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Advancements and Applications of Sustainable Forestry Materials in Engineering

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Abstract. The role of forestry in providing renewable, sustainable and environmentally friendly materials in engineering is increasingly being emphasized. This paper explores the recent advancements and diverse applications of sustainable forestry materials in several engineering sectors. A systematic and structured review was conducted, using literature from Web of Science, Scopus, ScienceDirect, and Google Scholar databases in the past decade. The results revealed that integration of sustainable forestry materials, such as timber, bamboo, cork, and engineered wood products like cross-laminated timber (CLT) and laminated veneer lumber (LVL), offers significant environmental benefits, including renewable sourcing, reduced carbon footprints, and versatile applications across various engineering sectors. Forestry sustainable materials provide viable replacements for traditional building materials in construction, automotive and aerospace. In addition, forestry materials are also being used in consumer goods, appreciating their aesthetics and performance properties. Furthermore, the results revealed that advanced processing techniques, such as thermal modification and chemical treatments, enhance the durability and performance of these materials for demanding applications. However, challenges like material degradation, high initial costs, unsustainable harvesting practices, and slow updates to building codes hinder their widespread adoption. Overcoming these barriers will require the development of standardized testing methods, improved processing technologies, greater market acceptance, and supportive policies, alongside advances in biotechnology. Therefore, sustainable forestry materials offer environmentally friendly and renewable alternatives in construction, automotive, and aerospace engineering. Advanced processing techniques enhance their durability, enabling their use in demanding applications while reducing carbon footprints.

1.0 Introduction

The increasing focus on sustainability in engineering and material sciences has addressed the importance of sustainable forestry materials. Made from sustainably managed forests, the materials present a renewable and eco-friendly solution compared to traditional resources like steel, concrete and plastics [1]. Engineers play a vital role in nature, structure, economics, and society, making their contributions essential for sustainable development. [2].

When it comes to the environmental impact, sustainable forestry products such as timber, bamboo, cork and engineered wood product holds key to protecting environment in numerous forms. One of the biggest pros is probably their renewable source. Forestry materials, as opposed to finite resources like metals or fossil fuels, can be renewed under sustainable forest management practices [3]. Sustainable forestry uses algorithms and tools to manage natural resources responsibly, maintaining ecological balance and environmental capacity for the long term [1].

Trees, as they grow larger over time, act as carbon sinks that absorb carbon dioxide from the atmosphere [4]. The carbon is stored in soil or biomass formed by the leaves, stems and roots of trees. Thus, trees reduce greenhouse gases by sequestering carbon in their biomass and surrounding soil. Moreover, when wood is used in long-term applications such as construction the stored carbon remains locked away and therefore further reduces carbon emissions. Forestry materials have a smaller overall environmental footprint than traditional resources since production and processing forestry do not require as much energy or generate as many emissions [5].

Furthermore, sustainable forest materials offer structural and functional benefits, enhanced by advanced techniques like thermal modification and cross-lamination, making them attractive for diverse applications [6]. Cross-laminated timber and laminated veneer lumber provide strength comparable to or greater than traditional building materials. They help enhance the use of wood in tall buildings and other challenging structures since it provides strength and durability. But forestry materials are so versatile. They can be configured for a range of engineering applications from building to production [7]. Additionally, forestry materials reduce carbon footprints in construction through energy-efficient designs and excel in automotive and aerospace industries with their lightweight, high-strength properties that boost fuel efficiency and performance [8].

Sustainable forestry provides economic and social benefits, supporting rural development and self-sufficiency in areas with high forest ownership but limited job opportunities. Thus, sustainable forestry brings job-creation to these areas, encouraging economic stability and growth. Rising demand for sustainable products gives wood and forest materials a competitive edge for companies. It is possible for a company to improve its reputation by utilizing eco-friendly materials [9].

