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Life cycle assessment of hardwood cross-laminated timber production in the eastern United States

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HIGHLIGHTS

- The GWP of hardwood CLT production is 141.9–377.4 kg CO_2 eq per m^3.
- The net carbon storage of hardwood CLT is 430.2–988.3 kg CO_2 eq per m^3.
- Using biomass energy can enhance the environmental sustainability of hardwood CLT.
- Hardwood doesn't cause more environmental impact than softwood in CLT production.

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ABSTRACT

Cross-laminated timber (CLT) is an emerging sustainable construction material with the potential to replace concrete. Life cycle assessment (LCA) has been widely applied to quantify the environmental impact of CLT materials and buildings. However, current research on CLT LCA mainly focuses on softwoods, lacking reports on hardwood CLT. Despite the less frequent utilization of hardwood by CLT manufacturers, hardwood CLT is technically feasible and provides value-added uses for low-quality timber. This study developed a cradle-to-gate life cycle modeling framework to produce hardwood CLT in the eastern United States to address this research gap. The framework integrates process-based modeling of log production, lumber production, and CLT production and explores the influences of hardwood species, supply chain network, and energy sources through sensitivity analysis. The global warming impact of producing 1 cubic meter (m^3) of hardwood CLT ranged from 141.9 to 377.4 kilograms (kg) of carbon dioxide equivalent (CO_2 eq). The results showed that to satisfy the manufacturing requirements of CLT, lumber production caused more energy consumption and emissions than CLT production. Compared to selecting low-density hardwood species and minimizing transportation distance, increasing the use of biomass energy can more effectively reduce the overall environmental impact. Furthermore, the amount of carbon stored in hardwood CLT exceeded the carbon emitted during its production, with net carbon storage of 430.2–988.3 kg CO_2 eq per m^3. This study provides valuable insights for the development of environmental product declarations for hardwood CLT and proposes improvement strategies to enhance the sustainability and market competitiveness of hardwood CLT.

1. Introduction

Cross-laminated timber (CLT) is a prefabricated engineered wood product made from at least three layers of graded sawn lumber or structural composite lumber that are arranged orthogonally and bonded together with structural adhesives (APA, 2019). CLT originated in Austria and Germany in the early 1990s, driven by the goal of finding a value-added use for the side boards in sawmills (Mohammad et al.,

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2012). Nowadays, European CLT manufacturers have earned a global reputation and market share, contributing to over half of the total global CLT production (UNECE/FAO, 2021). Since the introduction of CLT to North America in the early 2000s, there has been progress in facilitating pilot building projects in the United States and Canada utilizing this novel construction material (Pei et al., 2016), which has become more mainstream in construction. Across the United States, it was reported that 645 buildings incorporating CLT had either been built or were starting construction, and 710 buildings using CLT were in the design stage (Woodworks, 2024).

The advantages of CLT encompassed its load-bearing capacity in both in-plane and out-of-plane configurations when used as a laminar product, resistance against shear in-plane and tension perpendicular to the grain as a linear structural element, ease of positioning openings, high prefabrication, and dimensional stability in-plane (Brandner et al., 2016). In addition to engineering advantages, the development of CLT unlocked additional markets for lumber, especially for low-quality lumber. With the construction sector contributing 37 % of global carbon dioxide (CO_2) emissions, inclusive of emissions from building material production, CLT emerged as a sustainable alternative for traditional concrete and steel, offering a significant measure to mitigate climate change (UNEP, 2022). Previous studies have demonstrated the benefits of CLT buildings in reducing greenhouse gas (GHG) emissions and sequestering carbon, with some employing life cycle assessment (LCA) methods (Chen et al., 2020; Liang et al., 2020, 2021). Nevertheless, most CLT manufacturing continued to rely on softwood species, making hardwood-based CLT comparatively rare.

Hassler et al. (2022) explained that the challenges hindering the adoption of hardwood in CLT manufacturing were rooted in the differences between hardwood and softwood in grading, drying, gluing, and available sizes. Specifically, softwoods were primarily used for dimensional and structural purposes, graded by the size and location of defects. In contrast, hardwood lumber was based on appearance grading rather than structural grading, graded by the amount of clear wood in the board. Consequently, softwood lumber had readily available standardized sizes and grades, facilitating compliance with the requirements for CLT manufacturing. Additionally, hardwood and softwood lumber were typically dried to moisture content (MC) of 6–8 % and 15 % or less, respectively. Softwood lumber more easily met the 12 ± 3 % MC requirement for CLT laminates (APA, 2019). Furthermore, due to the inherent properties of hardwood, coupled with its higher swelling and shrinkage coefficients, there was a risk of delamination in CLT panels.

Despite these challenges, there was still a growing interest in the development of hardwood CLT, particularly in regions with abundant hardwood resources. CLT provided a pathway for value-added uses of low-quality hardwood species. Hardwood CLTs made from birch (*Betula pendula*), beech (*Fagus sylvatica* and *Fagus grandifolia Ehrh.*), eucalyptus (*Eucalyptus urophylla* × *Eucalyptus grandis*), ash (*Fraxinus excelsior*), poplar (*Liriodendron tulipifera*, *Pacific albus*, and *Populus* × *euroamericana*), chestnut (*Castanea sativa*), maple (*Acer*), and aspen (*Populus tremuloides*) have been proven technically feasible (Espinoza and Buehlmann, 2018). Shi et al. (2023) conducted an in-depth investigation into the feasibility of poplar CLT. The study results indicated that the mechanical properties of poplar CLT were only 8 % lower than spruce (*Picea*) CLT, and its failure mode was similar, further confirming its suitability as an alternative material for mass timber structures. Moreover, some hardwood CLT showed better strength properties. For instance, sweetgum (*Liquidambar styraciflua*), red maple (*Acer rubrum*), and sycamore (*Acer pseudoplatanus*) CLT panels exhibited higher average compressive strength compared to Douglas fir (*Pseudotsuga menziesii*) and yellow pine (*Pinus echinata*) panels when used in the primary orientations for structural walls (Palacio-Betancur et al., 2023). Additionally, in floor system applications, black locust (*Robinia pseudoacacia*) CLT panels demonstrated higher strength and stiffness compared to softwood CLT panels (Crovella et al., 2021). The structural feasibility, mechanical properties, and durability demonstrated by hardwood species in other engineered wood applications also provided important justification for their use in CLT, including strength grades comparable to traditional softwood, improved strength and dimensional stability after thermal treatment, and lower charring rates when exposed to fire (Yue et al. 2020, 2021, 2023; Li et al., 2024; Qian et al., 2024).

