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Embodied Carbon of Mass Timber Buildings in the United States: A Systematic Review of Life-Cycle Assessment (LCA) Evidence

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ABSTRACT

This review synthesizes peer-reviewed life-cycle assessment (LCA) studies evaluating the embodied carbon and global warming potential (GWP) of mid-rise mass-timber buildings in the United States. Prompted by regulatory changes in the 2021 International Building Code that permit taller timber construction, the review focuses on the policy, market, and environmental context. A rigorous, structured protocol incorporated comprehensive database searches, systematic screening, clearly defined inclusion and exclusion criteria, and critical methodological appraisal. 30 peer-reviewed studies were identified that quantitatively assessed embodied carbon, GWP, and biogenic carbon flows in mass-timber systems, typically in comparison with reinforced concrete and steel alternatives.

The reviewed literature demonstrates that mass-timber buildings exhibit lower GWP than conventional construction systems. Reported reductions range from 10–20% to 20–60%, depending on system boundaries, functional units, and modeling assumptions. Representative findings indicate cradle-to-gate reductions of 19–41% and cradle-to-grave reductions of 34–51%. Greater reductions are observed when biogenic carbon storage and end-of-life (EOL) recovery or recycling credits are considered.

This review critically examines methodological variability across the evaluated studies. Principal sources of divergence include inconsistent system boundaries, heterogeneous functional units, non-standardized biogenic carbon accounting methods, and uncertain EOL scenarios. Regional factors, such as energy-grid composition, transportation, forest management, and climate conditions, further influence outcomes and limit direct comparability. The findings substantiate the embodied-carbon mitigation potential of mass-timber construction while underscoring the need for harmonized LCA methodologies, transparent reporting, region-specific data sets, and improved treatment of uncertainty to inform robust design and policy decisions.

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1. Introduction

The construction sector represents nearly 33% of global CO_2 emissions, with building construction alone responsible for nearly 7% [1, 2]. Although operational energy efficiency has improved, embodied carbon from material extraction, manufacturing, transportation, and assembly now represents a growing share of a building's environmental impact. Conventional materials such as reinforced concrete and structural steel are energy-intensive and generate high embodied carbon [3, 4]. In contrast, mass timber construction (MTC) offers a renewable alternative that sequesters carbon and is consistent with decarbonization and sustainable building goals [5, 6].

Mass timber includes engineered wood products such as cross-laminated timber (CLT), glued-laminated timber (Glulam), nail-laminated timber (NLT), and laminated veneer lumber (LVL). These materials support the construction of taller, more complex buildings and offer design flexibility comparable to that of steel and concrete systems [7, 8]. In the United States, mass timber adoption increased following the 2021 International Building Code (IBC) update, which permits mass timber buildings up to 18 stories [9].

This literature review compiles recent life-cycle assessment (LCA) studies of mid-rise mass-timber buildings in the United States. Studies were selected based on specific inclusion criteria, emphasizing peer-reviewed research that evaluates the carbon footprint and life cycle of mid-rise mass-timber structures within the U.S. This specialized approach provides insights relevant to the environmental and regulatory context of the United States. The review investigates research methodologies, compares mass timber with steel and concrete systems, and studies the role of regional factors on environmental impacts. It also evaluates digital tools such as Tally and OneClick LCA, which integrate building information modeling (BIM) with LCA databases to support embodied carbon analysis. Comprehensive knowledge of the structural systems used in mid-rise buildings, along with the evolution and adoption of mass timber in the U.S., is critical for assessing the environmental performance and market potential of mass timber. The main findings reveal significant reductions in embodied carbon when using mass timber compared to traditional materials, highlighting mass timber's potential as a sustainable building material.

1.1. Evolution and Adoption of Mass Timber Construction in the U.S.

The U.S. mass timber market has developed rapidly due to changes in building codes, sustainability incentives, and increased climate awareness. While mass timber has a long history in Europe, its national adoption in the U.S. is recent [10, 11], Fig. (**1**) illustrates the global distribution of mass timber buildings that are eight stories or higher, categorized by building function, as reported up to the year 2022 [11], whereas Fig. (**2**) presents the worldwide distribution of mass timber buildings of eight stories or higher according to their project stage as of 2022. The Council on Tall Buildings and Urban Habitat (CTBUH) notes that over 200 multi-story (7 stories or higher) timber projects have been built globally, defining milestones for U.S. projects [12]. Early U.S. adoption experienced difficulties, including limited supply chain infrastructure, inconsistent codes, and considerable costs for engineered timber panels [13].

Recent policy changes and incentives have addressed many of these challenges. The 2021 International Building Code (IBC) update allows taller buildings with mass timber as the primary structural material. States such as Oregon, Washington, and California have promoted timber construction through research grants and green certification credits [14, 15]. The U.S. Forest Service's Wood Innovation Grant Program supports domestic CLT production, reducing supply concerns [16, 17]. As a result, mass timber has moved from pilot projects to mainstream use in mid-rise residential and mixed-use buildings.

With the increased adoption of mass timber, research and industry focus has shifted from regulatory, policy, and supply chain challenges to technical considerations such as structural performance, environmental impacts, and system optimization.

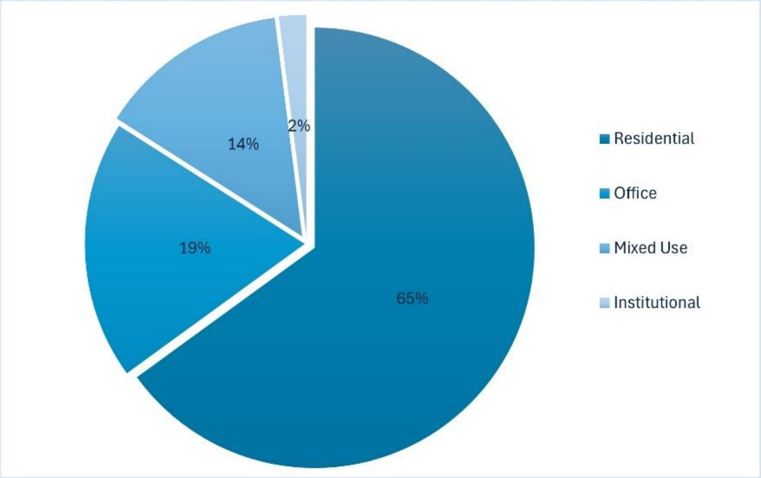

Figure 1: Mass timber buildings worldwide, 8 stories or higher, categorized by function, as of 2022 (Total No. = 84) [11].

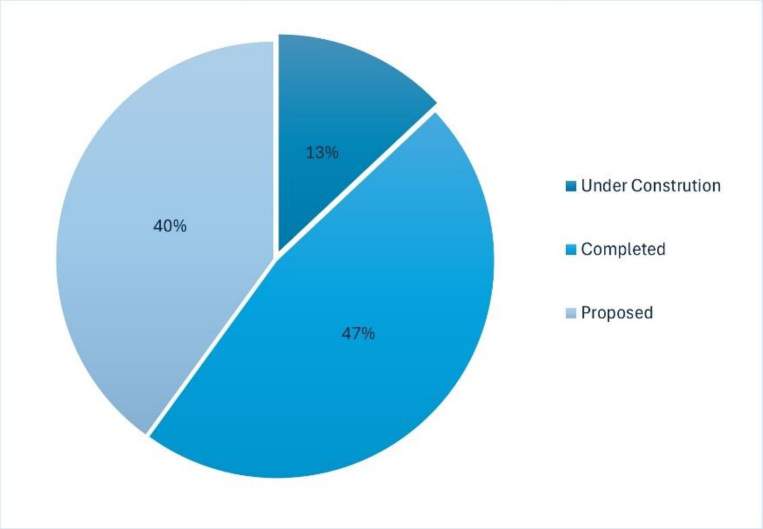

Figure 2: Mass timber buildings worldwide, 8 stories or higher, categorized by project stage, as of 2022 (Total No. = 139) [11].