In addition, green building is becoming a necessary part of new buildings as more and more sustainable forestry materials are used. They are viable substitutes for conventional building materials in construction, helping to reduce energy demand in buildings and support the UN development goals [10]. Forestry materials are showcased in green buildings, renovations, and infrastructure projects, demonstrating their practicality and advantages. Their lightweight strength suits automotive, aerospace, and military applications, reducing costs, while their durability and aesthetics make them valuable for consumer goods [11, 12]. Sustainable forestry materials are crucial for promoting environmental sustainability, offering renewable and eco-friendly alternatives to traditional materials across various engineering sectors [9, 11]. This review uniquely focuses on the recent advancements and practical applications of materials like timber, bamboo, cork, and engineered wood products, highlighting their potential to reduce carbon footprints and replace conventional building materials in construction, automotive, and aerospace. The review also emphasizes the role of advanced processing techniques, such as thermal modification, in enhancing the durability and performance of these materials. By addressing challenges like material degradation and high costs, the review suggests ways to overcome barriers to their widespread adoption and further promote sustainability in engineering.

Therefore, this review aims to present a comprehensive survey on the progress of Forest sustainable materials, particularly based on their fabrication techniques and engineering applications in various fields. The specific objectives of this review study were: (1) to identity different types of sustainable forest materials (SFM) used in engineering, (2) to determine the processing techniques of engineered wood products for their effectiveness in improving material performance, (3) to determine the lifecycle analysis of these SFM by assessing their environmental impact from harvesting to end-of-life disposal or recycling, (4) to identify the potential engineering application of forestry material, and (5) to identify key challenges and future directions in the field.

2.0 Materials and Methods

The study employed a systematic and structured approach. The systematic and structured approach was adopted because it ensures comprehensive coverage, minimizes bias, organizes information effectively, and enhances the credibility and reliability of the findings [9]. The review process included the following key steps: (1) identifying primary and secondary terms related to sustainable forestry materials and their application in engineered systems, (2) gathering the literature, and (3) conducting data analysis and reporting the results.

The first step of the review process was to identify primary and secondary terms related to sustainable forestry materials and their application in engineered systems. This was achieved by clearly define the key topics (materials, applications, and engineered systems) and key word brainstorming that led to generation of a list of potential terms including synonyms and related concepts (e.g., sustainable wood, engineered timber, carbon sequestration, cross-laminated timber).

The second step was literature gathering (Figure 1) using Web of Science, Scopus, ScienceDirect and Google Scholar databases. The first two were selected because they are considered two of the largest online databases [11], while ScienceDirect provided comprehensive coverage of engineering shared pool studies. On the other hand, Google Scholar was used to identify any other relevant literature that might have been missed in the first three mentioned databases. A total of 634 peer reviewed academic articles were retrieved. Then, the articles were subjected to title and abstract screening. After this process, a total of 569 articles were removed, remaining with 65 articles. The excluded articles mostly did not reflect the current state of knowledge in the field of sustainable forestry and engineering advancements. Full-text screening resulted in the exclusion of further 25 articles. A total of 40 articles were considered for the in-depth review, where information on advancements and applications of sustainable forestry materials in engineering was analysed.

The third step was data analysis and reporting the findings. Firstly, data were extracted from each selected article using detailed analytical notes. The data were subjected to manual coding, which was categorized into five themes. The themes that guided the data collection were: “types of sustainable forest materials,” “processing techniques of engineered wood products,” “Life cycle analysis of sustainable forestry materials,” “potential engineering application of forest materials,” and “key challenges and future directions in the forestry and engineering sector.” The coded data were systematically organised in a Microsoft Excel spreadsheet, providing a structured framework for further analysis. The themes were then analysed to determine the nature of the outcomes.

