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# Preservation Strategies for Bamboo: Traditional Practices, Modern Technologies and Sustainability Considerations

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## ABSTRACT

This review paper presented a comprehensive synthesis of research on bamboo preservation, encompassing traditional non-chemical practices, chemical preservation techniques, eco-friendly and bio-based approaches and modern impregnation and processing technologies. Bamboo was a rapidly renewable lignocellulosic material with significant potential for sustainable construction, furniture and industrial applications. However, its high susceptibility to biological degradation caused by fungi, termites and insects severely limited its service life when left untreated. Bamboo preservation therefore played a critical role in extending durability, improving performance and enabling large-scale utilization. Particular emphasis was placed on the underlying anatomical and chemical characteristics of bamboo that influenced its durability, including high starch content, parenchyma distribution and moisture dynamics, which collectively increased vulnerability to biodeterioration. Traditional practices such as seasonal harvesting, water leaching and smoking were evaluated alongside chemical treatments including boron-based and copper containing preservatives. Emerging trends toward environmentally benign preservatives, such as plant extracts and tannin–boron systems, were critically evaluated in terms of effectiveness, sustainability and scalability. The paper further examined global advancements in bamboo preservation, highlighting successful models from China, Japan, Southeast Asia and Latin America, and contrasted these with the Indian context, where rich bamboo resources coexisted with technological and institutional challenges. The review concluded that while significant progress has been made, future research must focus on long-term field validation, species-specific treatment optimization and integration of preservation technologies into policy and building standards. Strengthening preservation practices was essential for realizing bamboo's role as a durable, low-carbon material in sustainable development.

**KEYWORDS:** Bamboo preservation, lignocellulosic biomass, durability enhancement, bio-based preservatives, construction

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## 1. INTRODUCTION

The global transition toward sustainable and bio-based economies has intensified the search for renewable plant biomass that can reduce dependence on fossil-derived and non-renewable resources. Among lignocellulosic materials, bamboo has emerged as a particularly promising bioresource due to its rapid growth, high biomass productivity, and wide distribution across tropical and subtropical regions (Sain et al., 2024). Its short rotation cycle and ability to regenerate without replanting make bamboo a highly renewable material with strong potential to support circular bioeconomy strategies and sustainable resource management (Kamble and Subramaniam, 2020). Historically, plant-based resources have been integral to human societies, providing materials for construction, agriculture, energy and traditional industries (Sharma et al., 2018). However, increasing deforestation, depletion of forest resources and the environmental impacts associated with conventional construction and industrial materials have heightened the demand for sustainable alternatives (Hao et al., 2021). To address these issues, non-wood forest products have gained increasing importance owing to their rapid renewability and lower ecological footprint. Bamboo, in particular, has attracted growing scientific and policy attention as a multipurpose bioresource, combining ecological benefits with significant socio-economic value and broad industrial applicability (Zmuda and Radomski, 2020). These attributes underscore the importance of bamboo as a strategic material for sustainable development and justify its selection as the focus of this review.

Bamboo Belongs to the subfamily *Bambusoideae* within the family *Poaceae* and comprises over 1,500 species distributed across tropical, subtropical and temperate regions of the world. Due to its high biomass yield, favorable mechanical properties and wide-ranging applications, bamboo has often been referred to as the “green gold,” “poor man’s timber,” or “friend of the people,” particularly in Asian countries (Lobovikov et al., 2007; Hao et al., 2021; Correal et al., 2025). Despite these advantages, bamboo faces a critical limitation such as poor natural durability. The high content of starches, sugars and proteins in bamboo culms makes them highly susceptible to biological degradation by fungi, termites, beetles and bacteria. When left untreated, bamboo products used in construction or storage may deteriorate within two to five years, severely restricting their long-term utility (Kaur et al., 2016; Mohan et al., 2022). This inherent vulnerability has historically constrained the wider adoption of bamboo as a structural and industrial material, notwithstanding its sustainability credentials.

