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Review

Timber Construction as a Solution to Climate Change: A Systematic Literature Review

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Abstract: The built environment significantly contributes to climate change. There is pressure on the construction industry to find and use alternative sustainable environmentally friendly building materials to reduce the climate impact. Timber is increasingly being considered in the literature and used as a viable alternative for steel and concrete in both residential and non-residential building projects as it is a renewable material and has multiple benefits for reducing carbon (CO_2) emissions and consequently climate change. This study aims to research the benefits of sustainable timber construction in terms of climate change. To achieve this aim, a systematic literature review was performed based on the research conducted between 1998 and 2022. For this purpose, research papers were searched from the Web of Science database and screened by applying a combination of keywords and the criteria for academic publication selection, including climate change, timber or wooden building, renewable material, sustainable material, carbon sink, carbon reduction, embodied energy, lifecycle assessment, and the circular economy. Further, a quantitative analysis of publications was performed using a science mapping approach, and qualitative content analysis was then conducted in three areas of research: timber as a sustainable construction material, the carbon storage of and reduction in GHG/CO_2 emissions, and the circular economy. Research trends, general findings, and knowledge gaps were identified, and future research directions were indicated. The literature review proves that timber construction is a potential solution to reduce climate change.

Keywords: timber construction; climate change; systematic literature review; science mapping; future research directions

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1. Introduction

Climate change has become a priority in recent academic research. In many countries across the globe, new regulations have been introduced to reduce energy consumption and greenhouse gas (GHG) emissions [1,2].

The construction sector is one of the largest consumers of energy and natural resources in the world [3,4], and one of the greatest contributors to GHG, especially carbon emissions [5–11]. In addition, the built environment is responsible for a high level of pollutants emitted into the air, water, and soil [12] and high amounts of waste, affecting the natural environment [13,14]. In the future, the prospective increase in and urbanization of the global population will result in increased demands for new residential and commercial buildings and infrastructure. The increased manufacturing of steel, cement, and other industrial building materials will produce a vast amount of GHG emissions [15]. According to Younis and Dodoo's [16] estimates, in the next 40 years, approximately 415 Gt of CO_2 will be produced by construction activities globally.

Based on the aforementioned facts, it can be assumed that improvements in the construction sector or considerable reductions in GHG emissions are vitally important to achieve national and global targets relating to climate change [8,17–19]. Therefore, there is an urgent need to find environmentally friendly solutions for the design and construction of new-generation buildings. One of the options that is increasingly being discussed in the recent scientific literature is the replacement of traditional industrial building materials, such as steel or concrete with natural timber materials. The use of timber in the building sector has less impact on the environment and consequently climate change due to carbon storage [20] and reduced CO_2 emissions [21–23] in the material production, construction, and use stages, among other substantial benefits. These benefits have attracted increased attention from scientists and practitioners to timber as a building material [24] and the development of multi-story timber construction in the USA, Canada, China, Europe, and other countries. Timber is also gaining popularity as a building material due to significant progress in technology and new engineered timber products, e.g., glue-laminated timber (glulam), cross-laminated timber (CLT), and laminated veneer lumber (LVL), among other options.

In the context of recent research, there is a need to analyze and summarize the benefits of timber construction and assess whether timber construction is a potential solution to climate change. Therefore, the study aims to research the benefits of sustainable timber construction in terms of climate change. To achieve this aim, a systematic literature review was performed, based on the research conducted between 1998 and 2022.

So far, only a few studies provided systematic literature reviews on timber construction. For instance, Weiss et al. [25] made a systematic literature review on innovation research in forestry and the forest-based industries; Harju [26] analyzed the perceived quality of wooden building materials; Jussila et al. [27] researched multi-story timber construction market development; Younis and Dodoo [16] reviewed life cycle assessment (LCA) studies on the carbon footprint of CLT buildings; and Minunno et al. [28] investigated the embodied energy and carbon footprint of buildings for alternative materials, including timber. None of the literature reviews analyzed timber construction in relation to climate change.

This article complements the existing literature on timber research. Moreover, a systematic literature review contributes to a better understanding of the environmental benefits of timber as a sustainable building material which has significant impacts on climate change.

The remainder of the study is structured as follows. Section 2 presents the methodology of the research. Section 3 provides a quantitative analysis of selected scientific publications. Section 4 presents a qualitative analysis of selected publications based on three thematic areas and distinguishes future research directions. The last section summarizes the results and provides conclusions.

2. Materials and Methods

A systematic literature review approach was selected to distinguish and analyze relevant scientific publications on sustainable timber construction and its potential impacts on climate change. The systematic review collects all related publications corresponding to pre-defined inclusion criteria to answer a specific research question: whether timber construction is a potential solution to climate change. Such an approach can provide reliable findings and conclusions for scientists and decision-makers [29].

The research methodology is presented and described in Figure 1.

Step 1. The selection of publications

The Clarivate Analytics Web of Science (WoS) database was chosen as a publication retrieval database. Although the number and variety of bibliographic databases are growing rapidly, WoS remains the most widely used, influential, and authoritative bibliographic database globally [30]. It has a wide literature coverage and is compatible with science mapping tools [31].

