Ann. For. Res. 69(1): 45-60, 2026
https://doi.org/10.15287/afr.2026.4342

ANNALS OF FOREST RESEARCH
www.afrjournal.org

Timber as a low-carbon material strategy: A systematic review of substitution effects and mitigation potential in building systems

Șerban Chivulescu[1], Gheorghe Raul Radu[1], Diana Pitar[1], Ștefan Leca[1], Alexandru Claudiu Dobre[1,2]✉, Ovidiu Badea[1,2]

Chivulescu Ș., Radu G.R. , Pitar D., Leca Ș., Dobre A.C.,Badea O., 2026. Timber as a low-carbon material strategy: A systematic review of substitution effects and mitigation potential in building systems Ann. For. Res. 69(1): 45-60.

Abstract The building sector is a major contributor to global greenhouse gas emissions. Substituting carbon-intensive materials with timber presents a significant, yet not fully quantified, climate mitigation opportunity. This systematic review synthesizes three decades of global research to quantify the timber as a substitute effect in the built environment. Its primary objectives are to: (1) consolidate displacement factors and emission reduction ranges from life-cycle assessments, (2) evaluate systemic barriers and enablers for adoption, and (3) provide actionable insights for policy and research. A structured literature search (1990–2024) was performed using Web of Science and Google Scholar. From 12,526 initial records, 12,320 unique studies were screened. Following a full-text review, 80 studies were included in the qualitative synthesis, with 68 providing quantitative data for meta-analysis. A mixed-methods framework combined bibliometric and thematic synthesis. The analysis confirms a robust substitution effect. Replacing steel with wood avoids 2.3 kg of CO_2 per kg of wood, while substituting concrete saves 1.4 kg CO_2/kg. In whole-building systems, emission reductions range from 36 to 530 kg CO_2-equivalents per m^3 of wood. When sourced sustainably, timber serves as a long-term carbon store, with life-cycle assessments showing 34–84% lower climate impact in multi-story applications. Scaling timber use could reduce sector emissions by 20–30% by 2050. Key barriers include prescriptive building codes, fire safety perceptions, and uneven forest governance. Timber as a substitute is a viable, scalable mitigation pathway. Realizing its potential requires updated building codes, carbon pricing mechanisms, and certified sustainable forestry. Future research must standardize life-cycle assessment methods and address geographic literature gaps. This transition can simultaneously advance climate goals, circular economy principles, and green job creation.

Keywords: timber substitution, cross-laminated timber (CLT), embodied carbon, displacement factor, systematic review, low-carbon construction, carbon sequestration.

Addresses: [1]Department of Management Planning, „Marin Drăcea” National Institute for Research and Development in Forestry, Ilfov, Romania. | [2] Forest Management Planning and Terrestrial Measurements, Faculty of Silviculture and Forest Engineering Department of Forest Engineering, Transilvania University, Brașov, Romania.

✉ **Corresponding Author:** Alexandru Claudiu Dobre (dobre.alexandruclaudiu@gmail.com).

Manuscript: received October 10, 2025; revised February 02, 2026; accepted April 16, 2026.

Introduction

The built environment is responsible for approximately 40% of global energy-related CO_2 emissions, making its decarbonization a critical priority for achieving the Sustainable Development Goals (SDGs) the goals of the Paris Agreement and the European Green Deal. A central mitigation pathway, therefore, involves replacing conventional, carbon-intensive materials such as concrete and steel with engineered wood products. Timber as a substitute offers a strategic solution that not only reduces greenhouse gas emissions but also enhances carbon sequestration throughout the life cycle of building materials (Maierhofer et al. 2024). This dual mechanism physical carbon storage and the displacement of emissions-intensive materials was formally recognized as a key climate strategy by the scientific community at forums such as the 2017 IUFRO World Congress. Forests serve as effective carbon sinks, absorbing CO_2 from the atmosphere as they grow. When trees are harvested for sustainable uses such as structural timber, the stored carbon remains locked in the wood for decades (Yu et al. 2024). In addition, replacing high-emission materials such as cement and steel with wood reduces the environmental impact of construction, contributing to an overall reduction in greenhouse gas emissions (Tsunetsugu et al. 2010, Maierhofer et al. 2024).

The fast-expanding applications of forest products - from processed wood in construction to cellulose for textiles, biochemicals, bioplastics and even niche markets such as cosmetics, pharmaceuticals and food additives - highlight the transformative potential of wood as a renewable, low-impact material (Tupenaite et al. 2023). This diversification emphasizes the importance of understanding the environmental and market dynamics of each use, ensuring that wood-based alternatives contribute significantly to both climate change mitigation and long-term sustainability goals (Hassegawa et al. 2022).

Wood has been mainly applied in low- and medium-rise buildings, either in hybrid systems or as the main structural material (Shin et al. 2023). The availability of long span engineered timber components has improved structural stability through durable and high-performance joints (Wieruszewski & Mazela 2017) When sourced from sustainably managed forests, wood continues to store biogenic carbon throughout its lifetime, effectively removing it from the atmospheric carbon cycle for decades (Wieruszewski & Mazela 2017). Bio-based building solutions, such as wood-concrete composites and engineered wood panels, offer innovative ways to increase energy efficiency and reduce carbon emissions (Becchio et al. 2009, Ligne et al. 2020, Pasternack et al. 2022).

Effective timber as a substitute depends heavily on forest management practices, processing efficiency, product longevity, and end-of-life strategies (Gustavsson & Sathre 2011, Malmsheimer al. 2011, Fan et al. 2020). Ensuring that harvested wood remains in circulation through reuse, recycling, or energy recovery extends its carbon storage capacity and supports circularity in the built environment. Reclaimed wood, in particular, not only helps conserve virgin forests but also adds historical and aesthetic value to new construction (Abera 2024).

A growing number of studies emphasize the need for life-cycle thinking in material selection, assessing a product's environmental impact from extraction to disposal (Amin et al. 2022). This perspective reinforces wood's value in low-carbon construction, especially when sustainable forestry and efficient manufacturing are in place. Furthermore, the use of nonconventional engineered wood products, such as cross-laminated timber (CLT) and laminated veneer lumber (LVL), offers a solution to sequester carbon during production and throughout the service life of the material (Singh et al. 2023).

The importance of Life Cycle Assessment (LCA) has grown accordingly, providing a comprehensive framework to evaluate the environmental impacts of timber products across all stages, from forest management and harvesting to processing, transportation, construction, and end-of-life treatment. These assessments consistently show that engineered wood products, especially those used in long-term applications, contribute positively to climate mitigation. A robust environmental assessment of timber construction must evaluate GHG emissions across the entire life cycle, from forest operations and raw material processing to transportation, in-use performance, and end-of-life management (Hafner & Schäfer 2011). LCA enables objective comparisons between timber and conventional construction materials, helping to quantify the true environmental impact of building systems.

Emerging materials like engineered wood products (EWPs), including glued laminated timber (glulam), CLT, and LVL further enhance the climate profile of wood. These materials not only possess favorable mechanical properties but also sequester carbon during production and use, preventing emissions that would have occurred had non-renewable materials been used instead (Singh et al. 2023).

