexural**	
			Parallel to the grain	Parallel to the grain	Parallel to the grain	MOR: MPa	MOE: GPa
Engineered Bamboo	Bamboo Scrimber [6]	1163	86	120	15	119	13
	Bamboo Scrimber [28]	1150	96	114	23	119	13
	Bamboo Scrimber [12]	720-1300	70.5-199.3	227.6-364.8	18.9-26.2	178.5-398.0	13.5-32.3
	Laminated Bamboo [6]	686 kg	77	90	16	77-83	11-13
	Laminated Bamboo [28]	720	63	< 90	13	80-110	8-11
	Laminated Bamboo Lumber [12]	690	77	90	16	77-83	11-13
Raw Bamboo	Phyllostachys pubescens [6]	666	53	153	16	135	9
	Phyllostachys pubescens [60]						
Timber	Sitka Spruce [6]	383	36	59	9	67	8
Engineered Wood	Wood Scrimber [12]	1010	---	97.3	14.4	142.4	19.3
	Douglas Fir LVL [6]	520	57	49	11	68	13
	LVL [28]	---	---	---	---	49.5 -	---
	LVL [12]	510	---	---	6.8	85.4	14.3
	3-layer Cross Laminated Timber (CLT) from reclaimed wood [59]	761-769	-----	-----	-----	72.80-44.74	-----
	5-layer Glulam pieces from reclaimed wood [59]	770	-----	-----	-----	38.11	-----

3.3. Interior Designer's Perspective

More than just being a functional surface, flooring has evolved over the years into a design component that influences comfort, user experience, and overall spatial character. Technically, floors are the horizontal planes designed to bear load, provide workable space, and withstand constant wear and use [61]. Flooring is regarded as an essential space-making element, defining the aesthetics of interiors, shaping the perception of scale, light, and texture. In current times, flooring material adds value by accommodating changing expectations of users, which include robustness, flexibility, and being environmentally friendly.

For any designer, functionality and performance are the prime considerations. Flooring materials are progressively gauged for their dimensional stability, hardness, moisture and wear resistance, insect resistance, fire resistance, color stability, adhesive integrity, ease of installation and maintenance, and environmental impact, especially in high-traffic and multi-use spaces. For environmentally conscious projects and clients, sustainability is the central concern. More and more building projects are aligning with green building certifications such as LEED (Leadership in Energy and Environmental Design). To ensure responsible sourcing and indoor quality compliance, designers are supporting certifications such as FSC and Greengard [10]. Challenges due to color inconsistency in manufacturing batch, moisture resistance, and VOC emissions from adhesives for bamboo flooring are still a matter of concern for most of the designers [36].

3.3.1. Durability and Performance

The durability of engineered bamboo is distinguished by its capability to retain mechanical properties and resistance to moisture absorption during its expected life span [28]. Outdoor bamboo flooring is consistently exposed to harsh weather conditions, such as rain and bright sunlight. Water and moisture content affect the mechanical properties of bamboo [31], which can alter its performance. The main component influencing water absorption is the pore structure of the material, in other words, the density of the finished product. Increased density of laminated composites leads to a drastic decrease in Water Absorption Rate (WAR) and Width Swelling Rate (WSR), while mechanical properties increase steadily, a behavior directly associated with a change in pore structure [62].

Bamboo scrimber exhibits low vulnerability to moisture and performs exceptionally well, due to extensive resin impregnation and high-density compaction. This creates a water repellent barrier and reduces the passage for water penetration, resulting in very low water absorption and thickness swelling [42]. With density surpassing 910 kg/m³, bamboo scrimber attains water resistance and mechanical properties corresponding to the highest benchmarks in relevant national standards, proving strong potential for flooring and outdoor structures [62]. On the other hand, laminated bamboo is sensitive to moisture, due to lower density (∼600-850 kg/m³), mainly due to its manufacturing process. Bamboo strips are planned together uniformly and are bonded with adhesives, leaving potential gaps at the glue line and through the strips for water penetration [28]. Nevertheless, laminated bamboo possesses adequate moisture resistance to be used as a flooring material in controlled interior environments, offering a desired surface finish for aesthetic applications. It is essential to give protective sealing for flooring in areas prone to moisture spills or high humidity [63]. Table 4 summarizes durability and performance for engineered bamboo and engineered wood.

