sustainability

Review

Life Cycle Environmental Sustainability and Energy Assessment of Timber Wall Construction: A Comprehensive Overview

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Abstract: This article presents a comprehensive overview of the life cycle environmental and energy assessment for all residential and commercial constructions made of timber walls, globally. The study was carried out based on a systematic literature analysis conducted on the Scopus database. A total of 66 research articles were relevant to timber wall design. Among these, the residential construction sector received more attention than the commercial sector, while the low-rise construction (1–2 stories) gained more attention than high-rise construction (>5 stories). Most of these studies were conducted in Canada, Europe, Malaysia, and the USA. In addition, the end-of-life phase received limited attention compared to upstream phases in most of the studies. We compared all environmental and energy-based life cycle impacts that used "m^2" as the functional unit; this group represented 21 research articles. Global warming potential was understandably the most studied life cycle environmental impact category followed by acidification, eutrophication, embodied energy, photochemical oxidation, and abiotic depletion. In terms of global warming impact, the external walls of low-rise buildings emit 18 to 702 kg CO_2 kg eq./m^2, while the internal walls of the same emit 11 kg CO_2 kg eq./m^2. In turn, the walls of high-rise buildings carry 114.3 to 227.3 kg CO_2 kg eq./m^2 in terms of global warming impact. The review highlights variations in timber wall designs and the environmental impact of these variations, together with different system boundaries and varying building lifetimes, as covered in various articles. Finally, a few recommendations have been offered at the end of the article for future researchers of this domain.

Keywords: life cycle assessment; timber wall; building construction; greenhouse gas emission; abiotic depletion; acidification; eutrophication; photochemical oxidation; primary energy; embodied energy

1. Introduction

The construction of buildings has an enormous environmental effect and, significantly, buildings carry a substantial proportion of carbon dioxide emissions [1–4]. The production, construction, use, and demolition of building materials significantly contributes to the worldwide usage of resources and waste [5–8]. Around 40% of all raw resources are used in construction and demolition worldwide [9–11]. Furthermore, construction operations require 32% of global energy use, and are responsible for one third of greenhouse gas emissions globally [5,10,12–16]. Therefore, 25% of landfill wastes, 10% of airborne particulates, and 35% of greenhouse gases (GHGs) are produced by buildings [8]. Due to these adverse environmental impacts, sustainable alternatives such as less energy-intensive materials or recycled or biodegradable materials need to be introduced in the construction sector [8,17–23]. The circular economy of construction materials in this context also plays a significant role, helping to maximize the efficient material use of construction and demolition waste, and minimize fossil fuel energy use and resource consumption [24,25]. Recently, researchers have nominated timber as a less energy-intensive structural material that accounts for lower carbon emissions [1]. Around 88% of timber can be used as lumber or raw materials with little to no waste generation. This type of reuse system is known as a closed-loop circular economy. Construction and demolition wood or wood fiber waste are used in engineering wood panel products which are known as open-loop circular economy [24,25]. Besides engineering wood products, different types of industrialized wooden products (such as particleboard and laminated floors) can be manufactured [26]. However, at present, 63% of waste wood goes to incineration and landfill without energy recovery [26]. Incineration and landfill activities produce little or no energy, but these activities have adverse impacts on human health and the environment. As waste-wood reuse, reduction and recycling (bio-concrete, wood–plastic composite) are part of the circular economy, these activities will reduce environmental impacts [26–28]. For sustainable development, a systemic evaluation is thus needed to evaluate the construction of wooden-frame structures.

Timber is the only building element that absorbs CO_2 from the environment and has a positive environmental impact on its end of life [1,29]. Numerous wood engineering products, such as glue-laminated timber (GLT) and cross-laminating timber (CLT), have been introduced and are used in low- and high-rise building industries [7]. These materials have higher structural integrity, strength, and rigidity, increasing building project life and reducing carbon emissions [7,30]. However, these engineered wood products need additional energy due to various industrial processes involving harvesting, drying, sawing, production, and transport, and have negative environmental impacts [12]. In addition, several negative environmental consequences (global warming, acidification, photochemical oxidation, eutrophication, and toxicological effect) have been identified in the production processes of boards, such as the use of fossil-based synthetic resin (urea or phenol-formaldehyde) and the limited recyclability of the final product [8,12,31]. So, sustainable timber selection is a critical decision for building construction.

The authors, at this moment, have concentrated only on wood-framed walls. Walls are essential components of a building envelope that includes the roof, walls, floor, ceiling, door, and windows. Although all components of the building envelope are responsible for energy use and carbon emission, the wall is more significant due to its different elements, such as exterior doors, windows, ventilators, and exterior walls. It is a ventilated part that includes the window and exterior door, and moisture may enter through the windows and doors. Moisture may cause decay and mold development, leading to the poor air quality inside, health issues, early structural failure, extra maintenance expenses, and GHG emissions due to removing, repairing, or substituting damaged parts or whole components [13,32]. Moreover, the wall is the largest part of the structural envelope responsible for carbon emission (26%) [16]. So, suitable material selection for timber walls is crucially important.

Green building initiatives, including certification schemes and eco-labeling, have developed and gained in popularity to reduce the environmental impacts of buildings [6,33,34]. Recently, various initiatives have been taken to incorporate life cycle assessment (LCA) results into green building certification and rating systems. Life cycle assessment methodology can quantify energy consumption and environmental pollutant emissions by defining a scope of analysis for each type of building or fabrication method, types of manufacturing or construction material, and each stage of its life cycle. There are four stages during the life cycle of buildings, material manufacturing, construction, use and maintenance, and the end of life [13,35–37]. All stages are responsible for energy consumption, material use, and carbon emission. LCA can quantify which stage has a higher impact on the environment. At the same time, LCA is also used to compare different alternative building materials and elements [38]. Therefore, LCA has been used in the construction sector for two decades [9]. Some researchers have reviewed the environmental impacts of wood products and alternative materials in buildings and found that wood outperforms alternative materials in terms of greenhouse gas emissions. Compared to other materials, wood has been found to produce less waste, and has performed better across different impact categories, except preservative-treated wood [39]. At present, different engineering timber (GLT, CLT) is used in the building industry that need preservatives. As researchers have concluded that preservative-treated timber carries a greater negative environmental impact than natural timber, full life cycle assessment is required for all timber material used in building construction.

The LCA process needs a large data set or bill of materials. Due to its complexity, most of the life cycle experts tend to apply simplifications or modifications to the process. The most common modification is to reduce the number of stages involved in the life cycle process by ignoring the stages which have a smaller contribution to the total environmental impacts [3,40,41]. For example, repair and maintenance are less frequently considered in the LCA of building construction [4,5,32]. Similarly, many earlier studies were simplified LCAs focusing on only a few environmental or energy impacts for the construction industry. Some researchers reviewed embodied and operational energy consumption and carbon emission within building lifetimes [10,42–46]. Some researchers reviewed different wood characteristics (seismic behavior, fire resistance, durability, thermo-physical properties, and acoustic properties) and discussed embodied energy and the embodied carbon emission of different wood products [47]. Some researchers quantified and determined the potential environmental impacts caused by office buildings [8,16,47,48]. There is also some LCA research on the environmental impact of windows [11,49,50]. Notably, few researchers have reviewed the environmental impact of ventilated wooden walls through LCA methodology [40].

Although the wall is a significant part of building construction, limited research indicates more study is required to ensure a comprehensive or holistic assessment of energy and environmental sustainability impacts. The current evaluation will assist LCA practitioners in understanding the current state-of-the-art situation regarding carbon emission, acidification, eutrophication, photochemical oxidation, abiotic depletion, and the embodied/primary energy of wooden-frame wall structures. It will also assist them in comparing their results with this review paper. Moreover, this study describes various knowledge gaps and possible research perspectives related to different LCA phases applied to timber wall structures. It will also give some guidelines to decision makers regarding timber materials and strategies to minimize environmental impacts.

2. Review Methodology

The life cycle assessment methodology is an appropriate tool for determining the environmental impact of materials, services, and products. As a result, numerous researchers are now undertaking studies on LCA. LCA is increasing in popularity as a decision-making tool for sustainability. The histogram in Figure 1 illustrates the trend in research interest in building analysis using LCA. A systematic literature review is a comprehensive method to identify and analyze results from the selected literature. In this literature review, the authors followed three steps in relevant result finding: (1) keyword searching, (2) database search, (3) article exclusion and shortlist creation.

Step (1): Keyword search. The keywords were related to research gaps, and the search string used for this study was: {"life cycle assessment" OR "lifecycle assessment"} OR {"life cycle analysis" OR "lifecycle analysis"} AND {"wood" OR "timber"} AND {"wall"}.

Step (2): Database search. The purpose of the study was to assess a representative sample of peer-reviewed articles to examine the environmental implications of wooden walls. Scopus is a database that allows for the discovery of peer-reviewed scientific articles. There are a total of 1588 peer-reviewed articles on this database that include the terms "life cycle assessment", "life cycle analysis", and "timber or wood", as of Aug 2021. Following a reference to another keyword, "wall", 103 publications were categorized (Figure 2).

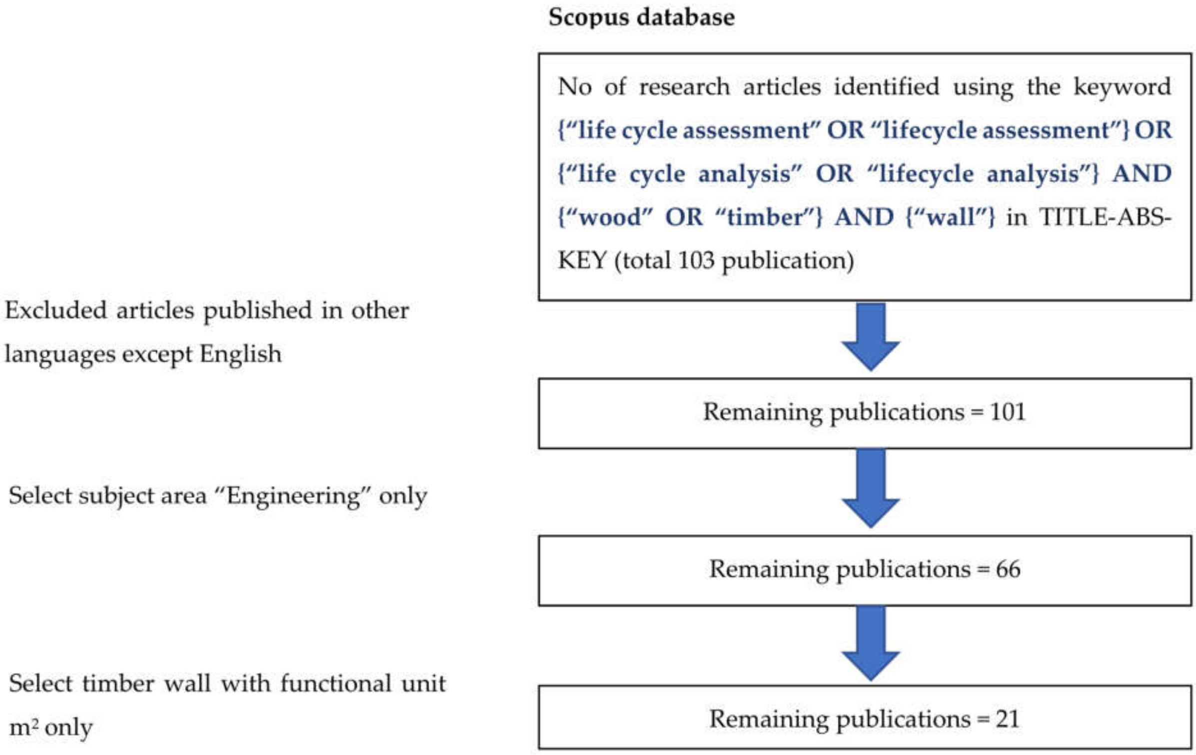

Figure 1. Histogram of the reviewed published articles regarding timber walls.