While the reduction of GHG emissions remains a central objective of wood substitution, a truly sustainable building transition requires a broader perspective that takes into account the full spectrum of environmental impacts. In general, timber buildings typically deliver better performance than concrete and steel structures not only in terms of global warming potential, but also in reducing acidification, eutrophication and photochemical smog formation (McDevitt & Allison 2011). However, these benefits may be offset by increased pressure on land and water resources, particularly if forest management and harvesting are not carried out in a sustainable manner. Despite the growing trend of green building construction (Awaludin et al. 2021), the broader environmental trade-offs associated with increased wood use remain underexplored in the literature. Many comparative studies rely on single building assessments, which limits their applicability (Cordier et al. 2021). A robust environmental assessment of material substitution needs to assess the entire life cycle - from extraction and manufacture of raw materials through to construction, use and eventual disposal (Sahoo et al. 2021, Choosing Materials and Products Available online). Only with this comprehensive approach can we ensure that wood substitution is environmentally justified across multiple indicators (Krueger et al. 2019).

The adoption of a circular wood economy depends on sustainable forest management and long-term resource planning, as uncontrolled logging poses a threat to forest regeneration (Roque et al. 2021). Wood processing technologies such as CLT and glulam improves the structural performance of wood, allowing it to be used in taller and more complex buildings (Hassegawa et al. 2022). However, their use must be carefully managed to prevent further resource depletion.

Beyond environmental benefits, wood substitution offers significant economic and social advantages, particularly in emerging economies. It can stimulate job growth in forestry, the wood industry, and green construction, while supporting climate goals (De Araujo et al. 2022). However, obstacles remain: the high initial cost of engineered wood can discourage its adoption in price-sensitive markets (Howard et al. 2022), and public skepticism about fire safety, durability, and structural reliability continues to influence its acceptance, despite growing evidence confirming the performance of wood under appropriate design and regulatory conditions (Mayer 2021, Hassegawa et al. 2022).

Replacing conventional building materials with wood requires an understanding of its anisotropic properties strength and stiffness vary depending on the direction of the fibers (Holmes 1990, Baszen & Miedzialowski 2019). This affects structural design, particularly in load-bearing roles, where grain orientation, joint placement, and moisture sensitivity must be carefully managed. Moisture fluctuations can lead to deformation and loss of strength, making proper drying, preservation, and design essential for long-term performance (Cordier et al. 2021). Advances in fire-retardant coatings, bio-resistant treatments, and protective finishes have expanded the use of wood in diverse climates (Mariani & Malucelli et al. 2022).

While these studies lay a crucial foundation, the literature remains fragmented. Existing reviews often lack a systematic, global synthesis that integrates quantitative displacement factors, full life-cycle assessment (LCA) outcomes, analysis of policy barriers, and circular economy potential, creating a gap between scientific evidence and scalable implementation. To address this gap, this systematic review aims to provide a comprehensive, global synthesis of the climate mitigation potential of timber as a substitute in the built environment. Specifically, it addresses the following research questions:

i) What are the consolidated displacement factors and life-cycle assessment outcomes that quantify the climate mitigation potential of substituting concrete and steel with timber?

ii) What are the principal technical, regulatory, and market barriers hindering the widespread adoption of timber in construction, and which policy and innovation strategies can overcome them?

iii) How can the integration of circular economy principles and sustainable forest management maximize the net environmental benefit of a transition to timber-based construction?

The paper is structured as follows. Section 2 (Materials and methods) details the systematic literature review protocol, search strategy, and analytical framework. Section 3 (Results and discussion) presents the bibliometric findings, synthesizes the evidence on displacement factors and LCA performance, and analyzes the key barriers and enablers for adoption. Finally, Section 4 (Conclusions) summarizes the main findings and provides targeted recommendations for policy, industry, and future research.

Material and methods

To achieve a robust and comprehensive analysis, a structured methodology comprising several key steps was utilized (Figure 1). The process began with an extensive literature search of several academic databases including Web of Science and Google Scholar. The

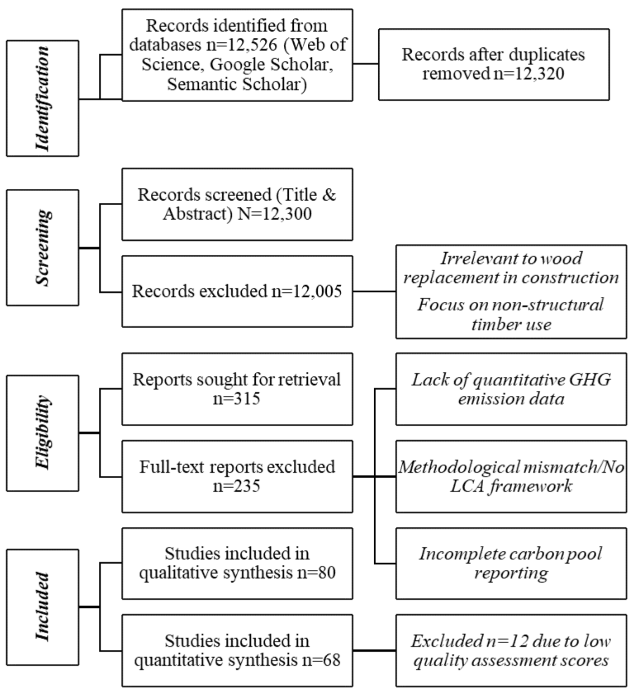

Figure 1 PRISMA flow diagram.

search terms used were the keywords "timber substitution effect" and "timber life cycle assessment" in order to capture a wide range of relevant research. Our systematic review began with initial searches of electronic databases, which yielded a total of 12 526 records. Following removal of duplicates, 12 320 records were subjected to a full screening of titles and abstracts against predefined inclusion and exclusion criteria. This rigorous initial screening phase led to the exclusion of 12 005 records due to their lack of relevance to wood replacement in construction.

Subsequently, the full texts of the remaining 315 items were assessed for eligibility. During this review of the full texts, 235 articles were excluded, mainly because they lacked quantitative greenhouse gas emission data. In the end, 80 studies, published between 1990 and 2024, were deemed suitable for inclusion in the qualitative synthesis, and of these, 68 studies met the criteria for inclusion in the quantitative synthesis (Table 1).

In order to examine how the scientific debate on timber as a substitute and climate change mitigation has developed, we carried out a bibliometric analysis of peer-reviewed articles by year and country of origin (Figure 2).

It can be notice, that most contributions originate from industrialized countries, with the United States, the United Kingdom, and Switzerland emerging as leading centers of research. Several European countries, including Sweden, Germany, Finland, Portugal, Poland, and Romania, also show a consistent presence, linked to their long-standing interest in sustainable forestry and the use of timber in construction. A marked increase in publications appears after 2015, in line with the global policy focus on climate mitigation following the Paris Agreement, while earlier years are characterized by scattered and infrequent studies. After 2020, the literature expands significantly, both in the number of articles and in the range of contributing countries. Nevertheless, regions such as Africa, Latin America, and parts of Southeast Asia remain weakly represented, despite their forest resources and dynamic construction sectors. This imbalance highlights the need for a more geographically diverse body of research to fully assess the global

