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Review

Life Cycle Assessment of Engineered Wood Products in the Building Sector: A Review

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Abstract

Engineered wood products have become key sustainable alternatives to conventional building materials, offering strong potential for reducing climate impacts in the construction sector. This review systematically assesses recent life cycle assessment studies on engineered wood products to compare their environmental performance and support low-carbon building practices. The peer-reviewed literature published over the past decade was analyzed for publication trends, geographic focus, and methodological approaches, including goal and scope definition, life cycle inventory, and life cycle impact assessment. Comparative analyses examined climate change impact and key parameters influencing environmental outcomes. Results indicate a steady growth of research in this field, led by China, the United States, and Europe. Volume-based functional units (e.g., 1 m^3) are predominant in structural wood studies, while mass-based units are more common for composites. Cradle-to-gate boundaries are most frequently used, and data are primarily drawn from Ecoinvent, Environmental Product Declarations, and regional databases such as GaBi and CLCD. Common impact assessment methods include CML-IA, ReCiPe, and TRACI, with climate change identified as the core impact category. Cross-laminated timber and glue-laminated timber consistently show lower and more stable climate change impacts, while fiberboards exhibit higher and more variable results due to adhesive content and energy-intensive manufacturing. Key factors influencing environmental outcomes include service life, wood species, and material sourcing. The review highlights the need for standardized methodologies and further exploration of emerging products, such as nail-laminated and dowel-laminated timber and laminated bamboo, to improve comparability and inform sustainable design practices.

Keywords: engineered wood products; life cycle assessment; systematic review; environmental impacts; low-carbon construction

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1. Introduction

The construction sector is responsible for approximately 37% of global carbon dioxide emissions and nearly 40% of total energy consumption, making it one of the largest contributors to environmental degradation worldwide [1]. In this context, the growing emphasis on decarbonization has prompted a renewed interest in renewable, low-impact alternatives, among which wood has emerged as a viable option [2]. Compared to traditional construction materials like concrete and steel, wood offers the advantage of renewability and carbon sequestration, making it an attractive candidate for reducing the environmental footprint of buildings [3]. However, the inherent heterogeneity, anisotropy, and limited

dimensions of solid wood can compromise its structural performance and durability [4]. Moreover, challenges related to forest management and unsustainable harvesting practices, such as the use of increasingly younger trees, may limit the quality and availability of raw timber for construction [5].

Engineered wood products (EWPs) have emerged as a solution to these limitations, offering enhanced mechanical properties, dimensional stability, and material efficiency. EWPs are manufactured by bonding together wood components such as veneers, strands, fibers, and sawn timber using adhesives or mechanical fasteners [6]. These products include widely used types like cross-laminated timber (CLT), glued-laminated timber (GLT), plywood (PW), laminated veneer lumber (LVL), particleboard (PB), and medium-density fiberboard (MDF), as well as emerging or less common variants such as dowel-laminated timber (DLT), nail-laminated timber (NLT), and wood–plastic composites (WPCs). EWPs are applied in various structural and non-structural contexts including floors, walls, beams, insulation layers, and decorative elements [7].

Despite their sustainability potential, the manufacturing and end-of-life processes of EWPs involve environmental trade-offs, particularly due to the extensive use of adhesives and energy-intensive processing stages [8,9]. To holistically evaluate their environmental performance, Life Cycle Assessment (LCA) has become an indispensable methodology. LCA is a standardized framework for quantifying the environmental impacts of a product, system, or process across its life cycle, from raw material extraction to manufacturing, use, and end-of-life (ISO 14040/44) [10]. It enables multi-impact assessment including, but not limited to, global warming potential (GWP), acidification, eutrophication, and particulate matter formation. Importantly, LCA supports decision-making by enabling comparisons among materials, identifying hotspots in production chains, and guiding improvements in material selection and design [11].

LCA has been increasingly applied in the assessment of wood-based products. For example, studies show that among the manufacturing stages of plywood, veneer preparation and panel pressing contribute most significantly to environmental burdens [12], while adhesive-free options like DLT can yield lower GHG emissions than CLT or NLT [13]. In the case of MDF and PB, manufacturing impacts often outweigh those from end-of-life processes such as landfilling or energy recovery [11]. A number of review articles have attempted to consolidate LCA research on wood products [14–16]; however, these reviews often face limitations. The scopes of these studies are frequently constrained by specific product categories, narrow temporal or regional contexts, or restricted methodological dimensions, which hinder a holistic understanding of the comparative environmental performance of EWPs. These limitations also restrict the broader application of findings in policy and practice, limiting their utility for making more generalized recommendations.

This study addresses these limitations by offering a comprehensive and up-to-date systematic review of LCA applications across the full spectrum of EWPs. It is guided by three central research questions: (1) What are the current developments and research trends in EWPs? (2) What are their environmental impacts across different geographic regions, time periods, and production contexts? and (3) How do variations in LCA methodologies and product typologies influence the reported results? By synthesizing peer-reviewed literature from a wide geographic and temporal range, the review captures diverse methodological practices and product characteristics, enabling cross-comparisons that were previously lacking. It focuses particularly on GHG emissions and related indicators, while also investigating the influence of key methodological parameters such as system boundaries, functional units, data sources, and impact assessment methods. By filling existing gaps in scope, comparability, and methodological transparency, this review advances the state of knowledge on EWP sustainability performance and offers a foundation for more standard-

ized LCA practices. These contributions are intended to inform future research, support evidence-based decision-making in material selection, and promote the adoption of low-carbon construction strategies globally.

2. Materials and Methods

This study was conducted in accordance with the PRISMA (preferred reporting items for systematic reviews and meta-analyses) guidelines to integrate and analyze related research data and findings transparently and effectively [17]. The methodology was structured into three main stages: literature searching, screening, and data synthesis and analysis. An overview process of this study is illustrated in Figure 1.