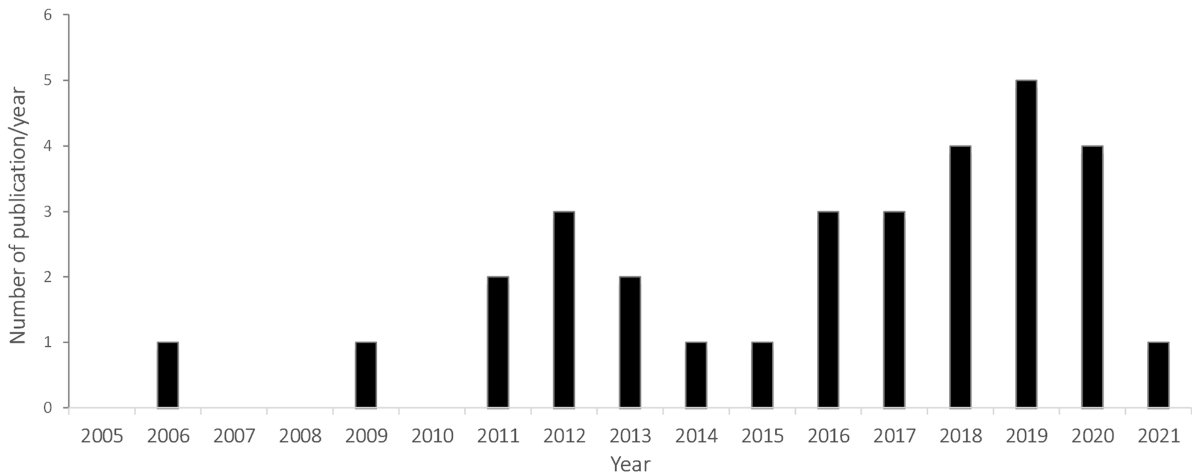

Figure 2. Flowchart of research article searching methodology.

Step (3): Article exclusion and shortlist creation. Article exclusion is important to avoid bias. In this stage, the authors performed a thorough examination of each article to ascertain the specifics of the wooden wall material and its functional unit "m^2". Two articles were eliminated due to language difference. Here, only English articles were chosen. Engineering subject area-related articles were shortlisted due to the relevant field. Later, all articles were eliminated except m^2 functional unit. To compare the environmental impacts, choosing a uniform functional unit is a main criterion. The authors found 21 articles relating to wooden walls with the same functional unit (m^2). By searching Google and Web of Science, only 11 relevant articles were shorted. Altogether, 32 articles were selected for data analysis and impact assessment. The publication years of these articles are shown in Figure 1. Next, additional information about each article was gathered, including the LCIA technique, the impact category, the location, the end of life, the software, the database, and the system boundary.

3. Life Cycle Impact Results

3.1. Life Cycle Inventory and Life Cycle Impact Assessment Methodologies

In many of the studies, Ecoinvent was the most frequently utilized life cycle inventory library [4–6,13,15,29,30,51,52] The Athena library was utilized in four articles [2,8,15,42,49,50]. Some researchers employed an environmental product declaration (EPD) for impact evaluation, while others utilized an Australian database for their study [7,14]. There were significant data gaps, since no precise LCI data are accessible for any construction material, particularly in developing countries. There may not be accurate data due to geographic variables such as varied weather conditions, manufacturing methods, fuel sources, international databases, or computer programs [32].

Several impact assessment methodologies are based on a single impact category (e.g., primary energy, energy, and global warming potential), while others are based on multiple impact categories [3]. There are two multi-category LCIA methods: problem-oriented and damage-oriented [3]. The problem-oriented approaches model the cause–effect chain up to the midpoint impact categories, while damage-oriented approaches model the cause–effect chain up to the endpoint impact categories. The cumulative energy demand (CED) and the IPCC GWP are single-issue methodologies. The CED considers life cycle primary energy requirements, while the IPCC GWP method evaluates climatic change. The Intergovernmental Panel on Climate Change (IPCC) publishes comprehensive assessment reports on the current level of scientific, technological, and socioeconomic knowledge about climate change, its consequences and future dangers, and strategies for slowing the pace at which climate change occurs. The IPCC GWP is a new approach for measuring environmental impact established by the IPCC. In contrast, ReCiPe, TRACI, CML 2001, IMPACT 2002+, Environmental design of the industrial product (EDIP), Environmental priority strategy (EPS), and Eco-inidcator'99 are multi-category impact assessment techniques, while TRACI, CML 2001, EDIP, and IMPACT 2002+ are problem-oriented assessment techniques. EPS and Eco-indicator'99 are impact assessment methods that focus on damage. IPCC GWP [1,4,5], IMPACT [3,12], TRACI [10], Eco-indicator [3,12], CML [11,12,38,40,41], and CED [41] were utilized in these peer-reviewed articles (Table 1).

Table 1. Project location of the relevant article.

S. No.	Name of Author	Location
1	Marsono et al., 2015	Malaysia
2	Frenette et al., 2020	Quebec, CANADA
3	Monteiro et al., 2011	Portugal
4	Balasbaneh et al., 2017	Johor Bahru, Malaysia
5	Balasbaneh et al., 2017	Malaysia
6	Corradini et al., 2018	Northern Italy
7	Lolli et al., 2019	Norway and Sweden
8	Nassar et al., 2016	Canada
9	Santos et al., 2020	No location is provided
10	Balasbaneh et al., 2019	Malaysia
11	Fufa et al., 2018	Norway (NO), Germany (DE), Sweden (SE), and France (FR)
12	Rios et al., 2019	USA
13	Maodus et al., 2016	No location is provided
14	Crippa et al., 2018	Brazil
15	Kahhat et al., 2009	Phoenix, USA
16	Mitterpach et al., 2019	No location is provided
17	Rajagopalan et al.	Pennsylvania
18	Culakova et al., 2013	Slovakia
19	Medgar L, 2006	Miami, Phoenix, Seattle, Washington, and Chicago
20	Broun et al., 2011	UK
21	Fu et al., 2014	Midland, UK
22	Garcia et al., 2012	Spain
23	Santi et al., 2016	Italy

Table 1. *Cont.*

S. No.	Name of Author	Location
24	Mequignon et al., 2012	France
25	Goswein et al., 2021	Portugal
26	Norby et al., 2013	UK
27	Pomponi et al., 2017	UK
28	Monteiro et al., 2020	Portugal
29	Potkany et al., 2018	Slovakia
30	Kim et al., 2012	USA
31	Lu et al., 2019	USA
32	Hong et al., 2020	USA

An LCA study can focus on a broad perspective of environmental, social, and economic concerns by assessing all cradle-to-grave stages of a process, or consider products from raw material extraction to manufacturing, construction, distribution, use, repair and maintenance, and end-of-life (disposal or recycling). The LCA tool and database connected to the construction sector are classified into three levels, depending on where they are utilized in the assessment process and their purpose [33]. For example:

- Level 1: Product comparison tools (Simapro, GaBi, Umberto NXT, Team TM, Level 1B Tools, BEES, LCAiT);
- Level 2: Whole building decision support tools (Athena, BRI LCA, EcoQuantum, Envest 2, LISA);
- Level 3: Whole building evaluation system and frameworks (BREEM, SBTool, Green Globes, LEED v4).

In the 32 articles we focused on, Simapro software was the most widely used one [1,3–5,8,10,13,14,29,38,53], while some researchers utilized Athena software to examine the whole house [2,54].

The authors reviewed 32 articles where different locations were chosen for research (see Tables 1 and 2) and different timber designs were applied (see Table 3).

Table 2. Project location.

Name of the Location of the Research Project	No. of Research Items
Malaysia	4
Canada	2
Portugal	3
Italy	3
Norway	2
Sweden	2
Germany	1
France	2
United States of America	5
Pennsylvania	1
Slovakia	2
United Kingdom	4
Miami	1
Phoenix	1
Seattle	1
Washington	1
Chicago	1
Brazil	1
Spain	1

Table 3. List of articles with author name and related timber material.

Serial No.	Timber Wall Material
1	Hardwood
2	Wood siding, furring, FB, brown cellulose, GB
3	Wood frame, cladding and extruded polystyrene
4	Hardwood
5	Hardwood
6	Norway spruce.
7	For tower A, timber cladding, WP, insulation, GB, For tower B, timber cladding, WP, insulation, CLT, GB
8	Wood
9	Maritime pine (Pinus pinaster) and polyurethane foam
10	Hardwood
11	In Norway, WP, glass wool, VB, GB. In Germany, wooden cladding, wood frame, MDF, OSB, GB, insulation. In Sweden, wooden cladding, wood frame, insulation, GB. In France, wooden cladding, glass wool, OSB, insulation, GB
12	Wood stud
13	GB, OSB, insulation, wooden stud, OSB.
14	Wood stud, rock wool, OSB, GB
15	Metal mesh, vapor barrier, wood frame, insulation, GB
16	S1: plaster, insulation, I beam, GB. S2: plaster, insulation, OSB, joist, OSB, PB. S3: Facade cladding-larch, beam, insulation, OSB, PB. S4 and S5: plaster, VB, PB. S6: Larch, foil. FB, box beam, straw, OSB, plaster. S7: plaster, spruce joist, insulation, OSB, PB. S8: Larch cladding, CLT panel, hemp boards, PB
17	wood frame with polyisocyanurate
18	Plaster, WP, VB, FB and insulation. Wood boarding-larch, wooden I-joists, OBS, GB, FB, insulation. Wood boarding-larch, FB, wooden I-joists, OSB, bricks, plaster Wood boarding-larch, OSB, insulation, wooden joists, CLT, GB. Wood boarding-larch, FB, straw bales, VB, WP, plaster. Wood boarding-larch, insulation, wooden box beams, OSB, PB, insulation.
19	Aluminum siding, plywood, insulation, GB
20	Studs, PB
21	Wood frame, PB
22	OSB, MDF, wooden sheet, metal pieces, plastic pieces, fiber
23	PB, spruce board, geotextile, FB, mortar, plaster mesh, plaster
24	Mineral coating, solid wood, insulation and plaster coating
25	Mineral coating, straw, timber stud, OSB, straw
26	Wood with wood fiber and wood with hemp-lime
27	Additional glass skin with existing timber wall
28	Wood wall
29	Plaster, insulation, HDF, timber frame, insulation, OSB, PB
30	Glulam structure with glazing
31	Vinyl siding, OSB, batt insulation, gypsum board
32	Wood stud, insulation, OSB sheathing, vinyl siding

GB = gypsum board, FB = fiberboard, GW = glass wool, PB = plasterboard, VB = vapor barrier, WP = wood panel. MDF = medium-density fiberboard.

In Figure 3, the blue color bar indicates the number of articles published in that country. Number 1 (light blue) shows the lowest number of (one) articles published, and number 5 (deep blue) indicates the highest (five) number articles published.

Figure 3 demonstrates that most studies were conducted in cold regions of developed nations such as Canada, Europe, and the United States. However, only three hot weathered nations (Brazil, Malaysia, and Portugal) were researched in the peer-reviewed studies for wooden wall-related LCA. The LCI data library and LCA methodology are the causes for a significant increase in research in industrialized nations. The majority of accessible LCI statistics, including forest management and wood products, and other building materials and processes, only reflect conditions in industrialized nations (Australia, central Europe, New Zealand, North America, and Scandinavia). Differences in forestry and wood products may be attributed to local climate, forestry techniques, timber densities, species and construction, and manufacturing procedures and processes. However, energy consumption and environmental implications differ across developed and developing countries due to architectural styles, the technology employed, and situations such as family size, temperature, geography, and energy sources. According to studies conducted in Europe and the United States, the usage phase of a building contributes the most to GWP, owing to high energy demand, particularly for heating, ventilation, and air conditioning. On the other hand, developing countries may lower GWP by minimizing the environmental effect of construction materials. Due to a lack of adequate LCI databases, the LCA implementation is comparably low in developing countries and is mainly limited to academic or research institution levels.