To overcome this limitation, preservation plays a pivotal role in enhancing the service life of bamboo. Bamboo preservation encompasses a range of treatments and management practices designed to protect bamboo from biological, physical, and environmental degradation during storage and service (Latini et al., 2024). Effective preservation not only enhances durability but also improves economic returns, reduces pressure on natural bamboo resources, and promotes sustainable utilization. As global interest in renewable and low-carbon materials intensifies, bamboo preservation has emerged as a key research and policy priority (Dutta et al., 2025).

The primary objectives of this review paper is to provide a comprehensive and critical synthesis of bamboo preservation research, by integrating traditional knowledge, scientific advancements and recent innovations. The study aims to review the fundamental properties of bamboo and the key durability challenges associated with its use, while examining traditional, chemical, and eco-friendly preservation techniques. It also seeks to analyze the effectiveness, advantages, and limitations of these methods in the context of global developments, and to evaluate the Indian scenario in terms of bamboo resources, preservation practices, and relevant policy frameworks.

By integrating global and Indian perspectives, this review seeks to highlight future research directions and promote sustainable bamboo utilization through effective preservation strategies.

## 2. STRUCTURAL, CHEMICAL AND TECHNOLOGICAL DIMENSIONS OF BAMBOO DURABILITY

### *2.1. Bamboo as a lignocellulosic material: anatomical and chemical basis of durability*

Bamboo is anatomically and chemically distinct from wood, despite superficial similarities in appearance and use. Unlike dicotyledonous trees, bamboo exhibits longitudinal growth without secondary radial growth, resulting in a culm structure characterized by nodes, internodes and a hollow cylindrical geometry. The bamboo culm wall consists primarily of vascular bundles embedded in parenchymatous ground tissue, with a higher concentration of fibers toward the outer periphery, conferring superior tensile strength and stiffness ( (Correal et al., 2025)

Chemically, bamboo is composed of cellulose (40–50%), hemicellulose (15–25%), lignin (20–30%), and minor constituents such as starches, sugars, proteins, extractives and ash (Fattah et al., 2014; Zhang et al., 2018). The high proportion of parenchyma cells, which function as storage tissues, leads to elevated concentrations of starch and simple carbohydrates. These nutrients serve as a primary food source for fungi, termites, and beetles, explaining bamboo’s inherently low natural durability (Liese, 1987; Tang et al., 2012; Kaur et al., 2016).

Studies on processed bamboo for structural applications have demonstrated that chemical composition varies with species, age, internode position, and processing method (Fattah et al., 2014). Sharma et al. (2018) reported that industrial treatments such as bleaching significantly alter lignin and hemicellulose fractions, influencing both durability and mechanical performance. While removal of sugars during processing may enhance resistance to biodegradation, it can simultaneously weaken structural integrity if not carefully controlled.

### *2.2. Natural durability and mechanisms of bamboo degradation*

Untreated bamboo is widely reported to have a service life of only 2–5 years under storage or service conditions, particularly in humid tropical environments. Degradation occurs due to a combination of biological, physical, and environmental factors. Among these, biological agents namely fungi, termites, beetles (*Dinoderus minutus*), and bacteria, are the most destructive (Kaur et al., 2016).

Fungal degradation is primarily caused by white-rot and brown-rot fungi, which attack cellulose and lignin, leading to loss of mass and mechanical strength. Brown-rot fungi preferentially degrade carbohydrates, whereas white-rot fungi degrade lignin as well as cellulose (Tang et al., 2012). Termite attack, particularly by subterranean termites, can lead to catastrophic failure of bamboo structural elements in a short period.

The susceptibility of bamboo to biodeterioration is exacerbated by high moisture content at harvest (up to 150% on a dry-weight basis), absence of protective extractives such as resins and tannins, poor radial permeability due to lack of ray cells, presence of silica and waxy outer layers that restrict preservative penetration (Sen et al., 2009; Shi et al., 2023). These factors collectively necessitate the application of preservation treatments to ensure durability in service.