Initially, the literature search was carried out using the query TITLE-ABS-KEY ("climate change" AND "timber" OR "wood*" AND "construction" OR "building").

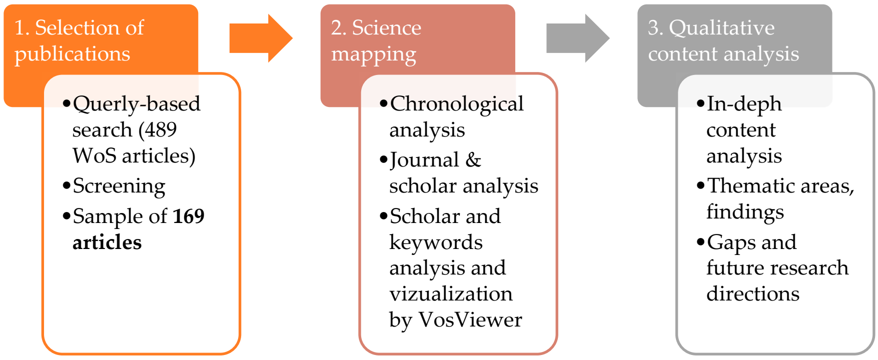

Figure 1. Research flowchart.

In addition, based on Mengist et al.'s [29] recommendations, papers were included if they used:

- Pre-defined keywords existed in the title, abstract, and keywords;
- The article was published in a scientific journal;
- The article was in the English language;
- The article contained original research.

Based on inclusion criteria, book chapters, proceeding papers, extended abstracts, gray literature, presentations, keynotes or similar literature, as well as journal articles not in the English language were omitted and 489 journal articles remained.

For further screening, titles, abstracts, keywords, and bodies of text in the remaining articles were carefully reviewed based on a combination of keywords and criteria, including climate change, timber or wooden building, renewable material, sustainable material, carbon sink, carbon reduction, embodied energy, lifecycle assessment, and the circular economy; articles that did not tackle timber construction in terms of climate change were excluded. After this procedure, 169 articles remained for further analysis.

Step 2. Science mapping

Science mapping can be defined as a generic process, usually facilitated by a bibliometric tool that helps to mine and analyze scientific output [32,33]. It has been widely applied in systematic literature reviews of scientific research.

In this study, science mapping was applied to analyze chronological data of publications, and distinguish the top journals in terms of the number of publications and the top author's contributions in terms of publications and citations. For this purpose, quantitative analysis, using a WoS datasheet, was performed.

For the further analysis and visualization of results, the VOSViewer tool [34] was selected because it allows bibliometric maps and examination results to be constructed and visualized through different views, including density and cluster views [35]. It uses a distance-based approach to visualize bibliometric networks of units (represented as nodes), including keywords, authors, journals, organizations, and countries [31]. In this study, the VOSViewer tool was used to analyze and visualize the networks of authors, countries, and highly used keywords.

Step 3. Qualitative content analysis

Finally, an in-depth content analysis of the selected 169 articles was performed to analyze the potential impacts of timber construction on climate change. Three thematic areas were distinguished: (1) timber as a sustainable material, (2) the carbon storage of and reduction in GHG/CO_2 emissions, and (3) the circular economy. After analysis, existing research gaps were identified and future research directions were suggested.

3. Results

3.1. Quantitative Analysis Results

In total, 169 articles, with publication dates ranging from 1998 to 17 October 2022, were selected from the Web of Science (WoS) database for analysis. Analysis of publications in chronological order revealed that the first publication, targeting climate change and timber construction, was published in 2006. It can be explained by the fact that the Kyoto Protocol on climate change entered into force on 16 February 2005.

The distribution of publications according to publishing year is provided in Figure 2. It can be observed that the interest of scientists in climate change and its mitigation possibilities by sustainable timber construction was not high until the year 2018 when the number of publications started to increase each year. The highest number of articles (39) was published in 2021.

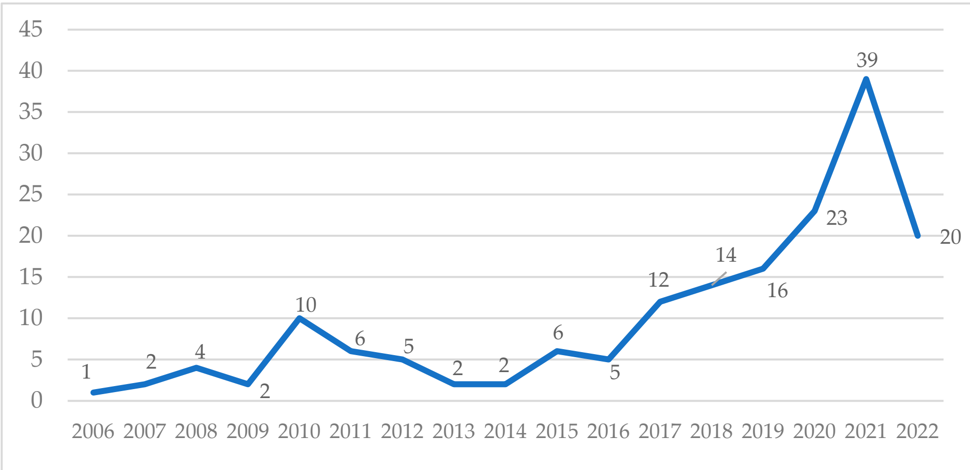

Figure 2. The number of publications per year (until 17 October 2022) (N = 169).