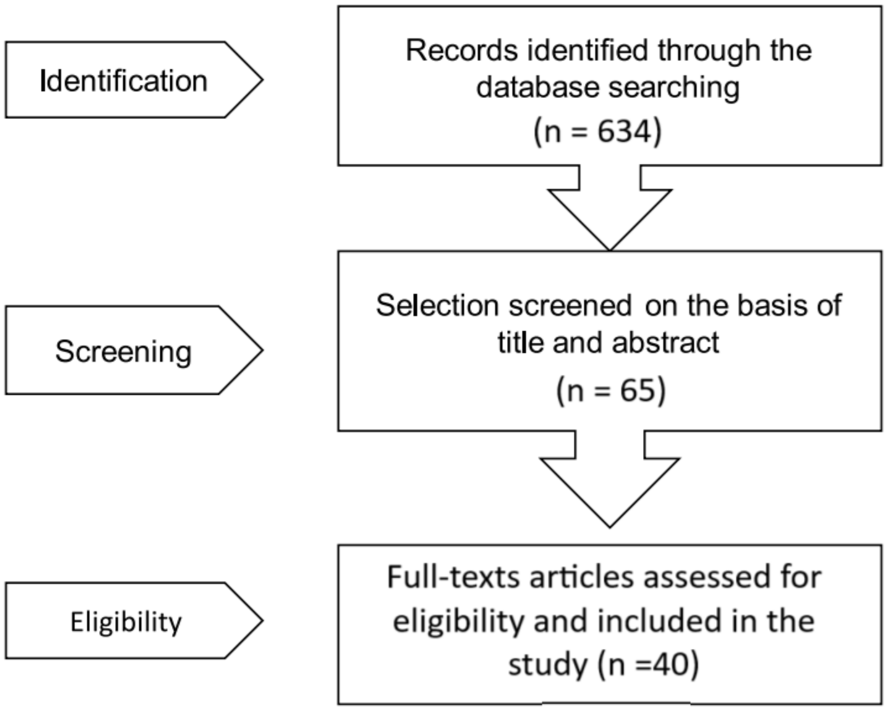

Fig. 1 Methodological approach to the literature review

3.0 Results and Discussion

3.1 Sustainable Forest Materials Used in Engineering

3.1.1 Timber

With its renewable nature, versatile finish and damn near unbeatable strength-to-weight ratio timber is firmly entrenched as the cornerstone of sustainable forestry materials (Figure 2A). Novel applications are extending the traditional uses in construction and furniture manufacture. Recent research shows that responsibly harvested timber can store more carbon dioxide than it emits during its lifecycle. Thus, sustainable forestry practices ensure ecological integrity and natural forest regeneration [13, 14].

3.1.2 Bamboo

Bamboo grows very fast with great mechanical properties. It has some of the highest tensile strength comparable to steel, enabling it for structural uses. Since some species of bamboo mature within as little as three years (on the opposite end, but up to 120 years in others), its renewability is pretty much unparalleled [15]. This is especially relevant in construction where bamboo is abundant or naturally exposed due to material disruption. Research also suggests that bamboo has a large capacity of carbon sequestration - which is one amongst its environmental strengths [16] (Figure 2 B).

3.1.3 Cork

Cork is derived from the bark of cork oak trees and has many interesting properties due to its unique impermeability, buoyancy, elasticity and thermal insulation [17]. Previously it was only used in wine stoppers but today, it finds extensive usage for even innovative applications such as flooring, insulation, and aerospace components. This naturally sustainable harvesting does not damage the tree and allows for bark to be harvested every nine or so years, making cork one of the most renewable materials around [3] (Figure 2C).

3.1.4 Engineered Wood Products

Cross-laminated timber (CLT) (Figure 2D) and laminated veneer lumber (LVL) (Figure 2E) are leading the charge in engineered wood products that will change how buildings are constructed. CLT panels are constructed with layers of timber glued at right angles, they provide high strength and stability as well as fire resistance [18]. LVL is composed of thin wood veneers bonded together into large billets. Together, the technologies form a suite that will enable architects and builders to construct tall wooden buildings rather than using steel or concrete - each of which has its own massive carbon footprint. Scientific research has even suggested that buildings, made of engineered woods products (EWP), may reduce greenhouse gas emissions relative to those built with traditional materials [7].