1.2. Structural Systems and Performance of Mass Timber Buildings

Over the past decade, mass timber structural systems, engineered wood products used as primary building structures, have become a focal point in sustainable construction research and practice [18]. These systems are generally categorized as all-timber (using only wood), timber–concrete hybrid (combining wood and concrete), steel–timber hybrid (combining wood and steel), or composite systems that utilize all three materials [19]. All-timber systems are structures in which wood is the sole material used for load-bearing purposes. Timber–concrete hybrids are structures that combine wood framing and components with concrete elements to enhance properties like stiffness. Steel–timber hybrids integrate steel and timber members to provide greater design flexibility and strength. Composite systems integrate timber, steel, and concrete into a single structure to optimize the strengths of each material. Each approach takes advantage of timber's lightweight and renewable qualities. Hybrid and composite systems address performance challenges by integrating materials and leveraging digital optimization [20].

All-timber systems utilize engineered wood products, such as cross-laminated timber (CLT), glued-laminated timber (Glulam), and nail-laminated timber (NLT), for both vertical and lateral load-bearing elements [21]. CLT panels offer high in-plane stiffness and dimensional stability, making them suitable for multi-story diaphragms and shear walls. Glulam beams and columns, valued for their ductile behavior and high strength-to-weight ratios, are commonly used as primary framing members in mid-rise structures. These systems have demonstrated strong mechanical reliability under gravity and lateral loads, particularly when combined with advanced connection details, such as self-tapping screws and steel plates [22, 23].

Hybrid systems combine timber with concrete or steel to address specific structural and regulatory challenges. Timber–concrete hybrids incorporate CLT slabs with concrete topping and/or reinforced concrete structural cores into timber frames [24]. This improves aspects such as acoustics (sound insulation), fire resistance, and stiffness (resistance to deformation). The composite action (joint functioning) between cross-laminated timber (CLT) panels and thin concrete toppings, often connected with shear connectors (devices that help transfer loads between materials), enhance floor vibration performance and increase thermal mass (the capacity of a material to absorb and store heat) [25, 26]. This method keeps embodied carbon, the total greenhouse gas emissions associated with producing construction materials, lower than those of all-concrete floors. Steel–timber hybrids use steel bracing or framing for lateral load resistance (resistance to forces such as wind or earthquakes) and long structural spans (the distance between supports) [27]. This increases design flexibility and ductility (the ability to withstand deformation without breaking), which is especially important in seismic regions [28].

High-rise and complex structures increasingly use composite systems that combine concrete, steel, and timber. They use a concrete core for lateral stability, steel beams or trusses for long spans, and mass timber decking to distribute gravity loads. This combination delivers high strength, reduces self-weight, and improves environmental performance. Studies indicate that these composite solutions can lower embodied carbon by 30–40% compared to equivalent reinforced concrete (RC) or steel structures [7].

In addition to structural performance, researchers focus on fire safety, acoustic control, and moisture resistance as important factors influencing the adoption of mass timber. Recent studies show that well-designed encapsulation layers and accurate char-rate models enable timber structures to meet stringent fire codes, providing up to two hours of fire resistance [12, 29]. Layered assemblies and hybrid floor systems are used to achieve acoustic isolation and vibration control. Moisture durability is improved with surface coatings, vapor barriers, and maintaining controlled indoor humidity [8, 30].

1.2.1. Structural Typologies

Mass timber systems can be categorized into four primary structural configurations:

1. **All-Timber Systems:** In these systems, all gravity and lateral loads are supported by timber members. They typically use CLT wall and floor panels, along with Glulam columns and beams. Their lightweight and prefabrication enable faster construction and lighter foundations. Designers must address fire and moisture protection [31].
2. **Timber–Concrete Hybrids:** These systems combine concrete elements, such as cores or floor toppings, with timber framing to enhance stiffness, fire resistance, and sound control [32]. Shear connectors link CLT and concrete slabs. This results in thinner floors and better vibration performance [33, 34].
3. **Steel–Timber Hybrids:** These systems, commonly used in offices and mixed-use buildings, utilize steel cores or braces to resist lateral loads, while timber frames and floors support gravity loads [35]. This mix combines timber's sustainability with steel's flexibility, offering good seismic resistance and long spans.
4. **Composite (Concrete–Steel–Timber) Systems:** used in some tall buildings, these systems combine concrete, steel, and timber to optimize each material. Concrete provides stiffness. Steel handles long spans. Timber offers lightweight decking and adds visual warmth [36].

Each structural system shows distinct strengths and trade-offs. For instance, hybrid systems can reduce embodied carbon by up to 40% compared to conventional concrete frames while maintaining comparable strength [37]. The integration of multiple materials enables more flexible and sustainable solutions for urban buildings [38].

Advances in digital fabrication and modular prefabrication have improved the efficiency and practicality of mass timber construction. Computer numerical control (CNC) machining and parametric modeling allow for precise panel cutting and rapid on-site assembly, reducing construction time by 20–30% compared to traditional methods [39]. Prefabricated timber modules enhance build quality and reduce construction waste and on-site emissions. BIM-integrated structural optimization tools enable engineers to model structural and environmental performance simultaneously, supporting both design and sustainability objectives.

The blend of strong mechanical performance, modular efficiency, and sustainability makes mass timber a practical and scalable alternative to steel and concrete in mid-rise construction [40]. However, ongoing research on hybrid systems, long-term durability, and region-specific criteria remains necessary for broader market adoption in the United States.

Although these structural innovations expand the capabilities of mass timber, a rigorous analytical framework is necessary to accurately assess their sustainability over the entire building lifespan.

1.3. Life Cycle Assessment (LCA) Framework for Mid-Rise Buildings

Life Cycle Assessment (LCA) is a scientific method, standardized in ISO 14040, ISO 14044, and EN 15978, for evaluating the environmental impacts of buildings throughout their entire life cycle, from raw material extraction to end-of-life [41-45]. LCA consists of four phases: A (product and construction), B (use), C (end-of-life), and D (beyond the system boundary), as illustrated in Fig. (**3**). Depending on the scope of the study, LCA boundaries can be cradle-to-gate (A1–A3), cradle-to-grave (A–C), or cradle-to-cradle (A–D).

- Cradle-to-gate (A1–A3): includes raw material extraction, manufacturing, and prefabrication.
- Cradle-to-grave (A–C): encompasses the entire lifecycle, extending from construcion through operational use, maintenance, and demolition.
- Cradle-to-cradle (A–D): incorporates recycling and reuse pathways, emphasizing principles of the circular economy.