3.3.2. Adhesive Types and Performance

Phenol-Formaldehyde (PF) is the most widely used adhesive in the bamboo composite industry. Research indicates that modifying rigid PF with ductile polymers like Polyvinyl Acetate (PVA) or low Molecular Weight (MW) PF significantly improves bonding in bamboo [64]. Also, UV-cured polyurethane polish paired with PF offers a good combination for bamboo flooring. PF resin provides higher moisture resistance and stable bonding, reducing vulnerability and risk of delamination to a great extent for laminated bamboo [42].

UV-cured polyurethane topcoat forms a hard, transparent, and abrasion-resistant film that protects the bamboo surface from wear and tear, stains, and moisture penetration with minimal cleaning and maintenance. This pairing safeguards the flooring's structural integrity against moisture, making it suitable for application in residential and commercial spaces. As the industry shifts away from formaldehyde, isocyanate-based resins are emerging as a viable alternative [64] for bamboo strand composites.

For engineered bamboo products, Sewar et al. [52] confirm that both Melamine Urea Formaldehyde (MUF) and Phenol Resorcinol-Formaldehyde (PRF) adhesives are appropriate for interior and exterior bamboo structural applications. MUF provides superior bond strength even at low temperatures, like solid wood, while PRF performs better at high temperatures, where MUF's strength decreases due to thermal degradation of its chemical structure.

3.3.3. Aesthetic Versatility

Manufacturing process of engineered bamboo permits customization in colors - ranging from light, natural tones to darker caramelization—and textures, facilitating smooth integration for both residential and commercial applications [6]. Its aesthetic versatility is significantly enhanced by the deliberate orientation of its grains, allowing it to achieve unique contemporary looks. Laminated bamboo can be arranged with strips in parallel, edge-grain (vertical), or flat-grain (horizontal) orientations, each revealing distinct linear patterns and light-reflective qualities, while cross-laminated configurations introduce a checkerboard-like visual rhythm [6]. In terms of texture, bamboo composite material bears great resemblance to natural wood and its composites [8]. Figure 4 shows various flooring patterns created with bamboo flooring.

Fig. 4 Patterns made by grain orientation, color, finish, and types of engineered wood (a) Geminifloors.com, (b) Indiamart.com, and (c) kadvacorp.

Table 4. Comparative chart of durability & performance for engineered bamboo & engineered wood

Durability & Performance	Bamboo Scrimber or SWB	Horizontal/Vertical Laminate Bamboo	Engineered Wood (Plywood, CLT, LVL)
1. Moisture & Rot Resistance	Highest. Highest density and resin saturation decrease water absorption [12] [6]. Very low permeability to moisture; however, not waterproof.	Moderate. Glued laminated strips are more prone to moisture ingress at joints. Vertical grain (edge-grain) is slightly more stable than horizontal (flat-grain).	Ranges widely. Exterior-grade plywood with PF adhesive performs well in moisture conditions. CLT/LVL requires coating or treatment for wet service. MDF and particle board are poor in wet resistance.
2. Dimensional Stability	Excellent. Positive linear relationship between density & MOR in both parallel and perpendicular fibre direction, and high resin minimizes expansion or contraction [12] [65].	Good (Vertical) to Moderate (Horizontal). Vertical laminate (edge grain) is more stable. Horizontal (flat grain) is more prone to width-wise swelling [12].	Good to Excellent. Cross-lamination in plywood/CLT provides high stability. LVL is stable along its length, but warps in prolonged moisture conditions
3. Hardness & Wear Resistance	Extremely High (Janka ~3000-4000+ lbf). Scratch and dent resistant; ideal for heavy-traffic commercial flooring [6]	High (Janka ~1400-2000 lbf). Abrasion resistance correlates with density and resin content. The grain pattern can be seen at regular intervals.	Moderate. Hardwood veneers overlay improves surface hardness. Softwood-based based are susceptible to denting. Resin impregnation & thermal modification improves wear.
4. Insect/Pest Resistance	High. The resin process and dense structure further impede pests.	High. Natural high silica content makes it resistant to subterranean termites.	Low for natural wood. Requires chemical treatment for pest resistance.
5. UV & Color Stability	Good. High density and resin-rich surface resists colour fading [12]. Carbonized (darker) types may show more fading.	Moderate. More natural grain exposure can lead to faster colour change/aging with UV.	Moderate. Like bamboo, lignin degradation causes surface erosion. Coating is essential for UV protection.