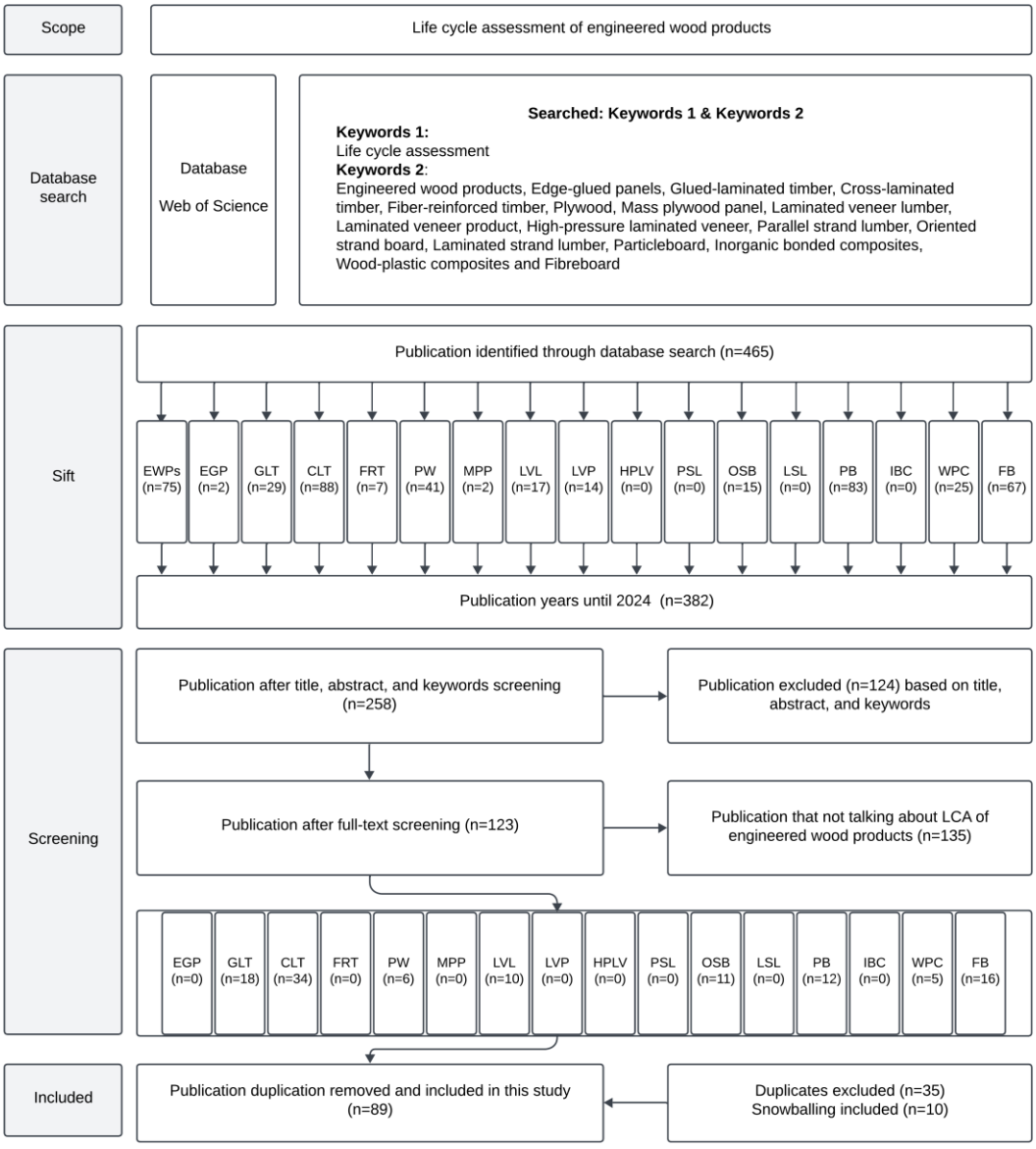

Figure 1. Review process. Note: EWPs = Engineered Wood Products; EGP = Edge-Glued Panels; GLT = Glued-Laminated Timber; CLT = Cross-Laminated Timber; FRT = Fire-Retardant Treated Wood; PW = Plywood; MPP = Mass Plywood Panel; LVL = Laminated Veneer Lumber; LVP = Laminated Veneer Panel; HPLV = High-Performance Laminated Veneer; PSL = Parallel Strand Lumber; OSB = Oriented Strand Board; LSL = Laminated Strand Lumber; PB = Particleboard; IBC = Industrial Board Composite; WPC = Wood–Plastic Composite; FB = Fiberboard.

2.1. Literature Searching

The literature search was performed using the Web of Science Core Collection, which offers comprehensive coverage of over 12,000 international peer-reviewed journals and is widely used in environmental and engineering research [18]. It was selected as the sole database source to ensure the inclusion of peer-reviewed journal articles with standardized indexing and citation data, thereby enhancing the consistency and comparability of extracted information. The search strategy employed a combination of keywords encompassing "life cycle assessment OR LCA", "environmental impact", "carbon emissions", "buildings", "construction", and various types of EWPs. The definitions of different types of EWPs are based on the US Engineered Wood Association (APA) and related literature reviews [7,16]. This review includes peer-reviewed studies published up to 2024, representing the most recent period with sufficient data availability and indexing completeness to ensure methodological consistency and comparability across studies.

The initial search resulted in a total of 465 publications, including review articles, articles, proceeding papers, and early access papers. These publications covered a range of EWP types, including 75 studies on general EWPs, 88 on CLT, 83 on PB, 67 on FB (mainly MDF), 41 on PW, 29 on GLT, and 25 on WPC. A smaller number of studies were found on other EWP categories, including 17 papers on LVL, 15 papers on OSB, 14 papers on LVP, 7 on FRT, and 2 papers each on EGP and MPP, respectively.

2.2. Research Screening

A two-stage screening procedure was employed to ensure the relevance and quality of the included studies. In the first stage, a preliminary review of titles, abstracts, and keywords was conducted to filter out publications that clearly fell outside the scope of this study. Articles were excluded if they were non-original research (e.g., review articles, commentaries), lacked substantial focus on EWP-related environmental assessment, or mentioned relevant terms without engaging in LCA as a primary analytical framework.

In the second stage, a full-text evaluation was performed to verify the alignment of each study with the predefined inclusion criteria. Only studies that explicitly conducted LCA of specific EWP types in building sector, such as CLT, LVL, OSB, MDF, PB, and WPC, were retained. Further, studies were excluded if they lacked transparency in key methodological elements (e.g., system boundaries, functional units, or inventory sources), or if their primary subject matter was unrelated to wood-based materials, even when acronyms overlapped. For instance, all retrieved studies on FRT materials focused on fibre-reinforced polymers rather than timber-based products and thus were excluded from the final dataset. Additionally, to ensure comprehensive coverage, snowballing was conducted, identifying further relevant studies that may have been missed in the initial search. This structured and criteria-driven screening process yielded a final dataset of 89 peer-reviewed articles published between 2016 and 2024, which formed the empirical basis for the subsequent synthesis, classification, and analysis.

2.3. Data Synthesis and Analysis

The final set of 89 selected studies was systematically analyzed to extract key information related to the implementation of life cycle assessment. For each article, data were collected on system boundaries, functional units, geographic context, life cycle inventory (LCI) databases, methodological approaches, and application scenarios. These parameters were examined to identify methodological similarities and differences across literature, as well as to assess the consistency and comparability of the reported outcomes.

Qualitative data were analyzed using content analysis, in which all selected papers were reviewed in detail to identify recurring methodological patterns, assumptions, and

findings. Quantitative data were compiled and examined using Microsoft Excel, with human-recorded data entry and validation to ensure reliability (details are provided in Supplemental Files). Regional differences were explored by categorizing studies according to their geographic context and comparing the corresponding environmental performance results.

Hotspots within the life cycle were identified through an interpretive synthesis that combined qualitative content review and quantitative comparison. This process involved evaluating each study's methodological setup and reported results to determine which life cycle stages or parameters (e.g., material sourcing, manufacturing, transportation, end-of-life) contributed most significantly to total environmental impacts. The variables considered in this paper include building lifespan, height, material source, wood species, and adhesive type. This combined approach facilitates a structured understanding of regional variability and the key drivers of GHG emissions in engineered wood product systems.

3. Overview of the Selected Papers

The selected papers, as shown in Figure 2, indicate that CLT and GLT are focal points in terms of LCA of EWPs, particularly due to their prominent role in mass timber construction. CLT and GLT are recognized as major players in the global construction market, with their use steadily growing in both residential and commercial building projects. By 2017, around 70% of the worldwide CLT production was accounted for by Europe, which contributed significantly to the rapid expansion of CLT usage in mass timber structures [19]. In contrast, other EWPs such as EGP, FRT, MPP, LVP, HPLV, PSL, LSL, and IBC, have a more limited presence in the market, which partly explains the paucity of LCA studies on these products. These products tend to occupy niche markets or are utilized in specialized applications, leading to fewer LCA studies and reduced emphasis on their environmental impact. For instance, MPP has a similar gluing, orientation, and pressing technology to PW, with the only difference being that MPP requires a secondary gluing process to make thicker veneer-based composite panels [20]. These technological similarities could result in comparable environmental performance across their functional units, possibly explaining the lack of focused research on these products.

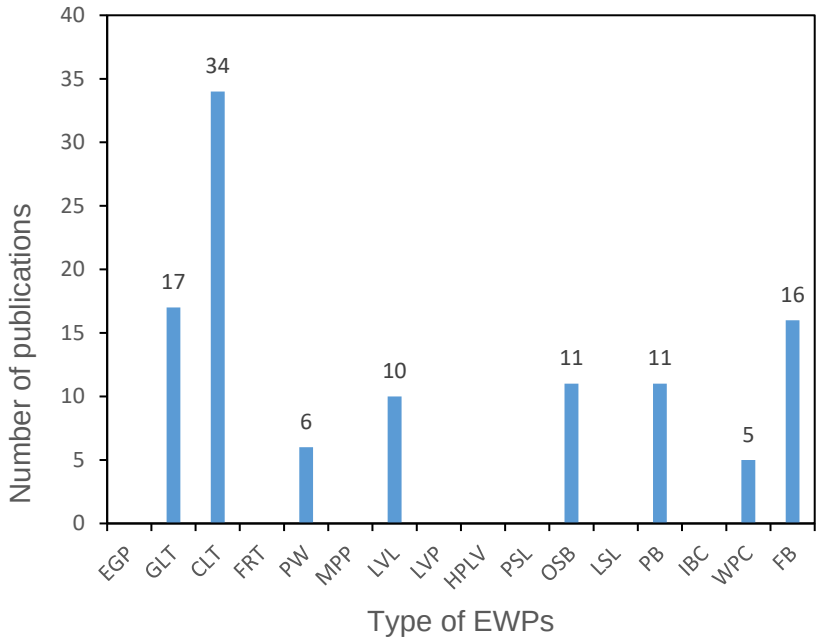

Figure 2. Number of selected papers on each type of EWPs.