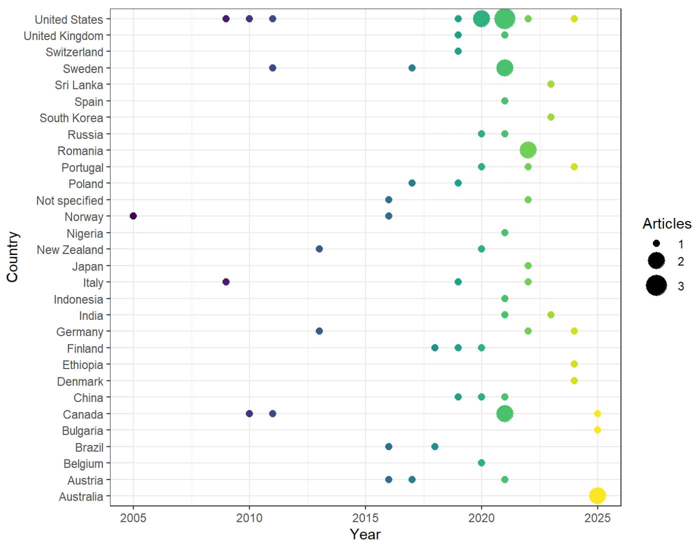

Figure 2 Mapping Global Research Activity Over Time (1990-2023). Bubbles indicate both the volume of articles and their temporal and geographical spread. The horizontal axis represents the year of publication, the vertical axis lists the countries of author affiliation, while bubble size corresponds to the number of articles and the color scale reflects their relative intensity.

Table 1 Inclusion and exclusion criteria.

Criterion	Inclusion Criteria	Exclusion Criteria
Study Focus	Timber as a substitute for mineral-based construction materials (steel, concrete).	Timber use in energy (biomass), furniture, or pulp/paper industries.
Data Metric	Displacement Factors (DF) or Greenhouse Gas (GHG) emission values.	Qualitative reviews or theoretical framework papers without data.
Methodology	Standardized Life Cycle Assessment (LCA)	Economic input-output models without material-specific GHG flows.
Timeline	1990 – 2024.	Publications prior to 1990.

mitigation potential of timber as a substitute.

The review prioritized peer-reviewed journal articles, conference proceedings, and reports from governmental and international organizations (Hansen et al. 2024). Data extraction focused on key metrics such as displacement factors, carbon storage potential, and system boundaries. The synthesized findings were analyzed to identify trends, patterns, and knowledge gaps in the literature. In order to systematize the literature collected through the bibliometric analysis, the reviewed studies were grouped into thematic categories that reflect the main research directions on timber as a substitute and climate change mitigation (Table 2). The classification was based on the central focus of each article, covering topics such as carbon storage, substitution effects, comparative analyses of construction materials, methodological developments, and policy frameworks. This thematic organization allows for a clearer understanding of how different dimensions of timber as a substitute have been addressed and provides a structured basis for identifying both consolidated areas of knowledge and aspects that require further investigation.

Each study was critically evaluated in terms of methodological transparency, data quality and consistency to make sure that the conclusions of the review were supported by evidence (Qian et al. 2025). This systematic approach not only offers a comprehensive assessment of timber substitution's climate mitigation potential but also offers actionable insights for policymakers, industry stakeholders, and researchers. Additionally, the review investigated the implications of mass timber adoption on sustainable timber supply chains.

A mixed-methods framework was applied, combining quantitative bibliometric analysis with qualitative thematic synthesis (Araújo et al. 2020). The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology guided the selection and evaluation of studies to minimize bias and enhance reproducibility.

This systematic and rigorous review process assessed the quality and relevance of each study based on pre-defined criteria, including methodological rigor, peer-review status, and direct alignment with the objectives of the review. To complement the bibliometric overview and the thematic classification, the literature was grouped into four main domains that capture the principal directions of research in this field (Figure 3). This framework provides a structured basis for synthesizing the studies and for comparing their approaches. The first domain, Wood Products, covers topics such as mass timber, engineered wood, and material substitution. The second, Environmental Analysis, includes life-cycle assessment, embodied carbon, climate mitigation, and carbon storage. The third, Structural Systems, addresses aspects related to connections, composite structures, and prefabrication. The fourth domain, Sustainable Strategies, refers to circular economy concepts, forest management, and sustainable construction practices.

The selected studies employed diverse methodologies (based partially on different displacement factors), including life cycle assessments to evaluate the environmental impacts of timber versus conventional materials, material flow analyses to quantify resource efficiency and carbon sequestration potential and econometric modeling to assess market dynamics and scalability of timber-based solutions.

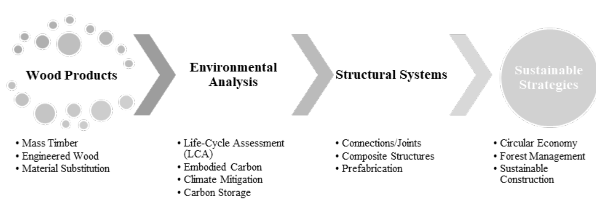

Figure 3 Conceptual framework of research themes.

Results and discussions

Keyword Co-Occurrence Network and Research Landscape Overview

A co-occurrence network of keywords was generated from the selected articles to systematically review the existing literature and identify primary themes and interconnections within the field of timber as a substitute for climate mitigation. The network analysis visualizes the relationships between key concepts, highlighting the most central and frequently discussed topics and their structural links. The size of each node in the network is proportional to its frequency, and the edges represent the co-occurrence of keywords within the same document. The analysis of the conceptual pathway linking research themes in sustainable timber construction (Figure 4), provides a high-level overview of the research landscape and sets the foundation for a deeper thematic discussion.

The network reveals a research landscape centered on Material Substitution for Climate Mitigation, structured around several interconnected clusters. One cluster highlights specific wood products, with strong links between Mass Timber, Cross-Laminated Timber (CLT), and Engineered Wood reflecting a research emphasis on advanced, large-scale wood-based construction solutions. A second cluster focuses on critical assessment tools, where Life-Cycle Assessment (LCA) is closely connected to Carbon Storage and Energy Analysis. The close link of Embodied Carbon to both engineered wood and climate mitigation emphasizes the importance of analyzing manufacturing carbon footprints. A final cluster addresses application and long-term benefits, with keywords like Structural Performance, Sustainable Construction, and Circular Economy. This indicates that the use of mass timber is a technical and environmental discussion, and that researchers see timber as a key component of a more sustainable, closed-loop building sector.

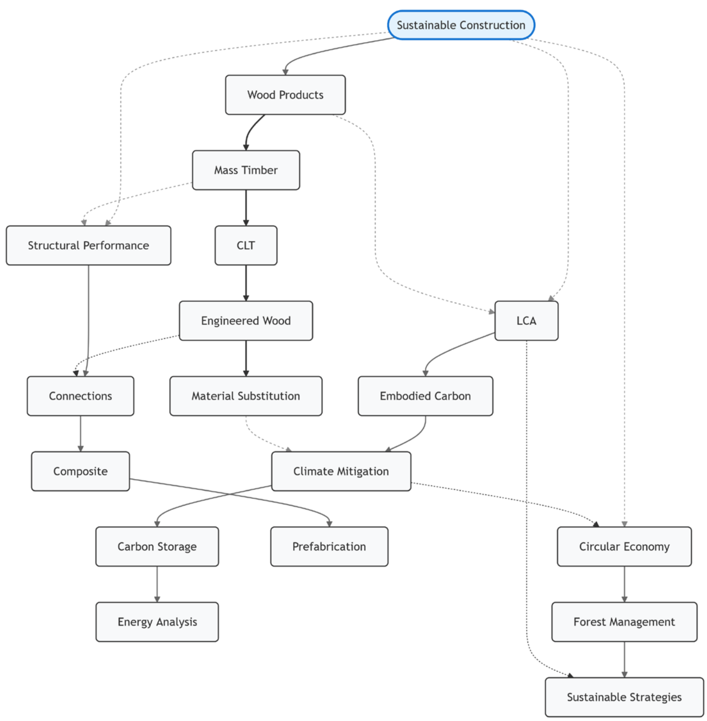

Figure 4 Conceptual pathway linking research themes in sustainable timber construction.