6. Adhesive Integrity & VOC	Good. High water resistance as adhesive, MDI penetrates well into less porous, permeable bamboo, low VOC [64]	Delamination in external application, UF is less moisture resistant. Potential for higher VOC. [64]	Adhesives are standardized. PF, MF, or MDI for exterior/structural, UF common for interior grades (lower moisture resistance).
7. Fire Resistance	Moderate. High silica content leads to slow charring and better performance. High-density chars slowly. [49]	Moderate. Burns slightly faster as density is moderate to low, better than solid wood [49]	Moderate. All types require fire-retardant treatment, which significantly improves ignition resistance
8. Application-Specific Durability	Best suited for commercial flooring, decks, high-wear surfaces, and high-traffic areas, structural components essentially need strength.	Best suited for Residential flooring, cabinetry, countertops, and furniture where aesthetic grain pattern is desired.	Best suited for Structural framing (CLT, LVL), sheathing, roofing, panelling, subflooring, and versatile construction needs.

3.4. Execution of Bamboo Flooring

Correctly executed bamboo flooring minimizes issues related to movement, moisture, and overall wear and tear [66]. Engineered bamboo comes in a combination of a few standard sizes. Typically, plank lengths have a range from 1900-1920 mm, and plank width 90–190 mm, with the thickness of 10-15 mm. Installation of bamboo plank is easy with tongue-and-groove on edges that snap together or click-lock, which do not require any glue. Due to this modular system, less dust is created, resulting in less polluted air on site, compared to conventional flooring of stone, marble, wood, and ceramic tiles. Installation of bamboo flooring is quick and time-saving.

The successful execution of bamboo flooring installation requires systematic attention to material acclimatization, subfloor preparation, and method-specific protocols to ensure long-term performance and durability. Figure 5 explains key features of the entire installation process. Proper execution ensures linkage of mechanical properties as described in theory to its performance, also addressing its environmental benefits.

Pre-Installation: Prior to installation, Bamboo flooring must undergo an acclimation to reach moisture equilibrium with its service environment. The study by Yuan et al [67] validates that due to the hygroscopic nature (absorbing moisture from the air), bamboo exhibits significant dimensional change, such as swelling and shrinking, in response to changes in relative humidity. Material must acclimate for 72 hours in the installation environment at 30-50% relative humidity and 15-27°C temperature according to best industry practices [68]. Subfloor moisture content should not go beyond 12% for concrete slabs, with mandatory vapor barriers below grade. Unlike traditional wood, strand-woven bamboo's high density (≥1000 kg/m³) requires greater dimensional stability considerations [6].

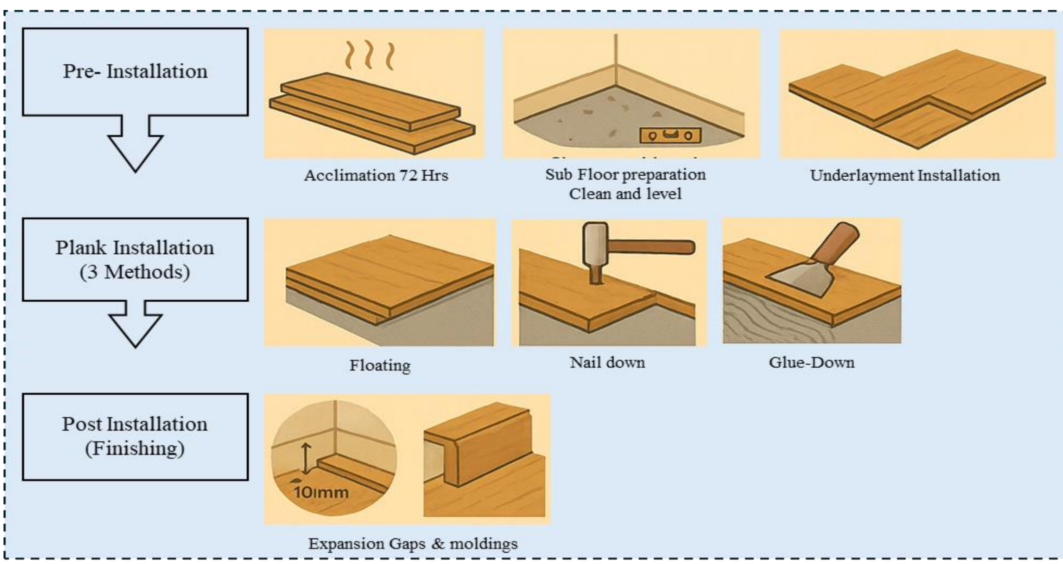

Fig. 5 Engineered bamboo installation

Source: romerohardwoodfloor.com

Installation: Floating, Glue-down, and Mechanical fastening are the three primary methods of installation. 'Floating floor' systems utilize click-lock mechanisms with foam underlayment suitable for strand-woven planks up to 8 meters in continuous span. It is essential to have a perfectly leveled subfloor, like concrete, for this installation. Click-lock is an ideal choice for residential construction as it facilitates fast installation, as no adhesives are used in this. Figure 6 shows a floating (click-lock) floor installation system.