Table 1 summarizes the top journals based on the number of publications. A selected sample of articles was published in 70 journals. The results reveal that the *Sustainability* journal made the biggest contributions in terms of the number of publications (17), followed by *the Journal of Cleaner Production* (16 publications), *Energy and Buildings* (9 publications), and *Building and Environment* (8 publications). The aforementioned journals are dedicated to sustainability, energy efficiency, environmental issues, buildings, and construction. Other journals included in Table 1 target the forestry sector, wood science, industrial ecology, and the circular economy.

Table 1. Top ten journals.

No	Publisher	Journal	Number of Publications
1	MDPI	*Sustainability*	17
2	Elsevier	*The Journal of Cleaner Production*	16
3	Elsevier	*Energy and Buildings*	9
4	Elsevier	*Building and Environment*	8
5	Elsevier	*Forest Policy and Economics*	6
6	MDPI	*Forests*	6
7	Elsevier	*Resources Conservation and Recycling*	6
8	Allen Press Inc.	*Wood and Fiber Science*	5
9	Wiley	*Journal of Industrial Ecology*	4
10	MDPI	*Buildings*	4

In the next step, we selected samples of articles and analyzed them based on the author's contributions. Table 2 summarizes the top twenty authors in terms of the number of citations. Analysis revealed that Sathre, R. published seven publications in relation to climate change and timber construction. His articles were cited 764 times. The second author on the list, Gustavsson, L., also published seven articles, which received 518 citations. Skog, K. E. and Heath, L. S. published two articles each, but these articles received a high number of citations, i.e., 323 and 285, respectively. Balasbaneh, A. T. and Bin Marsono, A. K. published seven articles, which received 160 citations.

Table 2. Top twenty authors in terms of the number of publications and citations.

No	Author	Number of Publications	Number of Citations
1	Sathre, R.	7	764
2	Gustavsson, L.	7	518
3	Skog, K. E.	2	323
4	Heath, L. S.	2	285
5	Freire, F.	2	199
6	Churkina, G.	2	181
7	Reyer, C. P. O.	2	181
8	Schellnhuber, H. J.	2	181
9	Balasbaneh, A. T.	7	160
10	Bin Marsono, A. K.	7	160
11	Hofer, P.	2	139
12	Taverna, R.	2	139
13	Werner, F.	2	139
14	Lahtinen, K.	2	132
15	Wilson, J. B.	3	126
16	Taylor, A.	2	114
17	Pingoud, K.	2	109
18	Malmqvist, T.	2	102
19	Beauregard, R.	3	87
20	Chen, J.	2	87

In addition, we conducted analysis on the networks between authors using the VOSViewer tool. A minimum number of 2 and a maximum number of 25 documents were set. Of the 596 authors, 82 met the selected thresholds. For each of the 82 authors, the total strength of the co-authorship links with other authors was calculated (see Figure 3). Each node represents a scholar and the size of the node indicates the total number of citations the scholar has received.

The selected sample of articles was also analyzed in terms of the countries. The VOSViewer tool was used for this purpose. A minimum number of 2 and a maximum number of 25 documents were set. Of the 45 countries, 30 met the selected thresholds. For each of the 30 countries, the total strength of the co-authorship associated with other countries was calculated, and 24 connected countries were distinguished (see Figure 4). Each node represented a country and the size of a node denoted the total number of articles. The analysis revealed that the highest number of publications was published by authors from the USA (25 articles, 1609 citations), Finland (27 articles, 498 citations), Sweden (16 articles, 1021 citations), and Canada (16 articles, 679 citations).

The selected articles were also analyzed in relation to the keywords. The keywords covered both the title and the abstract fields, and a binary counting method in WOSViewer was selected. A minimum number of 10 occurrences of the term was used; of the 5215 terms, 98 met the threshold. For each of these 98 terms, a relevance score was calculated and 60% of the most relevant terms were selected.