### *2.3. Early research and traditional knowledge on bamboo preservation*

Traditional bamboo preservation practices represent some of the earliest documented attempts to enhance durability using low-cost, locally available methods. The literature indicates that traditional bamboo preservation practices include water soaking, mud coating, smoking, lime application and harvesting during specific seasons (Singha et al., 2017).

Water leaching, involving immersion of fresh culms in running or stagnant water for several weeks to months, facilitates the removal or fermentation of starches and sugars. Studies have shown reduced susceptibility to fungal and insect attack following prolonged water soaking (Ashaari and Mamat, 2000). Smoking exposes bamboo to heat and smoke-derived phenolic compounds, which may impart limited antifungal properties (Li et al., 2022; Xia, 2023).

While environmentally safe, traditional methods suffer from inconsistent efficacy, long treatment durations, and lack of standardization. Their protective effects are often temporary and insufficient for modern structural or industrial applications. Nonetheless, these methods laid the conceptual foundation for understanding the relationship between nutrient removal and durability.

### *2.4. Development of chemical preservation techniques*

The mid-20$^{th}$ century marked a transition from traditional methods to chemical preservation, driven by the need for longer service life and standardized performance. Chemical preservatives such as boric acid–borax mixtures, copper-based formulations, creosote, and chromated copper arsenate (CCA) became widely adopted (Sen et al., 2009; Handana et al., 2020; Tomak et al., 2022).

Boron compounds emerged as particularly effective due to their broad-spectrum biocidal activity against fungi and insects. Boron-based preservatives are water-soluble, self-diffusing, and relatively low in mammalian toxicity. However, their major limitation is high leachability, which restricts their use in exposed outdoor conditions (Kaur et al., 2016).

Copper-chrome-arsenic (CCA) and copper-chrome-boron (CCB) preservatives offer higher fixation and durability but pose significant environmental and health risks due to the presence of chromium and arsenic (Tomak et al., 2022). Increasing regulatory restrictions have led to a decline in their use, especially in residential and rural applications. The literature consistently highlights a trade-off between durability and environmental safety in chemical preservation, motivating the search for alternative solutions.

### *2.5. Emergence of eco-friendly and bio-based preservatives*

Growing environmental awareness and regulatory pressures have stimulated extensive research into eco-friendly bamboo preservation technologies (Bih et al., 2025). Kaur et al. (2016) provided a comprehensive review of developments in plant-based preservatives, organic acids, essential oils, and modified natural polymers.

Plant extracts derived from neem (*Azadirachta indica*), camphor (*Cinnamomum camphora*), and other species contain secondary metabolites such as terpenoids, phenolics, and alkaloids with antifungal and insecticidal properties (Hao et al., 2021). Xu et al. (2013) demonstrated that bamboo treated with camphor leaf extract exhibited improved decay resistance, particularly when combined with a fixing agent such as melamine-urea-formaldehyde resin, enhancing thermal stability and controlled release of active compounds (Zhang et al., 2018).

Similarly, tannin-based preservatives have gained attention due to their natural origin and multifunctional properties. Tannins extracted from *Acacia mearnsii* have been shown to improve resistance against fungal decay and weathering. However, tannins and boron compounds used individually suffer from leaching issues (Gauss et al., 2021b).

Gauss et al. (2021a) reported that tannin-boron formulations, particularly when cross-linked with hexamine, significantly improved fungal resistance, thermal stability, and mechanical properties of *Dendrocalamus asper*. These findings represent a critical advancement, suggesting that hybrid organic–inorganic systems may overcome the limitations of single-component preservatives.