Scientific Foundations of the Substitution Effect

Among commonly used construction materials, substituting steel with wood in construction applications yields a median emissions reduction of approximately 2.3 kg CO_2 per kg of wood used (Howard et al. 2021). Replacing concrete results in about 1.4 kg CO_2 savings per kg, while substituting plastics can lead to even higher reductions up to 3.1 kg CO_2 per kg of wood

(Howard et al. 2021). Research shows that using wood instead of energy-intensive materials such as steel and concrete can make a real difference in reducing emissions. Studies show the strong potential of wood to help tackle climate change when it replaces these carbon-intensive options in construction (Gustavsson & Sathre 2011, Howard et al. 2021).

Although the immediate impact of new timber buildings on global annual CO_2 levels may seem modest, their cumulative effects are significant. As Heräjärvi notes, the substitution effect amplifies the benefits of physical carbon storage, making timber construction a critical component of climate-smart building strategies (Heräjärvi 2019).

Environmental Benefits Beyond Carbon Mitigation

Additionally, to carbon mitigation, wood offers several environmental advantages compared to conventional construction materials. These include lower sulfur dioxide emissions, reduced solid waste generation, and lower fossil energy consumption. However, the use of preservative-treated wood raises concerns regarding toxicity and environmental health (Petersen & Solberg 2005, Malmsheimer et al. 2011). End-of-life considerations are thus vital. Wood products that are no longer needed can often be reused or recycled in new applications, extending carbon storage and further reducing net emissions (Fan et al. 2020).

In fact, carbon accumulation from used and stored wood products was estimated at 88 million tons of CO_2 equivalent in 2008 - about 12% of the total annual rate of forest sequestration (Malmsheimer et al. 2011), highlighting the often-underestimated contribution of harvested wood products to long-term carbon management.

Structural Systems and Engineered Wood Technologies

Connection systems remain a key consideration in timber construction. Mechanical fasteners such as bolts, dowels, or proprietary connectors must be designed to manage load paths, slip resistance, and fire performance (Kuznetsov & Gimranov 2020). Hybrid connections, where timber is reinforced with steel, can increase structural efficiency while meeting sustainability goals (Eldeib et al. 2025). Among modern innovations, CLT enables taller and more complex buildings through excellent dimensional stability and strength in both directions (Hassegawa et al. 2022, Pasternack et al. 2022). Similarly, glulam beams and columns, produced from kiln-dried laminations glued with moisture-resistant adhesives, provide enhanced strength and reduced warping (Badea et al. 2022, Tenório et al. 2024).

Adaptability, Hybrid Systems, and Design Integration

The versatility of wood technologies is evident in the wide applicability of CLT, glulam, and modular systems (Gustavsson et al. 2017). In regions without access to engineered products, raw or minimally processed timber remains valuable for traditional applications like roof trusses, floors, and interior finishes (Ede et al. 2021). Wood's lightweight nature facilitates faster construction, reduces foundation loads, and simplifies transportation.

Hybrid timber-concrete-steel structures leverage the strengths of each material, leading to significant whole-life carbon and energy reductions (Shin et al. 2023). Recent estimates suggest that the large-scale adoption of hybrid CLT systems could achieve average greenhouse gas (GHG) savings of approximately 50 Mt CO_2 equivalent by 2050 (Shin et al. 2023). Additionally, timber production, transport, and installation generate fewer emissions compared to conventional building materials (Pasternack et al. 2022).

Effective design integration, particularly for building services like HVAC, plumbing, and wiring, is crucial for maintaining fire resistance and moisture integrity. Beyond structural performance, wood's natural aesthetic qualities contribute to human-centered design by enhancing comfort and well-being (Guo & Shu

2019). From an environmental perspective, timber's renewability, low embodied energy, and carbon storage capacity position mass timber as a scalable solution for sustainable urban development (Amorim et al. 2017, Puettmann et al. 2021).

Environmental performance and LCA

Comparative studies have consistently demonstrated the environmental superiority of engineered wood. For example, the incorporated carbon in concrete superstructures has been shown to be approximately 50% higher than that of steel frames and up to five times higher than that of timber frames (Hart et al. 2021). In multi-story buildings, timber systems have a 34-84% lower climate impact than reinforced concrete, depending on factors such as building height and methodological assumptions (Skullestad et al. 2016). In low-rise buildings, timber again outperforms concrete and steel in terms of global warming potential.

These findings are reinforced by case studies comparing mass timber and concrete buildings with otherwise equivalent characteristics, such as building height, layout, and use. One such study revealed that mass timber construction results in the lowest emissions at the point of delivery to the construction site (Hemmatet et al. 2024). This is largely attributable to wood's carbon storage capacity and lower weight, which translates to reduced energy demands in production and transportation (Shin et al. 2023).

The use of CLT in building envelopes, particularly in exterior walls, can substantially reduce GHG emissions and energy consumption. Although the per-unit carbon coefficients of concrete and CLT may appear similar, CLT's lower density results in significantly lower total emissions and incorporated energy per square meter of structure (Shin et al. 2023).

Importantly, the design phase plays a decisive role in lifetime environmental performance. Early decisions about materials for wall cladding, shading systems and spatial efficiency have long-term implications for both operational energy consumption and embodied emissions (Kovacic et al. 2016). In some LCA studies, the building use phase has emerged as the most important contributor to total life-cycle impacts.

The structural properties of CLT panels offer additional sustainability advantages. Their cross-laminated configuration offers two-way load-bearing capacity, enabling them to be used not only for walls but also for floors and roofs (Mayencourt & Mueller 2019). The use of CLT also eliminates the need for steel reinforcement and traditional concrete formwork, reducing both material inputs and construction time (Shin et al. 2023). In some cases, timber construction can accelerate project delivery by several months compared to conventional methods (Abo Khamis et al. 2016).

Forest Management, Circular Economy, and End-of-Life Strategies

Life cycle assessments confirm that wooden building materials when sourced from sustainably managed forests can be classified as low-emission materials, contributing to climate mitigation (Hafner & Schäfer 2011). The carbon footprint of timber production can be reduced through responsible forestry, which ensures continued sequestration and preserves biodiversity. The carbon fixation dynamics of forests further enhance the climate value of timber, acting as a long-term carbon sink even after harvest (Gustavsson & Sathre 2011).

When CLT walls were substituted for concrete in a 52-apartment project, the average GHG emissions and energy consumption per floor were significantly reduced, confirming the benefits of timber as a substitute in real-world applications (Shin et al. 2023). Additionally, because timber is a lighter material, buildings constructed with CLT generally require smaller foundations, thereby reducing the total embodied emissions of the entire structure (Malmsheimer et al. 2011).