'Glue-down' installation provides superior stability for commercial applications, requiring moisture-curing urethane adhesives compatible with bamboo's silica-rich surface. With this installation, it is difficult to remove flooring and is also labor-intensive; thus, it should be used where long-lasting flooring is required for heavy traffic. 'Mechanical fastening' with specialized carbide-tipped fasteners is essential due to bamboo's extreme hardness [10]. Table 5 summarizes the installation criteria based on the published guidelines by the industry report [68]

Table 5. Key installation criteria [68]

Plank Installation Method	Essential requirement	Advantages	Disadvantage	Suggested Application
Floating (click-lock)	Perfectly leveled subfloor. Mandatory underlayment for moisture barriers, acoustics, and cushioning	No Adhesive, Fast installation, Accommodates subfloor movement	Not suitable for non-level floors	Residential spaces, Concrete Subfloors
Glue-Down	Requires a full-spread, compatible adhesive. Concrete must be fully cured and dry.	Stable, moisture-resistant, and ideal for heavy traffic	Difficult to remove, labor-intensive, requires a perfectly clean subfloor	Commercial spaces, Moisture areas, Concrete subfloor
Mechanical Fastening (Nail /Staple)	Wood subfloor. Correct fastener type, length, and spacing	Strong and durable, Accommodates subfloor movement	Not suitable for concrete floors, risk of damaging the tongue with fasteners	Residential over plywood subfloor

Post-Installation: Expansion gaps of 10-15mm must be maintained at all vertical obstructions. Surface protection during construction prevents micro-scratches that compromise the wear layer.

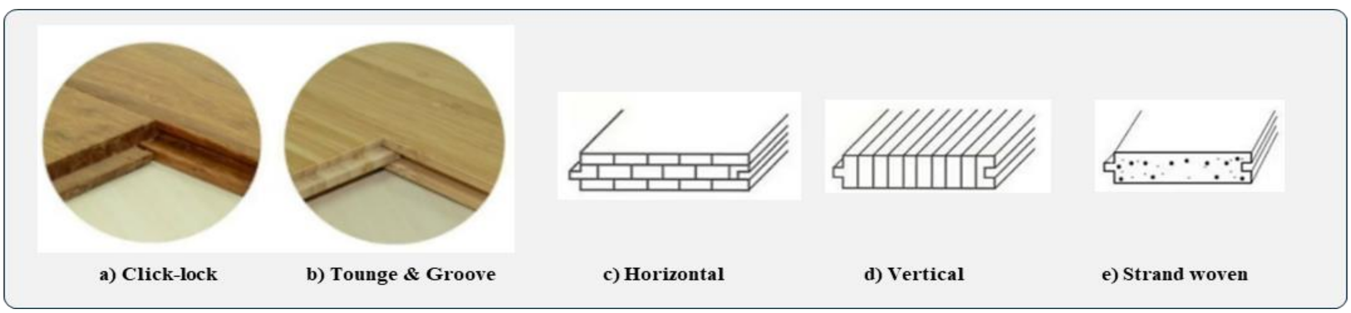

Fig. 6 Floating (click-lock) floor installation system

Source: geminifloors.com

Table 6. Comprehensive summary of the application of engineered bamboo and engineered wood

Material type	Physical Form & Size	Key performance characteristic	Construction application	Interior Design application	Aesthetic
Bamboo scrimber	Rectangular Lumber	High and uniform density, High bending strength, Wear resistance, low water absorption	Structural - beams and columns, Outdoor deck [6] [12] [69]	Built-in Shelves, Interior columns, Framing of door and window [15]	Similar to wood, with a variety of patterns on the surface [12]