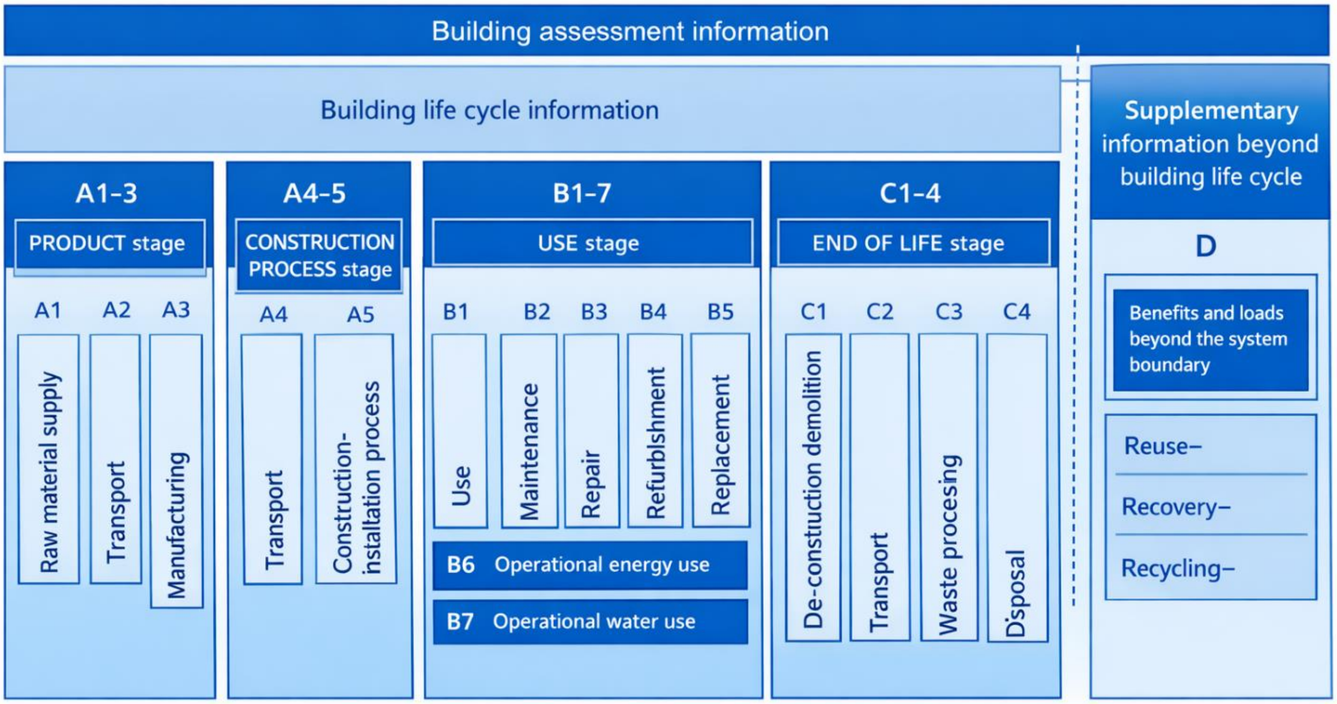

Figure 3: Life Cycle Assessment (LCA) stages in the building sector [40, 43].

Within this framework, LCAs for mass-timber buildings evaluate how engineered wood products, such as cross-laminated timber (CLT) and glulam, compare in environmental performance with traditional materials such as steel and concrete. A key feature of timber LCAs is biogenic carbon accounting, which tracks the carbon absorbed by trees during growth, stored in the building, and released at the end of life [46]. The method used to model this carbon, whether as a one-time credit during construction, spread over the building's lifespan, or assessed dynamically, has a significant impact on Global Warming Potential (GWP) results [47]. LCAs also consider substitute effects, where using timber instead of more carbon-intensive materials lowers overall emissions; displacement factors for CLT and glulam typically range from 0.20 to 0.50, depending on manufacturing energy use and recycling practices [48].

Studies consistently find that mass timber buildings have much less embodied carbon and GWP than traditional structures. For example, one study [4] reported reductions of 19–41% in GWP for the cradle-to-construction phases (A1–A4). When the analysis expands to cradle-to-grave (A–C), another study [2] reported total emissions that were 51% lower than those of reinforced concrete and 34% lower than those of structural steel. If biogenic storage and recycling credits (module D) are included, total reductions can exceed 90%.

Mass timber also excels in primary energy demand (PED) and resource efficiency. Engineered wood products typically require 30–35% less material than reinforced concrete, resulting in lighter foundations and lower transportation impacts [48-50]. Prefabrication helps reduce waste and rework. Recent advances, such as biomass-powered kiln drying and low-VOC adhesives, have reduced manufacturing energy use by up to 50% [51, 52]. Still, kiln drying and adhesive curing remain energy-intensive steps.

Operational energy use (module B6) remains the most significant contributor to a building’s life-cycle impact. Mass timber’s natural insulation reduces heating energy demand by 10–25% and improves energy efficiency by 15–20% compared with concrete [8]. Case studies, such as Adohi Hall, Fayetteville, AR, demonstrate how combining renewable energy, high-performance building envelopes, and timber structures can maximize overall performance [47].

Despite their benefits, LCAs can vary significantly due to differences in databases (e.g., USLCI vs. Ecoinvent), regional energy mixes, transportation modeling, and end-of-life scenarios. These factors can lead to differences of 30–40% in Global Warming Potential (GWP) results for similar buildings [48, 53]. As a result, standardized reporting protocols, such as EN 15978-compliant documentation, are recommended to increase transparency and enable fair comparisons between studies.

Modern LCA methods now employ dynamic modeling to track carbon emission rates over time, rather than treating them as a single event. This is especially relevant for timber buildings, since delaying carbon release through reuse or recycling can extend carbon storage past the building’s first life. When combined with BIM-integrated tools such as Tally or OneClick LCA, these models enable architects and engineers to simulate a building’s entire life cycle digitally, supporting early design decisions that improve both structural and environmental performance [54].

However, even with advanced digital integration, the accuracy of LCA outcomes still depends heavily on regional variables, such as local energy sources, transportation distances, and material production practices, which shape environmental performance across the U.S.

In summary, published LCA studies consistently demonstrate that mass timber provides significant environmental benefits, including substantial reductions in embodied carbon, increased material efficiency, and operational performance. Upcoming research must focus on standardizing system boundaries, harmonizing biogenic carbon accounting, and integrating region-specific data to improve the accuracy and comparability of mass timber assessments.

1.3.1. Regional and Environmental Factors Influencing LCAs in the U.S.

Life Cycle Assessment results for mass timber buildings vary widely by region. Factors such as energy grid mix, transportation distances, forest management practices, and climate all influence embodied and operational carbon emissions. Region-specific data is therefore essential for accurate analysis [54].

The Pacific Northwest, where most North American CLT is produced, shows favorable LCA results. The area benefits from well-managed forests, short transport distances, and predominantly renewable hydroelectric power, all of which reduce manufacturing and transport emissions. Conversely, the Southeast has less local production of mass timber, so CLT panels must travel farther, resulting in higher transport and construction emissions [55].

Differences in electricity generation are also significant. States that rely more on fossil fuels, such as those in the Midwest and South, have higher greenhouse gas emissions during building production and operation. States with cleaner energy sources, such as hydropower or wind, achieve significantly lower life-cycle emissions [56]. Climate also plays a role: timber's insulation is especially beneficial in cold northern states, while passive cooling strategies are more important in the warm South [57].

To improve the accuracy of LCAs, subsequent research studies should utilize region-specific models that incorporate local data on transportation, energy sources, and construction practices. This strategy supports more equitable comparisons between cities and enables more precise evaluation of the benefits of mass timber across the United States.

Steel construction has a unique regional and environmental profile because its production consumes significant energy and relies on either primary or recycled materials. Areas with electric arc furnaces (EAFs) powered by renewable energy, such as parts of the Pacific Northwest and Northeast, produce steel with lower embodied carbon than areas that use traditional, coal-fired blast furnaces [58].

Transportation also plays a role: the closer a project is to steel mills and fabrication plants, the lower the emissions from transporting materials. Since steel is widely recycled, regions with strong recycling systems usually see lower environmental impacts from production. Still, the manufacturing stage is highly carbon-intensive and accounts for the majority of steel's overall ecological footprint [59].

Reinforced concrete construction is also shaped by local factors such as the types of materials available, the type of cement used, and the energy sources used in production. Cement manufacturing alone accounts for approximately 7–8% of global CO_2 emissions, primarily due to the chemical reactions and the use of fossil fuels in kilns [60]. In the U.S., regions with access to supplementary cementitious materials (SCMs), such as fly ash, slag, or natural pozzolans, primarily in the Midwest and Gulf Coast, can reduce embodied carbon by replacing some Portland cement with these alternatives [61]. Using local aggregates and keeping transport distances short also lowers life-cycle emissions. However, in dry or earthquake-prone regions, higher concrete durability standards may require greater cement or reinforcement, which can offset these benefits. Therefore, using concrete mix designs tailored for local conditions and switching to low-carbon cements are key steps for improving the environmental performance of concrete structures [62]. Research studies differ in their definitions of system boundaries, the selection of functional units, the categorization of building types, methodological assumptions, and approaches to biogenic carbon accounting. This variability complicates direct comparisons and the establishment of clear conclusions. Noteworthy examples can be found in the work conducted by these studies [63-66].