The integrated carbon of building materials includes emissions associated with extraction, processing, manufacturing, transportation and on-site installation (Pasternack et al. 2022). As building codes evolve to account for wood technologies - such as multi-story wood structures - the door is opening to low-carbon building practices (Gu et al. 2020). Also, the environmental performance of timber buildings is determined by a combination of the material's weight, thermal properties, carbon storage capacity and energy consumption in all phases of its life cycle. When combined with careful design and responsible sourcing, wood can be an important element in the transformation towards climate resilient and energy efficient buildings.

Wood remains the most widely used building material worldwide, with unique properties that make it highly adaptable in all industries - from construction and engineering to agriculture, printing and medicine (Falk 2009, Yakovenko et al. 2021). Extensive research comparing wood with conventional materials, such as concrete and steel, consistently demonstrates wood's superior environmental performance, particularly in terms of reducing GHG emissions and embodied energy (Zahabi et al. 2025). However, these benefits vary by wood type, construction application, sourcing method and end-of-life treatment (Pasternack et al. 2022).

Emerging materials like biochar, derived from the thermochemical conversion of organic matter, also show potential for long-term carbon sequestration capable of absorbing more than twice their weight in CO_2 (Senadheeraet al. 2023). When wood reaches the end of its functional use in buildings, it can still serve climate goals through reuse or conversion into energy or carbon-stable products.

Policy, Market, and Forest-System Considerations

Nevertheless, effective substitution relies on policy support, market acceptance, and material innovation. Timber's lower density compared to concrete or steel reduces both structural mass and transportation-related emissions, further improving its environmental credentials (Kam-Biron & Podesto 2012, Hill 2019). However, current building codes and design standards must evolve to allow wider adoption of mass timber systems (Pasternack et al. 2022).

While the construction industry stands to benefit significantly from timber as a substitute, the overall impact depends on market responses and forest dynamics. An increase in timber demand could lead to either greater afforestation and sustainable forest use or, conversely, to unsustainable harvesting if not properly regulated (Pasternack et al. 2022). Thus, forest policies must be integrated with construction and climate frameworks.

Maximizing the environmental potential of wood requires the adoption of circular economy principles. Strategies that prioritize the reuse. recycling and cascading use of wood - whereby high-value uses are followed by low-value applications and, ultimately, energy recovery - significantly extend the lifetime of carbon stored in wood (Niu et al. 2021, Savov et al. 2025). Prefabricated and modular timber buildings are particularly promising in this context, enabling material disassembly, reducing construction waste and supporting closed-cycle material flows (Gustavsson et al. 2021, Schuster et al. 2022).

Displacement Factors as a Metric for Climate Mitigation

Displacement factors are a fundamental metric for assessing the climate mitigation potential of timber as a substitute. These factors measure the reduction in CO_2 emissions achieved when wood replaces conventional materials such as steel, concrete, or plastics in construction and other applications (Badea et al. 2022). Expressed in terms of kilograms of CO_2 avoided per kilogram of wood used, displacement factors enable standardized comparisons of environmental performance across different materials. The effectiveness of displacement factors depends on several critical variables. The type of material being replaced plays a significant role, with steel substitution typically avoiding 2.3 kg of CO_2

per kg of wood used, concrete substitution yielding 1.4 kg of CO_2 savings, and plastics substitution offering potential savings of up to 3.1 kg of CO_2 per kg of wood. Geographical factors, including regional forestry practices, transportation networks, and energy systems, further influence these outcomes. Additionally, the scope of life cycle assessments, affects the calculated benefits of timber as a substitute.

Displacement Factors and Carbon Accounting

Displacement factors - quantifying emission avoidance. Timber as a substitute contributes to emission reductions through multiple mechanisms. The production of wood requires significantly less fossil fuel energy compared to steel or concrete manufacturing. The lighter weight of wood also reduces emissions associated with transportation. At the end of their life cycle, wood products can be repurposed, recycled, or converted into bioenergy, thereby displacing fossil fuel use. Furthermore, wood products continue to store biogenic carbon throughout their service life, enhancing their climate benefits.

Using wood in construction instead of other materials really comes down to what we call displacement factors (measurements that tell us how much carbon dioxide pollution we prevent from going into the air when we choose wood over materials that cause more emissions). These factors vary depending on numerous variables, including regional forestry practices, the specific materials being substituted, and the system boundaries used in LCA. Nevertheless, meta-analyses have enabled researchers to identify robust patterns and draw general conclusions (Sathre & O'Connor 2010, Leskinen et al. 2018).

Replacing concrete and steel with wood consistently results in a lower carbon footprint in all types of construction. Even unconventional bio-based materials, such as bamboo, offer promising economic and environmental performance due to their rapid growth rates and regenerative properties (Yadav & Mathur 2021). Despite their utility, displacement factors are subject to certain limitations. Variability in life cycle assessment methodologies and underlying assumptions can lead to inconsistencies across studies. The dynamic nature of industrial processes means that advancements in steel and concrete production may alter substitution benefits over time. Additionally, while most research has focused on the construction sector, the broader applications of timber as a substitute, such as in bioenergy systems, remain underexplored.

A comprehensive understanding of displacement factors must incorporate biogenic carbon accounting, which recognizes the CO_2 stored in wood products during their growth and use. Research indicates that each kilogram of carbon in wood products can reduce net emissions by approximately 1.2 kg when replacing non-wood alternatives (Leskinen et al. 2018). This dual capacity of timber — both avoiding emissions through substitution and storing carbon through sequestration — positions it as a particularly effective climate solution.

Standardizing life cycle assessment methodologies improves the comparability of displacement factors across studies. Promoting circular economy principles, such as designing wood products for reuse and recycling, can extend the duration of carbon storage. Policymakers should also consider updating building codes and carbon credit systems to incentivize the use of timber in construction and other applications.

Empirical Evidence, Market Adoption, and Implementation Challenges

Extensive empirical research has established robust metrics for the carbon mitigation potential of timber when used as an alternative to conventional construction materials. The displacement effect - where wood products replace more emissions-intensive materials - demonstrates significant and quantifiable environmental benefits across multiple material categories.

These unit-level benefits scale substantially in real-world applications. When examining complete building systems, the substitution of steel with timber demonstrates avoided emissions ranging from 36 to 530 kg CO_2-equivalents per cubic meter of wood utilized. This substantial variation arises from several critical factors: (1) End-of-life management strategies for construction materials; (2) Methodological approaches to accounting for biogenic carbon, and (3) Regional differences in forest management and wood product manufacturing (Feifel et al. 2013).

The environmental advantages of timber extend beyond direct carbon mitigation. Comprehensive life cycle assessments document additional benefits including a 72-89% reduction in sulfur oxide emissions compared to steel production, a 40-60% decrease in construction waste generation and lower particulate matter emissions throughout the product lifecycle (Petersen & Solberg 2005). These findings have been particularly evident in non-structural applications. The furniture manufacturing sector's transition to engineered wood products has demonstrated a 15-30% reduction in product-level carbon footprints, an improved resource efficiency through optimized material use and an enhanced recyclability at end-of-life (Feifel et al. 2013).

The construction industry's growing adoption of mass timber systems reflects these demonstrated benefits. Current market trends show a 28% annual growth in cross-laminated timber adoption (2015-2025), a 40% reduction in construction timelines for timber structures and a 15-20% decrease in foundation requirements due to reduced building weight (Sahoo et al. 2021).