LCA is a comprehensive methodology for evaluating the environmental impacts of a product or activity throughout its entire life cycle, encompassing raw material extraction, material processing, manufacturing, use, and end-of-life stages. Most previous studies focused on the LCA of CLT buildings (Chen et al., 2020; Liang et al., 2020, 2021) or softwood CLT (Chen et al., 2019; Lan et al., 2019; Puettmann and Sinha, 2019; Nakano et al., 2020), with an absence of research on the LCA of hardwood CLT. Recent LCAs of softwood CLT varied notably in system boundaries (ranging from cradle-to-gate to cradle-to-grave), allocation methods (mass- or economic-based), and modeling approaches (static or dynamic). Some studies incorporated forest growth and end-of-life scenarios, while others focused solely on manufacturing. Additionally, species selection, energy sources, and the treatment of wood residues can all significantly influence results, with reported global warming potential (GWP) ranging from 156.7 to 252 kg CO_2 eq/m^3 for cradle-to-gate assessments and from 113 to 375 kg CO_2 eq/m^3 for cradle-to-grave assessments (Chen et al., 2019; Lan et al., 2019; Puettmann and Sinha, 2019; Nakano et al., 2020). According to a comparative analysis of construction materials, the GWP values for dimensional stone, concrete products, and steel products were 135 kg CO_2 eq/m^3, 246–514 kg CO_2 eq/m^3, and 22,294–29,202 kg CO_2 eq/m^3, respectively (Kerr et al., 2022). Since CLT was typically made from softwood, and hardwood was often overlooked, creating a notable gap in the literature on the environmental impact of hardwood CLT.

To explore the environmental sustainability of hardwood CLT as a potential substitute for conventional building materials, this study conducted a process-based attributional LCA of hardwood CLT production in the eastern United States. The primary objective was to evaluate the environmental impact of hardwood CLT throughout its cradle-to-gate life cycle, including extraction and upstream production (A1), transport to the factory (A2), and manufacturing (A3). Sensitivity analysis was utilized to understand the influence of variations on LCA outcomes. By quantifying and analyzing key environmental impact categories, this study provided the scientific basis for the development of Environmental Product Declarations (EPDs) for hardwood CLT.

2. Data and methods

This cradle-to-gate LCA focuses on the production stage, encompassing three key processes: log production, lumber production, and CLT production. Log and lumber production fall under the A1 module, lumber transportation to the CLT factory is classified as the A2 module, and CLT production is categorized as the A3 module. The LCA was conducted in accordance with ISO 14040 and ISO 14044, following their guidelines on defining the goal and scope, establishing system boundaries, collecting data, and interpreting results (ISO 2006a; 2006b). Furthermore, the modeling framework was aligned with ISO 21930, which specifically addresses environmental declarations for building products, by structuring the inventory indicators and emissions data (ISO, 2017). The system boundary is depicted in Fig. 1. The functional unit was defined as the production of 1 cubic meter (m^3) of hardwood CLT. Due to the generation of co-products within the system boundary, the mass allocation rule was applied to allocate environmental burdens. Life cycle inventory (LCI) data were gathered from literature and simulations based on sawmill and hardwood CLT pilot manufacturing case studies. Impact assessment was conducted using two life cycle impact assessment (LCIA) characterization models: the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) and Cumulative Energy Demand (CED). CED evaluates primary energy usage, while TRACI quantifies stressors with potential effects, including global warming, smog, acidification, eutrophication, ozone depletion,

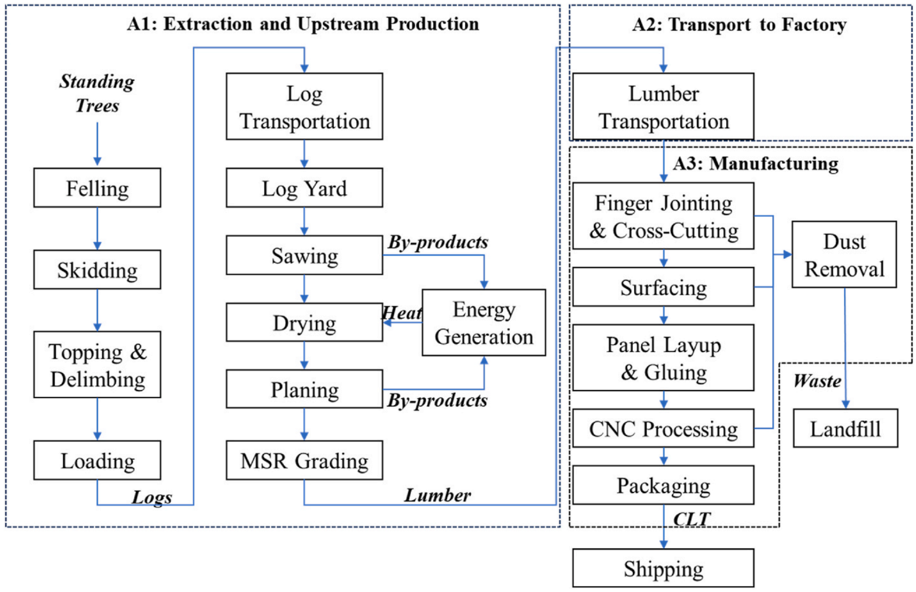

Fig. 1. System boundary for hardwood CLT production.

human health criteria-related effects, human health cancer, human health noncancer, ecotoxicity, and fossil fuel depletion. The LCIA results were calculated using SimaPro 9 (PRé Sustainability, Amersfoort, Netherlands) with US-EI 2.2 and US LCI databases.