Beyond chemical impregnation, thermal modification and processing treatments have been investigated as indirect preservation strategies. Thermal treatment reduces hygroscopicity, removes sugars, and alters hemicellulose composition, thereby improving resistance to biological attack (Zmuda and Radomski, 2020). Sharma et al. (2018) demonstrated that caramelization and bleaching processes used in laminated bamboo production reduce starch content and modify lignin structure. While these treatments enhance durability and dimensional stability, excessive thermal degradation can compromise mechanical strength. Thus, optimization of treatment parameters is essential. Heat treatment, when combined with chemical or bio-based preservatives, has been suggested as a synergistic approach, though long-term field performance data remain limited (Li et al., 2022).

## 3. DIFFERENT TECHNIQUES OF BAMBOO PRESERVATION

Bamboo preservation techniques have evolved in response to increasing demand for durability, environmental sustainability and structural reliability. Preservation methods can broadly be classified into traditional non-chemical approaches, chemical treatments, eco-friendly and bio-based systems, and modern impregnation and processing technologies (Putri et al., 2020). Each category reflects distinct technological paradigms, with varying implications for effectiveness, cost, environmental impact and applicability.

### *3.1. Traditional (non-chemical) methods of bamboo preservation*

Traditional bamboo preservation methods are deeply rooted in indigenous knowledge systems and have been practiced for centuries across Asia, Africa and Latin America. These methods rely on physical processes and environmental exposure rather than synthetic chemicals and are generally low-cost and environmentally benign (Baharuddin et al., 2022).

#### *3.1.1. Seasonal harvesting*

Seasonal harvesting is one of the earliest forms of bamboo preservation. Culms harvested during the dry season or after flowering are believed to contain lower starch and moisture content, reducing susceptibility to insect and fungal attack. Studies have shown that bamboo harvested at maturity (3–5 years) exhibits enhanced durability compared to younger culms (Shi et al., 2023).

#### *3.1.2. Water leaching and soaking*

Water leaching involves immersing freshly cut bamboo culms in flowing streams or stagnant water bodies for several weeks to months. This process facilitates the removal or fermentation of soluble sugars and starches present in parenchyma cells, thereby reducing nutrient availability for biodegrading organisms. While effective in reducing beetle attack, prolonged soaking may lead to surface staining, reduced mechanical strength, and logistical constraints (Kaur et al., 2016).

#### *3.1.3. Smoking and heat exposure*

Smoking bamboo over low-intensity fires introduces phenolic compounds and organic acids derived from wood smoke into the culm surface. These compounds impart limited antifungal and insect-repellent properties. Additionally, heat exposure reduces moisture content and may partially degrade hemicellulose (Xia, 2023). However, smoking provides only superficial protection and lacks long-term effectiveness (Li et al., 2022).

### *3.2. Chemical preservation techniques*

Chemical preservation represents a major advancement in bamboo durability enhancement, offering systematic and long-lasting protection against biodeterioration (Fattah et al., 2014; Khadiran et al., 2023). Chemical preservatives are typically applied through diffusion, soaking, pressure impregnation, or sap displacement methods.

#### *3.2.1. Boron-based preservatives*

Boron compounds, such as boric acid and borax mixtures, are among the most widely used preservatives for bamboo. Their advantages include broad-spectrum biocidal efficacy, low mammalian toxicity and cost-effectiveness. Boron acts by disrupting enzyme activity and metabolic processes in fungi and insects (Handana et al., 2020).

However, boron preservatives are highly water-soluble and prone to leaching, limiting their suitability for exposed or outdoor applications. Kaur et al. (2016) emphasized the need for fixation strategies to improve boron retention in bamboo.

#### *3.2.2. Copper-based and chromium-containing preservatives*

Preservatives such as copper-chrome-boron (CCB) and chromated copper arsenate (CCA) offer enhanced fixation and resistance to leaching. Copper acts as the primary fungicide, while chromium functions as a fixing agent. Despite their effectiveness, environmental and health concerns related to chromium and arsenic have led to regulatory restrictions in many countries (Tomak et al., 2022).