2. Review Process

The process for this systematic review adhered closely to a rigorous and multi-step methodology to ensure accuracy and reliability of findings. Initially, a clear research question was defined, which focused on evaluating the life cycle, carbon footprint, or embodied carbon of structural mass-timber products. Subsequently, a detailed protocol was developed to guide the review process. A comprehensive literature search was conducted across multiple databases, including Scopus, Web of Science, and Google Scholar. Specific search terms and Boolean operators were employed to capture a wide range of relevant studies. This was followed by a structured screening process where studies were included or excluded based on predefined criteria, such as alignment with ISO standards or addressing regulatory factors. Quality appraisal of the included studies was then performed, ensuring that only those with methodological rigor were considered. The process concluded with data extraction, synthesis of findings, and structured reporting, as illustrated in Fig. (**4**).

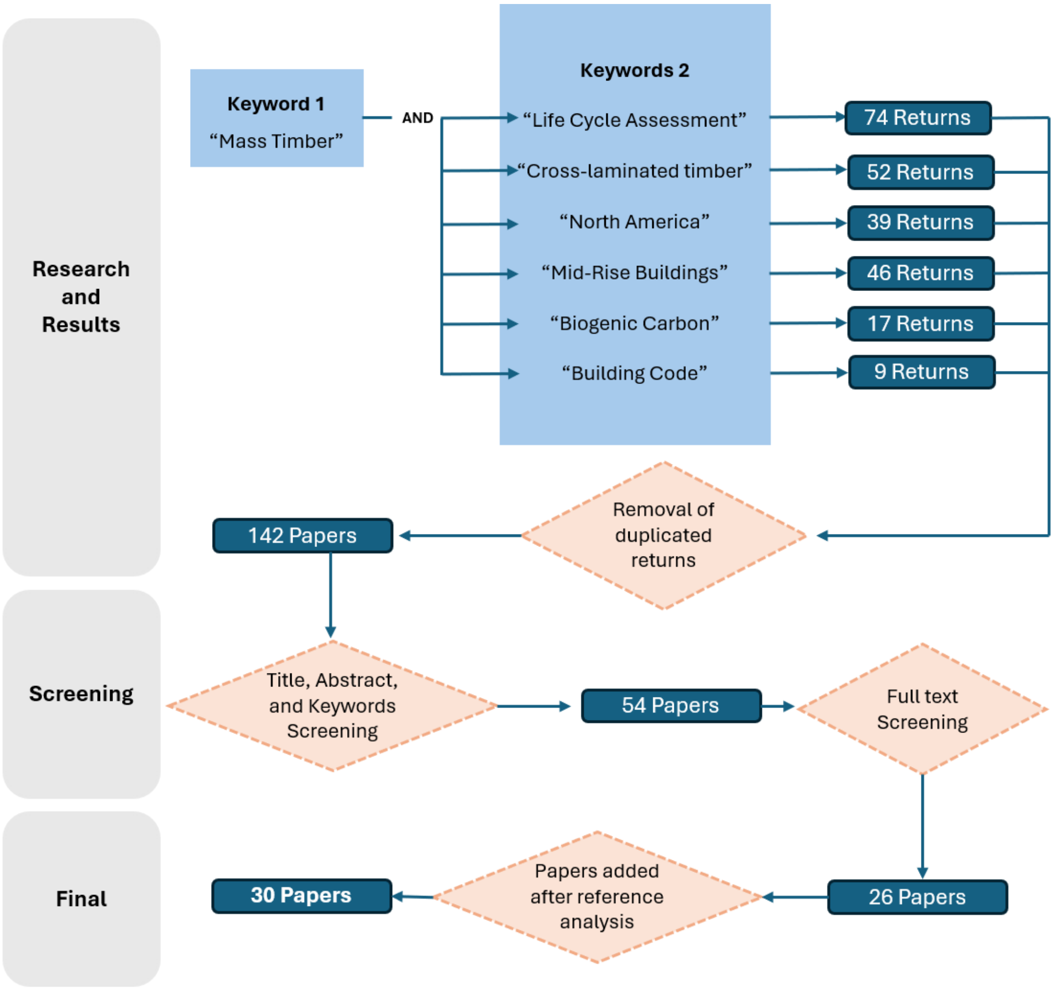

Figure 4: Schematic diagram of the review process, based on inclusion/exclusion criteria for papers published between 2009 and 2025.

2.1. Databases Searched

- **Scopus** (primary database)
- **Web of Science** (citation chaining)
- **Google Scholar** (grey literature & standards cross-check)

2.2. Inclusion and Exclusion Criteria

This review examined peer-reviewed studies indexed in Scopus that evaluated the life cycle, carbon footprint, or embodied carbon of structural mass-timber products. These products include cross-laminated timber (CLT), glued laminated timber (glulam), nail-laminated timber (NLT), and dowel-laminated timber (DLT). While the primary focus was on research relevant to North America, studies from other regions were also considered if their methodologies could be applied more broadly.

To be included in this review, studies were required to report at least one of the following metrics: global warming potential (GWP), embodied carbon, or biogenic carbon flows. Additionally, studies had to employ life cycle assessment (LCA) methods that aligned with ISO standards or demonstrated an equivalent level of methodological rigor. Another key criterion was the consideration of regulatory factors, such as building codes, height restrictions, or recent regulatory changes that might influence the adoption and use of mass timber in construction projects.

Several exclusion criteria were applied. Studies focusing on non-structural wood products, such as interior finishes or furniture, were excluded because the review was limited to structural elements. Research studies were excluded if authors addressed only operational energy use, without examining the embodied carbon of construction materials. Studies lacking clear definitions of system boundaries or data sources were omitted to ensure transparency and comparability of results. Additionally, purely conceptual papers, research limited to regions with minimal relevance to North America, and marketing materials without detailed methodologies were excluded. Finally, studies that did not compare mass timber with conventional construction materials such as steel or concrete were excluded from this review, as shown in Fig. (**5**).

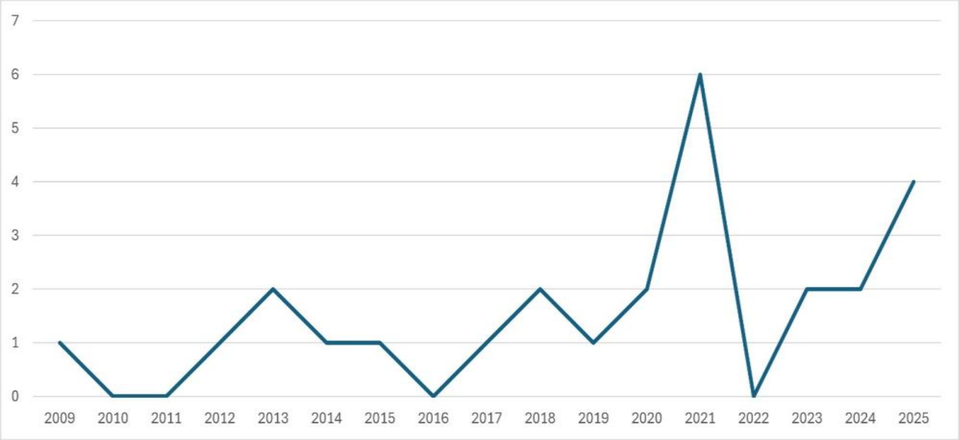

Figure 5: Number of research papers included in the review process per year.

3. Literature Overview

Mass timber and hybrid timber–concrete systems demonstrate significant potential for reducing the carbon footprint of buildings. As interest in sustainable construction increases, the number of life-cycle assessment (LCA) studies on these systems has grown. However, studies vary in their definitions of system boundaries, selection of functional units, categorization of building types, methodological assumptions, and approaches to biogenic carbon accounting. This variability complicates direct comparison and the formulation of clear conclusions. Notable examples include work by these studies [56, 63, 67-71].