2.1. Log production

Log production consists of two unit processes: hardwood harvesting and transporting logs to the sawmill. Silvicultural systems in the eastern United States aimed at timber harvest and forest regeneration include both even-aged management and uneven-aged management (Dey et al., 2012). Even-aged management refers to the establishment of stands with trees of a single age class through clearcutting, shelterwood, and seed-tree methods. Even-aged management often includes intermediate commercial thinning that can generate pulpwood and sawlogs used for lumber. On the other hand, single-tree and group selection methods result in uneven-aged stands, with thinning typically taking place at the same time as the harvest of mature sawlogs. In both management scenarios, harvesting involves sequential processes of felling, skidding, processing (topping and delimbing), and loading. In most operations, some level of sorting happens on the log landing, separating different classes of logs into sorts that are sent to different mills for processing. The diesel and lubricants consumed in harvesting machinery are the main input flows. The average fuel consumption for mechanized harvesting systems is 3 liters per cubic meter (L/m^3) of diesel and 0.14 L/m^3 of lubricants in eastern U.S. hardwood forests (Zhao et al., 2024). The average wood procurement distance for sawmills is 48–113 kilometers (km) (Anderson and Germain, 2007).

2.2. Lumber production

Lumber which has a modulus of elasticity above the minimum required value of 1.2×10^6 pounds per square inch was considered the base material for manufacturing CLT. Existing research has established standardized processes for hardwood lumber production, including log yard, sawing, drying, planing, and energy generation as an auxiliary process (Ahmad et al., 2020; Bergman et al., 2008; Bergman and Bowe, 2009, 2010; Hubbard et al., 2020). However, as highlighted by Adhikari et al. (2020) and Hassler et al. (2022), the lack of readily available structurally graded hardwood is a major obstacle to the acceptance and commercialization of hardwood CLT. Therefore, integrating structural grading into lumber production is necessary.

2.2.1. Log yard

Lumber production begins as log trucks roll into the yard for unloading, sorting, measuring, and inventorying. Important decisions regarding the log's value are made immediately upon its arrival. Log value is determined by three main factors: species, grade, and scale. Hardwood logs are graded into veneer logs, sawlogs, and other log classes based on quality and intended use (Taylor, 2007). Scaling measures the amount of wood to be sawn from a log, with the Doyle log rule being the most common scaling method (Hassler et al., 2021). Lumber made from lower-grade sawlogs is economically feasible as a feedstock for CLT production, while the highest grade is sorted for the appearance market. Depending on species and market demand, use in cabinets, furniture, flooring and other aesthetic products generally makes high grade lumber too valuable for use in CLT. In practice, the decision-making process for log allocation is dynamic. For simplification, this study focuses solely on the subset of logs assigned to CLT production, with the system boundary limited accordingly. The log yard is equipped with loaders and forwarders to efficiently handle and transport logs within the yard. These machines are powered by a combination of diesel and a small amount of gasoline, consuming 1.22 L of diesel and 0.14 L of gasoline per 1 m^3 of logs (Hubbard et al., 2020).

2.2.2. Sawing

Debarking is the first step in the sawing process. Subsequently, debarked logs pass through a metal detector, which identifies metal in the log if present, moves the log off the sawline, and prevents damage to the saw blades. Logs are then conveyed for size and shape scanning, position adjustment, slab cuts and jacket boards removal to form square four-faced cants (Bergman and Bowe, 2009). Once squared, the logs are conveyed to the resaw to produce boards with specific dimensions. Hardwood boards are typically produced at sawmills with a thickness of 25 millimeters (mm), a length of 2.44 m, and random widths (Bergman and Bowe, 2009; Hubbard et al., 2020). Additionally, an extra 3 mm thickness will be retained to prevent shrinkage in the drying process. Finally, the boards are sent to the edger for width adjustment and the trimmer for length adjustment.

The sawing yield rate is approximately 59–64 %, referring to the proportion of useable lumber recovered from roundwood (Table 1). The sawing process yields sawn lumber and co-products known as mill

Table 1
Process parameters for hardwood CLT production.

Item	Unit	Mean	Minimum	Maximum
Green hardwood density [a,b]	kg/m^3	915.5	854	977
Dry hardwood density [a,b]	kg/m^3	636	624	648
Sawing yield rate [a,b,c,d]	%	62	59	64
Drying yield rate [a,b,c,d]	%	92	88	94
Planing yield rate [a,b,c,d]	%	76	73	80
Surfacing waste mass fraction [e,f,g]	%	3.6	3.4	4.0

[a] Bergman and Bowe (2009).
[b] Bergman and Bowe (2010).
[c] Bergman et al. (2008).
[d] Hubbard et al. (2020).
[e] Puettmann and Sinha, 2019.
[f] Chen et al. (2019).
[g] Lan et al. (2019).

residues, including bark, sawdust, wood chips, wood fuel, and hog fuel (a ground mixture of wood waste). The sawmill sector is a major producer and user of wood-based bioenergy, mostly through the on-site production of heat (i.e., steam) and power. Given the significant reduction of fossil-based GHG emissions by 59–61 % through the utilization of mill residues, especially hog fuel, for energy recovery instead of selling them for durable wood product production (Lan et al., 2019), this study assumed that all wood residues, including shavings, sawdust, and mixed residues generated during the subsequent planing process, are used for energy generation in industrial boilers. The analysis recognizes that in many markets mill residues may be sold and used in durable products, such as manufactured panels, but this energy assumption is more conservative regarding the fate and GHG emissions associated with these materials. Sawing is the most electricity-intensive unit process, incorporating equipment such as debarker, metal detector, conveyor, head saw, scanner, linear positioner, resaw, stacker, sorter, edger, trimmer, grinder, and chipper. The process selected for sawing is "sawn lumber, hardwood, rough, green, at sawmill" in the US-EI 2.2 database. This dataset captures the typical equipment configurations (predominantly band headrigs and circular resaws), cutting patterns, and operational practices associated with an aggregate sawing process from multiple sawmills in the Northeastern and North Central United States.