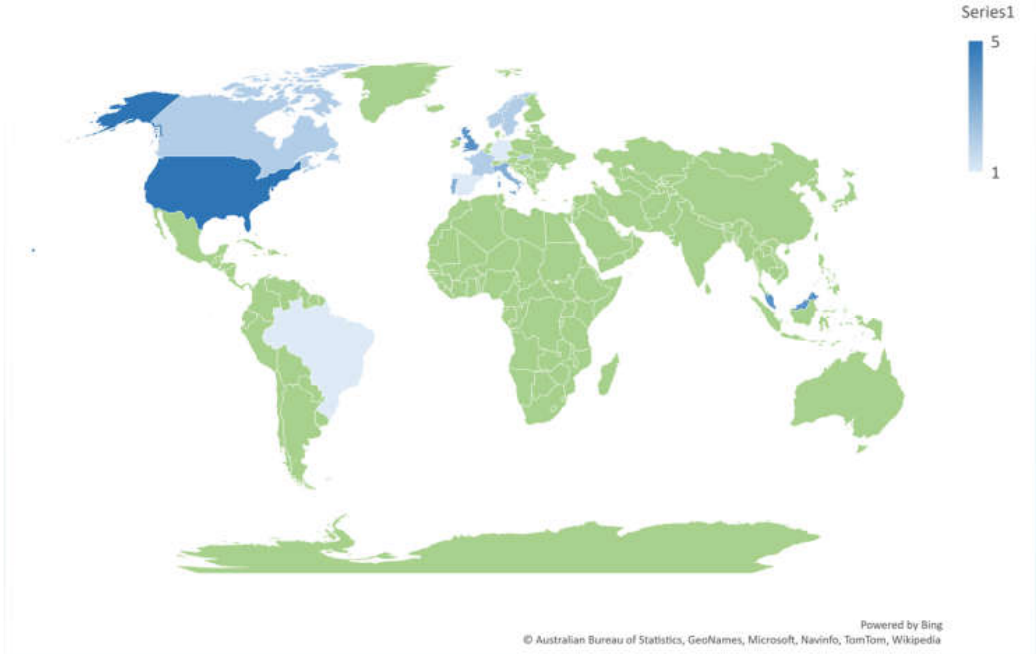

Figure 3. Geographical distribution of the number of the studies for LCA of timber wall.

The LCA method is also dependent on the system boundary of product life. Product life is divided into four stages: raw material procurement, construction, usage, and end of life (see Table 4). Sometimes researchers do not use all the production processes in LCA methodologies. In LCA approaches, different system boundaries include cradle to cradle, cradle to grave, cradle to gate, and gate to gate. The system boundary is a conceptual line that separates the system from everything else. Cradle to cradle (C2C) envisions a promising future in which goods are significantly remade to benefit both people and the environment. LCA is frequently referred to as a cradle-to-grave assessment of systems, including everything from the extraction of raw materials from the earth through production, product usage, and recycling/disposal at the end. Some studies focused on cradle to grave, but not all stages were well defined [2,4,5,10,13,15,29,35]. Most phases contain transportation activity responsible for environmental burden, although transportation usage was not stated in those publications. Cradle to gate evaluates a portion of a product's life cycle that includes resource extraction (cradle) and when a material is ready on the factory gate but not delivered yet to the customer. A gate-to-gate LCA analysis is only one value-added part throughout the complete manufacturing chain which can be linked together in their respective manufacturing chains to produce a comprehensive cradle-to-gate assessment. In our selected studies, researchers chose different system boundaries as per the importance of the study and the focus of their research.

Table 4. System boundary of the articles.

Serial No.	Product Stage		Construction Stage			Use Stage				End of Life				
	Mat * A	Raw Mat * Supply	Tra *	Tra *	Cons *	H/C	Mai *	Repa *	Rep *	Tra *	Dem */Decon *	Lan *	Inc *	RC/RU
1		✓	✓				✓							
2	✓	✓	✓		✓		✓				✓			
3	✓		✓			✓	✓							
4	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓			✓
5	✓	✓	✓		✓			✓	✓				✓	✓
6	✓	✓			✓	✓							✓	✓
7	✓		✓									✓		
8														
9	✓	✓	✓							✓	✓	✓	✓	
10	✓		✓				✓		✓		✓	✓		
11	✓	✓	✓	✓			✓			✓	✓	✓		
12	✓											✓	✓	✓
13	✓	✓	✓		✓	✓								
14	✓	✓												
15	✓	✓			✓	✓					✓			
16	✓	✓	✓											
17	✓	✓	✓			✓				✓	✓	✓		
18	✓	✓												
19	✓	✓			✓	✓	✓							
20	✓		✓	✓	✓	✓	✓			✓	✓			
21	✓		✓			✓					✓			
22	✓	✓	✓				✓							
23	✓	✓	✓											
24	✓	✓	✓											
25					✓	✓	✓							
26	✓	✓			✓	✓	✓							
27	✓	-	✓			✓					✓			
28	✓	✓			✓	✓	✓							
29	✓	✓	✓											
30	✓		✓	✓	✓	✓	✓			✓	✓			
31	✓	✓	✓											
32	✓		✓	✓	✓	✓	✓			✓	✓			

Mat * A = Material acquisition; Mat * = Material; Tra * = Transportation; Cons * = Construction; H/C = Heating and Cooling; Mai * = Maintenance; Repa * = Repair; Rep * = Replacement; Dem * = Demolition; Decon * = Deconstruction; Lan * = Landfilling; Inc * = Incineration; RC = Recycle; RU = Reuse.

Like different system boundary variations in the research studies, the selection of midpoint impact can depend on the LCA goal. Life cycle impact assessment is also a part of the LCA method. LCIA is a phase in assessing possible environmental consequences that involve converting LCI data into specific impact indicators. LCIA must be carried out through a number of steps. The first step is to identify midpoint impact categories for analysis. The major impact categories are grouped into three general groups (ecosystem impact, human impact, and resource depletion impact). The second step is to categorize the LCI results based on their effect (classification). Finally, possible effect indicators are computed (characterization). These three stages are required for LCIA. More optional LCIA processes include relating the effect indicators to reference conditions (normalization), grouping, and weighing effects. The authors only focused on the midpoint impact categories. According to Table 5, although different impact assessment methodologies have varied mid-point impact categories, only a few researchers studied a diverse range of midpoint impacts [3]. Most studies focused on carbon emissions, followed by eutrophication, acidification, embodied energy and primary energy, and abiotic depletion [3,5,12–14,47,49,52]. Some articles discussed endpoint impacts such as human health, ecosystem quality, climate change, and resource availability [2,7,40,54]. Different LCA approaches, such as Impact 2002+, Eco-indicator 99, and TRACI, were used on the same timber material [2], but the midpoint impact was given as the normalized result. As a result, the authors did not utilize that midpoint impact in Table 5 for data consistency reasons.

Table 5. Midpoint environmental impact of the different articles.

Serial No.	CO_2	EE	PE	WF	AD	Acidi *	E	OLD	PO	ET	HT	FWET	MET	TET
1	✓													
2			✓											
3	✓		✓		✓	✓	✓	✓	✓		✓	✓	✓	✓
4	✓													
5	✓													
6	✓					✓	✓	✓			✓			
7	✓													
8														
9	✓					✓	✓	✓	✓					
10	✓													
11	✓													
12	✓		✓	✓										
13														
14	✓													
15	✓		✓											
16														
17	✓							✓						
18	✓	✓				✓								
19														
20	✓	✓				✓								
21	✓													✓
22	✓				✓	✓	✓	✓	✓		✓	✓	✓	✓
23	✓							✓	✓		✓			
24	✓													
25	✓													
26	✓													
27	✓													
28	✓				✓	✓	✓	✓	✓					
29	✓					✓	✓	✓	✓					
30	✓					✓	✓							

CO_2 = CO_2 100 (kg CO_2 eq./m^2); EE = Embodied energy (MJ/m^2); PE = Total primary energy (MJ/m^2); WF = Water footprint (L); AD = Abiotic Depletion (kg SBeq./m^2); Acidi * = Acidification (kg SO_2 eq./m^2); E = Eutrophication (Kg PO_4 eq./m^2); OLD = Ozone layer depletion (kg CFC 11 eq./m^2); PO = Photochemical oxidation (kg C_2H_4 eq./m^2); ET = Ecotoxicity (kg 1.4 DB eq./m^2); HT = Human toxicity (kg 1.4 DB eq./m^2); FWET = Fresh water ecotoxicity (kg 1.4 DB eq./m^2); MET = Marine ecotoxicity (kg 1.4 DB eq./m^2); TET = Terrestrial ecotoxicity (kg 1.4 DB eq./m^2).

3.2. Life Cycle Impact Comparison

To assess environmental impacts, researchers use different LCA methods. Different methods assess different types of midpoint impacts such as carbon emissions, water footprint, abiotic depletion, acidification, eutrophication, ozone layer depletion, photochemical oxidation, ecotoxicity, human toxicity, fresh water ecotoxicity, marine ecotoxicity, and terrestrial ecotoxicity. Although all researchers assess carbon emission, few researchers have discussed abiotic depletion, acidification, eutrophication, photochemical oxidation and energy use based on similar units. The detailed descriptions are explained in the following section.

3.2.1. Effect of Different Materials of a Timber Frame Wall on Global Warming Potential

Greenhouse gases are responsible for global warming. There are 207 greenhouse gases (carbon dioxide, methane, nitrous oxide, chlorofluorocarbon, and others), as mentioned in the ReCiPe LCA manual [55]. For global warming impact analysis, the effect of all GHGs is referred to as CO_2 equivalent. GHGs lead to an increase in the global mean temperature. These increased temperatures cause damage to health, terrestrial ecosystems, and freshwater ecosystems [33]. Timber wall production, construction, use, and end of life greatly impact global warming [11,56]. For timber wall production, timber is collected from the forest; then, it needs to be transported to the sawmill. For construction and use of timber wall, it requires electricity and fuel. GHGs are released into the environment at the end of life due to decomposition and incineration that causes global warming [11].

Although the authors primarily focused on wooden walls, the environmental impact varied due to various LCA methods and system boundaries. Researchers used different LCA methods such as TRACI, Impact 2002+ and Eco-indicator 99, and selected various goals and work scopes in these peer-reviewed publications. Different goals and scopes of work will have a major impact on carbon emissions. From Figures 4 and 5, the authors conclude that the carbon emission was significantly high (159.1–702 kg CO_2 eq./m^2) in some research articles [1,3–5,7,9,15,16,54]. Malaysian researchers investigated the usage of hardwood for timber frames [1,4,5,32]. Carbon emission generated from these timber frame structures was in the range of 95.65–702 kg CO_2 eq./m^2. During a previous study, the researchers gathered inventory data from books, journal articles, and manufacturers [1,4,5]. Recently, Malaysian academics have begun collecting data from the Malaysia lifecycle inventory database. After utilizing the new database, the carbon emission computation has been revised, yielding a reduced carbon emission result. The authors recognize that there are two factors responsible for high carbon emissions. For example, hardwood requires much energy to prepare, contributing to the environmental burden. Secondly, since Malaysia is a hot and humid nation, no insulation or heat-transfer material is employed contributing to GHG reduction. Suppose the wall frame does not include insulation, air and vapor barrier, exterior cladding, and interior board. In that case, it requires a significant amount of energy, which results in substantial carbon emissions during the usage phase. Another study found that wooden wall design employed wood with plasterboard [10]. Due to fewer parts used in the wooden wall design, it had limited control over air and heat flow, resulting in more energy throughout the usage stage of the building's life cycle. That carbon footprint (~363 kg CO_2 eq./m^2) was comparable to Malaysian house emissions.

A timber element with 2×4 untreated wood studs (conventional timber dimension in the US corresponding to a section of 38 mm by 89 mm) was utilized in another study [9]. This focused on a particular dwelling type known as a tiny house, ranging from 9 to 37 m^2 in size. This house received attention because of its lack of regulation, although its lifespan was shorter (30 years) than typical dwellings. The primary source of increased carbon emissions in this house was frequent disassembly. According to Figure 5, houses with fewer components release more carbon. As fewer elements were employed in this tiny home, it represents one of the core reasons for increased emission.

A peer-reviewed article studied two high-rise residential buildings (nine stories) [7]. Both structures were built of wood and concrete (hybrid construction). These two structures utilized additional materials, such as exterior timber cladding, wooden frames, glass wool insulation, and gypsum board. Both towers were made of a large quantity of concrete in construction structures (base, floor, and staircase), contributing to carbon emissions in the environment (227.3 kg CO_2 eq./m^2 for Tower A and 114.3 kg CO_2 eq./m^2 for Tower B). Cement is a major component of concrete manufacturing that directly and indirectly emits greenhouse gases. Calcium carbonate is the main ingredient of cement. During cement production, calcium carbonate becomes thermally decomposed, producing life and carbon dioxide. Coal-based fossil fuels also generate carbon during energy production [57–59]. Another research study concluded that one ton of cement is responsible for 900 kg of carbon emission into the environment [60].