Additionally, the naming conventions of some EWPs suggest relationships between different products. For instance, LVP seems to encompass LVL, which may account for the limited research specifically addressing LVP. Consequently, the categorization and definition of each EWP might benefit from further refinement. Future research could explore these under-investigated areas to provide a more comprehensive understanding of the environmental impacts of various EWPs.

The total number of studies on the LCA of EWPs has shown an increasing trend over time. Having originated in the early 1990s, CLT has gained the most popularity among all EWPs in the past 5 years. Similarly, research on LCA of GLT presents a relatively high popularity in the past 5 years. Before 2019, the LCA of EWPs was conducted mainly on LVL and FB, and the exploration remained relatively stable afterward. The research on WPC is mostly concentrated in the year 2019. For PW and OSB, the number of studies remained relatively stable throughout the period. This trend shows a rising awareness of the environmental impact of EWPs, with an increasing emphasis on the environmental assessment of more structural materials, particularly mass timber products.

Figure 3 presents the geographical distribution of the selected research on the LCA of EWPs. Asia leads with the highest contribution of 45 articles, followed by the Americas with 29 articles, Europe with 28 articles, and Oceania with 4 articles. In terms of individual countries, the United States has the most publications (23 articles) on the LCA of EWPs, followed closely by China (22 articles), and then Malaysia (10 articles).

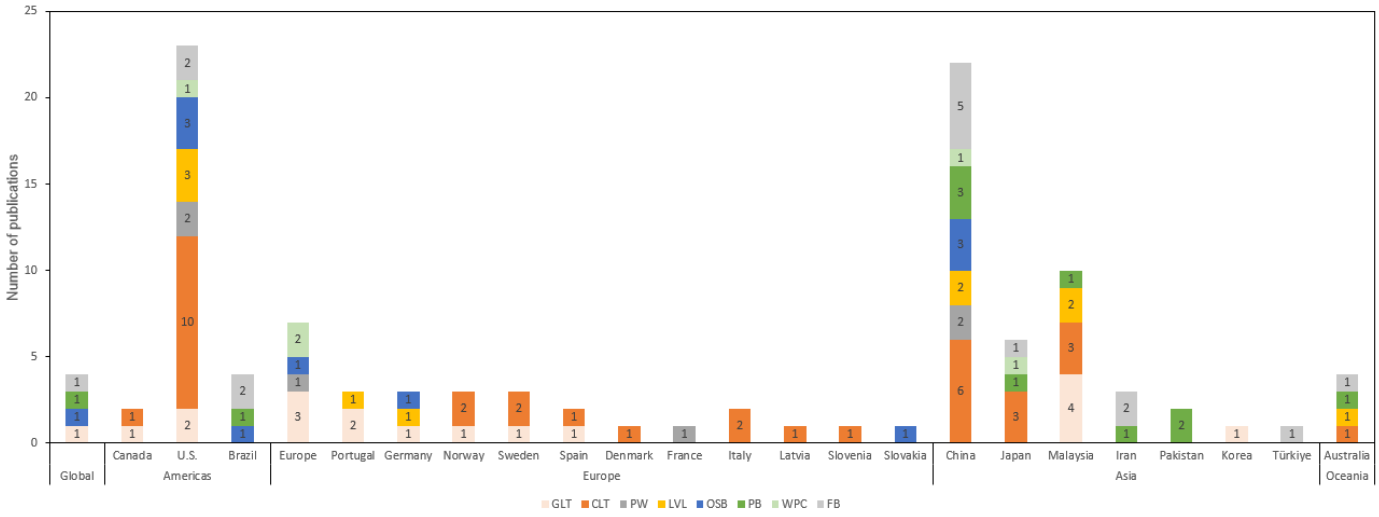

Figure 3. Number of selected papers of each type of EWP in different countries.

The geographical spread indicates that mass timber products, such as CLT and GLT, are primarily researched in regions with a strong presence in sustainable building practices, including Europe and North America, while other wood-based products like PW and PB see more research activity in countries like China and Brazil, where there are greater industrial capacities for wood panel production. The focus on mass timber in developed countries may be attributed to the significant forest resources in the Americas and Europe, which account for approximately 40% and 25% of the world's forest stock, respectively. Additionally, Europe is where mass timber was initially developed [15].

4. Detailed Review Results

The final selected papers were analyzed in detail, focusing on the processes for LCA method. The analysis of LCA approaches in these studies follows the guidelines outlined in the ISO 14040 and ISO 14044 standards [10,21], which structure the assessment

into four key phases: goal and scope definition, inventory analysis, impact assessment, and interpretation.

4.1. Goal and Scope Definition

The goal and scope of an LCA comprise the scope of the study, system boundary, and functional unit, as shown in Supplemental Material.

4.1.1. Scope of the Study

EWPs are assessed in LCA studies for a wide range of structural and non-structural applications. These studies typically focus on the environmental performance across different life cycle phases, including production, use, and sometimes the end-of-life phase. A key objective of these studies is to compare the environmental impacts of EWPs with traditional materials such as concrete and solid sawn timber, or with other EWPs. However, the scope of these studies varies, and their focus on specific life cycle stages, materials, and applications reflects both the market demand and technological development of the respective products. Table 1 summarizes the scope of LCA studies across different EWPs, highlighting primary applications, comparative materials, and life cycle phases considered.

Table 1. Summary of LCA scope for common EWPs.

EWP Type	Main Applications	Common Comparisons	Life Cycle Phases Covered	Notable Study Focus
GLT	Floor slabs, wall panels, beams, columns	Concrete, solid timber, CLT	Production, Use, End-of-Life	Hybrid structural systems
CLT	Walls, floors, roofs	Reinforced Concrete, NLT, DLT	Production, Use	High-rise buildings, recycling potential
LVL	Walls, framing, doors	GLT, OSB, Steel	Production, Use	Joinery and structural comparison
PW	Structural and non-structural panels	OSB, MDF	Mainly Production	New manufacturing techniques
OSB	Exterior walls, indoor panels	PW, FB	Production, some Use	Structural vs. indoor use
PB/FB	Indoor panels, furniture	OSB, PW, GLT	Mainly Production	Density-dependent performance
WPC	Specialized panels, decking	-	Production	Waste reuse, polymer modification

The research trends on GLT reveal a strong focus on its use in structural components such as floor slabs, wall panels, beams, and columns, with comparisons made primarily to concrete and solid wood, and also include comparisons with other EWPs such as CLT, LVL, and OSB [13,22]. Interestingly, some studies extend this comparison to hybrid systems or multi-material assemblies, reflecting the growing interest in hybrid construction methods. This trend indicates a shift in building practices that incorporate both traditional and engineered materials for enhanced performance.

For CLT, most LCA studies focus on its role in mid- and high-rise applications, particularly comparing it to reinforced concrete (RC) [23,24]. Studies also explore CLT use in recycled material applications [25], aligning with the growing emphasis on sustainability in construction. Furthermore, comparisons with other emerging products, such as NLT and DLT [26], have gained traction in recent years, reflecting a shift toward exploring alternative engineered wood technologies.

In contrast, LVL has seen its environmental impact assessed mainly in framing and non-structural applications. Its flexibility as an alternative to both solid timber and materials like steel is explored, but less attention is given to the end-of-life phase, a gap that warrants further research. Notably, studies compare LVL to both GLT and OSB, indicating its

potential for versatile applications but suggesting the need for more in-depth comparisons with other mass timber products [27].

PW and OSB studies generally focus on the production phase, with relatively few extending to use scenarios. While some studies on OSB examine its role in structural applications, such as exterior walls and indoor panels [28,29], research on PW predominantly addresses its use in non-structural applications, such as furniture. This focus indicates that the broader structural potential of these materials remains underexplored.

For PB/FB, research is mostly concentrated on the production phase, with studies comparing OSB, PW, and GLT [30,31]. A key area of focus in these studies is the density-dependent performance of different panel types (LDF, MDF, HDF), which highlights the need for further exploration into how variations in density affect both environmental impacts and material performance.