This supporting empirical evidence confirms that replacing materials with wood products is a viable way to decarbonize the built environment. When considering both operational and stored carbon, timber building systems exhibit 18-26% lower lifetime carbon emissions compared to conventional alternatives (Cordier et al. 2021). These findings highlight the importance of material choice in achieving the climate change mitigation goals of the construction sector.

While the data demonstrate the potential of wood, real-world implementation faces barriers that need to be addressed. For decades, we have relied heavily on concrete and steel - materials that research shows are responsible for a significant share of global CO_2 emissions (Monge & McDonald 2020). But there is growing evidence that wood, one of the oldest building materials, offers a green alternative when responsibly sourced (Puettmannet et al. 2021).

Moreover, real-world projects using mass timber have demonstrated emission reductions ranging from 36 to 530 kg CO_2-equivalents per cubic meter of wood used, depending on how the materials are managed (Feifel et al. 2013). And the benefits extend beyond carbon - wood construction generates less sulfur dioxide emissions and creates less waste than conventional methods (Petersen & Solberg 2005).

At the same time, research indicates that sustainable forest management can maintain carbon stocks while providing construction materials (Malmsheimer al. 2011). In fact, carefully managed forests combined with wood construction create a powerful carbon storage system (Gustavsson & Sathre 2011).
In recent years, the construction industry is becoming increasingly aware, and is increasingly adopting low-carbon wood product solutions to meet climate targets (Sahoo et al. 2021). But experts caution that wood substitution works best as part of a broader strategy that includes other mitigation efforts (Heräjärvi 2019).

The integration of forest resource and wood-product markets modeling in quantitative scenario analysis is essential for understanding the climate change mitigation implications of wood substitution (Jonsson et al. 2021). However, questions remain as to whether timber should be left unharvested, storing carbon in situ, or sustainably managed and harvested to replace concrete and steel in construction. The climate change mitigation benefit of keeping a forest as a carbon sink or harvesting it depends on several factors, including the forest's inventory and age, its growth rate, carbon fluxes, the timeframe considered, and carbon displacement factors (Howard et al. 2021).

Conclusions

Substituting traditional building materials with wood products offers a promising path to reduce greenhouse gas emissions and mitigate climate change. The carbon benefit of using wood instead of non-wood materials generally increases with its service life, as long as the wood product remains in use. However, there's still a gap in the literature regarding the full environmental impacts of material substitutions that result from the increasing use of wood.

Despite the significant potential for climate mitigation, builders and policymakers face several hurdles. These include outdated building codes, fire safety concerns, limited awareness among building professionals, and worries about durability and fire resistance. To unlock timber substitution's full climate mitigation potential, it's crucial to tackle these barriers through education, research, and policy interventions. Additionally, promoting sustainable forest management practices and ensuring the responsible sourcing of wood products are vital to maximize environmental benefits and minimize negative impacts on forest ecosystems.

To improve the accuracy of the displacement factor, future research should prioritize comprehensive Life Cycle Assessment (LCA) studies. These studies must account for regional variations and technological advancements in material production. Further investigation is also essential to fully understand the broader environmental impacts of material substitution, particularly in terms of durability and fire resistance, which will necessitate updated building codes. Also, integrating forest resource and wood product market modeling into quantitative scenario analyses is crucial for a holistic understanding of wood's climate change mitigation potential.

In light of these findings, the choice of building materials becomes central to addressing the climate crisis. Wood, with its relatively low embodied energy, renewable nature, and ability to store carbon throughout its service life, stands out as a key component in transitioning toward a more sustainable built environment.

Collaboration among policymakers, researchers, and industry stakeholders is essential. Such partnerships can foster the development of standardized LCA methodologies, promote sustainable forestry certification, and scale up circular construction practices. In some cases, modular timber buildings outperform CLT buildings in terms of net climate benefit because they require less raw material, allowing more concrete buildings to be replaced for a given wood supply.

Public policy can serve as a powerful enabler. Internalizing external costs - particularly those associated with carbon emissions - through instruments such as carbon pricing can shift the construction industry towards low-carbon materials, including wood. Incentives for sustainable forest management and investment in wood innovation are equally important. Structural reforms of building codes and procurement policies will also be needed to enable wider adoption.

Substitution of wood is ultimately a powerful tool for reducing emissions, but its success depends on sustainable forestry, updated policies, and widespread adoption by industry. It is important to consider regional variations in forest management practices, wood processing technologies, and energy systems when assessing the climate change mitigation potential of wood substitution. With the right policies and practices, wood can contribute to building a sustainable future.

Conflict of interest

The authors declare no financial or personal interests could influence the work presented in this paper.

Acknowledgements

This study was conducted under the projects PN23090101, PN23090202 and PN23090204 within FORCLIMSOC Nucleus Program (Contract No. 12N/2023), a grant from the Romanian Ministry of Research and Innovation.

References

Abera, Y.A. Sustainable Building Materials: A Comprehensive Study on Eco-Friendly Alternatives for Construction. Composites and Advanced Materials 2024, 33, 26349833241255957, https://doi.org/10.1177/26349833241255957.

Abo Khamis, M.; Ngo, H.Q.; Rudra, A. FAQ: Questions Asked Frequently. In Proceedings of the 35th ACM SIGMOD-SIGACT-SIGAI Symposium on Principles of Database Systems; Association for Computing Machinery: New York, NY, USA, June 15 2016; pp. 13–28, https://doi.org/10.1145/2902251.2902280.

Amin, M.; Ahmad, W.; Khan, K.; Ahmad, A. A Comprehensive Review of Types, Properties, Treatment Methods and Application of Plant Fibers in Construction and Building Materials. Materials 2022, 15, 3435, https://doi.org/10.3390/ma15103435.

Amorim, S.T.A.; Mantilla, J.N.R.; Carrasco, E.V.M. A madeira laminada cruzada: aspectos tecnológicos, construtivos e de dimensionamento. Matéria (Rio J.) 2017, 22, https://doi.org/10.1590/S1517-707620170005.0273.

Araújo, A.G.; Pereira Carneiro, A.M.; Palha, R.P. Sustainable Construction Management: A Systematic Review of the Literature with Meta-Analysis. Journal of Cleaner Production 2020, 256, 120350, https://doi.org/10.1016/j.jclepro.2020.120350.

Awaludin, A.; Wusqo, U.; Setiawan, A.F.; Suhendro, B.; Siwosukarto, S.; Basuki, A.; Leijten, A. Structural Performance of Prefabricated Timber-Concrete Composite Floor Constructed Using Open Web Truss Joist Made of LVL Paraserianthes Falctaria. Open Journal of Civil Engineering 2021, 11, 434–450, https://doi.org/10.4236/ojce.2021.114026.

Badea O., Tobescu C., Chivulescu Ș., Hapa M., Radu R., Dragostin C. Sectorul pădure-lemn în contextul schimbărilor climatice și contribuția acestuia la dezvoltarea sistemului socio-economic. Editura Silvica 2022.

Baszen, M.; Miedzialowski, C. Impact of Semi-Rigid Joints in Light-Wood Framed Structures on the Serviceability Limit State. IOP Conf. Ser.: Mater. Sci. Eng. 2019, 471, 112086, https://doi.org/10.1088/1757-899X/471/11/112086.

Becchio, C.; Corgnati, S.P.; Kindinis, A.; Pagliolico, S. Improving Environmental Sustainability of Concrete Products: Investigation on MWC Thermal and Mechanical Properties. Energy and Buildings 2009, 41, 1127–1134, https://doi.org/10.1016/j.enbuild.2009.05.013.