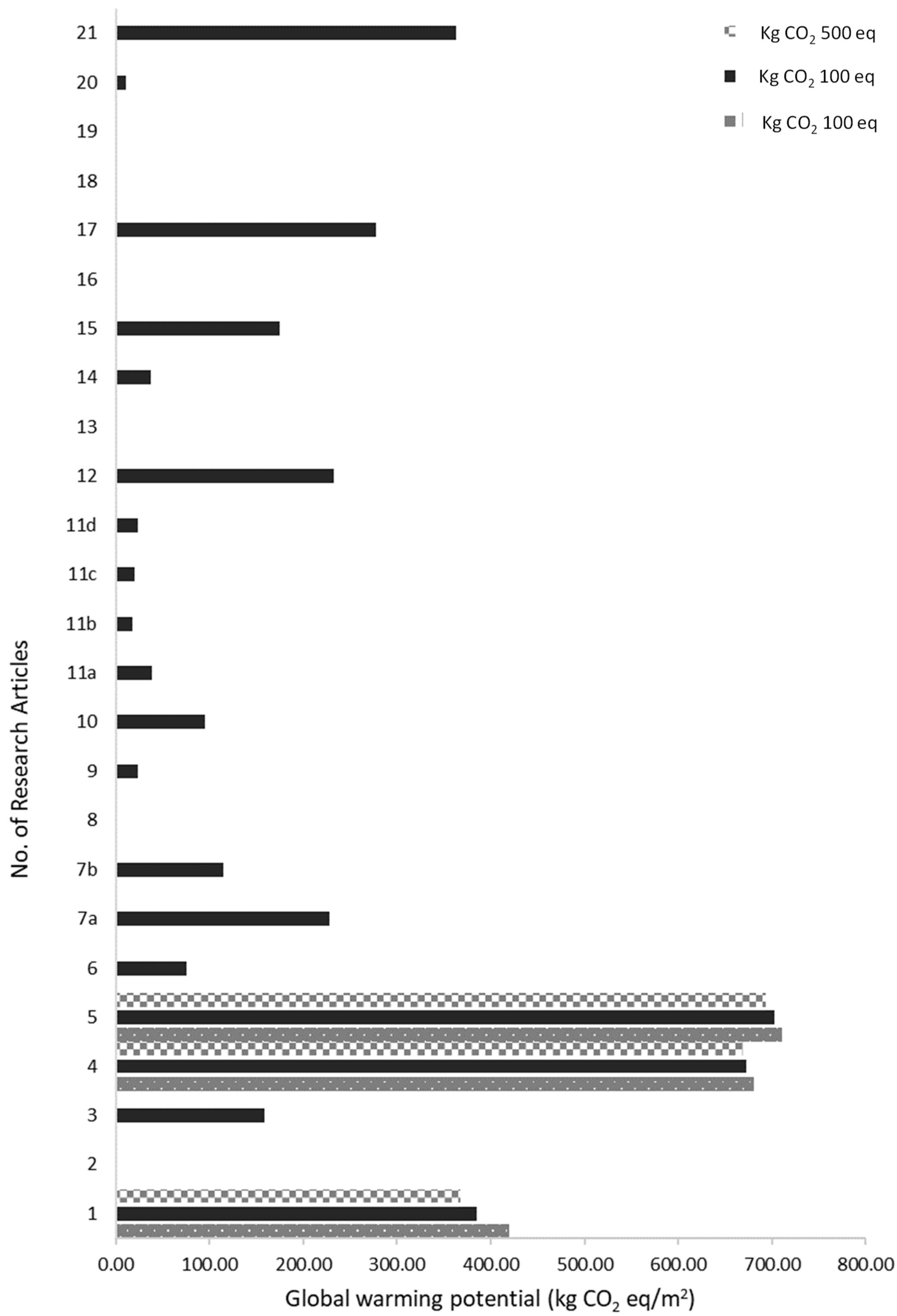

Figure 4. Impact of carbon emission in different research articles.

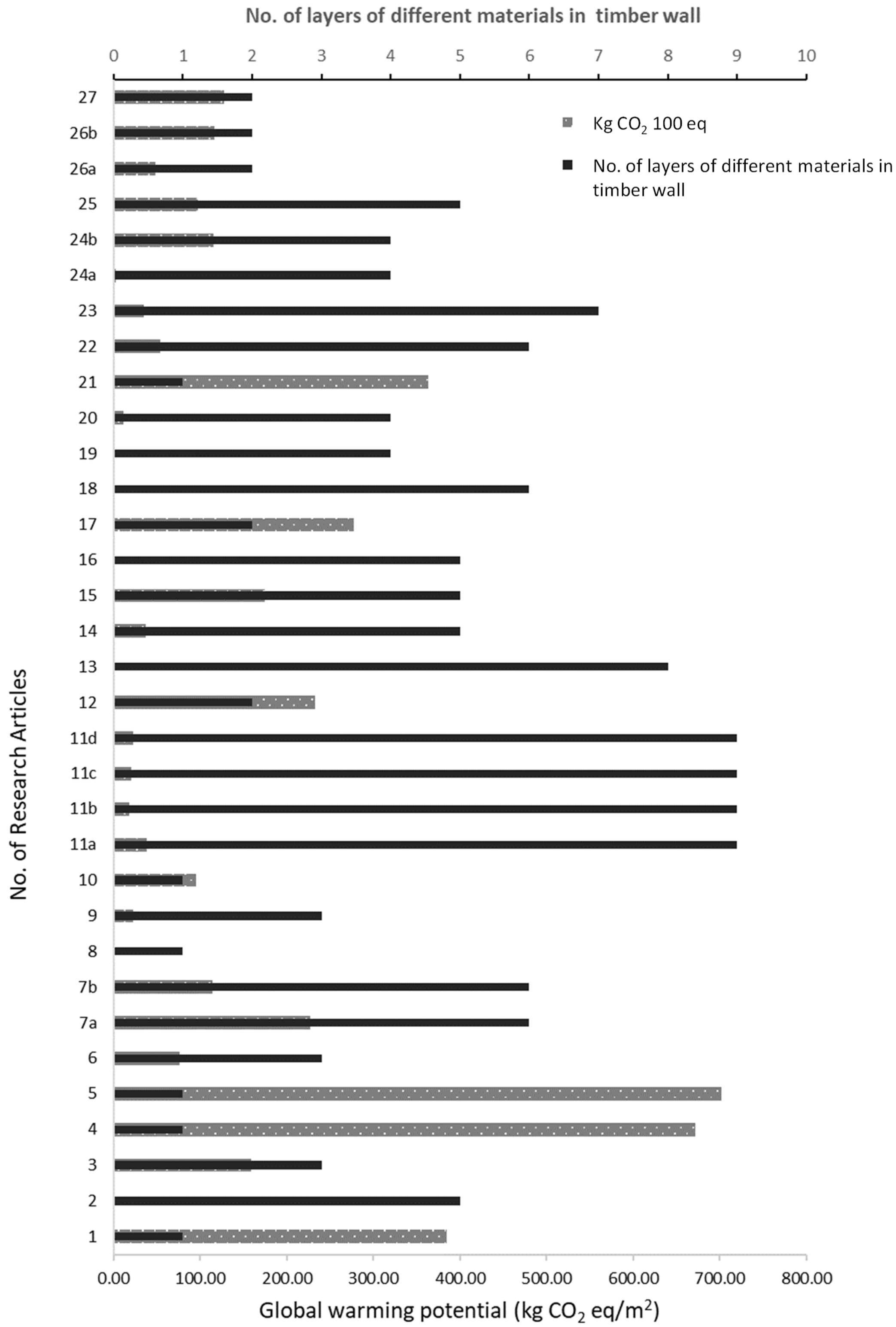

Figure 5. Impact of carbon emission (CO_2 kg eq./m^2) for different timber designs in different LCA studies.

Another study used a wood frame and cladding with 5-cm extruded polystyrene for the timber frame [3]. The carbon footprint of this house was 159.1 kg CO_2 eq./m^2. Similar carbon emission (112.49 kg CO_2 eq./m^2) was calculated for a CLT-based timber wall (with rock wool and silicate plaster) [61]. Insulation helps to limit heat and cold transmission, which may minimize energy usage during the operating stage, but it may also contribute to carbon emissions during the manufacturing stage. According to this study, extruded polystyrene emits more carbon than other types of insulation. Some researchers compared the carbon emission effect of different thermal mass walls from lightweight timber to concrete walls for 100 years (2000–2100). The results indicated that carbon emission percentage was lower during the early stage of the twenty-first century for heavier thermal mass than timber-frame walls. However, the difference will decrease during the later part of the century due to warmer climate conditions [62]. Although the combination of thermal mass and insulation can reduce heat transfer, leading to energy saving and lower GHG emission, additional insulation cannot save cooling energy but rather increases the cooling load. Another research study revealed that wall insulation was less effective in hot regions than cold regions [3]. Another study employed a wood frame with polyisocyanurate, which released significant CO_2 (277 kg CO_2 eq./m^2) due to the greater amount of energy required in the usage stage [15].

The same LCA technique is used with various wood products in Germany, Norway, France, and Sweden [38]. Although carbon emissions in Norway, France, and Sweden are almost identical (18 kg CO_2 eq./m^2, 20 kg CO_2 eq./m^2, and 23 kg CO_2 eq./m^2, respectively), Germany has a higher carbon emission (38 kg CO_2 eq./m^2) owing to the use of medium-density fiberboard. Similar carbon emission (43.5 kg CO_2 eq./m^2) for ventilated timber wall has been assessed by some researchers [13]. In this research, MDF was used as a timber wall element. Research has demonstrated that one constituent may boost carbon emissions by 10%. Research has also highlighted the significance of employing sustainable materials in the construction industry. The criteria for a wooden wall differ for exterior and interior walls. Some researchers concentrated on the inside wall, which does not control air or heat, but just regulates the movement of the sound [10]. As a result, this form of the interior wall requires fewer components in building construction, resulting in lower carbon emissions (11 kg CO_2 eq./m^2).

Some researchers further studied composite walls such as the concrete glulam framed panel (CGFP). They analyzed and calculated the greenhouse gas emissions and embodied energy of that composite wall and concluded that the panel had more negligible environmental impacts (60.63 kg CO_2 eq./m^2) than a similar study (363 kg CO_2 eq./m^2) [63]. The functional unit plays a significant role in the life cycle assessment study. The carbon emission (60.63 kg CO_2 eq./m^2) of that study was related to a 1 m^2 wall, whereas, in the supporting study, carbon emission (363 kg CO_2 eq./m^2) was related to 1 m^2 of floor [16].

Some researchers studied CLT building and compared them with masonry and reinforced concrete buildings. They concluded that CLT-based timber walls have less carbon impact (112.49 kg CO_2 eq./m^2) compared to M (152.17 kg CO_2 eq./m^2) and RC (121.21 kg CO_2 eq./m^2) buildings [61]. Researchers have also proven that using CLT building can reduce 9.22% (5.92 GtCO_2 eq.) of carbon emissions by 2060 [64]. Some researchers studied glulam and CLT panel application in 18-story buildings. The results indicated significantly less construction time (only ten weeks). The building mass was also 7648 tons lighter than the concrete building, suitable for the seismic zone. All these activities can reduce environmental impacts [31]. In another case study, glulam was used for column and beam, and a CLT panel with reinforced concrete was used in the slab area. Sixty per cent of the exterior wall was made of the glass curtain wall. Researchers applied two alternative designs for fire protection: the first one was "fireproofing design", where gypsum wallboard was used in the wall element; and the second one was "charring design", where an additional two layers of CLT were used in the floor panel. The results indicated that "charring design" was a better solution (328 kg CO_2 eq./m^2) compared to the "fireproofing design" (334 kg CO_2 eq./m^2) in respect to carbon emission [65]. A gypsum board was used in the "fireproofing design", and therefore it was responsible for significant carbon emissions because of a higher energy use. Higher energy use is responsible for greenhouse gas emissions. Renewable and non-renewable energy use are not directly proportional to greenhouse gas emissions. During manufacture, gypsum boards use ten times more energy than masonry (2167 MJ vs. 263 MJ), and release three times carbon compared to masonry [65]. The adhesive is another ingredient in gypsum board that significantly impacts the environment. In that study, the resin applied in the CLT panel construction had a lower impact on public health because it replaced formaldehyde with polyurethane and melamine. Formaldehyde has a carcinogen impact on human health, and formaldehyde-based resin requires a higher amount of energy than polyurethane [65]. In addition to gypsum board, oriented strand board and medium-density fiberboard are also responsible for global warming due to fossil fuel use for electricity production [13]. Researchers found that wood species used during the manufacture of CLT panels play an essential role in the impact assessment. Product weight is a factor in transportation. High-density wood is heavier than low-density wood, so a vehicle can carry less high-density wood than low-density wood. Although high-density species, such as Douglas-far, impact transportation, they can store more carbon per unit volume [65].