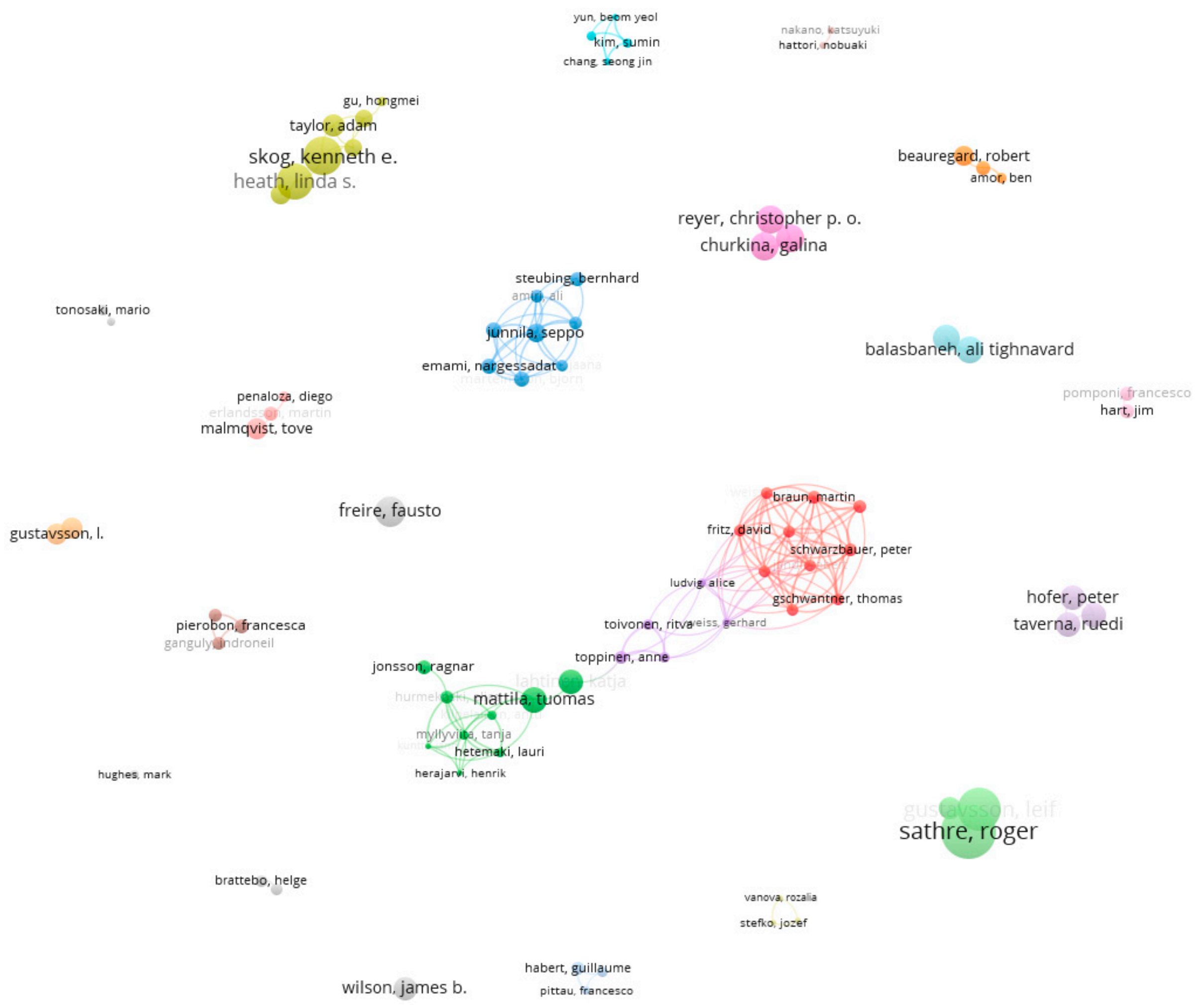

Figure 3. The co-authorship links of the authors.

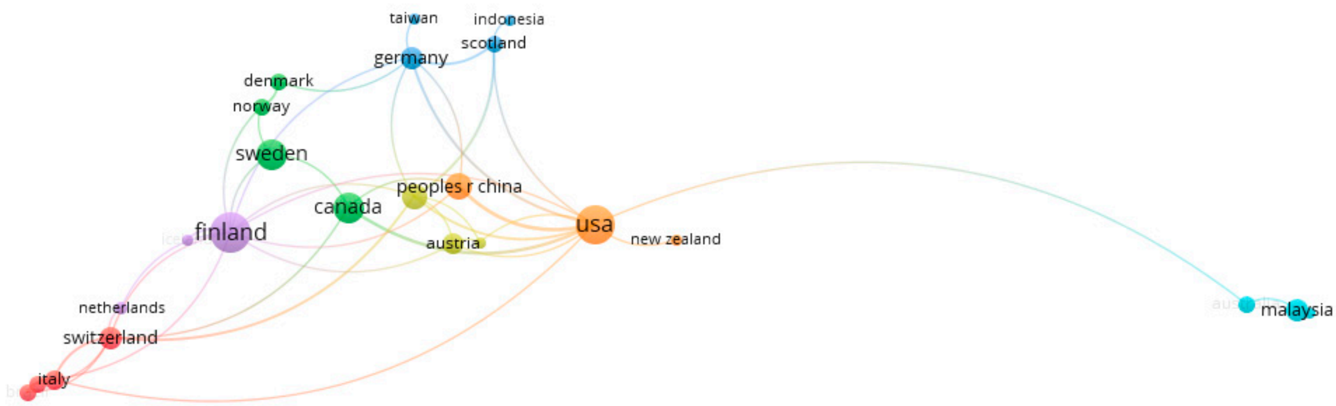

Figure 4. Country networks.

The sample of articles was used to analyze the links between climate change and timber construction. Therefore, the most used term was "change" (106 occurrences). A high number of occurrences was observed for the terms LCA/life cycle assessment (73 occurrences), product (50 occurrences), timber (49 occurrences), carbon (46 occurrences), and environmental impact (36 occurrences). Mostly used keywords in terms of relevance were forest (29 occurrences, with a relevance score of 3.53), wood product (37 occurrences, with a relevance score of 2.66), fossil fuel (19 occurrences, with a relevance score of 2.56), environmental performance (12 occurrences, with a relevance score of 2.23), carbon storage (25 occurrences, with a relevance score of 2.02), and substitution (19 occurrences, with a relevance score of 1.93). Therefore, it can be stated that the selected sample of articles was relevant to the topic (see Figure 5).