	Board	High-density, high-abrasion resistance [12]	Wall panel & cladding, Outdoor Deck [15] [6] Industrial flooring	Indoor flooring, surface application, [15] [6] [70] Counter top	Minimum grain visibility
Laminated bamboo	Sheet Laminated	Lightweight, Flexible, excessive water or humidity can result in surface damage.	Building material [55]	Indoor flooring [6], Concrete form work for Indoor flooring [69]	Refined appeal with uniform surface. Polished texture
	Vertical	Higher bending strength, better wear resistance	Load-bearing beams	High-wear Indoor flooring, stair-case treads, kitchen counter top edge, Table legs, Commercial Furniture [71]	Edge-grain appearance
	Horizontal	Moderate bending strength	Non-load-bearing walls, roof battens	Indoor flooring [6], feature wall, Decorative panels, and screen [70]	Visible natural nodes on the surface with a stripped appearance
	LBL (Laminated Bamboo lumber)	Superior in Compressive strength, also more brittle. Lower charring rate and better fire performance.	building moulding, deck flooring, Non-structural Column [18] [64]	Flooring, decorative wall panels. Furniture [18] [69].	Linear natural grain pattern of bamboo strips visible on the surface. Sophisticated look.
Engineered Wood	LVL (Laminated Veneer Lumber)	Maximum strength in one direction due to parallel veneer orientation. Can bear a high load in a straight line.	Structural: Load-bearing beams of long span, headers, rafters, and rims	Cabinet, furniture, accent wall cladding	Natural wood appearance
	CLT (Cross Laminated timber)	Maximum strength in both directions due to perpendicular lumber boards in alternate layers. Lightweight.	Load-bearing headers, rafters, and rims	Furniture, shelf, wall-cladding	Natural wood grain finish in a variety of light colour tones

3.4.1. Bamboo as Sustainable Construction Practice

Lifestyle changes in cities have triggered the re-functioning and renovating of existing spaces in a short time span. Flooring material and floor covering are changed with each renovation, even when it's functioning well, to create either a more aligned aesthetic or just for the desire to have a change. Bamboo flooring's relative affordability compared to premium hardwoods enables clients with varying budgets to achieve a natural wood-like aesthetic without compromising design quality.

Strength, efficiency, and cost are no longer the only factors used in the traditional material selection process for flooring; environmental performance and sustainability are now additional considerations [6]. Bamboo flooring is a promising material to mitigate climate change, lower carbon footprint, and expedite environmentally conscious project execution. Life Cycle Assessment (LCA) quantitatively validates bamboo flooring as a sustainable construction practice. Table 6 summarizes the application of engineered bamboo and engineered wood.

4. Life Cycle Assessment of Bamboo Flooring

The Life Cycle Assessment (LCA) is a standardized (ISO 14040/44) methodology that evaluates the total environmental impact of a product from cradle to grave (resource extraction to disposal/recycling), by quantifying all inputs (materials, energy) and all outputs (waste, emissions) across the product's life. The results are then analyzed to understand impacts across the categories like Global Warming Potential (GWP), air quality toxicity, and resource depletion [51]. Bamboo flooring's cradle-to-grave LCA typically includes assessment across all 6 categories - cultivation, transport, manufacturing, installation, use, and end-of-life; where cultivation, transport, and manufacturing are commonly bundled together, known as the cradle-to-gate phase.

Bamboo's environmental impact is difficult to correctly assess because of variations in growth and production [72]. It is important to note that the environmental impact data and results presented herein are specific to the parameters of each individual study and should not be generalized. Findings are specific to each study's context and scope. As per Gan et al. [36], divergent conclusions can be attributed to key methodological differences, including the choice of system boundary, manufacturing pathways, and data sources. Broadly, the Life Cycle Analysis of bamboo flooring includes three major stages: cradle-to-gate (raw material extraction to manufacturing), In-use, and end-of-life stages.

Bamboo’s growth cycle is notably short, where it matures in 5-7 years for use in many ways. It absorbs carbon dioxide at higher rates than hardwood species, making its cultivation climate positive. According to Scurlock et al. [73], bamboo plantations act as carbon sinks and help restore degraded lands. Bamboo absorbs CO_2 from the atmosphere as it grows (sequestration) and releases it back when it decomposes or is burned at end-of-life (emission). The stored carbon is not counted as a credit in LCA, except when bamboo is burned for energy recovery at the end of life, which generates a credit because it displaces fossil fuels, avoiding new emissions [13]. The environmental profile is heavily influenced by manufacturing energy and processes. Table 7 lists the environmental load of bamboo scrimber flooring and Laminated Bamboo flooring during the Production of 1.0m² material and at the disposal stage at the end of life. During manufacturing, bamboo uses less energy and water compared to other flooring options [36]. Electricity used during manufacturing and transportation from raw material to manufacturing units is the only stage where more energy is consumed. The production of 1 m³ of bamboo scrimber flooring generates notable emissions, with electricity consumption being the primary contributor, followed by additives and transportation [37, 74]. Laminated bamboo flooring, by and large, presents a lower environmental load compared to the more energy-intensive scrimber [39].