Fig. 2. Forest Material used in engineering: A, Timber; B, Bamboo; C, Cork; D, Cross Laminated Lumber, and D, Laminated Veneer Lumber

3.2 Processing Techniques

3.2.1 Thermal Modification

Thermal modification is when wood is heated using a specific treatment method and the removal of oxygen [19]. This process increases the materials' resistance to decay and reduces its likelihood of swelling or shrinking in response to humidity levels. Recently, there have been some advances to enhance the thermal modification processes so that substantial harm is not caused in terms of wood strength and energy-efficient controlling. The product is being used more and more in outdoor applications, such as decking and siding. This kind of use may be the key to its success – durability [11].

3.2.2 Chemical Treatments

Chemically treating the wood will add durability and resist pests, rot, and fire. Green chemical formulas are replacing traditional preservatives that can be harmful to the environment [20]. For example, work into the application of biopolymers and natural extracts as wood preservatives is showing potential to enhance longevity of wooden products with decreasing environmental footprint [10].

3.2.3 Mechanical Processing

Shaping and finishing of wood products require some mechanical techniques like milling and cutting. Advancements in precision engineering and automation have made workspace processes smoother, faster, more streamlined [21]. The design of high-precision machinery allows creating complex wood components for all branches of engineering - from the small parts to furniture designs and up to structural elements in buildings [22].

3.3 Life Cycle Analysis of Forestry Materials

Life Cycle Analysis (LCA) is a method used to assess the environmental impacts of a product or material throughout its entire life cycle, from raw material extraction to disposal [23]. Table 1 outlines the stages, or the processes involved in LCA for sustainable forestry materials. Life cycle analysis (LCA) is the important part that evaluates forestry materials and quantifying its overall environmental impact, from cradle-to-grave [23]. This is important to consider, as the majority of LCA studies in recent years have identified a significantly lower environmental footprint for forestry materials when compared with non-renewable alternatives. Thus, forest materials for engineering require less energy for production (embodied energy), generate fewer carbon emissions during its lifecycle, and produce less waste [24]. LCA is essential in environmental impact assessment for the following reasons [23, 24]:

- *Holistic Perspective:* It provides a comprehensive understanding of environmental impacts across the entire life cycle of a material, rather than focusing on one stage, such as production or disposal. This ensures a more accurate comparison between materials like sustainable forestry products and traditional alternatives.
- *Identifying Environmental Hotspots:* LCA helps pinpoint stages in the life cycle that contribute most significantly to environmental degradation, allowing for targeted improvements (e.g., reducing energy use in manufacturing or enhancing end-of-life recycling).
- *Informed Decision-Making:* LCA provides scientific, data-driven insights that help businesses, policymakers, and consumers make informed choices about materials and products, leading to more sustainable options in construction, manufacturing, and beyond.
- *Regulatory Compliance and Certification:* Many sustainability certifications and eco-labels require an LCA to demonstrate a product’s environmental credentials. This ensures products meet environmental standards and can gain certification, fostering credibility and consumer trust.

Table 1 Stages involved in LCA for sustainable forestry materials

No.	Stage Name	Stage Description
Stage 1	Goal and Scope Definition:	Determine the purpose of the analysis (e.g., comparing environmental impacts of bamboo vs. steel) and define the system boundaries (e.g., forest management, transportation, manufacturing, use, and end-of-life stages).
Stage 2	Inventory Analysis	Gather data on all resources used and emissions produced at each stage of the material's life cycle, such as energy consumption, water use, CO_2 emissions, and material extraction. For sustainable forestry materials, this includes tracking the growth of trees (carbon sequestration), harvesting, processing, transportation, and potential waste management.
Stage 3	Impact Assessment:	Analyze environmental impacts based on inventory data. This might include the calculation of global warming potential, resource depletion, water use, and toxicity levels. For sustainable forestry materials, impacts like carbon sequestration (absorbing CO_2) are crucial.
Stage 4	Interpretation:	Review the results to identify stages with the greatest environmental impact and opportunities for improvement. For example, comparing the carbon footprint of bamboo (which absorbs CO_2 during growth) versus concrete (which emits large amounts of CO_2 during production).