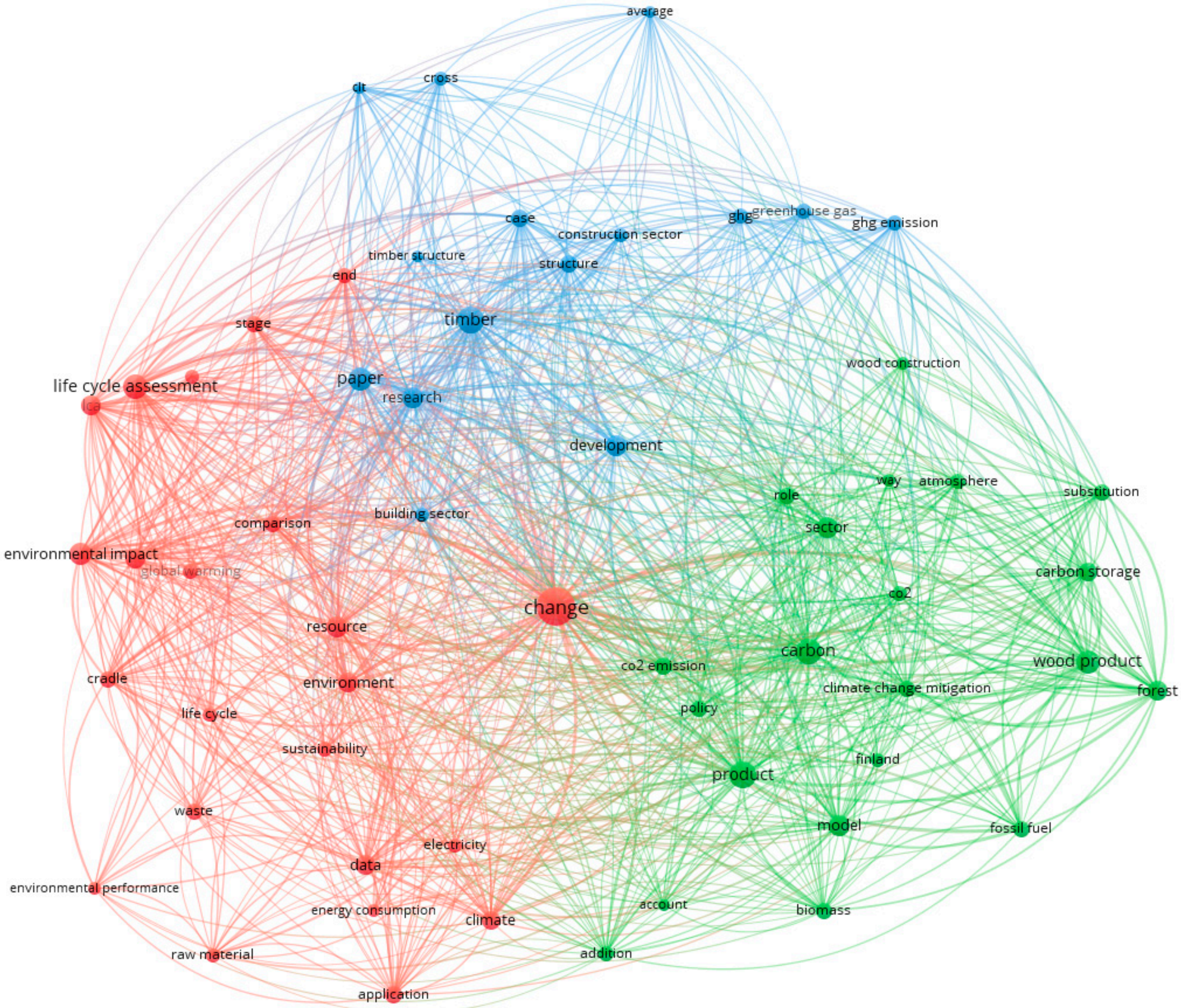

Figure 5. Highly used keywords.

Distinguished keywords were divided into three interconnected clusters. The green-colored cluster includes 21 items, mostly related to climate change mitigations, carbon emissions, wood products, and wood construction. The red-colored cluster with 23 items included life cycle assessment, environmental impact, energy consumption, waste management, and other related items. The blue-colored cluster included 15 items and was mostly related to timber structures and greenhouse gas emissions.

In the next step, based on WoS information, the list of the top twenty highly cited articles was developed (see Table 3). Indeed, the number of citations depended on the publishing year. In Table 3, two highly cited articles, published in the years 2019 and 2020, are distinguished [15,36]. Both articles are related to carbon reduction in the building sector.

It can be concluded that, in recent years, the number of publications on sustainable timber construction has grown across the globe. In the context of climate change, more and more authors recognize the environmental benefits of timber and propose it as an alternative solution to steel, concrete, and other materials. An increasing number of citations indicates overall academic interest in this topic.

Table 3. Top twenty highly cited articles.