Table 7. LCA comparative environmental load of bamboo scrimber flooring and laminated bamboo flooring during the production of 1.0m² material, at the disposal stage at the end of life [8]

			Unit	Laminated Bamboo Flooring	Bamboo Scrimber Flooring
Production Stage	Input of substance	Bamboo raw material (Absolute dry Weight)	kg	35.1	19.6
		UF Resin	kg	0.45	1.38
		water	kg	45	55
	Input of Energy	Electricity	kWh	8.8	11.1
		Heat	MJ	339	719
	Output of Combustion emission	Formaldehyde	kg	9.90E-04	4.45E-04
		Waste Liquid - COD	kg	1.60E-04	1.60E-04
		Waste Liquid - COD	kg	7.40E-03	7.40E-03
Disposal Stage	Solid waste	Ash	kg	1.07E-01	1.28E-01
	Heat recovery		MJ	-207	-251

As stated by Yu et al. [8], the manufacturing of bamboo flooring generates numerous environmental issues, such as water pollution and the release of greenhouse gases such as carbon dioxide, methane, and hydrogen fluoride. Therefore, minimizing electricity and energy use is essential for improving the environmental profile of both flooring types. His study demonstrated that the primary environmental burdens for bamboo floors occurred during strip production for laminated flooring (59%) and panel processing for scrimber flooring (56.9%). Consequently, laminated flooring was found to be the more sustainable option, with the total environmental impact of scrimber flooring being approximately 1.6 times higher. GWP is the key metric from an LCA that measures a product’s contribution to climate change, often called ‘carbon footprint’. It aggregates all greenhouse gas emissions like carbon dioxide, methane, and hydrogen fluoride, emitted during a product’s life cycle, and expresses them in terms of kg of CO_2 equivalent (CO_2e), allowing for a single comparable number [13]. Cradle-to-gate studies consistently demonstrate its low Global Warming Potential (GWP), often achieving a negative carbon footprint due to significant biogenic carbon sequestration within the product itself [37]. Studies show that bamboo has lower GWP values and superior environmental benefits compared with other materials (e.g., wood, metals, and plastics) [72, 38]. Composite timber boards like MDF often exhibit a higher GWP. While both materials (engineered wood and engineered bamboo) benefit from sustainable forestry, bamboo's higher annual biomass yield and shorter harvest cycle typically give it an advantage in carbon sequestration efficiency per unit area per year [39].

According to Yu et al. [8], the eco-indicator is the most prevalent LCA method, defining 11 environmental impact types through a computational process of classification, characterization, normalization, and weighting. These 11 categories are further grouped into three damage categories: human health, ecosystem quality, and resources. In-use phase contributes less than 1% of the life cycle emissions compared to production and end-of-life [13]. Maintenance activities mainly involve cleaning or mopping the floor with water [8]. Users also need to be careful regarding scratches.

The end-of-life stage for bamboo flooring typically involves one or more of the following waste treatments: landfill, incineration, recycling, or bioenergy conversion [36]. In a post-consumer scenario, waste is transported to nearby landfills, with studies assuming different levels of permanent carbon storage. In the incineration scenarios, burning 1 kg of bamboo waste produces about 19 MJ of heat, which could be used to replace the heat supply from other sources, like a natural gas boiler. Around 1% of the waste remained as ash and was landfilled. According to Lugt et al. [51], 1.2 kg of bamboo could provide one kilowatt-hour of power, which is comparable to the biomass needed for wood or timber and superior to other widely used forms of powdered biomass, such as sawdust or peanut, coffee, and rice husk. Incineration with energy recovery can enhance bamboo's carbon neutrality by offsetting fossil fuel use [75]. Thus, while inherently low-carbon, bamboo's full environmental benefit depends on renewable energy in production and responsible end-of-life management. As per Yu et al. [8], under the assumption that flooring is not recycled and is instead combusted for energy, the recoverable energy is calculated by multiplying the discarded mass by its lower heating value (LHV) of 18.87 MJ/kg. The resulting solid waste, or ashes, accounts for 0.96% of the original mass

4.1. Recycling and Reuse of Bamboo Flooring

While inherently biodegradable, the synthetic resins in engineered bamboo composites complicate recycling. Current pathways include down-cycling into particleboard or cement-bonded composites, where post-consumer bamboo is used as fibrous filler [3]. A more promising route is material reuse; high-quality planks from deconstructed buildings can be directly repurposed for new projects, extending the stored carbon's lifespan and avoiding new production impacts [37]. Engineered bamboo of click-lock variants can be disassembled and reused in a new space or repurposed to make paneling or medium-quality furniture pieces. For contaminated or degraded flooring, waste-to-energy incineration offers a solution, where the high calorific value of bamboo offsets fossil fuels, though this releases stored carbon [38].