To highlight key methodological differences: First, how system boundaries are defined differ significantly among studies, impacting the life-cycle stages they include, from cradle-to-gate to cradle-to-cradle. This affects the reported environmental impact metrics. Second, functional units vary; some studies measure impacts per square meter of floor area, while others use per cubic meter of material or per building component, leading to different interpretations of emissions intensity and reduction ratios. Third, inconsistent assumptions in biogenic carbon accounting, such as instantaneous oxidation versus stock-change methods, further compound variability, impacting Global Warming Potential outcomes. These differences stress the requirement for standardized methodologies to enable reliable comparison and interpretation across LCA studies.

Mass timber systems, such as CLT, glulam, LVL, and other engineered wood products, are considered beneficial for the climate because they generally generate fewer emissions during production and can sequester carbon over a building's lifetime [2, 43, 55, 72]. Yet the size and reliability of these benefits depend largely on the specific methods used in each LCA study. Because wood is a biological material with many possible end-of-life outcomes and is used within different building types, LCAs for mass timber need to clearly define system boundaries, functional units, carbon accounting, and data sources [18, 25, 45, 73].

As research into mass timber LCAs grows, methods are becoming more advanced, but there are also substantial differences in how studies are conducted. For example, some studies treat biogenic carbon in different ways; some use instantaneous oxidation, others use stock-change or dynamic methods [43, 63, 74, 75]. End-of-life scenarios are also modeled differently [76-78]. In addition, the way researchers define system boundaries and functional units is inconsistent, making it difficult to compare results across studies [18, 25, 43, 73]. When comparing mass timber to concrete and steel, it's clear that factors such as building type, hybrid systems, and material choices play a significant role in final environmental outcomes [2, 3, 55, 71, 79].

The diversity in LCA methodologies points to the need for greater alignment in research practices. Addressing these inconsistencies is essential for achieving more reliable and comparable results, which are critical as mass timber becomes increasingly prominent in sustainable construction. Concurrently, advances in research methods are emerging, including the adoption of dynamic LCA, scenario-based modeling, and the integration of Building Information Modeling (BIM) with automated LCA tools, although these approaches are not yet standard practice [39, 54, 68]. Long-standing problems, such as regional data variability, limited long-term information on timber use, and inconsistent approaches to uncertainty, continue to hinder direct comparison and the formulation of definitive conclusions [80-82].

Recognizing both the progress and the remaining challenges, the following sections analyze the main themes in current research. The following four sections synthesize these recurring themes in the literature. They address:

(1) variability in system boundaries and functional units,

(2) differences in biogenic carbon accounting and end-of-life modeling,

(3) typology- and substitution-driven variability in environmental outcomes, and

(4) remaining methodological challenges and emerging research directions.

Collectively, these key topics highlight both the potential of mass timber to mitigate climate impacts and the pressing need for methodological standardization in research. Standardization will facilitate more consistent, transparent, and actionable LCA results for policymakers and the construction industry.

This review synthesizes common trends in LCA system boundaries, approaches to biogenic carbon accounting, building typologies, the effects of material substitution, and key methodological uncertainties. It also highlights essential findings, sources of variability, and gaps that require further research.

3.1. System Boundaries, Functional Units, and Methodological Choices

LCA studies vary significantly in the life-cycle stages they consider and the functional units they use, both of which can influence results. While many studies adopt the EN 15978 standard for building LCAs, the extent and detail of coverage often differ:

- **Product stage (A1–A3):** Always included, encompassing raw material extraction, transport, and manufacturing; dominant for concrete and steel.
- **Construction stage (A4–A5):** Included selectively; [55, 69] consider transport and on-site assembly, whereas [67] provides limited detail.
- **Use phase (B1–B7):** Some studies assume identical operational energy, whereas [68] accounts for differences in thermal performance and airtightness.
- **End-of-life (C1–C4) and Module D:** Highly variable; [42, 65] provide detailed EoL modeling, whereas [69, 73] focus on demolition. Module D, reflecting avoided burdens from energy recovery or material substitution, is included mainly in forestry-focused and circular-economy LCAs.

These methodological differences make it challenging to directly compare emissions intensity and reduction ratios across studies.

A considerable challenge in the mass timber LCA literature is the lack of consistency in defining system boundaries and functional units. Some studies use cradle-to-gate [66, 67, 79, 83], cradle-to-grave [50, 56, 71, 84], or cradle-to-cradle approaches, which include recycling, cascading use, or energy recovery [52, 77, 85]. These differences make it challenging to interpret environmental results, particularly for embodied carbon, because factors such as forestry, manufacturing, and end-of-life processes can vary substantially and yield different global warming potential (GWP) outcomes. While some research follows established frameworks such as EN 15978 or ISO 14040/44, others adjust the stages based on available data or the specifics of the building design [18, 25, 73].

Functional units also vary widely. Some studies measure impacts per square meter of floor area [2-4, 31, 66], others use per cubic meter of material [65, 83], per building [48, 50, 72], or even per structural component, such as walls or floors [45, 62]. This choice significantly affects how results can be compared: building-level LCAs may obscure differences at the component level, whereas material-level LCAs don't capture whole-building performance. Because of differences in boundary and unit definitions, comparative LCAs often yield a broad range of results. This highlights the need for standardized reporting, as several review papers call for greater harmonization and transparency to support meaningful comparisons across studies [18, 25, 43, 73].

In summary, standardizing both system boundaries and functional units is essential for improving the comparability and reliability of LCA studies. Such standardization would enhance the consistency of conclusions regarding environmental impacts. The subsequent section examines another primary source of variation in mass-timber LCAs: biogenic carbon accounting and end-of-life modeling.

3.2. Biogenic Carbon Accounting Approaches and End-of-Life Modeling

Biogenic carbon accounting constitutes one of the most contested and influential aspects of LCA for mass-timber buildings. The reviewed literature reveals no consensus regarding the quantification, allocation, or temporal representation of biogenic carbon. Table **1** summarizes the studies of Biogenic Carbon and End-of-Life Modeling.

Methodological approaches range from instantaneous oxidation, which assumes all biogenic carbon is emitted at harvest, to stock-change and dynamic models that explicitly account for carbon storage and delayed emissions over time [63]. Module D credits related to mass timber highlight the advantages of substitution and restricted reuse, focusing on recycling and energy recovery methods, including incineration paired with recycling [66]. Furthermore, it emphasizes the significance of region-specific elements and assumptions regarding stock changes, indicating that mass timber systems possess considerable recycling potential contingent upon local infrastructure and end-of-life conditions [65, 66]. These methodological decisions exert a pronounced impact on reported GWP outcomes and serve as a principal source of variability among studies [67].

Recent methodological research has elucidated that inconsistencies in the definition of temporal boundaries and reference study periods substantially affect reported global warming potential (GWP) outcomes in timber life cycle assessments (LCAs) [74, 85]. Whereas certain studies employ a 50-year reference service life, others extend the analytical frame to 60 or 100 years, thereby modifying accounting for delayed biogenic emissions and maintenance schedules. Moreover, the choice of background data, the use of regionally adjusted datasets as opposed to global averages can systematically bias material-stage emission estimates [68, 76]. These methodological discrepancies highlight the necessity for transparency that encompasses not only declared life-cycle stages but also the explicit selection of time horizons, assumptions regarding service life, and the provenance of databases utilized. In the absence of such rigor, quantitative comparisons may conflate fundamental differences in structural performance with artifacts introduced by modeling choices.

Consequently, reported carbon reductions associated with mass-timber construction are highly dependent on the selected methodological approach. Studies employing stock-change or dynamic models typically report substantially greater climate benefits than those using instantaneous oxidation, even when analyzing comparable building designs. This divergence arises not from differences in physical building performance but from variations in accounting conventions. In the absence of a harmonized framework, results derived from disparate biogenic carbon models should not be considered directly comparable when absolute emission values or percentage reductions are reported without appropriate contextualization. The interpretation of temporary biogenic carbon storage introduces additional complexity. Although carbon stored in timber products may delay atmospheric emissions for several decades, such storage is inherently temporary and contingent upon end-of-life scenarios, including reuse, recycling, energy recovery, or disposal. Overstating temporary sequestration as permanent mitigation risks exaggerates the long-term climate benefits of timber systems. Therefore, biogenic carbon storage should be addressed with caution and transparency, explicitly acknowledging underlying assumptions and temporal boundaries. The lack of standardized protocols for temporary storage remains a significant challenge to producing credible, comparable LCA results.