*3.2.3. Oil-borne preservatives*

Creosote and other oil-borne preservatives provide excellent protection against termites and decay fungi. However, their strong odour, toxicity, and unsuitability for indoor applications have significantly limited their use in bamboo preservation.

*3.3. Eco-friendly and bio-based preservation methods*

Eco-friendly bamboo preservation techniques aim to balance durability enhancement with environmental safety. These approaches have gained prominence due to growing concerns over chemical toxicity and sustainability.

*3.3.1. Plant extracts and essential oils*

Plant-derived preservatives, including extracts from neem, camphor and eucalyptus, contain bioactive compounds such as terpenoids, flavonoids and phenolics. Xu et al. (2013) demonstrated that bamboo treated with camphor leaf extract exhibited enhanced resistance to fungal decay, particularly when combined with a resin-based fixing agent. The primary limitations of plant extracts include variability in composition, limited penetration depth, and reduced long-term effectiveness under outdoor conditions (Bih et al., 2025).

*3.3.2. Tannin-based preservatives*

Tannins are polyphenolic compounds capable of forming complexes with proteins and metal ions. Tannin-based systems have shown promise in enhancing fungal resistance and dimensional stability. When combined with boron compounds and cross-linking agents such as hexamine, tannin-boron formulations significantly reduce leaching and improve durability (Gauss et al., 2021a; Gauss et al., 2021b).

*3.3.3. Organic acids and natural polymers*

Organic acids, such as acetic and lactic acid, reduce pH levels unfavorable to fungal growth. Natural polymers, including chitosan and starch derivatives, have also been investigated as preservative carriers. While environmentally benign, these systems often require further optimization to achieve industrial-scale applicability (Kaur et al., 2016).

*3.4. Modern impregnation and processing technologies*

Modern preservation technologies focus on improving preservative penetration, fixation, and compatibility with engineered bamboo products.

*3.4.1. Pressure and vacuum impregnation*

Pressure-vacuum systems enhance preservative uptake by removing air from bamboo pores and forcing preservatives into vascular tissues. Although effective, these systems are capital-intensive and may be impractical for small-scale or rural settings.

*3.4.2. Sap displacement and boucherie method*

The Boucherie method utilizes transpiration to replace sap with preservative solution in freshly harvested bamboo. Modified versions of this method improve preservative distribution while reducing chemical consumption. However, the method is limited to green bamboo and requires immediate treatment post-harvest (Changchai et al., 2020).

*3.4.3. Processing-induced preservation*

Industrial processing techniques, such as bleaching, extractive removal, etc, indirectly contribute to preservation by reducing starch content and altering chemical composition. Sharma et al. (2018) and Gauss et al. (2020) noted that these processes enhance durability but must be carefully controlled to prevent degradation of mechanical properties.

*3.5. Comparative evaluation of bamboo preservation techniques*

A comparative assessment of preservation techniques reveals significant trade-offs among durability, environmental impact, cost and applicability. Traditional methods are low-cost and sustainable but lack long-term effectiveness. Chemical preservatives provide reliable durability but pose environmental and regulatory challenges. Eco-friendly methods offer promising alternatives but require further research to ensure consistent performance (Madhushan et al., 2023). Modern impregnation technologies enable high-performance applications but demand substantial infrastructure and technical expertise (Khadiran et al., 2023). The choice of preservation technique should therefore be guided by intended application, exposure conditions, available resources, and sustainability considerations. Integrated approaches that combine traditional knowledge with modern eco-friendly technologies may represent the most viable path forward for sustainable bamboo utilization.

## 4. GLOBAL SCENARIO OF BAMBOO PRESERVATION

The global landscape of bamboo preservation reflects diverse ecological conditions, technological capabilities, cultural practices, and regulatory frameworks. Countries with long traditions of bamboo utilization have progressively transitioned from empirical preservation practices to scientifically optimized and industrial-scale technologies (Dutta et al., 2025). This evolution has been driven by growing recognition of bamboo as a strategic renewable material for sustainable construction, furniture manufacturing, and composite industries (Sain et al., 2024).