Finally, WPCs are predominantly assessed for their production impacts, with particular attention to new manufacturing processes that incorporate waste materials or polymer modifications. These studies are often focused on material innovations and sustainability improvements, underscoring the potential of WPCs in addressing waste management issues within the construction industry [32,33].

4.1.2. System Boundary

The system boundary is a crucial factor in initiating LCA, typically set according to standards like EN 15978 [34]. Among the 89 selected articles, most studies adopt either a cradle-to-gate or cradle-to-grave boundary, with a smaller number using a gate-to-gate approach. Notably, for GLT and CLT, the number of studies using a cradle-to-gate boundary is almost equal to those adopting a cradle-to-grave approach, indicating a more comprehensive consideration of the product lifecycle. However, for other products such as PW, LVL, OSB, PB, WPC, and FB, cradle-to-gate boundaries are more commonly applied, focusing primarily on the production phase.

As shown in Figure 4, studies on GLT and CLT place a much greater emphasis on the use, end-of-life, and benefit and load stages than studies on other EWPs. This difference reflects a broader interest in the environmental impact of mass timber products, particularly in the context of long-term performance and sustainability. For example, GLT and CLT studies frequently address the construction stage (A4–A5), which is often overlooked in studies on PW, LVL, OSB, and PB. This suggests that the construction-phase impact of mass timber products is an important area of concern, likely driven by the increasing adoption of these materials in large-scale, high-rise, and multi-material building projects.

Moreover, the use stage (B6) and maintenance (B2) phases receive more attention for GLT and CLT, reflecting a growing interest in the operational performance of these materials, particularly in terms of energy use and maintenance needs. This is in contrast to other materials like PW and OSB, where research on operational impacts is less common. The end-of-life (C1–C4) and benefit and load (D1–D4) stages are also more extensively covered for GLT and CLT, indicating a recognition of the potential for these materials to contribute to circular economy models through recycling, reuse, or repurposing at the end of their service life.

In contrast, PW, LVL, and OSB are generally studied within more limited system boundaries, with the majority of studies focusing solely on the product stage (A1–A3). This narrower scope likely reflects the more traditional use of these materials and the focus on their production impacts, without a comprehensive evaluation of their full life cycle. PB, for instance, largely disregards the end-of-life phase, though one study does consider landfill impacts (D4) [35], highlighting an area where further research could be beneficial.

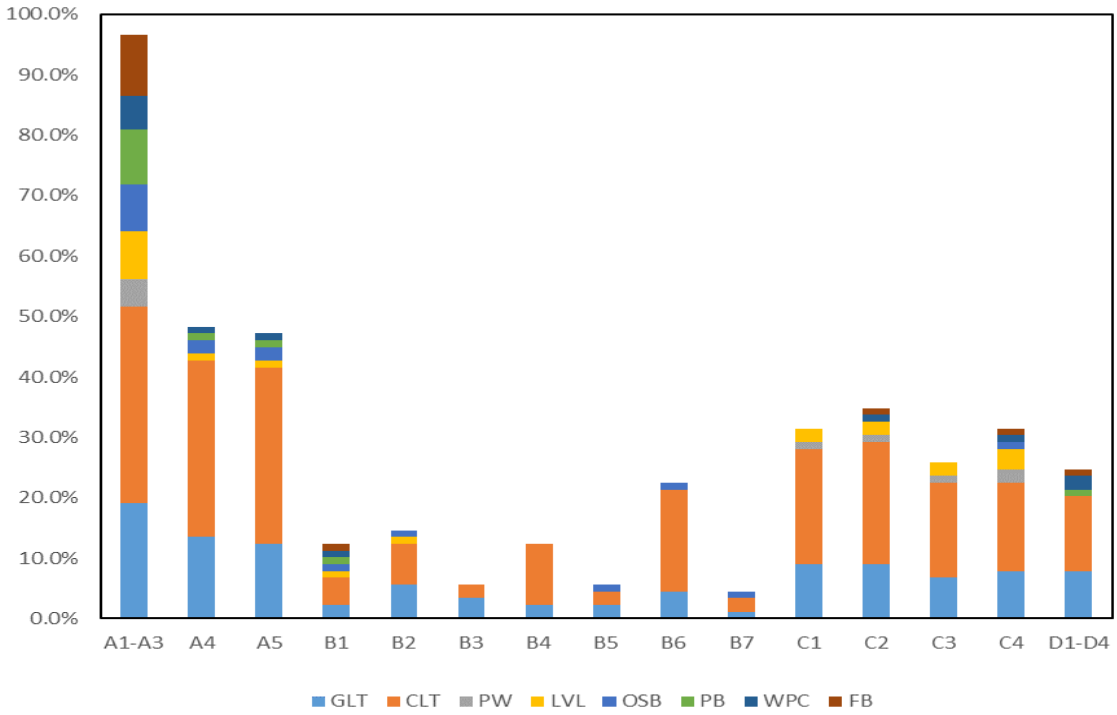

Figure 4. The percentage of articles of EWPs about each stage in the total articles.

Interestingly, WPC studies show a broader perspective, including the environmental impacts of recycling and its influence on production [36,37]. This approach indicates an awareness of the importance of closed-loop systems and material recovery, which could be an area of growing interest for other EWPs.

4.1.3. Functional Unit

The functional unit is a key quantitative measure in LCA, allowing for consistent comparison across different products [21]. However, the functional unit for EWPs varies significantly across studies, depending on the scope and application of the LCA.

As shown in Table 2, functional units for LCA studies of EWPs often differ based on the product type and the specific focus of the study. A large number of studies adopt 1 m^3 of product as the baseline unit, particularly for material-focused assessments, where the goal is to evaluate the environmental impact per unit of material. However, when assessing building-scale applications, some studies opt for more complex functional units, such as 1 m^2 of floor area, heated floor area, or even the entire building or wall system.

Table 2. Summary of Functional Units Used in LCA Studies of EWPs.

EWP Type	Common Functional Unit	Alternative Functional Units	Number of Studies Using Functional Unit	Study Focus
GLT	1 m^2 of floor or heated area	1 ton of recovered wood [38]	24 (floor area), 11 (entire system)	Structural applications, building systems
CLT	1 m^2 of floor or heated area	1 hectare of forest land [39], 0.1316 m^3 of CLT walls (5-story), 0.1064 m^3 of CLT walls (12-story) [40]	24 (floor area), 11 (entire system)	Mass timber buildings, high-rise
PW	1 m^3 of product	None	Majority of studies	Material-focused, production phase
OSB	1 m^3 of product	455,500 m^3 annual production volume (Lower Saxony) [41]	Majority of studies	Material-focused, production phase
PB/FB	1 m^3 of product	Full-scale wardrobe system [35]	Few studies	Indoor applications, furniture
LVL	1 m^3 of product or mass-based units (kg) [27,42]	Specific structural elements [43]	Few studies	Framing, structural applications
WPC	1 ton or 1 kg [33,37]	None	Majority of studies	Product-focused, polymer modification

This diversity in functional unit selection complicates comparative LCA across EWP types, particularly for products like LVL and WPC. While some researchers attempt to align functional units to enhance comparability, e.g., using 1 m^2 of floor area for both LVL and GLT in building applications [44], these efforts remain inconsistent. Therefore, a standardized and context-sensitive approach to defining functional units is essential to support more meaningful comparisons of environmental performance across the EWP literature.

4.2. Life Cycle Inventory Analysis

LCI is a critical phase in LCA, compiling and quantifying inputs and outputs based on the established goal, scope, system boundary, and functional unit. Table 3 summarizes data from 89 studies across various countries, each utilizing different data sources, including on-site measurements, surveys, literature reviews, and databases.

The Ecoinvent database is the most widely used for forest operations, raw material extraction, and transportation stages across multiple countries [45]. It serves as a primary source of secondary data globally, appearing in nearly every study. Environmental Product Declarations (EPDs) are also commonly used, particularly in mass timber studies (GLT and CLT), which relate to LCA of buildings.

However, the data source for the subsequent life cycle stages, such as the production stage, operation stage, and end-of-life stage of products varies hugely between different articles and different countries. For instance, AusLCI (Australia) [11] is often used for the end-of-life stage [46], while GaBi is prominent in Brazil [35] and Finland [32]. In China, the Chinese Life Cycle Database is commonly used, along with additional resources from the National Development and Reform Commission (NDRC), Intergovernmental Panel on Climate Change (IPCC), and the European Reference Life Cycle Database (ELCD) [15,42].