2.2.3. *Kiln drying and energy generation*

When hardwood logs arrive at the mill, they typically have a high MC, with a green density ranging from 854 to 977 kg/m^3. After kiln drying, the density decreases to 624–648 kg/m^3 as the MC drops (Table 1). Most lumber is dried in conventional steam-heated kilns (Bond and Espinoza, 2016). The steam flows into the kiln through pipes and radiates heat into the kiln's atmosphere. Water in the wood evaporates into steam, which is then discharged from the kiln with the hot air. The disadvantage of conventional kilns is their high energy demand, which leads to large emissions of volatile organic compounds (VOCs). Related research showed that electricity and energy consumption were reduced by 18.9 % and 38.5 %, respectively, with the use of energy-conserving kilns (Meng et al., 2019). Therefore, conventional kilns capable of recycling waste heat were assumed to dry the green lumber. Most well-managed kilns achieve relatively high yields. Table 1 shows a drying yield rate of 88–94 %, with minor losses usually attributed to end-splitting or boards that fail grading standards after drying. Energy generation involves on-site combustion of wood residues to supply heat and electricity to the sawmill. Furthermore, off-site electricity serves as the other energy source for the facility. According to APA PRG 320, the MC requirement for laminates in CLT manufacturing should be 12 ± 3 %, a specification more closely aligned with the target MC for drying softwood lumber. As a result, the product flow of the drying process is dried, rough hardwood lumber, while the unit process is referenced to "sawn lumber, softwood, rough, kiln dried, at kiln" in the US-EI 2.2 database.

2.2.4. *Planing*

Once the lumber is dried, it is planed to a uniform thickness, with a yield rate of approximately 73–80 % (Table 1). The primary surfaces of wood where shrinkage occurs are along the tangential and radial planes. The planer can flatten the radial surface, achieving a consistent thickness of 25.4 mm. The machinery used includes planers equipped with various rotating blades, as well as conveyors and forklifts for on-site lumber transportation. The primary output of this process is planed dry lumber, accompanied by co-products such as shavings, sawdust, fuel wood, and mixings. Input and output flows are referenced from the US LCI database as "sawn lumber, hardwood, planed, kiln dried, at planer mill".

2.2.5. *Grading*

Softwood dimension lumber can be graded either visually or using machine stress rating (MSR) technology following Northeastern Lumber Manufacturers Association (NELMA) rules. The minimum grade of lumber in the longitudinal layers of CLT shall be 1200F-1.2E MSR or visual grade No. 2, while in the transverse layers, it shall be visual grade No. 3 (APA, 2019). However, hardwood lumber grading follows rules established by the National Hardwood Lumber Association (NHLA). Based on cutting unit method, the standard grades of hardwood lumber are FAS, FAS One Face (F1F), Selects, No. 1 Common, No. 2A Common, No. 2B Common, No. 3A Common, and No. 3B Common (NHLA, 2023). Due to the lack of specifications for structural grading of hardwood lumber, the Appalachian Hardwood Center (AHC) at West Virginia University (WVU) studied how to utilize NHLA grades of hardwood lumber to yield structural grades of hardwood lumber. Research indicates that the MSR method showed a higher yield than visual grading, with 96.6 % of NHLA grades 2A and below yellow poplar lumber meeting the minimum modulus of elasticity specified for CLT panel production (Azambuja et al., 2022). WVU-AHC also assessed the yields of soft maple (*Acer saccharinum*) and red oak (*Quercus rubra*) structural boards, whose yield rates are similar to that of yellow poplar (Hassler et al., 2022).

Mechanical grading involves bending lumber flatwise, with a transducer measuring the deflection to estimate stiffness. By measuring along the length, the least stiff portion within that length of wood can be identified. Modern grading machines have varying throughput capabilities. Lumber producers targeting large markets often select high-capacity machines to match planer capabilities, while those with more limited capacity are suitable for operations focusing on a limited range of grades and sizes (Entsminger et al., 2020). It was assumed that a piece of lumber takes 15–20 s to pass through the grading machine. Thus, energy consumption was estimated at around 10.2 kW-hours (kWh) per m^3 for a lumber tester rated at 30 kilowatts (kW).

2.3. *CLT production*

As of May 2023, there are seven CLT panel manufacturers in five states and 20 glulam manufacturers in 11 states (CRS, 2023). Most of these manufacturers are concentrated in the Pacific Northwest (e.g., Oregon and Washington) and the Southeast (e.g., Arkansas and Alabama). Thus, the lumber transportation distance was assumed based on research by Adhikari et al. (2023). Considering facility size and lumber supply costs, the optimal distance from the sawmill to the CLT facility ranges from 80 to 257 km. The CLT production process is based on a study conducted by WVU-AHC on producing hardwood CLT from low-grade red oak lumber (Norris, 2023). The industrial-scale CLT production can include finger jointing and cross-cutting, surfacing, panel layup, gluing, pressing, computer numerical control (CNC) processing, and packaging. The dust collection system was also considered for the CLT factory.

2.3.1. Finger jointing and cross-cutting

To ensure sufficient board length for lamination and minimize material waste, finger jointing is applied to shorter boards. Shorter boards are finger jointed to form long boards. The ends of the boards are first cut into a zigzag profile to fit snugly with the profile of the corresponding board. One of the profiles then receives a thin layer of adhesive, and the two zigzag profiles are pressed together to create an immediate bond. Transverse laminates can be generated from the longitudinal laminates by crosscutting based on the dimensions of the press (Yeh et al., 2013). The process inputs include rough-sawn lumber, resin, and electricity required for the production line. Approximately 26.45 kWh of electricity and 1.33 kilograms (kg) of resin are needed for finger jointing 1 m^3 of lumber (Chen et al., 2019). The necessity to remove weak sections and provide margins results in approximately 7.4 % waste during production (Olsson et al., 2019). Melamine formaldehyde and polyurethane (PUR) are approved for use in softwood glulam in North America, and they are also applicable for hardwood (Morin-Bernard et al., 2021). This study assumed the application of PUR for finger jointing and face bonding.