Source [24]

3.3.1 Environmental Impact

In fact, forest-based materials (if they come from forests managed in a sustainable way) sequester carbon and preserve biodiversity. The practice of sustainable forestry, also referred to as selective logging allows forests teaming with biodiversity and carbon stores to keep on existing [25]. The use of bamboo and cork has been shown to have positive environmental impacts due to their rapid renewability and minimal processing requirements [2].

3.3.2 End-of-Life Disposal and Recycling

These available opportunities lead to a recycling and repurposing of forestry materials at end-of-life stage [26]. Recovering wood products as new material recycling or energy production, biomass for fuel can promote the vision of circular economy. Recent advancements in recycling technologies have increased the efficiency and quality of recycled wood products allowing them to be used for high-value applications [27].

3.4 Engineering Applications of Forestry Materials

3.4.1 Construction

The importance of forestry materials in making the construction industry more ecofriendly is clear. Several case studies highlight the successful application of timber, CLT and LVL for green building [1]. Another great example is the 18 story Tallwood Brock Commons (Figure 3) in Vancouver which showcases what we can do with forest products to significantly cut down on carbon emissions and lead towards sustainable construction practices [28].

Fig. 3. 18 story Tallwood Brock Commons in Vancouver: Made naturally from wood

3.4.2 Automotive and Aerospace

Automakers are also working on the use of wood-based composites inside vehicles and for basic auto structures, which could provide weight reductions that improve fuel economy [29]. Car and plane, for example, began keeping more widespread usage about recycling plant substances due to their uncomplicated gauge yet extreme lasting build (Figure 4). The thermal and acoustic insulating properties of cork are very useful: it is used in spacecraft heat shields, sound insulation material for submarines, fishing buoys or even soles of shoes [30].

3.4.3 Consumer Goods

Forestry materials are also being used in consumer goods, appreciating their aesthetics and performance properties [31]. Wood, bamboo - it lasts forever like furniture and stands out for its natural beauty (indeed the design is impressive) which can be used to make all kinds of products from wood or make packaging at home. This growing consumer inclination for turf underpinned by forestry materials, is influencing the demand in green spaces sector [32].

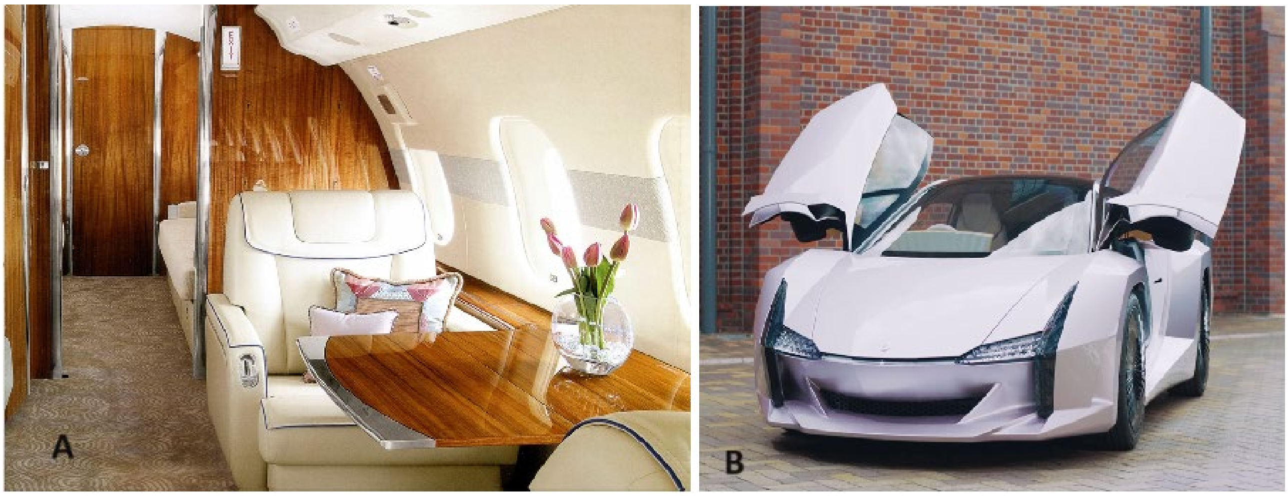

Fig. 4. (A) Inside of Aeroplane made of wood coatings A, and (B) Japanese supercar design made from strong wood-based cellulose nanofibers

Summary of the results on the advantages of sustainable forestry materials over traditional options in terms of construction, automotive, and aerospace are presented in Table 2. Overall, the tables highlight that sustainable forestry materials are more sustainable, efficient, and eco-friendly compared to traditional materials in construction, automotive, and aerospace industries.