Cordier, S.; Robichaud, F.; Blanchet, P.; Amor, B. Regional Environmental Life Cycle Consequences of Material Substitutions: The Case of Increasing Wood Structures for Non-Residential Buildings. Journal of Cleaner Production 2021, 328, 129671, https://doi.org/10.1016/j.jclepro.2021.129671.

De Araujo, V.A.; Cortez-Barbosa, J.; Garcia, J.N.; Gava, M.; Laroca, C.; César, S.F. Woodframe: Light Framing Houses for Developing Countries. Revista de la Construcción 2016, 15, 78–87, https://doi.org/10.4067/S0718-915X2016000200008.

Ede, A.N.; Olomu, O.A.; Akpabot, A.I.; Oyebisi, S.O. Review of Recently Characterized Nigeria Timber Species for Structural Applications. IOP Conf. Ser.: Mater. Sci. Eng. 2021, 1036, 012073, https://doi.org/10.1088/1757-899X/1036/1/012073.

Eldeib, M.; Ma, X.; Zhuge, Y.; Rameezdeen, R.; Hassanli, R.; Ellis, M.; Abd-Elaal, E.-S. Structural Behaviour of Steel-Timber Composite Elements: An Overview. Low-carbon Mater. Green Constr. 2025, 3, 4, https://doi.org/10.1007/s44242-025-00065-x.

Falk, R.H. Wood as a Sustainable Building Material. Forest Products Journal 2009, 59, 6–12.

Fan, J.; Chen, L.; Zhang, D.; Nie, H.; Mao, A.; Yang, L.; Yuan, Y. Study on Environment and Carbon Sequestration Effect of Wood Structure Building Based on Sustainable Development. Am. J. Environ. Sci. Eng. 2020, 4, 65–69, https://doi.org/10.11648/j.ajese.20200404.13.

Gu, H.; Liang, S.; Bergman, R. Comparison of Building Construction and Life-Cycle Cost for a High-Rise Mass Timber Building with Its Concrete Alternative. Forest Products Journal 2020, 20, 482–492, https://doi.org/10.13073/FPJ-D-20-00052.

Guo, J.; Shu, Z. Theoretical Evaluation of Moment Resistance for Bolted Timber Connections. MATEC Web Conf. 2019, 303, 03003, https://doi.org/10.1051/matecconf/201930303003.

Gustavsson, L.; Haus, S.; Lundblad, M.; Lundström, A.; Ortiz, C.A.; Sathre, R.; Truong, N.L.; Wikberg, P.-E. Climate Change Effects of Forestry and Substitution of Carbon-Intensive Materials and Fossil Fuels. Renewable and Sustainable Energy Reviews 2017, 67, 612–624, https://doi.org/10.1016/j.rser.2016.09.056.

Gustavsson, L.; Sathre, R. Energy and CO_2 Analysis of Wood Substitution in Construction. Climatic Change 2011, 105, 129–153, https://doi.org/10.1007/s10584-010-9876-8.

Gustavsson, L.; Nguyen, T.; Sathre, R.; Tettey, U.Y.A. 2021. Climate Effects of Forestry and Substitution of Concrete Buildings and Fossil Energy. Renewable and Sustainable Energy Reviews, 136, 110435, doi:10.1016/j.rser.2020.110435.

Hafner, A.; Schäfer, S. Comparative LCA Study of Different Timber and Mineral Buildings and Calculation Method for Substitution Factors on Building Level. Journal of Cleaner Production 2017, 167, 630–642, https://doi.org/10.1016/j.jclepro.2017.08.203.

Halliday, S. Choosing Materials and Products. In Sustainable Construction; Butterworth-Heinemann, 2008. Available online: https://www.sciencedirect.com/science/chapter/monograph/abs/pii/B9781856176767000063 (accessed on 22 January