As adhesive has a negative impact on the environment, a new timber material wall named Massiv–Holz–Mauer (MHM) has been introduced made of fiberboard and aluminum nail. During these two elements, nitrous oxide and sulfur hexafluoride gas produced and contributed to global warming. Methane gas is also formed during electricity production from non-renewable sources [59].

In this review paper, the authors studied exterior timber walls. However, commercial buildings often use glass curtain walls (CW) as exterior walls. Glass curtain walls can maximize natural lighting, reducing energy use. They can also maximize solar heat gain during the winter season. Glass curtain wall consist of load-bearing mullions, along with glass. In an interesting research study, three mullion materials named aluminum, carbon steel and glulam timber were analyzed. This research indicated that despite the higher mass (9%) of glulam mullions compared to steel, glulam-integrated curtain wall was less responsible for carbon emission (92 $kgCO_2$ eq./m^2) than steel. The glulam has a lower contribution than aluminum and steel in acidification, eutrophication, and human toxicity [11]. Additional façade can increase the aesthetic design of the existing house and reduce heat transfer. Some researchers have named these instances as double skin façade [52]. By taking a cradle-to-gate system boundary, carbon emission for these timber walls is 127 $kgCO_2$ eq./m^2 [52]. Some researchers have compared timber–glass composite profiles (L shape vs. I shape) [56]. The L shape profile needs more material named as the compression-edge bond. The results indicated that L shape composite profile façade wall emitted 6.76 $kgCO_2$ eq./m^2 compared to the I shape composite façade wall 2.6 $kgCO_2$ eq./m^2 [56]. Although several researchers have studied timber–glass façade walls, carbon emission quantity has been found to be significantly different due to different system boundaries. Some researchers used cradle-to-grave, and others used cradle-to-gate system boundaries [11,56]. Another study also compared wood-based CW with aluminum-based CW and concluded that all environmental impacts such as GWP, ODP, AP, EP, POCP and PE are lower for wood-based curtain walls than aluminum-based curtain walls [24]. Some researchers used thermal efficient insulated glazing instead of normal glazing for transparent wall systems. They also used photovoltaic systems to generate electricity. This new panelized system is referred to as a residential glazed wall panel system. This panelized system requires an intense manufacturing process and the glass needs frequent cleaning and maintenance. The service life of frame coating is only 8 years. During the maintenance phase, this chemical treatment may have a strong influence on the environment. All these activities have an impact on the environment and are responsible for higher carbon emission (90,000 kg CO_2 eq.). The project life of this system is not mentioned clearly. By assuming a 50-year project life, this system is responsible for 625 $kgCO_2$ eq./m^2 carbon emission, whereas wood-frame walls and wood-frame walls with windows are responsible for 62.5 $kgCO_2$ eq./m^2 and 312.5 $kgCO_2$ eq./m^2, respectively [64]. This study gave us a clear idea about the impact of timber walls, timber walls with windows, and photovoltaic system-based insulated glass panels. Although research has shown that timber is less responsible for global warming, timber mullions are suitable for low-rise buildings, and steel is preferred for high-rise buildings [11,64].

Some researchers studied fast-growing bio-based materials such as straw or hemp for building construction. Although timber also uptakes carbon, it needs 40 years to mature, whereas straw or hemp require only one year to harvest. These materials can be used as thick insulation for exterior walls. In that study, the researcher used lime as a binding material to construct a hemp block responsible for significant carbon emissions. However, these materials require further research on large-scale use [63,65–67]. If building wall construction is 100% bio-based, it is assumed reduce 2% of global French radiative forcing [43]. Another case study also showed a similar result [53,58]. Researchers used wheat straw as insulation for a prefabricated timber-based element system [60]. Wheat straw needs one year to grow. This wall system can store 114.9 kgCO_2 eq./m^2 and it is responsible for 97.3 kgCO_2 eq./m^2 carbon emission during refurbishment of the system [58]. Other researchers compared timber walls with insulation such as wood fiberboards, loose fill, and hemp fiber with lime [68]. Timber walls with wood fiber board and loose fiberfill can store 20 kgCO_2 eq./m^2, whereas timber walls with hemp fiber can store 46 kgCO_2 eq./m^2 [53,68]. During the manufacturing of these timber walls, wood fiber board-based timber walls release 48 kgCO_2 eq./m^2, but hemp fiber lime-based timber walls release 117 kgCO_2 eq./m^2 [53].

Carbon emission for this timber wall was 35.23 kg CO_2 eq./m^2. The GWP would be zero if the electricity was generated from a hydropower source [51]. Carbon emission can be significantly lowered (2.52–4.4 kg CO_2 eq./m^2) by considering the energy source from hydropower or a renewable energy source [51]. By considering carbon storage, carbon emission for timber-based walls can be negative (−53.74 kg CO_2 eq./m^2) [18]. In that research, the cradle-to-gate system boundary was used. Inventory system and project life are important factor for the carbon emission calculation of timber wall. Some researchers compared the carbon impact of timber walls on different project years (50–300 years). Researchers proved that by extending building project life from 50 years to 100 years, carbon emission would reduce 50%, whereas this emission would be reduced to 83% if the project life extend to 300 years [40]. Researchers also compared carbon emission of wood by using the INIES database and Ecoinvent-KBOB database. The INIES database provides negative carbon emission for wood as it counts carbon storage in wood, but other databases provide positive carbon emission for wood. Here, researchers concluded that carbon emission for timber wall is only 3 kgCO_2 eq./m^2 using the INIES database, whereas carbon emission is 115 kgCO_2 eq./m^2 using the Ecoinvent-KBOB database [40]. The researchers also concluded that insulation has great thermal resistance. However, insulation and coating are responsible for 50% of the carbon emission of timber walls as they have short life spans: 50 years for insulation (glass wool) and 30 years for coating [40]. Some researchers assessed the influence of insulation on environmental impact, and the results indicated that cork insulation had a smaller negative impact than XPS, EPS, PUR, and rock wools [30].

Figure 4 depicts carbon emissions from three distinct perspectives: individualistic, hierarchical, and egalitarian. The individualistic perspective is founded on short-term impact, where impact types are indisputable. The view of hierarchies is based on the scientific consensus model in terms of the temporal frame. As is common in scientific models, this is often the default model. Baseline technology is employed in this view. Egalitarian thought is long-term and based on the precautionary principle. This perspective is for the most prolonged period, and all effect pathways for which impact data are available are utilized here. Although the time frames for these three viewpoints are vastly different, the amount of carbon emitted is in about the same range.

Figure 5 describes the relation between timber element design and carbon emission. In hot-region areas, timber wall is constructed of less material because heating and cooling is not as essential as in cold-region areas. So, in the construction stage, carbon emission is less, but during the building operation stage it needs more energy. Carbon emission is highest (702 kg CO_2 eq./m^2) when only one element (hardwood) is used to construct timber wall [1,4,5]. In cold-region areas, more insulation and other elements are used to manage heat transfer. Figure 5 indicates that where nine different elements are used to construct a timber wall, it can control heat transfer and requires less operational energy. As a result, operational carbon emission is also less (less than 50 kg CO_2 eq./m^2) [38].

The primary vertical axis represents the number of research articles. The primary horizontal axis represents the global warming potential reported in these articles, and the secondary horizontal axis represents the number of layers of timber frame materials.

3.2.2. Effect of Different Materials of a Timber Frame Wall on Photochemical Oxidation

Photochemical oxidation represents secondary air pollution, also known as summer smog. It is formed in the troposphere caused mainly by the reaction of sunlight to emissions from the combustion of fossil fuels (coal, petrol, or gasoline), creating other chemicals (e.g., ozone) [6]. Ozone is formed because of photochemical reactions of NOx and non-methane volatile organic compounds (NMVOCs). Ozone can be inhaled by the human population and taken up by the plant. Ozone inhalation can inflame the airways and the damage lungs, which causes respiratory distress in humans, such as asthma and chronic obstructive pulmonary diseases [55]. Additionally, ozone negatively impacts plants and vegetation, including reducing growth, seed production, ability to withstand stressors, and the acceleration of leaf senescence [55]. Human uptake of ozone increases mortality rate, whereas plant uptake of ozone leads to the disappearance of plant species. Fossil fuels are widely used in building construction, such as raw material extraction, production, building construction, use, and end of life.

In Figure 6, the first five timber walls (P1–P5) are made of maritime pine [13]. There are three main ingredients of those timber walls: timber, adhesive, and insulation. Timber manufacturing requires logging, reforesting, debarking, sawing, and transportation. All these activities require energy that comes from fossil fuels. There is no information available regarding the manufacturing process in the first sample (wood frame with extruded polystyrene), such as adhesive. In contrast, other timber frames used a two-component polyurethane adhesive with a spread rate of 140 g/m^2 per glue line [3]. The application, press and curing processes of adhesive require a significant amount of energy, which has an adverse impact on photochemical oxidation. Different insulations have been used, such as polyurethane (PUR), insulated corkboard (ICB), rock wool (RW), and extruded polystyrene [3,40]. The reaction between isocyanates and polyols produces polyurethane (PUR). Different elements such as expansion gases, HFC, CO_2, or C_6H_{12} are used to fill the closed pores during the expansion process [33]. Cork thermal insulation is made of cork oak, and it can be produced as a filler material or board. Rock wool is produced from melting stone (diabase, dolerite) at a temperature around 1400 °C. Abatement oil and phenolic resin are also added to produce rock wool to bind the fibers together and improve the product properties. Extruded polystyrene (XPS) is produced from melted polystyrene (from crude oil). Different gases, e.g., HFC, CO_2, or C_6H_{12} are used to fill the closed pores during the expansion process. This information concludes that timber wall manufacture significantly impacts photochemical oxidation. Extruded polystyrene has the highest impact on photochemical oxidation, followed by ICB [33].

Although a service life of 50 years has been assumed for all timber walls, no refurbishment was considered for cross-insulated timber (CIT) and cross-laminated timber (CLT) walls. The last sample, P9, (wood frame with extruded polystyrene) included maintenance activities such as painting the interior and exterior walls, varnishing a wood surface, glazing a window, and fixing the bitumen layer. This maintenance phase adds an extra environmental burden. Researchers did not consider the construction process, use stage and deconstruction process for CIT and CLT walls. On the contrary, researchers included the heating and cooling system in the first sample (wood frame with extruded polystyrene). The building use phase is considerably longer than any other phase, and it requires much energy for heating and cooling systems. This energy comes from fossil fuels, having an impact on photochemical oxidation.