Table 2 Comparing sustainable forestry materials (e.g., bamboo, engineered wood, and other bio-based materials) versus traditional construction, automotive, and aerospace materials

Parameter / Criteria	Sustainable Forestry Material	Traditional Materials
Environmental Impact	Lower carbon footprint, renewable, biodegradable	High carbon emissions, non-renewable, energy-intensive to produce
Strength-to-Weight Ratio	Lightweight, strong (e.g., bamboo)	Often heavier, requiring more energy to move or support loads
Durability	Can be treated for enhanced durability (e.g., engineered wood), but may be less resistant to extreme weather without treatment	Generally durable but susceptible to rust (steel), corrosion (aluminum), or wear (plastics)
Energy Efficiency in Production	Requires less energy to produce, especially for materials like bamboo and wood composites	Energy-intensive production processes (e.g., steel and aluminum smelting)
Cost	Generally lower production and maintenance costs; scalable	Higher production costs (e.g., steel, aluminum); more maintenance for wear
Carbon Sequestration	Actively absorbs CO2 during growth (e.g., trees, bamboo), helping mitigate climate change	No carbon absorption capabilities once produced
Sustainability	Renewable resources can be replenished through responsible forest management practices	Limited renewability, dependent on finite resources
Biodegradability	Fully biodegradable, reducing waste in landfills	Non-biodegradable (plastics, metals, concrete) contributes to long-term waste
Flexibility in Design	High flexibility, especially in composite materials like laminated timber	Fixed designs often require complex engineering for alterations
Noise and Vibration Dampening	Good at absorbing sound and vibrations (e.g., wood in automotive applications)	Often requires additional materials or soundproofing solutions
Weight for Efficiency	Lightweight materials like bamboo and engineered wood can reduce overall weight, improving fuel efficiency in transportation sectors	Heavier materials increase fuel consumption and operational costs in both construction and automotive industries
Aesthetic Appeal	Natural aesthetic, often preferred for biophilic design and architecture	Industrial appearance often requires additional finishing for aesthetic purposes
Recyclability	Highly recyclable, especially for wood and bamboo materials	Some materials like aluminum and steel are recyclable, but plastics and composites are difficult to recycle

Source [3,5,8,12]

3.5 Key Challenges in Sustainable Forestry Material in Engineering

Sustainable forestry materials, such as engineered wood products, are increasingly being utilized in engineering due to their environmental benefits and versatility. However, their adoption and effective use face several challenges [12].

3.5.1 Limited Resource Availability and Unsustainable Harvesting Practices

The sustainable sourcing of forestry materials is hindered by overharvesting, deforestation, illegal logging, and insufficient reforestation [17]. These practices reduce the availability of high-quality raw materials, disrupting the balance between supply and demand. For example, China has implemented policies to manage bamboo harvesting sustainably. However, balancing rapid demand growth with ecological health remains challenging [33]. Similarly, in Brazil, the harvesting of tropical hardwoods like mahogany has led to deforestation in the Amazon. Efforts to regulate and promote sustainable logging practices have been undermined by illegal operations, affecting the long-term availability of quality wood [25].