Table 1: Summary of biogenic carbon & end-of-life modeling in 30 mass-timber LCA studies.

S. No.	References	Region / Context	Biogenic Carbon Approach	End-of-Life (EoL) Assumptions
1	[63]	North America / General	Stock-change; sensitivity cases	Landfill dominant; limited recycling
2	[64]	Canada (Vancouver)	Module D credits: substitution discussed	Limited reuse: recycling included
3	[65]	Italy & U.S. supply chain	Immediate release vs stock change	Incineration + recycling
4	[67]	Canada	Substitution factors; conservative storage	Landfill with slow decay
5	[68]	U.S. (tall timber)	Substitution & stock-change	Typical NA landfill behavior
6	[69]	Canada	Dynamic LCA + stock-change	High reuse potential
7	[70]	U.S.	Regional stock-change	CLT recycling discussed
8	[72]	Pacific Northwestern U.S.	Cradle-to-grave + stock-change	Recycling included
9	[74]	Global methodology	Stock-change & dynamic LCA	Highlights variable EoL assumptions
10	[75]	International review	Forestry & biogenic carbon focus	EoL impacts contextualized
11	[76]	U.S.	Module D explored; decay scenarios	Energy recovery, recycling
12	[77]	Sweden (method-focused)	Stock-change + decomposition	Landfill decay prominent
13	[79]	Global CLT overview	Production-stage carbon considerations	Minimal EoL detail
14	[81]	North America	Regional stock-change	Region-specific landfill & transport
15	[82]	North America	sustainable forest management and coordinated trade development	Detailed timber trading
16	[83]	United States	Stock-change + substitution	Recycling & reuse options
17	[84]	Europe	Storage + Module D	Recycling + energy recovery
18	[85]	United States	Storage & substitution discussed	Reuse + recycling considered
19	[86]	U.S. Pacific Northwest	Region-specific factors; stock-change	High recycling potential
20	[87]	North America (code review)	Notes implications for carbon storage	General EoL commentary
21	[88]	U.S.	Module D discussed	Standard-based EoL assumptions
22	[89]	Meta-analysis	Substitution factors surveyed	Varied EoL across datasets
23	[90]	Australia	Carbon decay modeling	Landfill methane modeling
24	[91]	U.S. & Canada	Code-driven carbon impacts	EoL scenarios included
25	[92]	UBC TallWood	Stock-change	High reuse & recovery
26	[93]	North America (industry)	EPD-style biogenic reporting	Limited EoL detail
27	[94]	Comparative study	Sensitivity of biogenic methods	Multiple EoL scenarios
28	[95]	Critical review	Advocates method harmonization	Inconsistent EoL practices highlighted
29	[96]	Canada (hybrid systems)	Stock-change + Module D	Hybrid EoL pathways
30	[97]	U.S.	Using multiple models to describe alternative futures for new mass timber construction	Replace traditional constructions with mass timber.

Different assumptions about what happens to timber at the end of its life also create uncertainty. Some studies assume wood is burned for energy [50], while others think it ends up in landfills, where it may decay slowly or only partially [76-78]. Because decay rates vary with factors such as climate and wood type, long-term carbon storage estimates differ significantly across studies [66, 78, 86]. Increasingly, researchers are exploring reuse options, such as downcycling wood into fiberboard, turning demolition wood into biofuel [65, 85], recycling [66, 86] , and reusing panels [76]. These varying assumptions can alter LCA results by up to ±40%, demonstrating the relevance of biogenic carbon modeling for assessing whether timber is more environmentally friendly than mineral-based alternatives.

End-of-Life (EoL) modeling remains a significant source of variability:

- Landfilling remains included, although regulations increasingly restrict it.
- Incineration with energy recovery.
- Material recycling and cascading reuse are increasingly included in recent studies.

Assumptions regarding carbon release during demolition, landfill decay, and reuse and recycling pathways have a substantial impact on the reported environmental benefits of mass timber. Including Module D in the assessment, which accounts for benefits from energy recovery or material substitution, can significantly offset end-of-life emissions. In contrast, studies that exclude Module D typically report only modest net reductions in greenhouse gas emissions.

Forest management, rotation length, yield, residue use, and mill efficiency affect the benefits of biogenic carbon. Authors of [68] demonstrate that Pacific Northwest practices substantially influence mass-timber LCA results.

Given the importance of both carbon accounting and end-of-life scenarios, standardized and transparent approaches are needed to avoid misleading results. With these complications in mind, the following section turns to how building design choices and material substitutions further influence the outcomes of timber LCAs.

3.3. Influence of Building Typology, Hybrid Systems, and Material Substitution

The type and function of building, whether it’s mid-rise, high-rise, modular, residential, or commercial, has a significant impact on the environmental profile of mass timber. LCAs show that smaller buildings often derive greater relative benefits from timber use, since their structures are simpler and require less reinforcement [48, 50, 52]. In contrast, high-rise buildings may need hybrid solutions that include steel or concrete for stability, fire safety, and noise control [7, 10, 87, 91, 98]. Comparisons between tall mass timber buildings and concrete or steel alternatives [2, 3, 72, 86] often find significant reductions in embodied carbon, but the actual amount depends on design choices such as structural efficiency, panel thickness, and the extent of hybridization.

3.3.1. Typologies and Systems Studied

- Mid-rise residential and office buildings [63, 68].
- Tall multi-story commercial buildings [69].
- Material substitution of structural elements [55, 73].
- Mass-timber production system modeling [66, 86].
- Mass-timber typologies: CLT, glulam, and LVL predominate, with fewer hybrid systems that combine concrete cores or steel bracing [25, 28, 62].

End-of-life (EoL) modeling constitutes a principal source of methodological uncertainty within LCAs of mass-timber buildings [83, 88, 89]. The extant literature reveals considerable heterogeneity in assumptions regarding demolition practices, landfill decay rates, incineration with or without energy recovery, recycling efficiencies, and cascading reuse pathways. These post-use processes will transpire several decades after initial construction and are contingent upon evolving regulatory frameworks, technological advancements, and fluctuating market conditions. Consequently, EoL scenarios are inherently speculative, and their modeling introduces significant uncertainty. Notably, discrepancies in EoL modeling often surpass those encountered in earlier life-cycle stages and exert a pronounced influence on net GWP outcomes. Assumptions regarding carbon release during demolition, carbon behavior in landfill storage and decay, and the fate of materials in reuse or recycling pathways directly affect the environmental performance of mass timber [79].

The treatment of Module D introduces an additional, highly consequential layer of methodological variability to mass-timber LCAs. Module D, as defined in EN 15978, accounts for potential environmental impacts and benefits arising from processes beyond the system boundary, such as energy recovery from incineration or material substitution resulting from recycling. The literature demonstrates that some studies incorporate Module D credits to account for avoided emissions, while others either omit Module D entirely or apply it selectively. Module D can substantially offset reported end-of-life emissions, resulting in more favorable net greenhouse gas reduction outcomes. In contrast, studies that exclude Module D typically report more modest reductions. Importantly, Module D should be regarded as an optional and strongly scenario-dependent component, not as an inherent or guaranteed benefit of mass-timber construction. Climate benefits that rely heavily on the inclusion of Module D are contingent upon assumptions about future recovery efficiencies, substitution ratios, and regulatory environments, parameters that are inherently uncertain and difficult to predict at the time of assessment. Thus, interpreting such reported advantages requires caution and transparency.