Additional country- or region-specific databases are also employed to reflect local practices, technologies, and waste management pathways. These include SoCa v.1 in Germany [27], ETH-ESU 96 database in Iran [47], IDEA ver.2.3 in Japan [30,48], MY-LCID in Malaysia [26] and IBO life cycle inventory database in Slovenia [49]. In the United States, a range of databases is used depending on the focus of the study, such as the National Renewable Energy Laboratory (NREL) LCI database, US LCI database, DATASMART, Athena Impact Estimator (AIE), and CORRIM, covering wood product manufacturing and end-of-life stages [50–52].

4.3. Life Cycle Impact Assessment and Interpretation

Life cycle impact assessment (LCIA) evaluates environmental impact categories to produce summarized, interpretable results. The interpretation of LCIA helps identify chances for improvement within the system boundary, compare different products based on their impact categories, and support informed decision-making [53].

4.3.1. Life Cycle Impact Assessment Method

Figure 5 illustrates the LCIA methods and impact categories used in the selected 89 articles. The most frequently used LCIA methods for LCA of EWPs are CML-IA, ILCD, IMPACT 2002+, IPCC, LIME2, ReCiPe, and TRACI. Among these, CML-IA is the most prevalent, used in about 20% of the articles, followed by ReCiPe at 18%, and TRACI at 17%. Some articles focus solely on the carbon dioxide emissions generated throughout the product's life cycle, likely using carbon footprint or embodied carbon emissions.

Table 3. Life cycle inventory data source from each country.

Country	Database	Reference	Country	Database	Reference
Australia	Literature review Forest and Wood Products Association Australia (FWPA) EPDs AusLCI version 36 EcoInvent version 3.71	Tokede et al., 2022 Farjana et al., 2023	Iran	Industry data literature review Ecoinvent database ETH-ESU 96	Kouchaki-Penchah et al., 2016 Kouchaki-Penchah, Sharifi, Mousazadeh, & Zarea-Hosseinabadi, 2016 Hafezi et al., 2021
Brazil	Industry data Literature review GaBi 6.5 LCI database Ecoinvent database	Freire et al., 2017 Piekarski et al., 2017 Ferro et al., 2018 D. a. L. Silva et al., 2020	Japan	Industry data IDEA database Literature review	Nakano et al., 2017 Nakano, Koike, et al., 2020 Iwase et al., 2020 Nakano et al., 2020
Canada	Ecoinvent database EPDs On-site measurement Literature review	Larivière-Lajoie et al., 2022 Shin et al., 2023	Korea	EPDs One Click LCA database.	Amoruso & Schuetze, 2022
China	On-site measurement Surveys/onsite interviews Literature review CLCD Ecoinvent Athena Sustainable Materials Institute USEI 2.2 ELCD Wood waste recycler ILCD IPCC NDRC	Liu et al., 2016 Guo et al., 2017 Hossain et al., 2018 S. Wang et al., 2018 Jia et al., 2019 Qiang et al., 2019 Liang et al., 2020 Zhang et al., 2020 C. X. Chen et al., 2021 Duan, Huang, Sun, et al., 2022 Duan, 2023 Wang et al., 2023 Lao & Li, 2023 Lao & Chang, 2023	Malaysia	Literature review Ecoinvent database Simapro database MY-LCID	Balasbaneh & Marsono, 2017 Azman et al., 2021 Balasbaneh & Sher, 2021 Balasbaneh, Sher, Yeoh, & Koushfar, 2022 Balasbaneh & Sher, 2022 Balasbaneh, Sher, & Yeoh, 2022 Balasbaneh, Sher, Yeoh, & Yasin, 2022
Denmark	EPDs Literature review	Felicioni et al., 2023	Latvia	Literature review	Vamza et al., 2021
Europe	Literature review Ecoinvent database EPDs GaBi professional database	Sommerhuber et al., 2017 Dias et al., 2020 Morris et al., 2021 Vaňová & Štefko, 2021 Sugahara et al., 2023	Norway	Databased provided by the building owners and from architectural drawings Ecoinvent v3.5	Lolli et al., 2019 Andersen et al., 2022
France	Ecoinvent	Pommier et al., 2016	Pakistan	Particleboard mill surveys Literature review	Hussain et al., 2017

Table 3. *Cont.*

Country	Database	Reference	Country	Database	Reference
Finland	Literature review GaBi LCI data	Liikanen et al., 2019	Portugal	Ecoinvent database	Silva et al., 2022
Germany	Literature review Ecoinvent database SoCa V.1	Risse et al., 2019 Taskhiri et al., 2019 Zeug et al., 2022	Slovakia	Industry data	Vilčeková et al., 2020
Italy	Ecoinvent databse Literature review	Corradini et al., 2018 Pittau et al., 2019	Slovenia	IBO life cycle inventory databases	Leskovar et al., 2019
South Korea	Literature review EPDs	Shin, Wi, et al., 2023	USA	Literature review EcoInvent database Industry data EPDs NREL Life Cycle Inventory Database U.S. LCI Database Athena LCI database DATASMART Athena Impact Estimator (AIE) ELCD GaBi database CORRIM reports	Salcido et al., 2016 Bowers et al., 2017 R. D. Bergman & Alanya-Rosenbaum, 2017 Chen et al., 2019 Al-Majali et al., 2019 Puettmann et al., 2019 Pierobon et al., 2019 Lan et al., 2020 Z. Chen et al., 2020 Allan & Phillips, 2021 Liang et al., 2021 Greene et al., 2023 Greene et al., 2023 Atnoorkar et al., 2024
Spain	Literature review Ecoinvent 3.0 EPDs	Vidal et al., 2019 Garnica et al., 2023			
Sweden	EPDs	Al-Najjar & Dodoo, 2022			
Türkiye	Industry data Literature review Ecoinvent database	Yılmaz, 2024			