3.5.2. Challenges with Material Performance and Durability

Forestry materials like wood and bamboo are prone to degradation due to moisture, pests, and environmental factors. Ensuring durability requires advanced treatments or engineered solutions, which can increase costs and complexity [20]. The implication is the reduced lifespan of structures, resulting in increased maintenance costs, and limited application in high-stress environments or long-term projects [26]. For example, in rural Colombia, bamboo used for pedestrian bridges faces significant challenges with durability, as it is highly susceptible to insect attacks and moisture damage in humid conditions, necessitating treatments like boron, which add complexity and cost [34]. In addition, in projects like the Mjøstårnet building in Norway, the tallest timber building in the world, CLT faces durability challenges that require the use of specialized adhesives and protective coatings to withstand demanding structural and environmental conditions, adding complexity to its application [30, 31].

3.5.3 High Costs and Limited Economic Viability

Producing sustainable forestry materials often involves additional costs, including certification, advanced processing, and transportation. These costs can make them less competitive compared to conventional materials like steel and concrete [22]. So, the implication is limited adoption in cost-sensitive projects, particularly in developing regions, and slow market growth due to price constraints [33]. For example, in modular housing projects, in Kenya, South Africa and Scandinavia, engineered wood like CLT faces challenges in balancing its benefits, such as reduced construction time, with its higher initial costs compared to traditional materials, which can hinder widespread adoption [24].

3.5.4 Difficulty in Integration into Mainstream Engineering Practices

Forestry materials often face resistance due to a lack of familiarity among engineers, architects, and contractors. Building codes and standards frequently fall behind advancements in engineered wood technologies, limiting large-scale adoption [35]. The implication is increased project risk due to unfamiliarity with performance characteristics. For example, in Tanzania, despite educational initiatives aimed at training engineers and architects on sustainable wood materials, the challenge remains that these programs are not yet widespread enough to significantly influence industry practices and improve confidence and expertise in using these materials [19]. In addition, a challenge in the U.S. has been that many building codes did not permit the use of CLT in high-rise construction. While updates to codes, such as the 2021 International Building Code (IBC), are beginning to allow greater use of timber in large-scale projects, the slow pace of these changes has hindered broader adoption [24].

3.6 Potential Future Directions in Sustainable Forestry Material in Engineering

3.6.1 Standardized Testing Methods

Establishing standardized test methods is vital for verifying the reliability and performance of materials used in forestry. Uniform and detailed testing criteria eventually leads to the broader side of these materials in different engineering domains [15, 33].

3.6.2 Improved Processing Technologies

Sustainability in the circular economies is also available to bio-based resources, requiring continued innovation of processing technologies to enable enhanced properties and applications for forestry materials [34]. More efficient and more eco-friendly methods are going to be the key drivers in developing sustainable materials [35].

3.6.3 Market Acceptance

Developing a National Bioeconomy Strategy will be essential for market acceptance for forest materials; however, greater awareness and education shall be needed [36]. Multi-stakeholder partnerships among industry, academia and policymakers are needed to drive the adoption of sustainable materials toward achieving a truly green building environment that is able endure over time [37].

3.6.4 Biotechnological Advancements and Policy Frameworks

There is a massive opportunity for innovations in biotech and policies to support the uptake of forestry materials [38]. Agricultural biotechnology also has potential to help in producing new species of wood that is main source for raw material which are easily processed than the traditional trees. Providing support in the form of policies - e.g., incentives for sustainable building practices and funding dedicated to researching forestry materials - can further ease barriers inhibiting mass-adoption [39, 40].

4.0 Conclusion

The study has revealed the advancements and applications of sustainable forestry materials in engineering. The integration of sustainable forestry materials, such as timber, bamboo, cork, and engineered wood products like CLT and LVL, offers significant environmental benefits, including renewable sourcing, reduced carbon footprints, and versatile applications across various engineering sectors. Advanced processing techniques, such as thermal modification and chemical treatments, enhance the durability and performance of these materials for demanding applications. However, challenges like material degradation, high initial costs, and slow updates to building codes hinder their widespread adoption. Overcoming these barriers will require the development of standardized testing methods, improved processing technologies, greater market acceptance, and supportive policies, alongside advances in biotechnology. Therefore, sustainable forestry materials have the potential to make a greater contribution to eco-friendly and sustainable engineering practices.

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