No	Reference	Times Cited, WoS Core	Times Cited, All Databases
1	Hepburn et al. [36] *	498	505
2	McKinley et al. [37]	254	268
3	Sathre and O'Connor [38]	270	280
4	Gustavsson et al. [39]	244	249
5	Churkina et al. [15] *	181	182
6	Monteiro and Freire [40]	154	155
7	Nunery and Keeton [41]	146	167
8	Dahlbo et al. [42]	129	133
9	Hacker et al. [43]	125	125
10	Malmsheimer et al. [44]	110	113
11	Werner et al. [45]	101	103
12	Hennigar et al. [46]	87	90
13	Wallhagen et al. [47]	85	86
14	Gustavsson et al. [48]	81	82
15	Sathre and Gustavsson [49]	71	72
16	Bergman et al. [50]	69	71
17	Invidiata et al. [3]	67	68
18	Bin and Parker [51]	63	65
19	Pingoud et al. [52]	62	63
20	Geng et al. [53]	56	60

* Highly cited articles.

3.2. Qualitative Analysis Results

An in-depth analysis of a selected sample of articles was performed and three thematic areas were distinguished. The findings of the authors are discussed in the following subsections.

3.2.1. Timber as a Sustainable Building Material

Studies emphasize the benefits of timber as a sustainable building material (see Table 4). According to many authors, timber can be an alternative to steel and concrete because of its lower environmental impact and other unique properties.

Table 4. Benefits of timber as a sustainable material.

Benefits	References
Timber is a natural ecological material	[54–56]
Timber facilitates the bioeconomy in construction	[54,56–58]
Timber is a renewable material	[23,57,59–63]
Timber is a recyclable material	[42,57,64–72]
Timber is a durable material	[73,74]
Timber has good insulation performance	[75–77]
Timber materials can be reused	[7,78–80]
Timber sequestrates/stores carbon	[10,15,20,41,46,50,59,61,62,73,74,81–90]
Timber construction reduces GHG/CO_2 emissions	[5,7,10,12,14,16,17,19,38–40,44,47,49,50,53,56,60–62,73,74,81,91–117]
Timber construction reduces waste	[56]
Timber buildings are aesthetical	[16,54]

According to various studies, the natural characteristics of wood, especially carbon sequestration, are seen as the upmost important advantage of timber compared to other building materials. For this purpose, harvested wood products are even considered in the Kyoto Protocol [80], which directly tackles the mitigation of climate change.

Some authors emphasize that wood is a renewable resource; thus, it helps to cope with the problem of limited raw material resources for the production of construction materials and products [114]. Being renewable, wood is considered to be one of the most important resources for a future bioeconomy [54,56–58,62,77].

Because of its specific characteristics pertaining to sustainability, timber construction is gaining popularity, especially in Europe and Northern America [23]. In Austria, Petruch and Walcher [54] found that young millennials positively evaluate timber construction, especially in terms of aesthetics and ecology, as well as the role of wood in climate change mitigation.

Studies reveal that an increase in the use of timber in the building sector is among the top priorities in some countries, e.g., the UK [5] and Germany [118]. Nakano et al. [89] reported an increase in the number of buildings built using cross-laminated timber (CLT) in Japan. Contrary, studies by Balasbaneh and Bin Marsono [17,119] showed that the rate of applying timber in the construction sector decreased from about 60% to 7% in Malaysia over the last 40 years. With regards to multi-story timber construction, Vihemki et al. [59] predicted that it will remain rather low in Austria and Finland by 2030.

Some of the authors researched the advantages of specific timber products in their studies. For instance, Younis and Dodoo [16], Le et al. [55], Chang et al. [120], and Cho et al. [121] emphasized the advantages of cross-laminated timber (CLT), namely carbon storage, relatively low carbon footprint, high strength-to-weight ratio, simple installation, aesthetic features, fire and seismic resilience, natural insulation and lightweight features, reduced construction period and cost, and an increase in productivity. Dong et al. [76], based in China, found that CLT buildings are more resistant to overheating than concrete buildings during the summer. Perkovi et al. [84] noted that the use of prefabricated construction systems, such as glue-laminated timber, reduces construction time and the need for construction machinery. Geno et al. [122] encouraged the use of minorly transformed timber, i.e., tree trunks, in their study. Sahoo et al. [60] discussed the advantages of lumber as a renewable construction material. Kirsch et al. [77] proposed substituting fossil-fuel-based insulation materials with wood fiber insulation boards.

Zemaitis et al. [56] in Lithuania and Suter et al. [114], based in Switzerland, researched the value chains of timber products. A Lithuanian case study showed that glue-laminated timber and sawn timber value chains have more positive sustainability impacts compared to site-cast concrete and precast reinforced concrete value chains: lower GHG emissions, water use, energy use, waste generation, and more positive socio-economic impacts [56].

Wood construction technologies are being integrated with low-energy-use solutions and tested in real environments. For instance, in Canada, the Wood Innovation Research Lab (a low energy building) sought to test engineered timber products and promote sustainable construction with timber [123]. Vilcekova et al. [109], in their study on detached family houses with a wooden structure, concluded that houses built entirely of wood and with a biomass boiler have significantly lower CO_2 emissions.

Other studies researched policy frameworks to promote timber construction. For instance, a study by Sathre and Gustavsson [124] indicated that higher energy and carbon taxation rates could increase the economic competitiveness of timber construction materials.