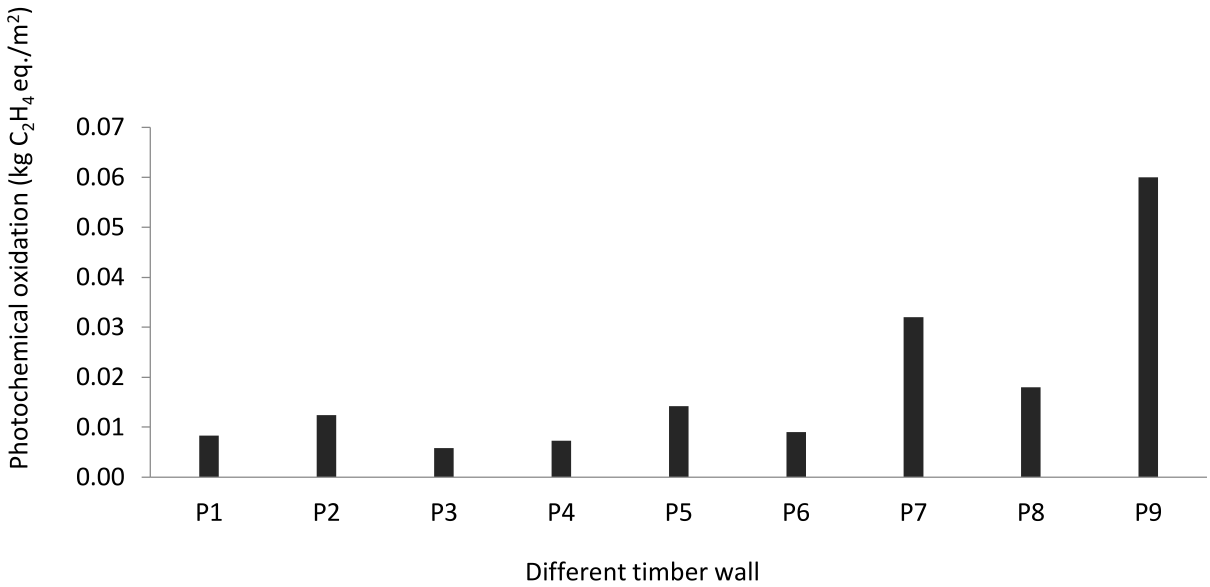

Figure 6. Comparison of the wall assemblies for photochemical oxidation (kg C_2H_4 eq./m^2).

Only manufacturing and end-of-life phases are considered during the environmental impact calculation of cross-insulated timber and cross-laminated timber, whereas full life cycle assessment (material production, transportation, maintenance, heating, and cooling process) except for end-of-life has been completed for wood frames with extruded polystyrene (Table 6). End of life was not considered in that study because this phase comprises less than 3.2% of the environmental impacts of south European dwellings [3]. Among all building phases, only the end-of-life phase can positively impact the environment, as proven in the research [3]. All CIT and CLT walls were sent for either incineration or landfill with an energy recovery model in that research. The researchers concluded that electricity would be produced from both processes, positively impacting the environment. A substantial part of the gases can contribute to global warming at the end-of-life stage in parallel to energy recovery. In addition to all building phases, transportation is the integrated part of all building construction activities. Transportation requires a significant amount of fossil fuel which negatively impacts photochemical oxidation.

Table 6. List of timber walls with photochemical oxidation.

P1	CIT and PUR
P2	CIT and ICB
P3	CLT and RW
P4	CLT and XPS
P5	CLT and ICB
P6	External plaster 8 mm, external thermal insulation 100 mm, HDF 15 mm, timber frame and mineral insulation 140 mm, OSB 315 mm, battens and insulation 40 mm, plasterboard 12.5 mm.
P7	Plasterboard, 9-layer spruce board, geotextile, fiberboard, mortar, plaster mesh, plaster.
P8	OSB, MDF, wooden sheet, metal pieces, plastic pieces, fiber (rock wool, gypsum-fiber sheet and polyester resin).
P9	Wood frame and cladding with extruded polystyrene.

Some researchers assessed timber walls (P6, P7) with cradle-to-gate system boundaries [29,59]. The results indicated that P6 timber wall was less (0.009 kg C_2H_4 eq./m^2) responsible for photochemical oxidation formation than P7 (0.032 kg C_2H_4 eq./m^2). P8 timber wall was also responsible for high emission (0.018 kg C_2H_4 eq./m^2) because of additional timber elements such as OSB, MDF and others [40]. Photochemical oxidation impact was considerably high for the P9 timber wall (wood frames with extruded polystyrene) compared to the other timber walls. Researchers considered every phase, such as construction (material production and transportation) and use phase (maintenance, heating, and cooling processes) for the environmental impact assessment. All these activities impact the environment, and the environmental impact of other timber walls could be high if the researchers considered the construction and use phases.

3.2.3. Effect of Different Materials of a Timber Frame Wall on Eutrophication

Without human interference, eutrophication is a prolonged natural process in which nutrients (phosphorus compounds and organic matter) accumulate in water bodies. These nutrients derive from the degradation and solution of minerals in rocks and by the effect of lichens and fungi actively scavenging nutrients from rocks [69]. At present, the nutrient accumulation rate has increased. These excess nutrients, such as phosphorus and nitrogen, have an impact on the environment called eutrophication. The visible effect of eutrophication is often a nuisance of algal blooms that can cause substantial ecological degradation in the water body and in streams flowing from that water body. The process may result in oxygen depletion of the water body after the bacterial degradation of the algae. Oxygen depletion causes fish and invertebrates to disappear [62]. There are three different types of eutrophication, e.g., freshwater eutrophication, marine eutrophication, and terrestrial eutrophication [55]. Extra nutrients are found in freshwater due to washing from plantation areas. Later, these get mixed with the water body, subsequently raising the nutrient level [4,55]. Marine waterbodies can also affect eutrophication because of dissolved inorganic nitrogen transfers from the soil and freshwater bodies directly into marine water [12]. Terrestrial ecosystems are subject to similarly adverse impacts from eutrophication.

Increased nitrates in soil are frequently undesirable for plants. Ecosystems receiving more nitrogen than the plants require are called nitrogen saturated. Saturated terrestrial ecosystems can then contribute inorganic and organic nitrogen to freshwater, coastal, and marine eutrophication, where nitrogen is also typically a limiting nutrient. This phenomenon is also the case with increased levels of phosphorus. However, because phosphorus is generally much less soluble than nitrogen, it is leached from the soil much slower than nitrogen. Consequently, phosphorus is much more important as a limiting nutrient in aquatic systems.

During wood production, fertilizer is used for all timber walls, which is responsible for eutrophication. In addition, formaldehyde-based compounds are used as a binder that impacts acidification [38]. During the use phase, heating and electricity production release a significant amount of nitrate and ammonia, responsible for marine eutrophication [53]. Researchers analyzed the impact of the wood frame with extruded polystyrene for each significant building phase, including construction, material production, transportation, maintenance, and use phase (Table 7). So, Figure 7 indicates that the eutrophication impact was significantly high for the timber wall with extruded polystyrene (0.148 $kgPO_4$ eq./m^2) [3]. In addition, the end-of-life phase, the landfill of timber, and insulation also have a negative impact on eutrophication. Other timber materials have a relatively lesser (0.016–0.059 $kgPO_4$ eq./m^2) impact on the environment, due to cradle-to-gate system boundary limitations [29,38–40].

Table 7. List of timber walls with eutrophication.

E1	CIT and PUR
E2	CIT and ICB
E3	CLT and RW
E4	CLT and XPS
E5	CLT and ICB
E6	External plaster 8 mm, external thermal insulation 100 mm, HDF 15 MM, timber frame and mineral insulation 140 mm, OSB 315 MM, battens and insulation 40 mm, plasterboard 12.5 mm
E7	OSB, MDF, wooden sheet, metal pieces, plastic pieces, fiber (rock wool, gypsum-fiber sheet and polyester resin)
E8	Wood frame and cladding with extruded polystyrene

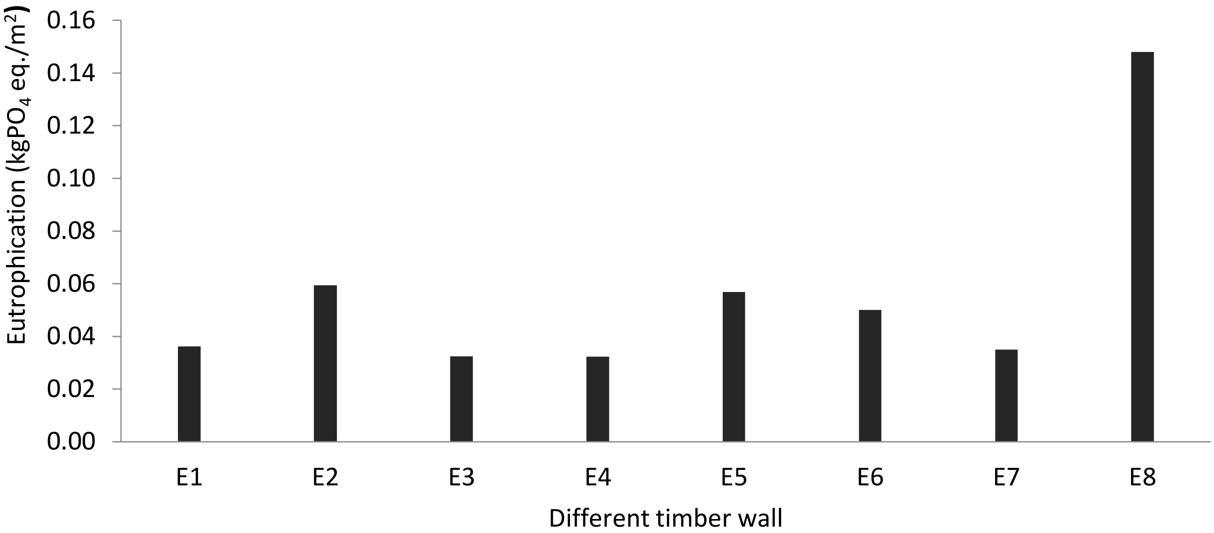

Figure 7. Comparison of the wall assemblies for eutrophication (kg PO_4 eq./m^2).

3.2.4. Effect of Different Materials of a Timber Frame Wall on Abiotic Depletion

About 30–40% of natural resources are used in construction [8,11,14]. Resources can be divided into biotic resources (wood, fish) and abiotic resources (mineral resources, such as metals; bulk materials, such as sand, gravel, lime; and energy resources, such as fossil fuels) [5,70,71]. Abiotic resources are not renewable, indicating that the resource's consumption is significantly faster than natural systems can replenish them. As a result, due to the utilization of abiotic resources, the number of resources will reduce every year, thereby taking more energy to extract them. The increase in fossil fuel extraction causes extra costs due to the production techniques or sourcing from a costlier location. For example, when easily accessible oil is depleted, alternative techniques, such as enhanced oil recovery, will be applied, or oil will be collected from an alternative location, such as the Arctic regions, with higher costs and technology. All these activities need more energy, leading to greater abiotic depletion [55]. Additionally, mineral resource extraction leads to an overall decrease in ore grade, which will increase ore production [55]. Resource depletion of fossils and minerals is caused by each building construction phase, namely the production, construction, use, and end-of-life phase.

Additionally, transportation is an integral part of every phase which requires fossil fuel. During the end-of-life stage, incineration has the most impact on abiotic depletion. Figure 8 shows a wooden frame with extruded polystyrene, ventilated wooden wall, cross-insulated timber, and cross-laminated timber [3,38,40]. The cross-insulated timber and cross-laminated timber used different insulation, and ICB insulation required more abiotic resources than ICB, RW, PUR, and XPS [38]. The ventilated timber wall consisted of OSB, MDF, wooden sheet and fibers responsible for abiotic depletion [40]. The project life for a wooden frame with extruded polystyrene material is 50 years. Its environmental impact has been assessed for different life cycle stages such as manufacture, construction, use, and maintenance. All stages impose an additional impact on that material, whereas only material manufacture and the end-of-life stage are considered for impact analysis for cross-insulated timber and cross-laminated timber. As the use phase of a building requires a significant amount of fossil fuel to generate energy and heat, this phase greatly impacts the environment. If the researchers include the use phase for cross-insulated timber and cross-laminated timber, the environmental impact could be significantly higher for those timber walls. At present, abiotic depletion for timber walls with extruded polystyrene is significantly high (1.65 kg Sb eq./m^2), compared to other walls (0.0134–0.99 kg Sb eq./m^2).