In addition to considerations related to (EoL) modeling and Module D, forest management practices, such as rotation length, harvest yield, residue utilization, and sawmill efficiency, exert a critical influence on the magnitude and persistence of biogenic carbon benefits in mass-timber LCAs. For instance, the authors' empirical analysis in [82] demonstrates that forestry practices in the Pacific Northwest substantially affect LCA outcomes for mass-timber buildings, underscoring the pronounced sensitivity of environmental outcomes to regional supply-chain characteristics. Given the cumulative significance of carbon accounting methodologies, forestry management assumptions, and EoL scenario selection, optimistic LCA findings for mass-timber construction must be interpreted as contingent and context-dependent rather than as universally applicable or absolute. Comprehensive transparency in documenting modeling assumptions, coupled with rigorous sensitivity and uncertainty analyses, is essential to prevent overstatement of timber’s climate benefits and to facilitate meaningful cross-study comparisons. Considering these methodological complexities, the subsequent section explores the way building design decisions and material substitution strategies further modulate the life-cycle environmental performance of mass-timber systems.

3.3.2. Substitution Benefits

Timber generally outperforms concrete and steel in cradle-to-gate GHG emissions due to lower embodied carbon, reduced process energy use, carbon sequestration, and, in some cases, lower transport energy use. Reported reductions range from 10% to 70%, depending on boundaries and methodology [69, 72]. Factors influencing variability include concrete mix design, steel recycling rates, timber sourcing, kiln-drying energy, inclusion of carbon storage, and Module D. Lightweight timber assemblies may further reduce the need for foundations and mechanical systems [68, 69, 99]. In contrast, operational differences are minimal when building envelopes and HVAC systems are considered.

Timber typically performs well on global warming potential (GWP) and non-renewable energy consumption. However, certain timber products may exhibit higher environmental impacts in categories such as eutrophication or acidification, often due to forestry operations or adhesive use. In some cases, concrete may outperform timber in terms of resource depletion or photochemical ozone formation [63]. Therefore, it is essential to evaluate the carbon benefits of wood within the broader context of all relevant environmental impacts.

Substituting conventional materials is a significant reason why timber can offer environmental benefits. Studies show that replacing concrete and steel with engineered wood results in substantial reductions in greenhouse gas emissions because wood production emits lower levels of greenhouse gases and can sequester biogenic carbon [55, 66, 86]. However, using hybrid systems complicates matters. For example, timber–concrete floors [25], steel–timber connections [35], modular timber units [100], and hybrid cores [91] can improve a building's performance. Still, they also add embodied impacts from materials such as adhesives, fasteners, rebar, and additional concrete [51]. These trade-offs mean it's important to model each system carefully rather than making broad assumptions about how all building types will perform.

The design and material selection for a building substantially affect the environmental outcomes reported in LCAs. Considering these factors, the following section addresses persistent methodological challenges and key gaps in current research.

3.4. Key Findings, Variability, and Uncertainties

3.4.1. Consistent Findings

- Timber systems have lower embodied GWP than concrete and steel.
- Material substitution can reduce GHG emissions by 20–60%, depending on the system boundaries.
- End-of-life modeling significantly affects results; Module D improves apparent performance.
- Regionalized LCAs yield more accurate outcomes.

3.4.2. Variability and Sources of Uncertainty

- Net emissions range from near-zero (with carbon storage and Module D) to modest 10–20% reductions (realistic EoL scenarios).
- Early studies [67, 77] often reported higher benefits due to simpler carbon accounting.
- Methodological challenges include carbon accounting (timing, allocation, decay), representation of regional variability in operational energy assumptions [68], and tall or complex buildings [69], and electricity, kiln-drying, transport, and forestry certification [86].

3.4.3. Synthesis and Implications

Mass timber consistently exhibits lower embodied carbon than conventional building materials such as concrete and steel. Conservative estimates indicate cradle-to-gate carbon reductions of 10–50%, while the highest potential benefits, 50–70%, are achieved when Module D is included and realistic assumptions about recycling and circular-economy practices are adopted. The environmental advantages of timber are highly context-dependent, with factors such as local sourcing, high recycling rates, access to low-carbon energy, and appropriate structural design playing critical roles. Nevertheless, the absence of standardized approaches to defining system boundaries, selecting functional units, carbon accounting, and end-of-life modeling continues to hinder direct comparison of results across studies.

3.5. Methodological Challenges and Data Gaps

Despite notable advances, several factors limit the reliability and comparability of current mass-timber LCAs. Data quality and regional differences remain significant issues. Factors such as forestry practices, sawmill technology, transportation distances, and local energy grids all vary by region and directly affect environmental outcomes [14, 81, 82]. These assumptions include system boundaries, biogenic carbon accounting methodologies, material quantities, energy sources, and end-of-life scenarios. This lack of explicit sensitivity analysis means that reported values frequently project an unwarranted sense of precision, thereby obscuring the substantial methodological and data uncertainties inherent to mass-timber LCA. The absence of uncertainty quantification is particularly problematic given the complex, multi-phase nature of building life cycles and the substantial influence of regional, temporal, and scenario-specific variables on assessment outcomes.

A limited subset of studies explores variability through scenario comparisons or basic sensitivity testing, while only a handful employ advanced probabilistic methods to quantify uncertainty formally. Therefore, the relative influence of competing assumptions, such as those about material sourcing, end-of-life treatment, or energy grid decarbonization, often remains ambiguous, and the robustness of comparative findings is seldom demonstrable. This lack of explicit characterization uncertainty should not be viewed merely as an oversight in individual studies;

rather, it constitutes a structural deficiency within the broader field of mass-timber LCA research. Addressing this gap is essential for enhancing the credibility, transparency, and policy relevance of LCA results, especially as these assessments increasingly underpin design decisions, regulatory development, and the adoption of low-carbon construction practices. To advance the field, future research should prioritize integrating thorough uncertainty analysis, incorporating scenario-based sensitivity analyses, and adopting probabilistic approaches to support more robust, context-sensitive conclusions.

Additionally, it's often difficult to obtain consistent, complete Environmental Product Declarations (EPDs), which makes it harder to ensure the accuracy of background data [92]. Furthermore, variability in methodological approaches, such as those in biogenic carbon accounting and system boundary definitions, introduces additional uncertainty into results. A lack of formalized processes for evaluating end-of-life scenarios further complicates comparisons across studies, as assumptions about carbon release during demolition or landfill decomposition can significantly alter outcomes. These limitations underline the necessity for standardized methodologies and thorough data compilation to improve the accuracy and transparency of mass-timber LCAs.

The most urgent data gaps include the need for region-specific Environmental Product Declarations (EPDs) and comprehensive end-of-life data, which should be prioritized in collaborative research efforts. Region-specific EPDs can provide more accurate environmental performance metrics by considering local production and resource management practices. Additionally, collecting detailed end-of-life data will enhance our understanding of carbon release and storage, particularly across various disposal and recycling scenarios. Addressing these critical gaps will improve the reliability of life-cycle assessments and aid in better policymaking and industry practices.

Recent studies have underscored the need to employ consequential life-cycle assessment (CLCA) methodologies in evaluating large-scale timber adoption scenarios [101]. In contrast to attributional LCAs, which quantify the environmental impacts of a delineated system, CLCA frameworks endeavor to account for market-mediated effects, encompassing shifts in land use, material demand elasticity, and the dynamics of global timber trade. Such system-level interactions may either augment or attenuate the net climate benefits associated with mass-timber deployment, contingent on the prevailing policy context and supply chain governance structures [25]. Furthermore, emerging literature advocates integrating LCA with biodiversity metrics, ecosystem service valuation, and land–carbon feedback modeling to mitigate the risk that climate mitigation strategies inadvertently engender ecological trade-offs [64, 94]. The incorporation of these expanded analytical dimensions would substantially enhance the methodological robustness and policy relevance of future environmental assessments of mass-timber construction.

Uncertainty analysis is another area where standard practice is lacking. Only a few studies employ methods such as Monte Carlo simulation, scenario modeling, or sensitivity analysis to examine how system boundaries, carbon accounting, and material properties affect results [43]. While dynamic LCA is beginning to be used, as it’s useful for long-lived materials, it has not yet become widespread. Digital tools that link Building Information Modeling (BIM) and LCA could improve data quality and automated processes, but these technologies are still not widely adopted in practice [53, 54, 68].