### *4.1. Regional practices and technological advancements*

Globally, bamboo preservation practices vary significantly depending on climatic conditions, species diversity, level of industrialization, and end-use applications. Tropical and subtropical regions face greater challenges due to high humidity, temperature and biological activity, necessitating more robust preservation systems. In East and Southeast Asia, bamboo preservation has evolved from traditional water soaking and smoking methods to advanced chemical impregnation and engineered bamboo technologies. Countries such as China and Japan have integrated preservation into the entire bamboo value chain, ensuring durability from harvest through final product manufacturing. In Latin America, particularly Brazil, bamboo preservation research has focused on adapting Asian technologies to local species and climatic conditions. Preservation efforts emphasize construction-grade bamboo for housing and infrastructure, supported by academic and governmental initiatives (Dewi et al., 2023). In Africa, bamboo preservation remains largely dependent on traditional methods, although pilot projects and international collaborations have introduced boron-based and eco-friendly treatments to support rural development programs (Mwanja et al., 2023).

China represents the most advanced and comprehensive example of bamboo preservation and utilization worldwide. As the largest producer and exporter of bamboo products, China has invested heavily in research, standardization, and industrial processing. Preservation is integrated into the production of engineered bamboo materials, such as laminated bamboo lumber, bamboo scrimber, and bamboo flooring. Boron-based preservatives are widely used in combination with pressure impregnation and heat treatment to ensure durability and dimensional stability (Xia, 2023). Research institutions have developed modified boron fixation systems to reduce leaching, enhancing suitability for exterior applications. Sharma et al. (2018) highlighted that industrial processing techniques in China significantly reduce starch content, indirectly improving resistance to biodegradation. China's success lies in its system-level approach, combining preservation, processing, and product standardization. This has enabled bamboo to compete directly with timber and steel in structural applications.

Japan's bamboo preservation practices emphasize precision, material longevity, and environmental safety. Historically, Japanese craftsmen relied on smoking, oil treatment and surface carbonization (yakisugi-inspired techniques) to enhance durability. Modern approaches integrate low-toxicity preservatives and controlled thermal modification. Japanese research focuses on long-term performance and aesthetic preservation, particularly for architectural and interior applications. Chemical usage is strictly regulated, encouraging the development of eco-friendly treatments and surface coatings. Preservation is often combined with meticulous design practices that minimize moisture exposure, demonstrating that design and preservation are complementary strategies.

Countries such as Indonesia, Thailand, Vietnam and Malaysia have rich bamboo traditions and extensive species diversity. Preservation practices historically relied on water soaking, mud coating, and smoking. However, increased demand for bamboo housing and furniture has accelerated adoption of chemical and bio-based treatments (Zheng and Zhu, 2021). Boron diffusion methods are widely employed due to their affordability and effectiveness. Modified Boucherie techniques are commonly used for freshly harvested bamboo, particularly for housing applications. Regional research has also explored plant-based preservatives, leveraging locally available resources such as neem and eucalyptus extracts (Kaur et al., 2016). Despite technological progress, challenges remain related to quality control, treatment uniformity, and limited access to advanced impregnation facilities.

In Latin America, particularly Brazil, Colombia, and Ecuador, bamboo preservation has gained importance in the context of social housing and sustainable construction. Species such as *Guadua angustifolia* are widely used for load-bearing structures, necessitating effective preservation. Preservation practices combine boron-based treatments with design strategies that minimize ground contact and moisture exposure. Research institutions have emphasized field performance evaluation and life-cycle assessment to validate preservation effectiveness under tropical conditions (Zheng and Zhu, 2021). Latin American approaches highlight the importance of context-specific preservation strategies, integrating chemical treatment with architectural design and construction practices.