2.3.2. Surfacing

Finger-jointed boards are surfaced on all four sides to achieve the exact size required for panel layup. Additionally, surfacing helps activate or refresh the wood surface, reducing oxidation and improving gluing effectiveness (Yeh et al., 2013). When passing through the planer, multiple cutting heads mounted on horizontal and vertical spindles simultaneously remove material from all four sides. Electricity consumption is influenced by factors such as the amount of material to be removed, feed speed, and cutting depth. For hardwood, it is recommended to control the feed speed at 6 m per minute (m/min) and maintain a cutting depth within 2 mm per pass. Taking the Wadkin GB Planer Moulder as an example, its power consumption is 36.26 kWh/m^3 (Wadkin, 2024). The percentage of surfacing waste is shown in Table 1.

2.3.3. Panel layup and gluing

Each layer of CLT panels consists of multiple lumber pieces, with adjacent layers aligned perpendicular to each other to achieve the desired structural performance. Higher-grade lumber pieces are tightly placed in the first layer on a platform, applied with adhesive, and then lower-grade lumber pieces are layered in the perpendicular direction. The typical glue application system used in the through-feed process is usually for PUR adhesive (Yeh et al., 2013). The extruder heads move and apply adhesives in parallel lines or threads within an airtight system, directly supplied from an adhesive container. The glue applicator comprises a series of side-by-side nozzles installed on a beam. This gluing and stacking process continues until 3, 5, 7, or even 9 layers are assembled. PUR was assumed to be used for face bonding, as it yields favorable resistance to delamination and shear results (Norris, 2023). The adhesive input is 4.16 kg/m^3, with an electricity input of 2.59 kWh/m^3 (Chen et al., 2019).

2.3.4. Pressing

Applying pressure to stacked layers of wood and adhesive facilitates the formation of a solid panel. This process is automated, with the press adjusting pressure, temperature, and clamping time based on preset parameters. The duration of pressing varies according to factors such as the panel thickness, pressing type, and the specific adhesive utilized. For PUR adhesive pressing, optimal conditions entail applying slight pressure to extrude the adhesive when temperatures range between 68 and 130 °F (20–54 °C), coupled with a clamping time of 40–120 min. It was assumed that pressing was conducted for 120 min at 20 °C. Taking the Carver Bench Top Auto Press as an example, equipped with 340,194 kg of clamping force and 3.048 m by 0.914 m platens, the estimated power consumption for pressing 1 m^3 of PUR adhesive-bonded solid panels amounts to 29.84 kWh (Norris, 2023).

2.3.5. CNC processing and packaging

CNC processing is used to customize panels for specific projects by trimming, cutting window and door openings, creating connection nests, and molding ducts for electrical and plumbing installations (Larasatie et al., 2020). CNC machining is a digital manufacturing technology that creates high-accuracy parts from computer-aided design (CAD) models. CAD models are converted into G-code, which serves as instructions for CNC machines. The CNC machine executes programmed instructions, utilizing tools such as mills, grinders, and routers to perform cutting operations. These operations are automated and controlled by a computer, ensuring very tight tolerances. The process produces waste in the form of sawdust or unused wood portions, constituting 13 % of the total output, while requiring an energy input of 31.75 kWh/m^3 (Chen et al., 2019). Packaging prevents direct water contact or sun exposure, with wrapping materials such as lumber paper and plastic.

2.3.6. Dust collection system

Dust collection systems are essential in the woodworking industry to ensure the health and safety of workers, prevent fire hazards, maintain equipment efficiency, and minimize environmental pollution. However, existing LCA studies of wood products have overlooked the electricity used for dust removal, as well as other infrastructure energy demands. This omission of infrastructural electricity demand constitutes 10 % of the overall impact on GWP (Wenker et al., 2018). Specifically, the dust collection system consumes 0.176 megajoule (MJ) per 1 kg of wood product production (Wenker et al., 2018).

2.4. Software and database

The SimaPro software developed by PRé Sustainability (version 9.3.0.3) was used for conducting LCA, utilizing the US-EI 2.2 and US LCI databases. The US LCI database, developed by the National Renewable Energy Laboratory, provides information on the material and energy flows in and out of the environment during the manufacturing of wood products. The US-EI 2.2 database is established upon Ecoinvent 2.2 and combined with the US LCI database. These databases are specifically adapted for LCI data in the United States, ensuring regional relevance and accuracy in assessments.

3. Results and discussion

3.1. Total impacts

Table 2 shows the inventory data for the production of hardwood CLT. It reveals that manufacturing 1 m^3 of hardwood CLT panels requires 3.07 m^3 of roundwood, similar to the 3.11 m^3 raw material needed for softwood CLT (Nakano et al., 2020). Lumber production consumes more electricity, biomass, and fossil energy compared to CLT production.

Table 3 shows the environmental impacts calculated through the TRACI and CED models. Transportation burdens the upstream processes, such as transporting logs from the forest, which is part of log production, and transporting lumber from the sawmill, which is part of lumber production. The production of 1 m^3 of hardwood CLT in the eastern United States resulted in an average emission of 360 kg of carbon dioxide equivalent (kg CO_2 eq) (Table 3). Notably, although the GWP of hardwood CLT is higher than that of softwood CLT, it remains lower than the average GWP of structural concrete. Previous LCA studies have reported GWP ranges of 156.7–252 kg CO_2 eq/m^3 for softwood CLT and 246–514 kg CO_2 eq/m^3 for concrete (Chen et al., 2019; Puettmann and Sinha, 2019; Nakano et al., 2020; Kerr et al., 2022). These softwood CLT related studies are all based on a cradle-to-gate system boundary and the mass allocation rule. Lan et al. (2019) found that under various scenarios of forest growth, energy supply, and disposal options for CLT, the results ranged from 113 to 375 kg CO_2 eq/m^3. Among the three system processes, CLT production accounted for 29 % of the GWP impact, while

Table 2
Inventory data for the production of 1 m^3 CLT panel.