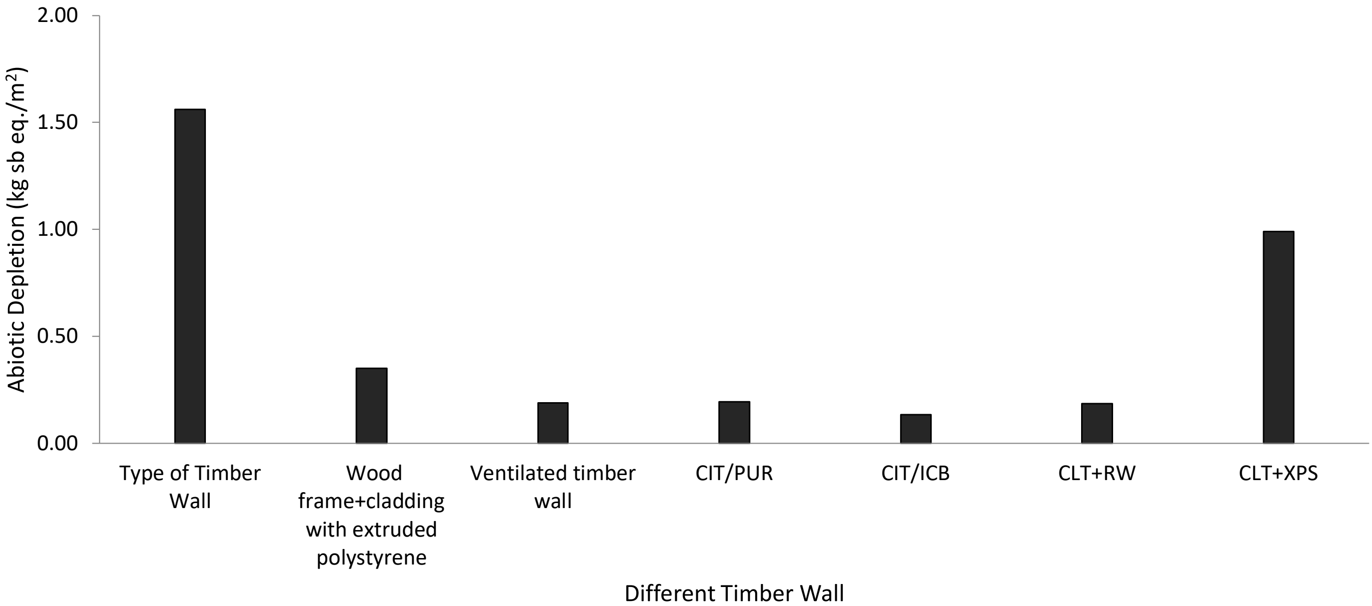

Figure 8. Comparison of the case study of wall assemblies for abiotic depletion (kg sb eq./m^2). CIT = Cross-insulated timber, CLT = Cross-laminated timber.

3.2.5. Effect of Different Materials of a Timber Frame Wall on Acidification

Acidification is caused by the atmospheric deposition of inorganic substances, such as sulphates, nitrates, and phosphates, that change the acidity of soil and water. Subsequently, these will leach into the soil and change the H+ concentration of the soil solution. There is an optimum level of acidity in all plant species. Deviation from this optimum level is harmful to specific kinds of species, causes them to disappear. The primary acidification emissions are NOx, NH_3, or SO_2 [55]. Raw material extraction (wood processing) has a comparatively smaller impact than the use phase, the production of the heating system (radiators, tubes, and heating pump), and the electricity generator. Acidification is the primary cause of air pollution and forest destruction. Air pollution is also responsible for human toxicity cancer. Fossil fuels in building construction are responsible for air pollution because burning fuel releases nitrogen oxide (NO_x) and sulfur dioxide (SO_2) into the air. Building construction requires fossil fuel during the raw material extraction and use phase. Transportation is integrated into building construction (raw material acquisition, production, building construction, and end of life), and this also needs fossil fuel. The application of fertilizer in the plantation is also responsible for acidification [30].

Table 8 is the list of timber wall elements. Wood frames and cladding with extruded polystyrene have been assessed for a fifty-year lifetime, impacting the manufacturing, construction, transportation, maintenance, and use phases. Acidification impact for this timber wall is 0.91 kgSO_2 eq./m^2 [3]. In comparison, other exterior timber walls have less impact (0.132–0.31 kgSO_2 eq./m^2), as those materials have no impact on the use and maintenance phase (Figure 9) [9,38,40]. The acidification impact for interior wall is 0.17 kgSO_2 eq./m^2, which is comparatively less, although it was assessed by the cradle-to-grave system boundary [10]. The impact is low because no insulation has been used in that interior wall.

Table 8. List of timber walls with acidification.

A1	CIT and PUR
A2	CIT and ICB
A3	CLT and RW
A4	CLT and XPS
A5	CLT and ICB
A6	External plaster 8 mm, external thermal insulation 100 mm, HDF 15 MM, timber frame and mineral insulation 140 mm, OSB 315 MM, battens and insulation 40 mm, plasterboard 12.5 mm
A7	OSB, MDF, wooden sheet, metal pieces, plastic pieces, fiber (rock wool, gypsum-fiber sheet and polyester resin)
A8	Wood frame and cladding with extruded polystyrene
A9	Timber wall with plaster board

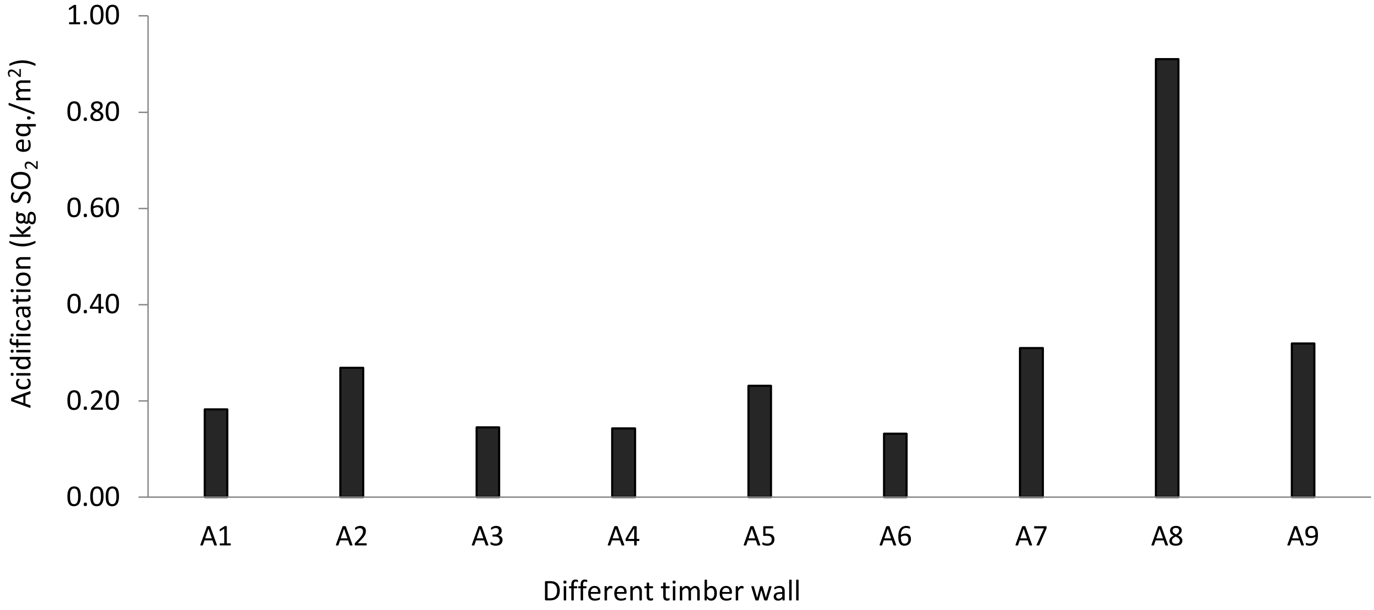

Figure 9. Comparison of the case study of wall assemblies for acidification (kg SO_2 eq./m^2).

3.2.6. Effect of Different Materials of a Timber Frame Wall on Primary Energy

Primary energy is the total energy required to produce a product or structure, including all fuel inputs and losses along the supply chain. The primary energy use in the building construction mainly depends on the processes in the energy supply systems for heat and electricity. The energy-efficient process has a significant impact to determine the primary energy use for the operational phase and the total life cycle. Energy resource selection is also important, as fuel results in GHG emissions [43].

Table 9 shows that T1 and T2 are similar materials (2 × 4 untreated wood stud with fiberglass batt insulation). However, T1 material was assessed with the hybrid LCA technique while T2 was assessed by process-based LCA [9]. Process-based LCA is a bottom-up LCI approach that uses industrial process-based LCI data within a product's life cycle. In contrast, hybrid LCA is the combination of an input–output model and process-based LCA. A hybrid approach was applied to extract and manufacture wood frames and process-based LCA for the remaining phase. Primary energy use depends on the system boundary. As the hybrid approach includes an input–output model also, this additional activity requires more primary energy.

Table 9. List of timber walls with primary energy.

T1	2 × 4 untreated wood studs (traditional lumber dimension in the US equivalent to a section of 38 mm by 89 mm) with fiberglass batt insulation.
T2	2 × 4 untreated wood studs (traditional lumber dimension in the US equivalent to a section of 38 mm by 89 mm) with fiberglass batt insulation.
T3	Traditional wood 0.05 × 0.1 m by 0.4 m (2 × 6 16oc)
T4	Traditional wood 0.05 × 0.15 m by 0.6 m (2 × 6 16oc)
T5	External plaster 8 mm, external thermal insulation 100 mm, HDF 15 mm, timber frame and mineral insulation 140 mm, OSB 315 mm, battens and insulation 40 mm, plasterboard 12.5 mm
T6	Traditional wood

Consequently, T1 (630 MJ/m^2) requires higher primary energy than T2 (514 MJ/m^2). For timber production, primary energy is required for logging, reforesting, debarking, sawing, and transportation. Glass wool is produced from borosilicate glass at about 1400 °C, where the heated mass is pulled through rotating nozzles that create fiber. Wood dust abatement oil and phenolic resin are used to bind the fibers together and improve product properties [33]. T3 and T4 timber walls are made of traditional wood [54]. In this assessment, the researchers used a cradle-to-grave system boundary. Every phase of the timber wall was assessed, requiring higher primary energy (1403–1411 MJ/m^2). The cradle-to-gate system boundary was taken during the energy impact assessment of the timber wall (T5) by the researcher [29]. As its system boundary was less than compared to T3 and T3, primary energy requirement was low (see Figure 10) [33,54]. Although the cradle-to-grave system boundary was chosen by the researcher during the T6 timber wall assessment, primary consumption was significantly low. Timber wall elements were not clearly indicated in that study, which could be a reason for this lower energy consumption.

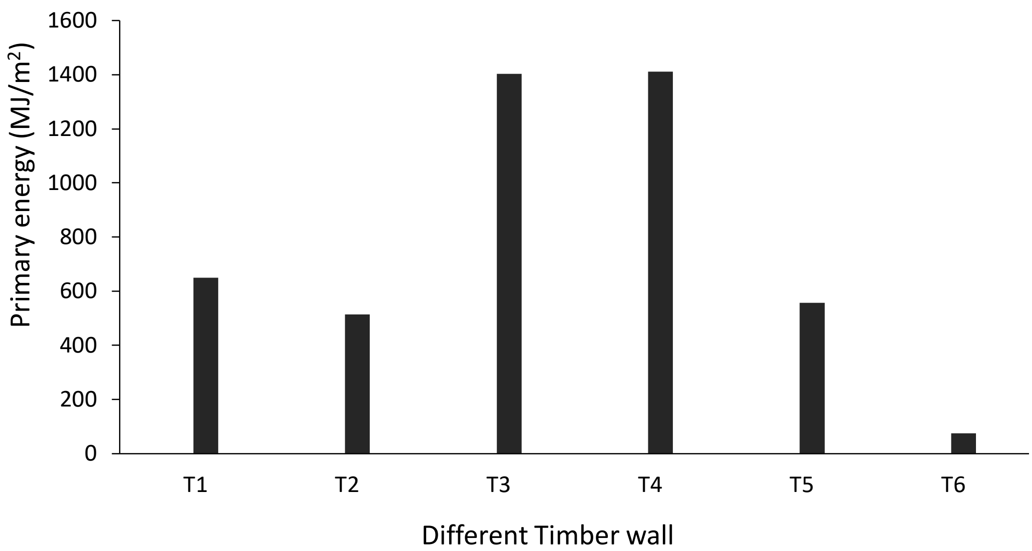

Figure 10. Comparison of the case study of wall assemblies for primary energy (MJ/m^2).