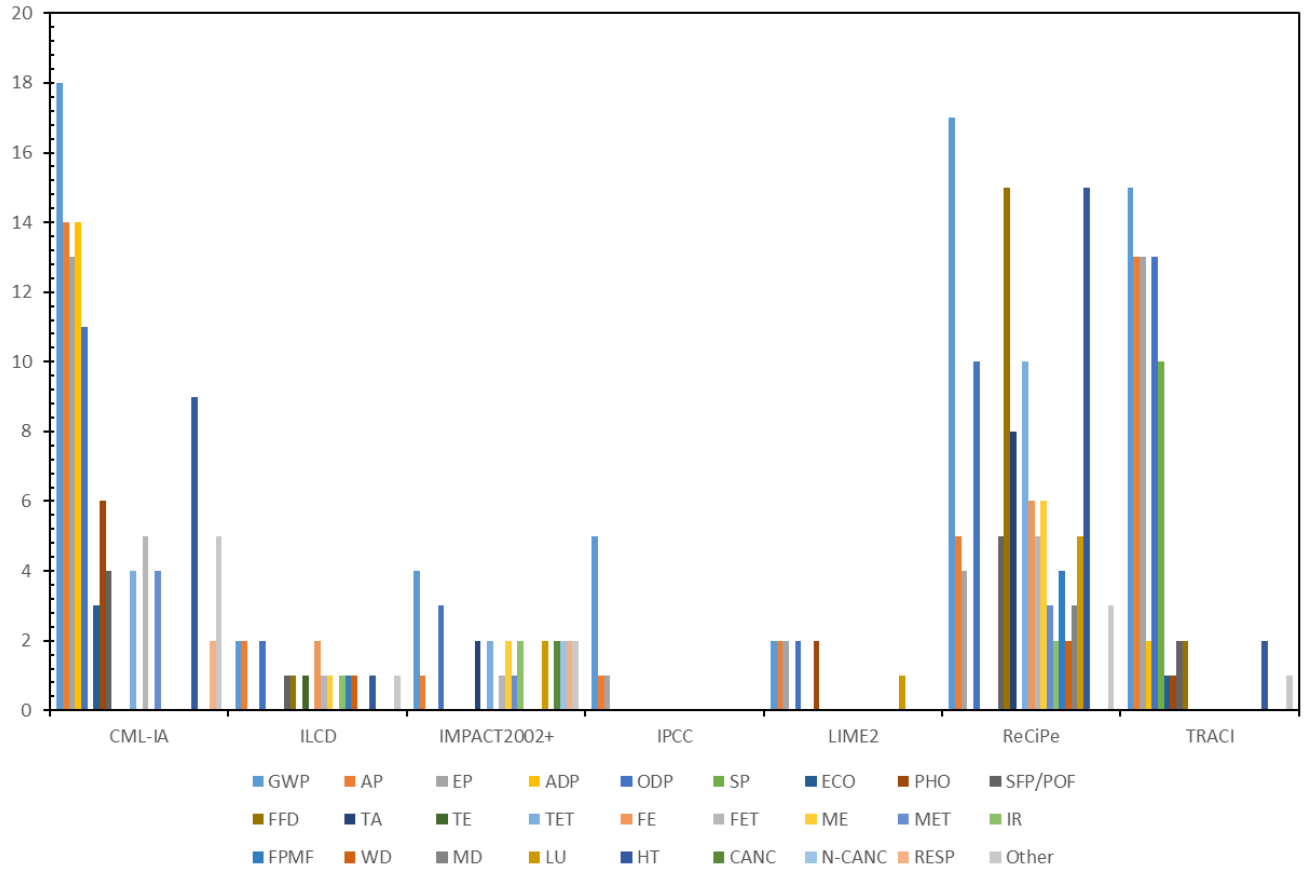

Figure 5. Life cycle impact assessment methods and categories. Note: Impact category abbreviations used in the figure are as follows: GWP—Global Warming Potential; AP—Acidification Potential; EP—Eutrophication Potential; ADP—Abiotic Depletion Potential; ODP—Ozone Depletion Potential; SP—Smog Potential; FFD—Fossil Fuel Depletion; TA—Terrestrial Acidification; TE/TET—Terrestrial Ecotoxicity; FE—Freshwater Eutrophication; FET—Freshwater Ecotoxicity; ME—Marine Eutrophication; MET—Marine Ecotoxicity; IR—Ionizing Radiation; FPMF—Fine Particulate Matter Formation; WD—Water Depletion; MD—Mineral Depletion; LU—Land Use; HT—Human Toxicity; CANC—Carcinogenic Effects; N-CANC—Non-Carcinogenic Effects; RESP—Respiratory Effects; SFP/POF—Secondary Formation of Particulate Matter/Photochemical Ozone Formation; ECO—Ecosystem Quality; PHO—Photochemical Ozone Creation. "Other" refers to method-specific or uncategorized indicators reported in selected studies.

4.3.2. Life Cycle Impact Assessment Categories

The impact categories of each LCIA method differ slightly but share many similarities. For example, the "ozone depletion potential (ODP)" in TRACI corresponds "stratospheric ozone depletion (OD)" in ReCiPe, and "ozone layer depletion (OLD)" in CML-IA. To streamline comparisons and simplify the table, 26 impact categories were analyzed in this study.

Among these, GWP is the most universally considered, appearing in all methods and articles. For studies focused solely on carbon footprint or embodied carbon, it is assumed that GWP is the primary indicator. Other frequently studied impact categories include ODP, AP, EP, HT, and ADP. TRACI primarily focuses on GWP, EP, AP, ODP, and SP, while CML-IA and ReCiPe cover a broader range, including SFP, FFD, TA, TE, TET, FE, FET, ME, MET, and HT. ILCD and IMPACT 2002+ have the widest range, also including CANC, N-CANC, and RESP. Some impact categories like energy demand, non-renewable energy, and mineral extraction were excluded from the analysis as they are less frequently considered.

4.3.3. Life Cycle Impact Assessment Comparison

In terms of the comparison of LCIA of different EWPs, several articles have compared the environmental impacts of different EWPs. While results differ due to methodological choices and regional factors, some consistent patterns emerge.

In Europe, studies generally find that solid wood tends to be more environmentally favorable than GLT, particularly in categories such as GWP, EP, and ADP. However, when compared with PW, GLT shows lower overall impacts under methods like IMPACT 2002+, especially in GWP, ODP, and TA [28]. Comparisons between GLT, solid wood, and concrete indicate that, while GLT has slightly higher impacts in some indicators, it still performs significantly better than concrete overall [35].

In Asia, findings are more mixed. In Malaysia, LVL and GLT show trade-offs: GLT exhibits higher GWP and LU impacts, whereas LVL scores higher in HT and FFD [26]. Similarly, CLT outperforms GLT in several categories, including GWP and LU, but GLT performs better in HT and FFD. Studies highlight that adhesives, drying, and manufacturing processes are the major contributors to impacts for both CLT and GLT. In China, CLT demonstrates lower carbon emissions than reinforced concrete (RC) across the cradle-to-grave system [54], while OSB consistently shows lower impacts than MDF [55].

In the United States, TRACI-based analyses indicate that PW typically has lower impacts than OSB and FB [56], though variability in FB types leads to inconsistent results [31]. In Japan, PB exhibits lower impacts than MDF across multiple categories (GWP, ADP, ECO, HT) [30]. Similarly, Brazilian studies suggest MDF performs better environmentally than HDF in most impact categories, including GWP, AP, ODP, FE, WD, and HT [45].

Globally, comparative analyses of carbon footprints show that among major EWPs, HDF has the highest CO_2 emissions per cubic meter, followed by MDF, OSB, PB, GLT, and LDF, in that order.

5. Comparative Results and Discussions

5.1. Greenhouse Gas Emission Comparison

GHG emissions, expressed as GWP in kg CO_2e, are a primary indicator in the LCA of EWPs. However, meaningful comparison across studies is constrained by differences in functional units, system boundaries, LCIA methods, and data sources. Functional units vary from material-based (1 m^3 or 1 kg) to application-based (1 m^2 floor area or building system), and only a subset of studies report comparable data. This inconsistency limits the reliability of cross-product conclusions, as few studies perform normalization or unit conversion to align disparate datasets. Consequently, while general trends can be identified, they should be interpreted cautiously.

As shown in Figure 6, which compiles data using the two most common functional units (1 m^3 and 1 m^2), solid wood generally exhibits the lowest GWP, reflecting its minimal processing energy. Among composite products, fiberboards (MDF) display the highest emissions due to their intensive resin use and pressing energy demands, while low-density variants (LDF) report substantially lower values [28]. OSB typically emits less than PB, owing to more efficient adhesive application and lower density [55].

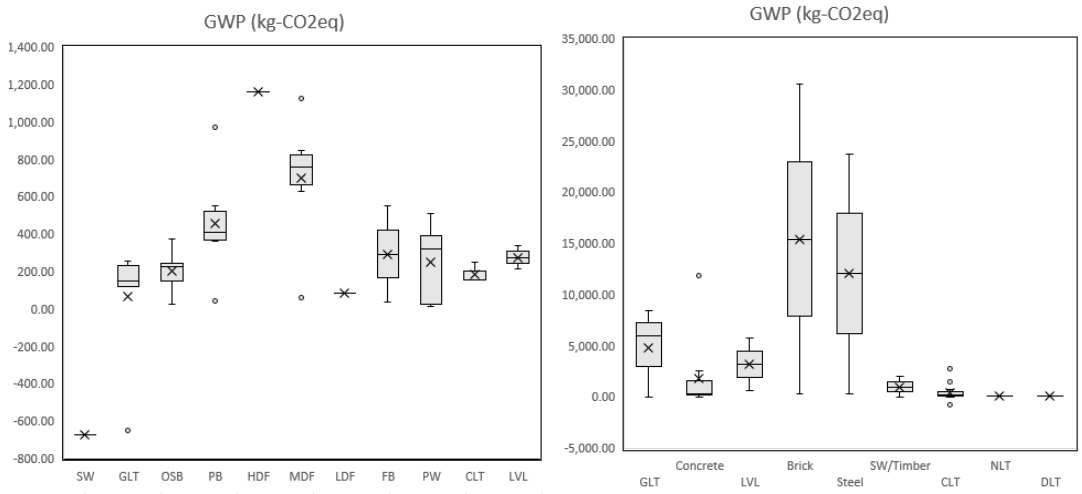

Figure 6. GWP comparison with functional unit of 1 m^3 of EWPs (**left**) and 1 m^2 floor area of EWPs buildings (**right**).