### *4.2. International standards and policy frameworks*

International organizations and policy frameworks have played a crucial role in promoting standardized bamboo preservation practices. The International Network for Bamboo and Rattan (INBAR) have been instrumental in disseminating technical guidelines, capacity-building programs, and best practices for bamboo preservation, particularly in developing countries ( Kumar and Sastry, 1999). Several countries have developed national standards for bamboo treatment, addressing preservative types, application methods, and durability requirements (Sen et al., 2009). However, unlike timber, bamboo lacks universally harmonized international standards, leading to variability in treatment quality and performance (Kamble and Subramaniam, 2020).

Global policy trends increasingly emphasize on reduction of hazardous chemicals, promotion of eco-friendly preservatives, integration of preservation into sustainable forest management, alignment with climate-resilient and low-carbon construction policies (Sain et al., 2024). Recent policy discourse also highlights the role of bamboo preservation in achieving circular economy objectives, extending product life cycles, and reducing material waste. The global scenario of bamboo preservation reveals a clear progression from traditional methods to advanced, integrated technologies. Countries with strong research infrastructure and industrial capacity have successfully mainstreamed bamboo preservation into modern construction and manufacturing systems (Auwalu et al., 2019). Conversely, regions with limited resources continue to rely on traditional methods, underscoring the need for technology transfer and capacity building. The global experience demonstrates that effective bamboo preservation is not solely a technical issue but a socio-economic and policy-driven process. Successful models integrate preservation with processing, design, regulation, and market development.

## 5. INDIAN SCENARIO OF BAMBOO PRESERVATION

India occupies a pivotal position in the global bamboo landscape due to its vast species diversity, wide ecological range, and strong socio-economic dependence on bamboo-based systems. Bamboo preservation in India is deeply intertwined with traditional practices, rural livelihoods, and emerging industrial demands. Despite abundant bamboo resources, the potential of bamboo as a durable structural and industrial material remains underutilized due to gaps in preservation technologies, infrastructure, and policy implementation.

India is home to one of the richest bamboo genetic resources in the world, with approximately 136 species across 30 genera, distributed across diverse agro-climatic zones. Bamboo forests cover nearly 14 m ha, primarily concentrated in the northeastern states, central India, and the Western Ghats. Dominant genera include *Bambusa*, *Dendrocalamus*, *Melocanna*, *Ochlandra*, and *Thyrsostachys* (Negi et al., 2022). Species such as *Dendrocalamus strictus*, *Bambusa bambos*, *Bambusa tulda*, and *Melocanna baccifera* are extensively used for construction, handicrafts, paper and pulp, and rural housing (Kaur et al., 2013; Dewi et al., 2023).

The durability of these species varies considerably, influenced by anatomical structure, chemical composition, and environmental exposure. Studies indicate that most Indian bamboo species possess low natural resistance to termites and fungi, necessitating preservation for long-term use (Kaur et al., 2016). Given the predominance of bamboo in tribal and rural livelihoods, preservation assumes importance not only as a technical intervention but also as a socio-economic necessity.

Traditional bamboo preservation practices in India represent centuries of indigenous knowledge adapted to diverse ecological conditions. These methods include seasonal harvesting, water immersion, smoking, and surface treatments such as mud or lime coating. Harvesting during low-sap periods helps reduce internal nutrient content that attracts insects. In northeastern India, bamboo culms are commonly submerged in rivers or ponds for several weeks to leach out starches and sugars, thereby lowering susceptibility to infestation. In rural housing systems, exposure to household smoke is used to reduce moisture content and provide limited resistance against beetles and fungi. Mud and cow dung plastering are applied to walls and structural components to create a protective external layer that restricts pest access. Although these approaches are economical and environmentally friendly, their effectiveness varies due to limited treatment penetration and dependence on local environmental conditions.

Consequently, while traditional practices remain relevant in low-income and remote areas, they are insufficient for modern structural applications or long-term durability requirements (Kamble and Subramaniam, 2020).