3.2.7. Effect of Different Materials of a Timber Frame Wall on Embodied Energy

Embodied energy is the summation of all energy required for raw material extraction, manufacture, construction, repair and maintenance, and end-of-life [54]. Primary energy is specially used in the building use phase for heating and cooling. All these energy activities impact GHG emission [43]. In Table 10, EE1–EE5 are external walls of a two-storied residential house in a cold-region area [44]. Researchers compared the embodied energy consumption of these walls. Energy consumption varied between 780 and 1138.5 MJ/m^2 [44]. EE6–EE11 timber walls were external walls only, and EE12 was an internal wall only [10,53]. The external wall was made of timber member with plaster, wood member, insulation for heat protection, and others. In contrast, the internal wall (EE12) was made of wood and plasterboard only, and the internal wall was not constructed from heat protection. So generally, no insulation was required for the internal walls. Figure 11 illustrates that the embodied energy requirements were significantly higher (346.476–932.107 MJ/m^2) for the exterior wall compared to the interior wall (119 MJ/m^2) due to the additional wall elements.

Table 10. List of timber walls with embodied energy.

EE1	Vinyl siding, OSB, batt insulation, gypsum board
EE2	Vinyl siding, OSB, batt insulation, gypsum board, wood stud
EE3	Vinyl siding, OSB, insulation, OSB, gypsum board
EE4	Vinyl siding, OSB, insulation, OSB, gypsum board
EE5	Vinyl siding, OSB, insulation, gypsum board, wood stud.
EE6	Plaster, insulation, insulation, wood paneling
EE7	Wood boarding-larch, insulation, I-joists, OBS, gypsum-fiberboard
EE8	Wood boarding-larch, fiberboard, I-joists SW60, OSB, bricks, Loam plaster.
EE9	Wood boarding-larch, OSB board, insulation, wooden I-joists, CLT, gypsum-fiberboard.
EE10	Wood boarding-larch, fiberboard, wooden I-joists, wood massive panel, loam plaster
EE11	Wood boarding-larch, insulation, wooden box beams, OSB 3 board, insulation, plasterboard
EE12	Studs, plasterboard on both sides and a latex cardboard layer placed on the plasterboard

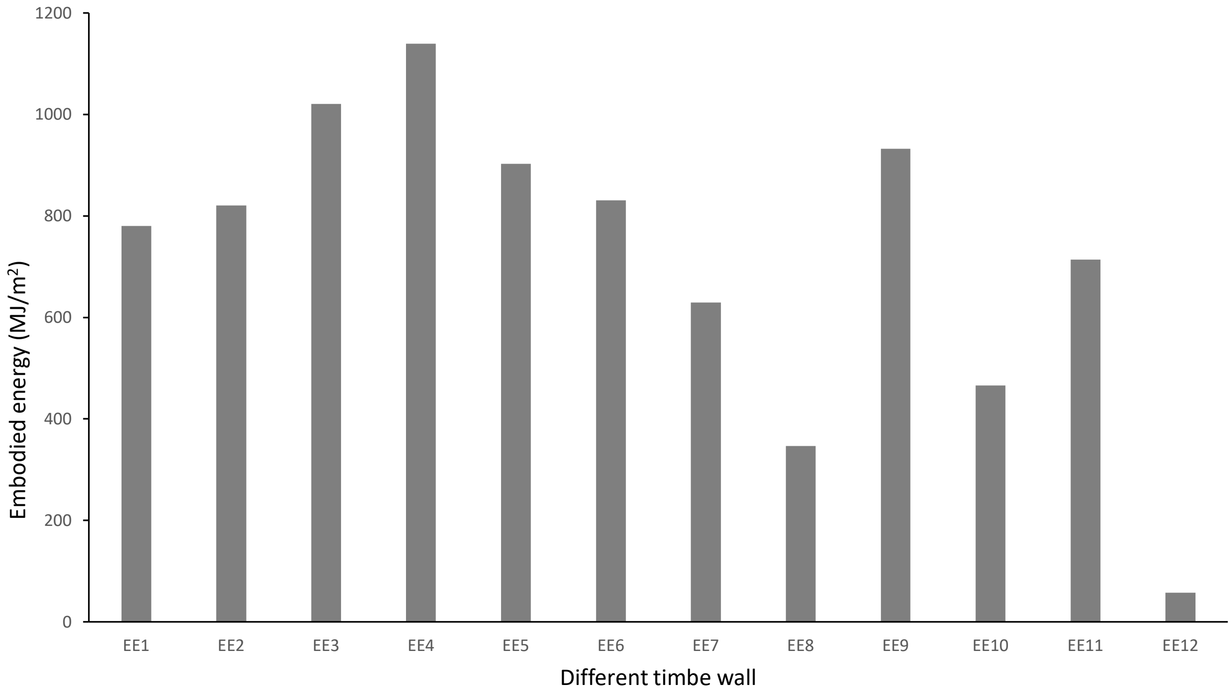

Figure 11. Comparison of the case study of wall assemblies for embodied energy (MJ/m^2).

Author compared several midpoint impacts and energy use for timber wall construction in this section. More reliable and uniform results can be achieved by standard material manufacture, construction methods, suitable timber elements and other element (insulation) selection, standard deconstruction, recycled and reused methods, efficient energy sources, and transportation modes.

In building construction, different timber and timber-based materials are used for structural and non-structural reasons. Sustainable adhesive insulation use can reduce the impact significantly. Standard timber material manufacturing processes need to be formalized to help decide suitable material selection. The circular economy concept is integrated with LCA assessment and the cradle-to-cradle method. Standard deconstruction methods, timber recycling and reuse can contribute to a circular economy. Timber deconstruction is possible through proper documentation of the material and the process for deconstruction, the design of accessible connections to ease dismantling, the separation of non-recycle, non-reusable, and non-disposal components, the standardization of components and dimensions, and design that reflects labor practices, productivity, and safety. A new technique is required for the disassembly of building elements. Timber can be recycled easily, but paint, adhesive, and other chemical use can hinder the recycling process. Structural timber elements can be reused depending on their integrity. Different wood-based materials such as particleboard, wood fiber, and wood-laminating board can be manufactured by recycling wood waste. The incineration of wood is the last step of energy recovery from wood. As wood can store carbon, using wood as fuel will release that carbon. So, no added impact will be considered for this action. All these recycling and reuse activity processes can reduce environmental impact and contribute to a circular economy. Material transport depends on geographic location and mode of transportation. In addition to these initiatives, transportation modes and energy sources can reduce environmental impacts. There are three different modes of material delivery: road, train, and shipping. Shipping transportation requires lower embodied energy and carbon emission. Renewable energy sources such as hydraulic power generation have the most negligible impact on the environment compared to other energy sources. All the above information can be used as guidelines for the future LCA practitioner.

4. Limitations

There are some limitations to this review methodology. The main reasons for this are: (1) as our search was carried out only in the English language, all the manuscripts in languages other than English were avoided; (2) some articles were automatically ignored as the title of those articles was not related to LCA application in buildings, though the content was strongly focused on LCA application in the building industry; (3) the choice of keywords might also have affected the literature search procedure and skipped some relevant studies. For example, using the word "life cycle" instead of "life-cycle" in the search keywords unintentionally omitted articles which were entitled with or included this comment. (4) The interpretation of the findings of the existing studies, as well as the authors' knowledge in this field, could be another source of limitation. (5) The functional unit was m^2 but most of the researchers did not mention this clearly. Some functional units of m^2 referred to floor, while some referred to walls. (6) Some researchers solely focused on timber walls only, whereas some researchers assessed timber walls within a composite building. (7) Project life: the project life of a building can vary depending on the integrity of the building materials. If project life is long, a timber-wall-integrated house can store carbon for longer. This also prevents new building materials from being manufactured. However, if more repair and maintenance is needed, this impacts the environment. Lower project life causes new materials to be frequently manufactured for new building construction. Standard project life is vital to compare these impacts and make a decision. In these research papers, researchers chose different project lives, between 30 and 100 years, which hindered proper comparison. (8) Materials of the timber walls: although some researchers used only hardwood in the timber walls, most of them used different elements such as wall cladding vapor barrier, insulation, timber-based materials, and timber materials. All these materials varied with different types and thicknesses. A number of materials used in the timber walls had a significant impact on the environment. Using fewer materials in timber walls can decrease embodied energy use, but increases operational energy use. So, total carbon emission will be higher the less material is used in the timber wall. This complexity is a significant limitation for impact comparison. (9) System boundaries: there are four stages in building life, the product stage, construction stage, use stage, and end-of-life stage. Although all the researchers considered the product and construction stage to calculate the environmental impact and energy use, other stages were mostly neglected. Some researchers considered all of the stages for impact calculation. There were different activities in the use stage such as heating and cooling, maintenance, repair, replacement, and transportation. Most researchers considered only heating, cooling, and maintenance for impact calculation by most researchers. All the activities are responsible for environmental impact, so consistency is required for impact comparison. (10) Standard database: although most of the researchers used the Ecoinvent database, some researchers used a national database or a local database. Different databases use different methods for impact analysis. So, use of various databases can limit the impact of comparison assessments.

5. Conclusions and Future Research

There were two literature gaps identified in this review paper. The first gap was a standard benchmark of LCA results, and another gap was standard guidelines for researchers to follow for proper impact comparison and to improve LCA results without bias. Among 1588 peer-reviewed articles, altogether 32 academic articles have been summarized in this review, and the environmental impacts of carbon emission, acidification, eutrophication, abiotic depletion, and energy use have been analyzed. Carbon emission can vary between 18–227 kg CO_2 eq./m^2 and 60.63–334 kg CO_2 eq./m^2 for timber wall only and hybrid timber wall (timber with concrete finish), respectively [28,51]. Carbon emission can be significantly less (3 kg CO_2 eq./m^2), and negative carbon emissions are also possible depends on biogenic carbon storage. When researchers considered only the manufacturing stage for carbon emission impact, carbon storage was higher than carbon emission. If those researchers calculated carbon emission for each building phase, carbon emission would be negative, matching other researchers' assessments. Environmental impacts of photochemical oxidation, eutrophication, abiotic depletion, and acidification can vary between 0.009–0.32 kg C_2H_4 eq./m^2, 0.03–0.15 kg PO_4 eq./m^2, 0.13–1.56 kg Sb eq./m^2 and 0.13–0.91 kg SO_2 eq./m^2, respectively. Primary energy and embodied energy use can vary between 75–144 MJ/m^2 and 57.16–932.11 MJ/m^2.

Environmental impacts and energy use vary due to different LCA methods, system boundaries, databases, project life, energy source, and material manufacturing processes. Most of the researchers assessed the environmental impacts of the low-rise residential building. Very few researchers focused on high-rise commercial buildings. Significant amounts of materials and energy are required for high-rise commercial buildings. So, more research is needed in this field to achieve sustainable building construction.

Although the authors have tried to resolve the uncertainties of the LCA results to help to predict LCA outcome, more detailed studies are required to achieve reliable results. Use of standard project life, inventory data, and broad system boundaries can reduce the results of the LCA method. The BIM-integrated LCA method can help sustainable material selection that can reduce environmental impact in the early stages of building construction. It is a straightforward method to analyze the emissions and energy consumption of building components at each stage of construction. Reused and recycled timber materials during the maintenance stage and the new building construction stage can integrate building materials with the circular economy and reduce environmental impact significantly. Further study is needed to assess the impact of the operational stage and the end-of-life stage, including additional environmental impact indicators.

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Nomenclature

LCA	life cycle assessment
CED	cumulative energy demand
LCIA	life cycle impact assessment
EPD	environmental product declaration
CLT	cross-laminated timber
EPS	expanded polystyrene insulation
CIT	cross insulated timber
XPS	extruded polystyrene insulation
LVL	laminated strand lumber
PE	primary energy
OSB	oriented strand board
ISO	international organization for standardization
GWP	global warming potential
IPCC	international panel on climate change
EE	embodied energy
EI'99	eco-indicator 99
EDP	ecosystem damage potential
DALY	disability-adjusted life years
VOCs	volatile organic compounds
EoL	end of life
MCDA	multi-criterion decision analysis
PUR	polyurethane rigid foam
LCI	life cycle inventory
ICB	insulated cork board

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