Module	Direction	Item	Value	Unit
Extraction and upstream production (A1)	Input	Roundwood [e, f, g, h, k]	3.07	m^3
		Truck transportation [c]	226.25	tkm
		Diesel [k, o, p, q]	19.17	L
		Gasoline [k, o, p]	0.88	L
		Natural gas [o, p]	0.20	L
		Lubricants [q]	0.35	kg
		Bark [p]	323.53	kg
		Electricity, at grid [d, j, l, o, p]	303.39	kWh
		Electricity, onsite boiler [l, o, p]	14.25	kWh
		Heat, onsite boiler [l, p]	4739.73	MJ
Transport to factory (A2)	Input	Truck transportation [b]	137.17	tkm
Manufacturing (A3)	Input	PUR resin [a, i]	6.50	kg
		Electricity, at grid [i, l, m, n]	177.50	kWh
		Kraft paper	1.23	kg
	Output	CLT panel	1	m^3
		Waste	0.28	m^3

[a] PUR resin: polyurethane.
[b] Adhikari et al. (2023).
[c] Anderson and Germain (2007).
[d] Azambuja et al. (2022).
[e] Bergman and Bowe, 2008a.
[f] Bergman and Bowe, 2008b.
[g] Bergman and Bowe (2009).
[h] Bergman and Bowe (2010).
[i] Chen et al. (2019).
[j] Hassler et al. (2022).
[k] Hubbard et al. (2020).
[l] Meng et al. (2019).
[m] Norris (2023).
[n] Olsson et al. (2019).
[o] US LCI database.
[p] US-EI 2.2 database.
[q] Zhao et al. (2024).

log production and lumber production accounted for 14 % and 57 %, respectively. However, previous studies have shown that CLT production contributes the most to GWP impact. This difference is attributed to two assumptions in this study: (1) the grading process was included within lumber production, and (2) partial planing occurred at the sawmill. Additionally, the average total energy required for 1 m^3 of hardwood CLT was 5370 MJ. The production of CLT accounted for 31 % of the total energy, while log production and lumber production consumed 14 % and 55 %, respectively. Non-renewable fossil fuels occupied the largest proportion of energy consumption throughout the cradle-to-gate life cycle (74 %). Renewable biomass accounted for 23 % of the primary energy consumption, mainly occurring during lumber production. As for other non-renewables and renewable energy sources, they collectively represented only 3 % of the primary energy consumption.

To explore the relative environmental impacts of different life cycle stages on key impact categories, Fig. 2 presents the characterization results. Five life cycle stages were considered: harvesting, log transportation, lumber manufacturing, lumber transportation, and CLT manufacturing. Categories with extremely low impact values were excluded. It's evident that CLT and lumber manufacturing were major contributors to almost all categories, although harvesting was the second biggest cause of smog. Furthermore, substantial emissions were observed during the transportation stage. The transportation of logs and lumber was responsible for 18 % of fossil fuel depletion, 12 % of smog potential, and 10 % of GWP.

Table 3
Cradle-to-gate LCIA results for 1 m^3 CLT Panel.

Impact Category	Unit	Total	Log Production	Lumber Production	CLT Production
Global warming	kg CO_2 eq	360.00	51.60	205.40	103.00
Smog	kg O_3 eq	42.50	16.20	25.00	1.30
Acidification	kg SO_2 eq	2.98	0.51	1.90	0.57
Eutrophication	kg N eq	0.34	0.04	0.23	0.07
Ozone depletion	kg CFC-11 eq	3.61×10^{-5}	3.90×10^{-7}	4.49×10^{-5}	-9.20×10^{-6}
Carcinogenics	CTUh	5.64×10^{-5}	8.79×10^{-7}	6.76×10^{-5}	-1.21×10^{-5}
Non carcinogenics	CTUh	4.31×10^{-5}	8.25×10^{-6}	2.67×10^{-5}	8.20×10^{-6}
Respiratory effects	kg PM2.5 eq	0.26	0.01	0.23	0.02
Ecotoxicity	CTUe	1.65×10^{3}	211.00	786.00	653.00
Fossil fuel depletion	MJ surplus	353.00	104.00	183.00	66.00
Total energy	MJ	5.37×10^{3}	751.18	2.97×10^{3}	1.65×10^{3}
Nonrenewable, fossil	MJ	3.97×10^{3}	739.00	1.76×10^{3}	1.47×10^{3}
Nonrenewable, nuclear	MJ	109.00	10.50	13.60	84.90
Nonrenewable, biomass	MJ	0.01	4.05×10^{-5}	2.91×10^{-5}	0.01
Renewable, biomass	MJ	1.25×10^{3}	0.34	1.18×10^{3}	72.28
Renewable, wind, solar, geothermal	MJ	2.41	0.39	0.66	1.36
Renewable, water	MJ	38.40	0.95	17.35	20.10

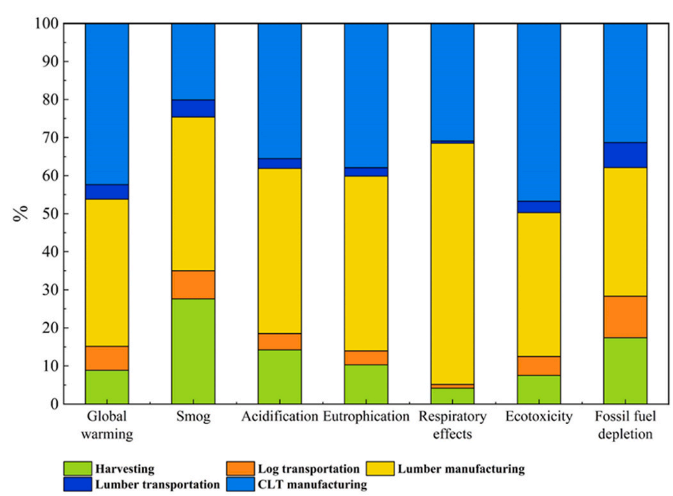

Fig. 2. Characterization results by life cycle stages.