4.2. Decision-Making Framework

This research has effectively combined fragmented data on bamboo flooring and derived a theoretically grounded, multi-criteria decision-making framework, which addresses the imparity of marketed sustainability of bamboo products and their practical application for commercial and residential spaces. The investigation reiterated that engineered bamboo products possess competitive mechanical characteristics, and their negative carbon footprint gives a clear advantage over conventional composite wood like MDF. Analysis also highlights that the environmental benefits of final bamboo products are dependent on the chemical process, manufacturing type, and its sub-stages, energy consumption, and the type of adhesive used. Its in-service performance is much dependent on the execution of protocols followed and taken care of during the use of the flooring. The culmination of these findings is integrated into the framework shown in Figure 7, which equips interior designers with a methodical checklist to comprehend these complexities. It moves bamboo flooring selection beyond just one focus, be it aesthetic appeal, performance, or carbon metrics. The framework offers holistic justification and limitations for the type of bamboo flooring specifications for various levels of traffic and types of projects. Framework logically evaluates technical Suitability (durability, moisture resistance), Environmental Impact (LCA results, carbon storage), and Socio-Economic factors (cost, supply chain transparency), and the resulting trade-off can work as the best choice.

When the project focus is on durability and optimizing budget, traffic and moisture level should be evaluated next. For standard traffic with low moisture content in residential areas like living, dining, cost-effective laminated bamboo will serve well, whereas for high traffic areas, even with low moisture content in residential spaces, both the choices - strand woven bamboo or laminated bamboo with high adhesive quality will serve best. For high moisture in spaces like the kitchen, strand-woven bamboo becomes the sole choice as laminated bamboo will have greater wear and tear with fading polish. For low moisture and high-traffic commercial projects, bamboo scrimber is the preferred choice, followed by high-adhesive-quality bamboo boards. High-traffic areas will need regular maintenance. Along with durability and performance, when the project focus is also on sustainability certification, low VOC adhesive, and manufacturing transparency will be evaluated next. A commercial project targeting LEED would carefully source bamboo flooring material from leading manufacturers who have standardized the process, minimizing waste and emissions. GWP and aesthetics are the prime considerations for Eco-luxury residential projects.

This research links scientific evidence and design practice, shifting the paradigm from relying on unverified marketing claims to a practice guided by a verified, comprehensive, and multi-dimensional assessment model. This framework positions bamboo not merely as an alternative material, but as a viable, high-performance, and truly sustainable choice when selected and specified with informed precision.