The limited number of peer-reviewed studies identified in this review highlights the nascent stage of mass-timber construction in the United States; the proliferation of mass-timber buildings has been principally influenced by the adoption of new construction classifications in the 2021 International Building Code. These provisions authorize timber structures up to 18 stories tall, contingent on stringent fire safety, structural integrity, and encapsulation standards. As a result, mass timber is primarily positioned as a mid-rise construction solution within the current U.S. building inventory. Accordingly, the pool of completed or in-progress projects appropriate for comprehensive life cycle assessment (LCA) and, thus, the number of peer-reviewed LCA studies remains small.

The predominant focus on the United States further limits the generalizability of findings. LCAs of mass-timber construction are highly sensitive to regional variables, including electricity grid carbon intensity, transportation logistics, forest management practices, manufacturing methods, and code-mandated design criteria. International contexts frequently differ in regulatory environments, timber supply chains, construction methodologies, and climatic conditions, often resulting in substantially different environmental performance metrics. Recent comparative analyses emphasize that LCA results generated within a specific regulatory and regional context should not be extrapolated to other settings without rigorous recalibration and reinterpretation.

Therefore, the conclusions presented in this review should be understood as reflecting code-compliant, mid-rise mass-timber buildings within the contemporary U.S. regulatory and market context, rather than serving as universal benchmarks for high-rise, hybrid, or internationally regulated timber structures. While this scope necessarily limits generalizability, it affords a consistent, policy-relevant analytical framework that aligns with prevailing construction practices. As mass-timber adoption increases, building codes are revised, and more varied building types are constructed, future research will be essential to determine whether environmental performance trends identified in mid-rise U.S. applications apply to other contexts [87, 89, 92].

4. Conclusion, Research Gaps and Future Directions

Mass-timber buildings are repeatedly shown to have lower embodied carbon than traditional concrete and steel structures, regardless of the boundaries, building types, or case studies considered [70, 71, 97, 102]. This is mainly because engineered wood products produce fewer emissions during production, and timber can store carbon for many years within a building. However, the magnitude and reliability of these environmental benefits vary substantially across studies, mainly because researchers employ different methods to track carbon. The handling of biogenic carbon is critical. Studies that use stock-change or dynamic accounting methods tend to show greater long-term carbon storage and delayed emissions, resulting in bigger greenhouse gas benefits for timber.

In contrast, studies that use instantaneous oxidation, assuming all carbon is released when the tree is harvested, downplay timber's advantages. How the end-of-life stage is modeled also makes a big difference: when LCAs include options like reuse, recycling, energy recovery, or long-term landfill storage, timber's results look much better than when studies use simple disposal assumptions or leave out Module D. Including Module D, which gives credit for the impacts avoided by using recovered materials or energy, can change a building's results by 20–60%. This stresses the critical nature of evaluating the circular-economy benefits of timber systems.

A primary source of uncertainty in mass-timber life-cycle assessments (LCAs) concerns the treatment of biogenic carbon. The reviewed literature indicates that estimates of climate benefits are highly sensitive to accounting assumptions, especially those related to carbon storage, emission timing, and end-of-life scenarios [103]. In the absence of standardized methodologies, results concerning biogenic carbon should be interpreted with caution, and reported reductions should not be regarded as definitive or universally generalizable. While temporary carbon storage may offer short-term emission delays, it does not equate permanent sequestration and must be evaluated within rigorously defined temporal and system boundaries. Enhancing consistency, transparency, and methodological alignment in biogenic carbon accounting is crucial for increasing the reliability and policy relevance of future assessments.

But carbon accounting isn't the only factor that shapes the environmental story. Other differences, such as which functional units are selected, where the study is conducted, and which background data are used, also greatly alter results. For instance, how forests are managed in different regions, including harvest cycles, leftover wood, and certification, changes the emissions that happen before the wood even reaches the factory. Energy grids and manufacturing technology in sawmills and panel production can also influence emissions. Even the distance traveled, whether from nearby forests or distant forests, can affect the results, especially if transportation impacts are underestimated. All these variables make comparing studies challenging, which is why there's a real need for more standardized boundaries, reporting, and data quality checks in LCAs.

These methodological and contextual differences help explain why results across the literature can vary substantially. Building on this, it's essential to look at how the type of building studied affects the outcomes reported in timber LCAs. Another critical issue is the type of buildings being studied. Most LCAs focus on low- to mid-rise residential or institutional buildings, where structures are relatively straightforward, and mass timber can readily replace concrete or steel. Few studies examine tall or complex timber buildings, which often require additional fire protection, sound insulation, specialized structural supports, or hybrid timber–concrete cores.

These requirements can increase material use and embodied carbon. Because of this, the evidence is strong for timber's benefits in standard mid-rise buildings, but less clear in high-rise buildings, where material mixing may reduce carbon savings.

The findings presented in this review should be interpreted within the context of several interrelated and persistent limitations that define the current body of mass-timber life cycle assessment (LCA) literature. Environmental outcomes reported across studies are subject to substantial methodological variability, notably manifesting in inconsistent system boundaries, divergent functional units, non-standardized biogenic carbon accounting methodologies, and varying end-of-life scenario assumptions. The treatment of Module D remains particularly inconsistent, with its inclusion being optional and highly scenario-dependent, thereby exacerbating the divergence of reported results. Furthermore, many studies present optimistic environmental outcomes that depend on assumptions about future reuse, recycling, or energy recovery, which are highly uncertain and context-specific. A further limitation is the widespread reliance on deterministic point estimates in the absence of formal quantitative uncertainty analyses, which constrains the ability to assess the robustness and reproducibility of reported results. The predominance of single-case studies and samples clustered in specific regions greatly limits the generalizability and broader applicability of the findings. Taken together, these limitations do not diminish the evidence supporting the embodied-carbon mitigation potential of mass-timber construction; rather, they highlight the critical need for cautious interpretation, rigorous and transparent methodological reporting, harmonization of assessment frameworks, and the development of larger, more diverse, and systematically varied datasets. Such advances are essential for enabling robust cross-study comparison, informing policy and design decisions, and advancing the reliability and impact of mass-timber LCA research.

Inconsistent treatment of Module D credits and limited consideration of region-specific factors, including electricity mix, transportation logistics, forest management, and climate, further restrict the transferability of reported results across geographic and regulatory contexts.

Identifying these gaps in the types of buildings studied clarifies priorities for future research. To enhance the reliability and validity of mass-timber LCAs, future studies should incorporate forestry and manufacturing data representatives of diverse regions, adopt standardized biogenic carbon accounting methods, and address tall and hybrid timber buildings. The use of dynamic carbon models improved long-term data on timber end-of-life outcomes, and more detailed scenario analysis will increase the trustworthiness and policy relevance of results. While current research provides a strong foundation for understanding the environmental performance of timber buildings, there remains a clear need for improved methodologies to ensure results are accurate, comparable, and actionable for sustainable construction.

The following critical areas were identified through the review process that require further research:

- Comprehensive lifecycle assessments of tall timber buildings should address fire-rated assemblies, moisture management, hybrid structural cores, vibration damping, and high-load connection details. These areas are foundational for providing safety and performance in mid-rise and tall structures.
- Advancements in carbon accounting, particularly the adoption of dynamic, time-based models that track carbon storage, delayed emissions, substitution effects, and carbon payback periods, will enhance the accuracy of results and are urgent for refining environmental impact assessments.
- Applying circular economy principles and cascading use strategies, such as enabling multiple lifespans for timber and increasing mechanical and chemical recycling, remains a key research priority, necessitating realistic Module D assumptions.
- Developing regionalized LCA databases that account for local forest types, silvicultural practices, climate conditions, and industrial energy sources will improve the relevance and precision of analyses and is critical for tailoring assessments to specific environments.
- Integrating structural design with LCA, emphasizing material efficiency, hybrid components, and unified frameworks that connect structural optimization to environmental assessment, will further support sustainable construction practices and should be prioritized to unify these disciplines.

Conflict of Interest

The authors do not have any conflict of interest with any known institutions, agencies, or individuals.

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