CLT and GLT show the lowest mean GWP values and narrower variation ranges. Their high solid wood content and lower adhesive-to-wood ratios, particularly when bio-based adhesives are used, reduce emissions compared with other EWPs. Several studies also confirm that GLT and CLT have markedly lower GWP than concrete or steel [57], reinforcing their potential as sustainable building materials. Nonetheless, comparisons between GLT and LVL yield mixed results, often influenced by structural efficiency assumptions and functional-unit inconsistencies. In addition, CLT consistently demonstrates superior GHG performance relative to both GLT and reinforced concrete [46,58], driven by its structural efficiency, reduced material mass, and carbon sequestration potential. Resin-free products like NLT and DLT perform even better, emphasizing the environmental benefits of mechanical bonding over adhesive systems.

In contrast, LVL presents greater variability. Some studies find that LVL has lower emissions than traditional construction materials, often due to the carbon sequestration potential of the wood fibers used in its production [59]. However, other studies report that LVL has higher emissions than materials like OSB or concrete [60]. This discrepancy is mainly attributed to the energy-intensive nature of veneer processing, which requires significant energy for tasks such as drying the wood and applying adhesives. Furthermore, the type of adhesive used in LVL production plays a significant role in determining its environmental impact. Some adhesives, especially synthetic ones, can contribute substantially to the product's GHG footprint, while more sustainable, bio-based alternatives may help reduce emissions. WPCs, typically analyzed per kg or ton, show relatively high GWP owing to fossil-based polymers, though substituting recycled plastics or biomass fillers can markedly improve their performance [61].

Based on the findings, EWPs offer substantial GHG advantages over traditional materials like concrete, steel, and masonry. However, their performance relative to solid sawn timber is generally lower, due in part to higher processing intensity and lower recyclability. Among EWPs, CLT and GLT stand out for their low average emissions and consistent performance across studies, positioning them as strong candidates for low-carbon construction. LVL also shows potential but requires further harmonized studies to confirm its role.

5.2. Impacts Comparison Across Different Life Cycle Stages

The LCA of EWPs covers various system boundaries, each including different life cycle stages, from forest operation to the end of products' life. The exploration of environmental impact in each stage is important for informed decision-making.

Across all EWPs, the production stage (A1–A3) consistently emerges as the most impactful phase. This stage encompasses raw material extraction, veneer or lamstock production, resin preparation, and manufacturing. For GLT, manufacturing processes, especially adhesive and chemical production, are the primary contributors to GWP and ODP [57], while lamstock production drives acidification and eutrophication impacts [62]. Similarly, for CLT, lumber production and panel assembly dominate GWP [63], while on-site energy use and resin application contribute significantly to ODP and EP [23]. The construction stage (A4–A5) adds additional impacts through transportation and installation, whereas the benefit and load stage (D1–D4) can partially offset these effects via recycling and carbon storage.

For other EWPs, production remains the dominant driver of impacts. In PW and LVL, veneer drying and pressing contribute most to GWP, AP, and EP [43,51]. OSB impacts are largely associated with hot pressing and resin synthesis [42,64], while MDF and PB are influenced by high energy demands during pressing and finishing [65]. In WPC, emissions are mainly tied to the use of fossil-based polymers during material production and end-of-life treatment [36,37].

The results clearly indicate that the production phase (A1–A3) is the environmental hotspot for nearly all EWPs, driven by adhesive use and energy consumption. However, end-of-life and benefit stages offer opportunities for impact mitigation through recycling, reuse, and carbon sequestration [66], especially for mass timber products (GLT and CLT). These stages can offset part of the GWP accumulated during manufacturing, underscoring the role of circular design in reducing overall emissions. Comparative studies across life stages also reveal that data inconsistency, stemming from differing system boundaries and functional units, limits direct comparability. Without normalization or cross-stage conversion, the magnitude of impacts between materials and stages may be over- or underestimated.

5.3. Influence of Key Parameters on LCA Outcomes

In the LCA of EWPs, several variables are examined to understand their impact on environmental outcomes, including the lifespan, material source, wood species, building height, glue type, and application environment.

(1) Lifespan

As the lifespan of steel, GLT, or CLT structures increases, the environmental impact during the use stage grows, primarily due to the extended energy consumption associated with the material's operation over time, such as heating, cooling, or other operational needs. Meanwhile, the embodied impact (e.g., raw material extraction, manufacturing, and transportation) decreases on a per-year basis due to the longer life span, as the total embodied impact is spread over a greater number of years [67]. Moreover, longer lifespans can lead to reduced GWP impacts during construction, especially for materials like concrete, steel, GLT, and LVL. This is due to the use of higher-quality materials that require less frequent maintenance, repair, or replacement, reducing their overall environmental impact [57]. However, when considering the end-of-life phase, longer lifespans typically result in higher GWP and AP impacts. This occurs because older materials may be more difficult to recycle or dispose of, requiring more energy for deconstruction or due to degradation and obsolescence over time [49]. Therefore, the overall environmental impact associated with lifespan depends on the balance between these stages and the material's durability.

(2) Material source

The location of the material source can affect the environmental impact of EWPs, though this is context-dependent. Generally, utilizing locally sourced materials tends to have lower environmental impacts, particularly due to reduced transportation distances and associated fuel consumption. For example, sourcing Douglas-fir from the closer Interfor sawmill rather than the Hampton sawmill significantly reduces GWP impacts in CLT production, with GWP values of 161.65 CO_2eq and 184.81 CO_2eq, respectively [63]. However, this trend is not universal, as other factors such as the transportation mode, energy efficiency of local manufacturing processes, and the specific energy mix in the region can also significantly influence the overall environmental outcomes [67]. Hence, when considering material sourcing, it is essential to take a holistic view of these additional variables to accurately assess the environmental benefits.

(3) Wood species

Wood species is a critical variable influencing the environmental impact of EWPs. Generally, species with lower densities tend to have less environmental impact. For example, Sitka Spruce has a lower GWP impact than Douglas-fir due to its lower density, which results in less energy required for its processing [63]. When comparing hardwood and softwood in different production scenarios, hardwood generally exhibits higher GWP, TA, ME, and MDP impacts compared to softwood, although it has lower impacts in terms of HT, MET, and FFD [68]. These differences highlight the importance of selecting wood species based on the specific environmental categories of interest and the trade-offs involved in each scenario. In LVL production, hardwood also shows greater environmental impact compared to softwood, underscoring the significance of wood species choice in influencing overall sustainability outcomes [60].

(4) Building height

Building height plays a complex role in determining the environmental impacts of construction materials, with its effects being context-dependent. In some studies, taller buildings have been shown to have lower GWP and AP impacts compared to shorter buildings, likely due to more efficient use of space and materials [49]. This is particularly true for RC and CLT constructions, where taller buildings can reduce the amount of material per unit of floor space. However, taller buildings tend to exhibit higher GWP impacts during the end-of-life phase, primarily due to more complex deconstruction and disposal processes [69]. This suggests that while taller buildings may benefit from operational efficiencies, the decommissioning process may offset some of these benefits. It is important to note that these findings are specific to the systems and building types studied, and similar trends may not be universally applicable across all building designs. Therefore, careful consideration of building height is crucial when assessing the overall environmental impact.

(5) Other factors

Other factors, although less frequently analyzed, also influence the LCA outcomes. These include the application environment and the type of glue used. For example, the environmental impact of GLT and PW materials can be lower when used indoors compared to outdoor applications, where exposure to weathering may require additional treatments or energy for maintenance [70]. The type of glue used in production also plays a significant role. In PW production, phenolic resin generally results in a higher GWP, HT, ME, MD, and FFD impact than polyurethane resin, although the impact on TA and MET may differ [68]. This highlights the importance of considering not just the base material but

also the adhesives and other chemicals used in manufacturing, as they can substantially influence the overall environmental footprint of EWPs.

The evidence suggests that CLT and GLT offer considerable promise as carbon-conscious materials, particularly when used in tall, long-lifespan buildings, constructed with locally sourced softwoods and optimized for indoor applications. Designers and policymakers should pay close attention to these influencing variables when interpreting LCA results and pursuing carbon mitigation in the built environment.

5.4. Recommendation for Future Studies

EWPs continue to gain prominence as renewable, recyclable, and potentially low-carbon alternatives to traditional construction materials. With applications spanning structural components in buildings, furniture, and interior elements, materials like CLT and GLT are among the most extensively studied and widely implemented. However, several knowledge gaps remain, limiting a comprehensive evaluation of EWP performance across the full spectrum of these materials. Future research should address these gaps to improve the environmental decision-making process in construction and manufacturing.