The aforementioned studies emphasized the positive impacts of timber construction in decreasing the impact of the construction sector on climate change. On the other hand, Almas et al. [125] in Norway and Jarvinen et al. [126] in Finland reported on the negative impacts of climate change on timber buildings, such as the risk of rot decay, increasing mold problems and the possibility of the spread of termites.

3.2.2. The Carbon Storage of and Reduction in GHG/CO_2 Emissions

Climate change is caused by increasing GHG emissions. Therefore, many selected articles tackled the carbon storage of and the potential reduction in GHG/CO_2 emissions by timber construction. The main findings are further discussed.

Carbon sink

A carbon sink is the potential of timber buildings to absorb and store CO_2 emissions. This effect was emphasized and estimated in many studies in Europe and other countries.

Timber buildings as a global carbon sink were researched by Churkina et al. [15]. Amiri et al. [10] estimated the carbon storage potential of new European buildings between 2020 and 2040. In their study, 50 different buildings were analyzed, the carbon storage per m^2 of each building was calculated, and three types of timber buildings were identified. The annual absorbed CO_2 varied between 1 and 55 Mt, equivalent to 1–47% of CO_2 emissions from the European cement industry. Herjrvi [20] estimated the building sink effect (BSE) in Finland. He found that the use of approximately 450 million m^3 of wood products (equal to 85% of the global production of lumber) could help to achieve a global BSE of 1%.

Potential reduction in GHG/CO_2 emissions following the increased use of timber in the building sector

The climate change reduction in greenhouse gas (GHG) emissions, in particular CO_2 emissions, is of utmost importance. Therefore, some of the authors evaluated potential the carbon storage or reduction in GHG/CO_2 emissions in the case of rapid timber construction development. Their findings are summarized in Table 5.

Table 5. Studies on the potential reduction in GHG/CO_2 emissions caused by the increased use of wood in the building sector.

Reference	Country/Region	Findings
Mishra et al. [60]	Global	106 Gt of CO_2 could be saved by 2100 if 90% of the new urban population lived in mid-rise wooden buildings.
D'Amico et al. [8]	Global	Replacing concrete floors and steel structural systems by CLT globally could prevent 1.5% of the annual construction GHG emissions by 2050.
Sathre and O'Connor [38]	21 different international studies	3.9 t CO_2 eq emissions can be reduced per ton of dry wood used.
Padilla-Rivera et al. [7]	Quebec, Canada	Prefabricated timber buildings could reduce the climate change impact by up to 25% per m^2 floor area. If low-carbon strategies are used, timber structures could generate a 38% lower climate change impact.
Cordier et al. [103]	Quebec, Canada	The use of wood in non-residential construction could help to avoid 2.6 Mt of CO_2 eq, an amount equivalent to 3.5% of Quebec's CO_2 eq. emission reduction target by 2050.
Allen et al. [116]	Australia	Net-zero or even net-negative operational and embodied emissions in the built environment could be achieved by increasing the share of mass timber buildings.
Stocchero et al. [104]	Auckland, New Zealand	The target of a 40% CO_2 emission reduction by 2040 could be achieved 20% faster than planned if the use of timber increases.
Malik et al. [87]	Jakarta, Indonesia	If housing needs increase to 800,000 units per year, the use of wood products could potentially store 0.44 million tons of carbon.
Tsunetsugu and Tonosaki [86]	Japan	The ratio of newly constructed wooden buildings/furniture has to be improved to 70% by 2050 to have a significant impact on climate change.
Kayo et al. [127]	Japan	The substitution of materials, e.g., concrete, cement, and steel with wood products, could significantly contribute to environmental impact reductions.

Table 5. *Cont.*

Reference	Country/Region	Findings
Braun et al. [91]	Austria	GHG emissions saved by building from harvested wood products and through emissions substitution could be as high as ∼20 years of total annual Austrian emissions in 90 years.
Penaloza et al. [128]	Sweden	The increased use of harvested wood products could result in reduced climate impacts.
Laturi et al. [88]	Finland	Wood products will store 39.6–64.2 million tons of carbon in 2050.
Werner et al. [73]	Switzerland	The increased use of wood in the building sector is a valid and valuable option for the mitigation of GHG emissions.
Suter et al. [114]	Switzerland	0.5 tons CO_2 eq. per m^3 of wood used could be saved.
Yang et al. [19]	Leiden, Netherlands	Wood construction has a 10% decarbonization potential.
Negro and Bergman [85]	Torino, Italy	For an apartment, the use of timber products stores 3531 kg of CO_2 eq., i.e., 45.8 kg/m^2 of an indoor walkable area.

It can be observed that authors from different countries across the globe agree that the increase in timber construction has a significant potential impact on reducing the impacts of climate change and achieving carbon reduction targets.

Comparisons of GHG/CO_2 emissions of timber and alternative building materials

Existing research highlights timber construction as the lower carbon option compared to traditional industrial building materials. Most commonly, environmental impacts are modeled through a life cycle assessment (LCA) or similar techniques. The results are summarized in Table 6.

Table 6. Studies that compare GHG/CO_2 emissions of timber and alternative building materials.