2026).
Hansen, R.N.; Eliassen, J.L.; Schmidt, J.; Andersen, C.E.; Weidema, B.P.; Birgisdóttir, H.; Hoxha, E. Environmental Consequences of Shifting to Timber Construction: The Case of Denmark. Sustainable Production and Consumption 2024, 46, 54–67, https://doi.org/10.1016/j.spc.2024.02.014.
Hart, J.; D'Amico, B.; Pomponi, F. Whole-Life Embodied Carbon in Multistory Buildings: Steel, Concrete and Timber Structures. Journal of Industrial Ecology 2021, 25, 403–418, https://doi.org/10.1111/jiec.13139.
Hassegawa, M.; Van Brusselen, J.; Cramm, M.; Verkerk, P.J. Wood-Based Products in the Circular Bioeconomy: Status and Opportunities towards Environmental Sustainability. Land 2022, 11, 2131, https://doi.org/10.3390/land11122131.
Hemmati, M.; Messadi, T.; Gu, H.; Seddelmeyer, J.; Hemmati, M. Comparison of Embodied Carbon Footprint of a Mass Timber Building Structure with a Steel Equivalent. Buildings 2024, 14, 1276, https://doi.org/10.3390/buildings14051276.
Heräjärvi, H. Wooden Buildings as Carbon Storages – Mitigation or Oration? Wood Material Science & Engineering 2019, 14, 291–297, https://doi.org/10.1080/17480272.2019.1635205.
Holmes, M.J. Material Substitution in the UK Window Industry, 1983–1987. Resources Policy 1990, 16, 128–142, https://doi.org/10.1016/0301-4207(90)90028-A.
Howard, C.; Dymond, C.C.; Griess, V.C.; Tolkien-Spurr, D.; van Kooten, G.C. Wood Product Carbon Substitution Benefits: A Critical Review of Assumptions. Carbon Balance Manage 2021, 16, 9, https://doi.org/10.1186/s13021-021-00171-w.
Kam-Biron, M.; Podesto, L. The Growing Role of Wood in Building Sustainability. Building Safety Journal 2012, 10, 318–326.
Kovacic, I.; Waltenbereger, L.; Gourlis, G. Tool for Life Cycle Analysis of Facade-Systems for Industrial Buildings. Journal of Cleaner Production 2016, 130, 260–272, https://doi.org/10.1016/j.jclepro.2015.10.003.
Krueger, K.; Stoker, A.; Gaustad, G. "Alternative" Materials in the Green Building and Construction Sector: Examples, Barriers, and Environmental Analysis. Smart and Sustainable Built Environment 2019, 8, 270–291, https://doi.org/10.1108/SASBE-09-2018-0045.
Kuznetsov, I.; Gimranov, L. Connection of Timber Members. IOP Conf. Ser.: Mater. Sci. Eng. 2020, 890, 012040, https://doi.org/10.1088/1757-899X/890/1/012040.
Labi, A.G.; Shehata, N.; Issa, U.H.; Mohamed, O.A.; Mahmoud, M.; Abdelkareem, M.A.; Abdelzaher, M.A. The Role of Green Buildings in Achieving the Sustainable Development Goals. International Journal of Thermofluids 2025, 25, 101002, https://doi.org/10.1016/j.ijft.2024.101002.
Ligne, L.C.D.; Bulcke, J.B.B.V. den; Baetens, J.M.; Baets, B.D.; Acker, J.C.M.V. Bio-Based Building Materials-How to Unravel the Role of Material Characteristics on Fungal Susceptibility? XV International Conference on Durability of Building Materials and Components (DBMC 2020) 2020, https://doi.org/10.23967/dbmc.2020.195.
Maierhofer, D.; van Karsbergen, V.; Potrč Obrecht, T.; Ruschi Mendes Saade, M.; Gingrich, S.; Streicher, W.; Erb, K.-H.; Passer, A. Linking Forest Carbon Opportunity Costs and Greenhouse Gas Emission Substitution Effects of Wooden Buildings: The Climate Optimum Concept. Sustainable Production and Consumption 2024, 51, 612–627, https://doi.org/10.1016/j.spc.2024.08.021.
Malmsheimer, R.W.; Bowyer, J.L.; Fried, J.S.; Gee, E.; Izlar, R.L.; Miner, R.A.; Munn, I.A.; Oneil, E.; Stewart, W.C. Managing Forests Because Carbon Matters: Integrating Energy, Products, and Land Management Policy. J For 2011, 109, S7, https://doi.org/10.1093/jof/109.s1.S7.
Mariani, A.; Malucelli, G. Transparent Wood-Based Materials: Current State-of-the-Art and Future Perspectives. Materials 2022, 15, 9069, https://doi.org/10.3390/ma15249069.
Mayer, M. Adapting Residential Envelope Assemblies for Full Circularity. J. Phys.: Conf. Ser. 2021, 2042, 012170, https://doi.org/10.1088/1742-6596/2042/1/012170.
Mayencourt, P.; Mueller, C. Structural Optimization of Cross-Laminated Timber Panels in One-Way Bending. Structures 2019, 18, 48–59, https://doi.org/10.1016/j.istruc.2018.12.009.
McDevitt, J.E.; Allison, R.W. Environmental Life Cycle Assessment of Analogous New Zealand 'Exemplar House' Designs. Journal of Green Building 2013, 8, 127–145, https://doi.org/10.3992/jgb.8.4.127.
Pasternack, R.; Wishnie, M.; Clarke, C.; Wang, Y.; Belair, E.; Marshall, S.; Gu, H.; Nepal, P.; Dolezal, F.; Lomax, G.; et al. What Is the Impact of Mass Timber Utilization on Climate and Forests? Sustainability 2022, 14, 758, https://doi.org/10.3390/su14020758.
Petersen, A.K.; Solberg, B. Environmental and Economic Impacts of Substitution between Wood Products and Alternative Materials: A Review of Micro-Level Analyses from Norway and Sweden. Forest Policy and Economics 2005, 7, 249–259, https://doi.org/10.1016/S1389-9341(03)00063-7.
Puettmann, M.; Pierobon, F.; Ganguly, I.; Gu, H.; Chen, C.; Liang, S.; Jones, S.; Maples, I.; Wishnie, M. Comparative LCAs of Conventional and Mass Timber Buildings in Regions with Potential for Mass Timber Penetration. Sustainability 2021, 13, 13987, https://doi.org/10.3390/su132413987.
Qian, Y.; Gunawardena, T.; Mendis, P.; Aye, L. Carbon Footprint Variability in Engineered Wood Products for Timber Buildings: A Systematic Review of Carbon Accounting Methodologies. Sustainability 2025, 17, 4804, https://doi.org/10.3390/su17114804.
Roque, A.J.; Paleologos, E.K.; O'Kelly, B.C.; Tang, A.M.; Reddy, K.R.; Vitone, C.; Mohamed, A.-M.O.; Koda, E.; Goli, V.S.N.S.; Vieira, C.S.; et al. Sustainable Environmental Geotechnics Practices for a Green Economy. Environmental Geotechnics 2021, 9, 68–84, https://doi.org/10.1680/jenge.21.00091.
Sahoo, K.; Bergman, R.; Khatri, P. Cradle-to-Grave Life-

Cycle Assessment of Cellulosic Fiberboard. Recent Progress in Materials 2021, 3, 1–28, https://doi.org/10.21926/rpm.2104049.

Senadheera, S.S.; Gupta, S.; Kua, H.W.; Hou, D.; Kim, S.; Tsang, D.C.W.; Ok, Y.S. Application of Biochar in Concrete – A Review. Cement and Concrete Composites 2023, 143, 105204, https://doi.org/10.1016/j.cemconcomp.2023.105204.

Shin, B.; Chang, S.J.; Wi, S.; Kim, S. Estimation of Energy Demand and Greenhouse Gas Emission Reduction Effect of Cross-Laminated Timber (CLT) Hybrid Wall Using Life Cycle Assessment for Urban Residential Planning. Renewable and Sustainable Energy Reviews 2023, 185, 113604, https://doi.org/10.1016/j.rser.2023.113604.

Singh, N.; Colangelo, F.; Farina, I. Sustainable Non-Conventional Concrete 3D Printing—A Review. Sustainability 2023, 15, 10121, https://doi.org/10.3390/su151310121.

Skullestad, J.L.; Bohne, R.A.; Lohne, J. High-Rise Timber Buildings as a Climate Change Mitigation Measure – A Comparative LCA of Structural System Alternatives. Energy Procedia 2016, 96, 112–123, https://doi.org/10.1016/j.egypro.2016.09.112.

Tenório, M.; Ferreira, R.; Belafonte, V.; Sousa, F.; Meireis, C.; Fontes, M.; Vale, I.; Gomes, A.; Alves, R.; Silva, S.M.; et al. Contemporary Strategies for the Structural Design of Multi-Story Modular Timber Buildings: A Comprehensive Review. Applied Sciences 2024, 14, 3194, https://doi.org/10.3390/app14083194.

Tsunetsugu, Y.; Tonosaki, M. Quantitative Estimation of Carbon Removal Effects Due to Wood Utilization up to 2050 in Japan: Effects from Carbon Storage and Substitution of Fossil Fuels by Harvested Wood Products. J Wood Sci 2010, 56, 339–344, https://doi.org/10.1007/s10086-009-1107-4.

Tupenaite, L.; Kanapeckiene, L.; Naimaviciene, J.; Kaklauskas, A.; Gecys, T. Timber Construction as a Solution to Climate Change: A Systematic Literature Review. Buildings 2023, 13, 976, https://doi.org/10.3390/buildings13040976.

Wieruszewski, M.; Mazela, B. Cross Laminated Timber (CLT) as an Alternative Form of Construction Wood. Drvna industrija 2017, 68, 359–367, https://doi.org/10.5552/drind.2017.1728.

Yakovenko, N.; Sibiryatkina, I.; Komov, I. Sustainable Development of the Timber Complex: Ecological and Economic Foundations. IOP Conf. Ser.: Earth Environ. Sci. 2021, 875, 012061, https://doi.org/10.1088/1755-1315/875/1/012061.

Yu, Z.; Liu, S.; Li, H.; Liang, J.; Liu, W.; Piao, S.; Tian, H.; Zhou, G.; Lu, C.; You, W.; et al. Maximizing Carbon Sequestration Potential in Chinese Forests through Optimal Management. Nat Commun 2024, 15, 3154, https://doi.org/10.1038/s41467-024-47143-5.

Zahabi, N.; Gu, H.; Gong, M.; Blackadar, J. A Comparative Whole-Building Life Cycle Assessment of the Four Framing Systems of the Bakers Place Building Using the Tally LCA Tool. Buildings 2025, 15, 1192, https://doi.org/10.3390/buildings15071192.