3.2. Impacts of CLT manufacturing

The manufacturing of CLT involves multiple unit processes and material inputs, each of which generates certain environmental burdens. According to Fig. 3, electricity from the grid was nearly the primary contributor to all impact categories. In fact, energy consumption accounted for 82 % of the total carbon emissions. However, in terms of fossil fuel depletion, both electricity and resin played significant roles. In comparison, the impact of packaging materials was minimal, accounting

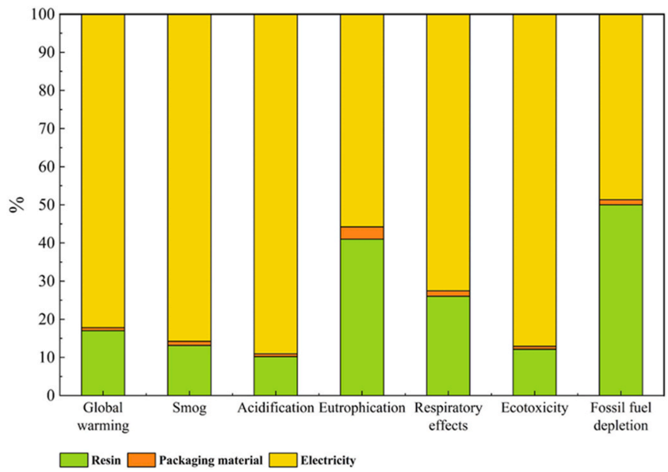

Fig. 3. Characterization results of CLT manufacturing based on material inputs.

for only 3 % of eutrophication and 1 % of other categories. The contribution percentages of different unit processes are shown in Fig. 4. Among all manufacturing steps, finger jointing and surfacing contributed the most to GWP (20 %). As surfacing and finger jointing were the top two electricity-intensive processes in CLT manufacturing, they led to large GHG emissions from electricity generation. Furthermore, surfacing also made the highest contribution to smog (21 %), acidification (22 %), and ecotoxicity (21 %). Burning fossil fuels for electricity generation also releases pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NOx), VOCs, etc. Meanwhile, panel layup and gluing contributed the most to eutrophication (32 %), respiratory effects (21 %), and fossil fuel depletion (39 %), primarily due to the synthesis of PUR.

3.3. Sensitivity analysis

Although lumber and CLT manufacturing represented the most environmental impacts, decreasing these impacts through process optimization is technically challenging and may require substantial capital investment (Chen et al., 2019). Therefore, alternative strategies such as feedstock selection, supply chain optimization, and increasing the utilization of biomass energy have become potential solutions. For this reason, this study conducted a sensitivity analysis to thoroughly analyze the influence of these factors.

The density of raw materials influences the transportation stage and transportation efficiency of the entire supply chain. Hardwood species with higher density have greater weight per unit volume, leading to

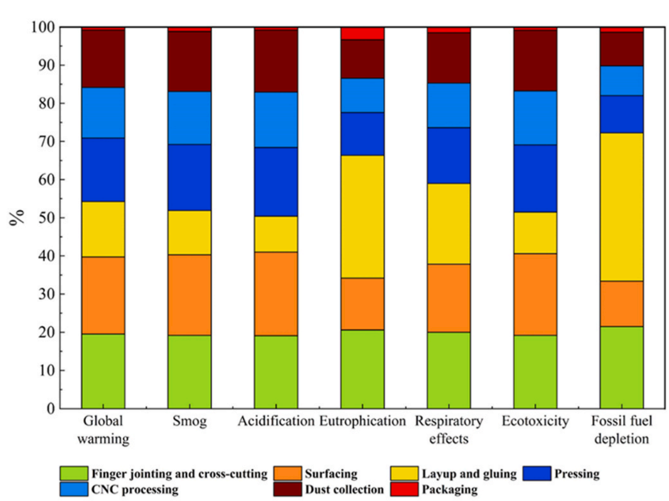

Fig. 4. Characterization results of CLT manufacturing based on processes.

increased costs and energy consumption on a volume basis in transporting both logs and lumber. This study's baseline scenario assumed a green density of 915.5 kg/m^3 and a dry density of 636 kg/m^3. However, there is considerable density variation among hardwood species utilized for CLT. For instance, some species are lighter, such as yellow poplar (green density: 778 kg/m^3), while others are heavier, such as red oak (green density: 977 kg/m^3). The sensitivity analysis revealed that selecting the low-density yellow poplar as the raw material reduced the GWP impact by 22 % compared to the baseline scenario and by 25 % compared to the high-density red oak scenario. Similar trends were observed across other impact categories. In addition to feedstock density, transportation distance also influences total emissions during the transportation stage. In the baseline scenario, it was assumed that the distance from the forest to the sawmill was 80.5 km and from the sawmill to the CLT factory was 168.5 km. When the three locations were closest, all impacts decreased by 45 % compared to the baseline scenario and by 62 % compared to the farthest scenario. If light-weight hardwood species were selected while minimizing travel distance, it was possible to reduce up to 71 % of the environmental impacts during the transportation stage and 10 % of the overall impact of CLT production.

In the baseline scenario, most of the electricity consumed in lumber manufacturing and all electricity consumed in CLT manufacturing were assessed based on the eastern U.S. grid. The U.S. grid, including the eastern interconnection, is sourced from various energy sources. According to data from the U.S. Energy Information Administration, in 2022, fossil fuels, including natural gas, coal, and petroleum, remained the primary sources of electricity generation, accounting for 60 % (EIA, 2023). However, the proportion of renewable energy is continuously increasing, reaching 22 %, with biomass-derived electricity contributing over 1 % (EIA, 2023). The utilization of biomass energy shows promises in substantially reducing GHG emissions. Therefore, an assessment was conducted for the scenario involving 100 % biomass electricity usage during the manufacturing stages. Biomass production, exemplified by poplar plantations, has a growth cycle of seven years. Biomass electricity generation involves the combustion of biomass to produce steam through thermal transfer, which drives a generator to create electricity, while excess heat is often captured for additional energy use. As a result, the GWP impact was diminished by 72 %, while concurrently decreasing the impacts on acidification, eutrophication, respiratory effects, ecotoxicity, and fossil fuel depletion by 63 %, 42 %, 49 %, 83 %, and 41 %, respectively. The only increase was in the impact of smog (increased by 62 %), due to the release of NOx and VOCs. The application of biomass electricity ultimately halved the overall impact, making it the most effective approach. If hardwood CLT production were to fully utilize biomass energy, the average emissions could be reduced to approximately 160 kg CO_2 eq/m^3. Fig. 5 illustrates the comparison of the impacts of different variables.