5.4.1. Expanding the Scope of LCA Studies

The scope of LCA studies varies significantly across different EWPs, reflecting differing research priorities. For example, CLT and GLT have received extensive attention due to their increasing use in high-rise buildings and hybrid structural systems, while panel products like PW and PB/FB are generally examined more for their production impacts rather than their use in structural applications. This reflects broader industry trends where mass timber products such as CLT are driving more comprehensive environmental assessments, while niche products with specialized uses may be overlooked.

Future studies should expand their scope to include more diverse EWP types, particularly those that have not been as widely studied. More attention should also be given to the end-of-life phase, particularly for materials like LVL and PW, where recycling potential and disposal impacts remain underexplored. By taking a more integrated, cradle-to-grave approach, LCA studies could provide more accurate and holistic environmental assessments that reflect the true sustainability of EWPs.

5.4.2. Broadening System Boundaries

Most LCA studies on products such as PW, LVL, OSB, PB, WPC, and FB are limited to the product stage (A1–A3), which captures only the material extraction, production, and transportation phases. These studies often neglect other critical life cycle stages, such as construction, use, and end-of-life, which are essential for a full understanding of environmental performance. In contrast, more holistic assessments of materials like CLT and GLT consider the broader life cycle impacts, including construction, operational phases, and end-of-life disposal, providing a more comprehensive view of their environmental footprint.

To better capture the full environmental impact of EWPs, future studies should expand the system boundaries for products like PW, LVL, OSB, and others. By including life cycle stages such as construction, use, and end-of-life, researchers can obtain more accurate and actionable data for sustainable material selection. Incorporating these additional stages would align these products with the more comprehensive assessments applied to materials like CLT and GLT, providing insights into their long-term sustainability. Moreover, examining the end-of-life and benefit and load stages for these materials could contribute to more sustainable practices within the construction industry, where recycling, reuse, and energy efficiency are increasingly prioritized.

5.4.3. Standardizing Functional Units

To enable meaningful comparisons between different EWPs, it is crucial to adopt a standardized, yet context-sensitive, approach to defining functional units. Currently, discrepancies in functional unit definitions across studies make it difficult to directly compare the environmental impacts of different materials. While some studies use a building-scale functional unit (e.g., per m^2 of building area), others rely on material-scale units (e.g., per m^3 of product). This variation complicates the interpretation of results and reduces comparability across studies. Future research should develop standardized functional units that account for both material and building-scale performance. These units should be flexible enough to consider product-specific applications while maintaining consistency across different EWP types. By adopting a common functional unit, researchers can enhance the ability to compare the environmental impacts of EWPs in a meaningful way, facilitating better decision-making for sustainable construction.

5.4.4. Developing Region-Specific LCI Databases

A major challenge in LCI analysis is the variability and inconsistency of data sources across regions and life cycle stages. Many LCA studies rely on secondary databases such as Ecoinvent or GaBi, which provide valuable data but may not accurately represent regional practices, technological advancements, or local production methods. This issue is particularly pronounced in developing countries, where outdated or foreign data may not reflect local production practices, waste management systems, or energy sources. Future research should prioritize the development of region-specific LCI databases that reflect current industrial practices and regional contexts. More primary data should be gathered through on-site measurements and surveys to improve the accuracy of LCI results. Additionally, greater international collaboration could help bridge regional data gaps and ensure a more consistent and comprehensive understanding of the environmental performance of EWPs worldwide. Standardizing frameworks for database selection and documentation would improve transparency and comparability across studies.

5.4.5. Adopting Standardized LCIA Frameworks

The choice of LCIA method (e.g., ReCiPe, TRACI, CML-IA) and regional context can significantly influence the environmental performance results of EWPs. While structural EWPs like CLT and GLT tend to outperform conventional materials such as concrete and steel, trade-offs arise across different impact categories, such as adhesive use, energy consumption, and end-of-life management. Panel products like OSB, PB, and MDF show strong environmental performance in production but can vary significantly based on their density and resin type. To improve the comparability of LCA results across studies, future research should focus on harmonizing methodological assumptions and adopting standardized LCIA frameworks. This would allow for more consistent cross-product and cross-regional comparisons, enabling better benchmarking and facilitating the identification of best practices for sustainable material selection. Moreover, including end-of-life scenarios in LCIA would enhance the comprehensiveness of assessments and help address potential environmental impacts associated with disposal and recycling.

5.4.6. Exploring Emerging and Understudied EWPs

Several promising EWPs, such as ESB, PSL, and hybrid bio-based composites like laminated bamboo, remain underrepresented in LCA studies. These products may offer untapped environmental and functional potential but are often excluded from comparative assessments. Additionally, newer products like NLT and DLT are emerging as alternatives to conventional glulam and CLT, particularly for their reduced reliance on synthetic ad-

hesives [71,72]. Future LCA research should expand coverage to include emerging EWPs such as ESB, PSL, MPP, LSL, and bamboo-based composites. These materials could provide viable alternatives to traditional products like CLT and GLT, especially in applications where environmental performance is a key consideration. Studies on glue-free alternatives like NLT and DLT should also be prioritized to assess their potential environmental benefits, especially in terms of reduced emissions from glue production and application.

5.4.7. Investigating the Potential of Bio-Based and Nanotechnology-Enhanced Materials

In recent years, bio-based composites, such as laminated bamboo, have gained attention due to their lower carbon profiles compared to conventional EWPs. Nanotechnology has also opened new possibilities for enhancing the functional properties of wood, such as thermal insulation, passive cooling, and optical applications [73]. Materials like delignified wood and thermal-insulating wood are gaining traction for use in energy-efficient buildings but require robust environmental profiling to verify their sustainability. Future LCA research should investigate the lifecycle impacts of bamboo-based materials and other hybrid bio-composites, examining their scalability, durability, and end-of-life scenarios. Additionally, nanotechnology-enabled EWPs, such as delignified wood or transparent wood, should be further explored, particularly in relation to their potential applications in thermal insulation and energy-efficient building designs.

6. Conclusions

EWPs have been introduced to the construction sector as sustainable alternatives with mechanical performance comparable to traditional materials. This study presents a systematic review and analysis of the LCA of EWPs globally from 2016 to 2024, based on 89 selected articles from the Web of Science. The study reviews these articles in terms of goal and scope, life cycle inventory, and life cycle impact assessment. The EWPs covered include GLT, CLT, FB, PB, OSB, LVL, PW, and WPC, with an increasing number of studies primarily from the U.S. and China. Common functional units are metric and cubic meters, with cradle-to-gate and cradle-to-grave being the most used system boundaries, particularly focusing on stages A1 to A3.

The findings reveal that CLT and GLT are the most frequently assessed EWPs and are increasingly favored for their lower GHG emissions, making them key materials for achieving carbon neutrality in construction. Their strong performance is especially evident when considering the entire life cycle, including recycling and reuse benefits in stages D1-D4. Factors such as building lifespan, material source, wood species, and building height have also been identified as critical determinants in minimizing environmental impacts. Notably, locally sourced softwood used in long-life, high-rise buildings appears to be an optimal choice for reducing the carbon footprint of EWP-based constructions.

Despite these insights, the study also identifies several important research gaps that hinder a comprehensive understanding of EWP performance. Certain EWPs, such as EGP, PSL, and FRT, remain underexplored in the context of LCA, with few studies addressing these products in detail. Additionally, the comparison of WPC is limited due to variations in functional units across studies, which complicates direct comparisons. Emerging EWPs, such as DLT, NLT, and bamboo-reinforced products, were not included in this review but present promising opportunities for future research. These products could potentially offer significant environmental benefits, particularly in reducing emissions from adhesives and promoting greater use of bio-based materials.

Furthermore, the study notes that many of the existing comparisons are limited by differences in system boundaries, LCI databases, and LCIA methods. These variations introduce uncertainty into the results, and future studies should incorporate uncertainty

analyses to better understand how these factors influence LCA outcomes across different product categories. By addressing these uncertainties, researchers can provide more robust, accurate insights into the environmental implications of EWPs, helping guide decision-making in both industry and policy.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings15224193/s1, Selected papers and raw data for all the figures.

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