Modern bamboo preservation practices in India have been significantly influenced by research institutions, forestry departments, and international collaborations. Boron-based preservatives are the most widely adopted chemical treatments due to their effectiveness, affordability, and relative safety. Methods such as soaking, diffusion, sap displacement, and modified Boucherie techniques are commonly employed, particularly for housing and handicraft applications (Kaur et al., 2013). Copper-based preservatives, including copper–chrome–boron (CCB), have been used for outdoor and ground-contact applications; however, concerns related to toxicity, environmental impact, and regulatory compliance have limited their widespread adoption (Kaur et al., 2016). Despite proven effectiveness, adoption of chemical preservation remains uneven due to limited access to treatment facilities, high initial investment costs, lack of technical training among rural users, and inadequate quality control mechanisms.

In recent years, Indian research has increasingly focused on eco-friendly bamboo preservation technologies aligned with sustainability goals and local resource availability. Studies on plant-based preservatives, including neem, camphor, and tannin-rich extracts, have demonstrated promising antifungal and insecticidal properties (Sen et al., 2009; Hao et al., 2021). Research on camphor leaf extract reported improved resistance to fungal decay when combined with polymeric fixing agents, highlighting the potential of hybrid bio-based systems (Xu et al., 2013). Similarly, tannin–boron formulations have gained attention due to enhanced fixation and reduced leaching behavior (Gauss et al., 2021b). These approaches are particularly relevant in the Indian context, where environmental regulations, rural livelihoods, and the availability of plant resources intersect (Gauss et al., 2020). However, challenges related to standardization, scalability, and long-term field performance remain significant.

Institutional support has played a crucial role in shaping bamboo preservation practices in India. The Indian Council of Forestry Research and Education (ICFRE), along with institutions such as the Forest Research Institute (FRI), Dehradun, has conducted extensive research on bamboo treatment and utilization. The National Bamboo Mission (NBM) represents a major policy initiative aimed at promoting bamboo cultivation, processing, and value addition. The mission emphasizes infrastructure development, skill training, and market linkages, thereby indirectly supporting the adoption of preservation technologies. The International Network for Bamboo and Rattan (INBAR) have also collaborated with Indian institutions to disseminate best practices, technical manuals, and capacity-building programs related to bamboo preservation and sustainable management (Dutta et al., 2025).

Despite policy support and research advancements, several challenges continue to hinder effective bamboo preservation in India. These include the lack of standardized preservation protocols tailored to Indian species, limited penetration of eco-friendly technologies into rural areas, high variability in treatment quality and durability outcomes, insufficient integration of preservation into bamboo value chains, and weak enforcement of quality standards and building codes (Dwivedi et al., 2019; Dutta et al., 2025). Addressing these challenges requires a coordinated approach involving research institutions, policymakers, industry stakeholders, and local communities.

Overall, while traditional methods continue to dominate rural practices, the growing demand for durable bamboo products necessitates the adoption of scientifically validated preservation techniques (Mohan et al., 2022). Eco-friendly and bio-based approaches offer promising pathways but require further research and institutional support to achieve scalability and consistency. India's rich bamboo resources, combined with targeted policy interventions and technological innovation, position the country to emerge as a global leader in sustainable bamboo utilization-provided preservation challenges are effectively addressed (Alexander, 2022; Choudhury and Shaw, 2024).

## 6. CONCLUSION

The literature consistently established that preservation constituted the foundation for advancing bamboo as a durable and structurally reliable material. Evidence on boron-based and emerging plant derived formulations demonstrated strong potential when scientifically optimized. However, long term field validation under diverse climatic conditions, standardized treatment protocols and stronger incorporation into national standards and building regulations remained essential. Sustained collaboration among research institutions, industry stakeholders and regulatory bodies was therefore critical to mainstreaming preserved bamboo within sustainable and low-carbon construction systems.

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