3.4. Biogenic carbon accounting

The environmental benefits of CLT are not only in replacing emission-intensive steel and concrete, but also in keeping CO_2 out of the atmosphere to slow climate change. Wood products can store biogenic carbon, which is captured through photosynthesis during the growth of trees, until they decompose or burn, releasing carbon back into the atmosphere. The accounting of biogenic carbon follows ISO 21930 guidelines, treating biogenic carbon entering a product system as a negative value (carbon removal) and leaving the system as a positive value (carbon emissions) (ISO, 2017). The calculations for carbon sequestration and carbon footprint are shown in Equation (1) and Equation (2). The carbon emissions from producing 1 m^3 of hardwood CLT amount to 141.9–377.4 kg CO_2 eq. However, the same 1 m^3 of hardwood CLT can store 770.7–1167.1 kg CO_2 eq, based on a density of 420–636 kg/m^3 and a carbon content of 50 %. Therefore, net carbon storage ranges from 430.2 to 988.3 kg CO_2 eq/m^3. When CLT is utilized in buildings, carbon will be locked up for 60 years (the expected lifespan

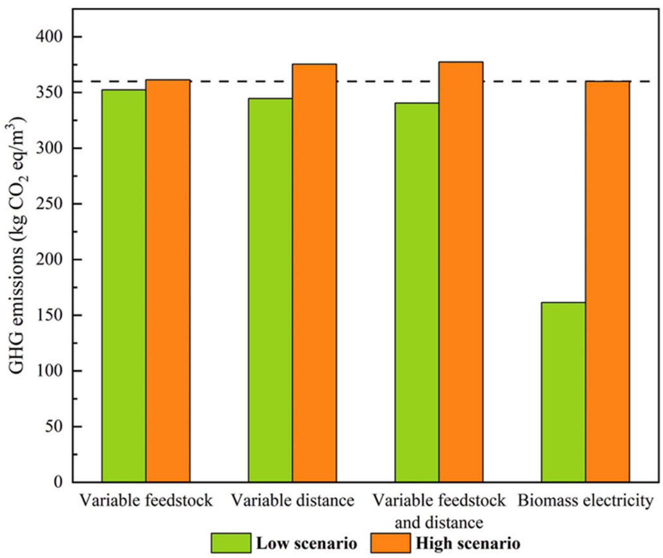

Fig. 5. Comparison of the impact of different variables on global warming. The dashed line represents the baseline scenario, which equals 360 kg CO_2 eq/m^3.

of CLT buildings). Even after the buildings reach the end of their lifespan, CLT panels can be reclaimed and recycled for use in furniture and other products, further reducing the carbon footprint of buildings.

$$Carbon\ Sequestration = \rho \times V \times f_C \times \frac{44}{12} \quad \text{(Equation 1)}$$

$$Carbon\ Footprint = \sum GHG\ flowing\ in + \sum GHG\ flowing\ out \quad \text{(Equation 2)}$$

Where ρ is the wood density (kg/m^3), V is the volume of the CLT panel (m^3), f_C is the fraction of carbon in the dry wood mass (%), and $\frac{44}{12}$ is the conversion factor from elemental carbon (C) to carbon dioxide (CO_2).

4. Conclusions

This study modeled the production of hardwood CLT in the eastern United States and conducted a process-based cradle-to-gate LCA. Several key findings were obtained through quantifying environmental impacts and sensitivity analysis, revealing the environmental performance and sustainability implications of hardwood CLT. Despite hardwood not being the common material for CLT, its production does not require more raw materials (i.e., boards) compared to softwood CLT of equivalent volume, allowing hardwood to be competitive in CLT manufacturing. Hardwood CLT production typically has a higher environmental impact than softwood CLT production, but not always. Selecting lightweight wood, sourcing materials locally, and utilizing biomass electricity can mitigate the environmental footprint of hardwood CLT, making it comparable to or even lower than softwood CLT, thereby further enhancing its sustainability competitiveness. Lumber production was identified as the stage with the most environmental impact in the life cycle of hardwood CLT production, highlighting the importance of optimizing resource efficiency and transportation logistics within the lumber processing sector. Among CLT manufacturing procedures, finger jointing and cross-cutting and surfacing were identified as the processes with the most environmental impact. However, achieving emissions reduction through process optimization may be challenging, given the wood products industry's well-established manufacturing standards. Accounting for biogenic carbon, the net carbon emissions of hardwood CLT ranged from - 430.2 to - 988.3 kg CO_2 eq/m^3, highlighting its substantial carbon sequestration benefits as a sustainable construction material. This study addressed the lack in assessing the environmental impacts of hardwood CLT, providing valuable insights for the future development of EPDs. Based on these findings, future research should further explore variations in mechanical properties across different hardwood species, as differences in density and strength can affect material usage, structural performance, and overall environmental impact. Additionally, integrating real-world production data where multiple stages are interconnected on a single manufacturing line would offer a more holistic perspective and reduce the inaccuracies inherent in isolated process-based modeling. Expanding the system boundaries to include use and end-of-life stages could also capture long-term carbon storage and the potential for reuse or recycling. These efforts would not only refine suitability indicators for hardwood CLT but also enhance its competitiveness and promote broader industry adoption.

CRediT authorship contribution statement

Jinghan Zhao: Formal analysis, Methodology, Data curation, Writing – original draft, Investigation. **Jingxin Wang:** Writing – review & editing, Supervision, Resources, Conceptualization, Validation, Software, Funding acquisition, Project administration. **Levente Denes:** Validation, Project administration, Resources, Funding acquisition, Writing – review & editing. **Zhichao Liu:** Writing – review & editing, Resources, Validation. **Nathaniel Anderson:** Writing – review & editing, Resources. **Richard Bergman:** Resources, Methodology. **Kai Lan:** Writing – review & editing, Resources, Methodology. **Wanhe Hu:** Investigation, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.146669.

Data availability

Data will be made available on request.

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