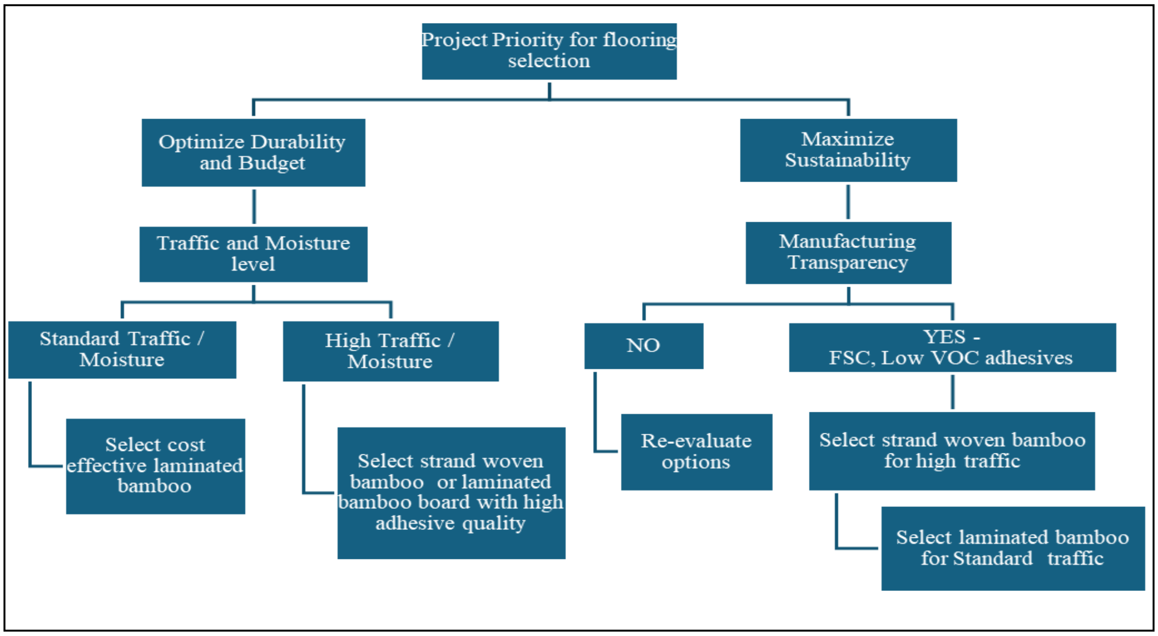

Fig. 7 Decision-making framework

5. Conclusion

Use of bamboo flooring is increasing manifold in residential and commercial spaces over engineered wood, due to its rapid renewability and high carbon sequestration. Apart from strength and durability, the low environmental impact has also been added to the list of essential requirements. This research positions engineered bamboo flooring as an outstanding solution that can meet the demand for high-performance and sustainability concerns in modern interior design practices.

Grain versatility and color tones of bamboo flooring enable customization for preferred aesthetic, surpassing premium wood grains, and broaden bamboo flooring's application in commercial and residential spaces. The benefits of engineered bamboo products are dependent on the choice of bamboo species, manufacturing techniques, consumption of energy, and end-of-life scenario. When manufacturing techniques are environmentally friendly, energy is consumed in a responsible manner, the end-of-cycle stage is verified, and practical disposition options, laminated bamboo, and scrimber become the desired choice. Engineered bamboo flooring has superior suitability for high traffic areas, with bamboo scrimber advancing in hardness, moisture resistance, and longevity.

Awareness, access to information, and implementation of local bamboo sourcing strategies can benefit from a stronger socio-economic equilibrium and overcome the limited reach barrier. To produce positive effects on the environment and human health, builders and designers should prefer engineered bamboo with reliable certifications (such as FSC) and low-VOC adhesives. This can further promote bamboo flooring as a strategic material for reducing the ecological footprint of the built environment, rather than merely an alternative.

Future work should focus on quantifying bamboo flooring's capacity to reduce renovation waste through designed-in reusability. This is possible by developing standardized deconstruction procedures and assessing the material's performance over multiple life cycles. Exploration of how to develop a robust market for reclaimed bamboo by analyzing its economic viability and structural integrity post-reclamation could add more value to verified LCA practices.

Glossary

1. Moso Bamboo - Denser species of bamboo culm, such as Phyllostachys edulis.
2. Bamboo Scrimber - Manufactured from crushed bamboo culm sections, impregnated with resin and hot or cold compressed for the final product - beam section. It is also known as strand-woven bamboo.
3. Laminated Bamboo - Long rectangular sections produced from strips of bamboo and then laminated to form a board.
4. Engineered Bamboo - Processed bamboo that is transmuted into standardized forms for enhanced structural performance.
5. Engineered Wood - Processed wood-based board comprising wood strands, particles, fibers, and veneers bound with adhesive under heat and pressure, of uniform standards.
6. Composite Bamboo / Bamboo composite - Bamboo fiber modified and combined with other materials to leverage the strength of each to overcome the limitation of any

single material. Composites of bamboo have better strength properties.

7. LVL - Laminated Veneer Lumber is one type of engineered wood. High-strength beam manufactured from thin (softwood) wood veneer laid parallel to the grain and glued together (with adhesive) and by hot pressing. Type of engineered wood.
8. LBL - Laminated Bamboo lumber. High-density beam manufactured from bamboo strips (laid parallel or perpendicular) by boiling and gluing together (with adhesive) under compression.
9. CLT - Cross-Laminated Timber. Type of engineered wood made from solid-sawn lumber boards layered perpendicular to panels, which creates structural strength in both directions.
10. GluBam - Glue-laminated timber. An engineered wood product manufactured by sawing thick solid wood pieces, grain laid parallel to length, and laminating them together with adhesives and under high pressure.
11. Glulam - Glue-laminated timber. An engineered wood product manufactured by sawing thick solid wood pieces, grain laid parallel to length, and laminated together with adhesives and under high pressure.

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