Reference	Country/Region	Method	Findings
Chen et al. [129]	USA	Cradle-to-grave LCA	They compared 12-story buildings constructed from CLT and reinforced concrete. In the case of CLT building, a 20.6% reduction in embodied carbon was achieved.
Malmsheimer et al. [44]	USA	Review	Wood products store carbon and have low embodied energy compared to metals, plastic, and concrete.
Head et al. [106]	Canada	Assessment of life cycle inventories (LCIs) and dynamic climate change impacts (DCCIs)	Most wood-building products have overall net-negative climate change impact scores.
Hahnel et al. [101]	Western Australia	LCA	They compared alternative structural flooring systems. Timber has the lowest environmental impact followed by steel and 'GreenStar' concrete.
Bhochhibhoya et al. [105]	Sagarmatha National Park and Buffer Zone, Nepal	LCA	If local materials, e.g., wood, are used in building construction instead of industrial ones, the emissions from production and transportation could be significantly reduced.

Table 6. *Cont.*

Reference	Country/Region	Method	Findings
Escamilla et al. [108]	Colombia	LCA	They analyzed the construction of single- and multi-story buildings, and then measured the environmental impact of bamboo, brick, concrete hollow block, and engineered bamboo. The engineered bamboo construction system has the lowest environmental impact.
Chen et al. [97]	China	Cradle-to-gate LCA	Timber building has a 25% lower global warming potential in contrast to the concrete one.
Yang et al. [98]	China	LCA	They analyzed 7 timber buildings. Timber buildings can reduce CO_2 emissions in the production stage by 64.5% compared to reinforced concrete buildings; from a lifecycle perspective, 11.0% of carbon emissions could be saved.
Balasbaneh and Bin Marsono [17]	Malaysia	LCA	They performed a LCA on the alternative residential building schemes. The timber-based structure produced 85% fewer CO_2 emissions compared to the precast concrete frame and 90% less compared to the brick structure over its lifetime.
Balasbaneh and Bin Marsono [119]	Malaysia	LCA	They applied LCA to assess 6 different types of prefabricated building systems. Prefabricated timber construction is the best choice to achieve lower emissions.
Balasbaneh, Bin Marsono [94]	Malaysia	LCA and life cycle cost (LCC)	They compared 5 types of building materials (common brick, concrete block, steel wall panels, wood, and precast concrete framing). Timber is the best material for constructing buildings with reduced environmental impacts.
Hart et al. [5]	UK	LCA	They analyzed different building frame configurations in steel, reinforced concrete, and engineered timber frames. In the case of timber, on average, 36% of emissions occur in the post-construction stage. Results for the whole-life embodied carbon (WLEC) revealed that CO_2 emissions were 52% lower compared to the steel frame.
Morris et al. [18]	UK	LCA	They investigated whether glulam has a significantly lower WLEC than functionally equivalent structural steel. They found that glulam has the lowest GWP when incinerated, including energy recovery, at end-of-life.
Wallhagen et al. [47]	Gävle, Sweden	Simplified LCA-based calculations	Changing construction slabs from concrete to timber in office buildings is one of the most effective measures to reduce the contribution to climate change in a building.

Table 6. *Cont.*

Reference	Country/Region	Method	Findings
Sathre and Gustavsson [49]	Sweden	Energy balance calculations	They compared timber and reinforced concrete-framed buildings. They found that the production of timber building materials uses less energy and emits less carbon.
Amiri et al. [130]	Iceland	LCA, LEED system	They researched optimized concrete, hybrid concrete–timber, and timber building scenarios. The lowest environmental impact was achieved for the timber building. followed by the hybrid concrete-timber building.
Ottelin et al. [113]	Finland	Survey, multi-regional input–output model	Residents of timber houses have a 12(±3)% (950 kg CO_2-eq/year) lower carbon footprint on average compared to residents of non-wooden houses.
Monteiro and Freire [40]	Portugal	LCA	For single-family houses, timber wall is the preferable solution compared to non-timber alternatives.
Tavares et al. [14]	Portugal	Inventory of Carbon and Energy (ICE)	They assessed the embodied energy, GHG emissions of different prefabricated modular house design scenarios (steel, concrete, timber, and light steel framing), and variations in house size. Light steel framing or timber have the lowest environmental impacts, while steel and concrete have the highest.
Pasternack et al. [92]	International studies	Review	Substituting steel and concrete with mass timber in mid-rise buildings can reduce the CO_2 emissions associated with manufacturing, transporting, and installing building materials by 13–26.5%.
Younis and Dodoo [16]	International studies	Review of LCA studies pertaining to the carbon footprint of CLT buildings	On average, the carbon footprint could be reduced by about 40% in multi-story buildings when using CLT compared to other construction materials (steel/concrete).

From these studies, it can be concluded that timber as a building material produces lower CO_2 emissions and therefore has the lowest environmental impact compared to traditional concrete, steel, and other materials. In addition, the embodied energy is significantly lower in wooden construction compared to building constructions with inorganic materials [74,95].

3.2.3. Circular Economy

The circular economy is an alternative to the linear economic model which was inspired by natural metabolisms and the circular use of resources [64].

According to Jahan et al. [131], the circular economy can be achieved in different life cycle phases of construction, namely raw material extraction, design/pre-construction, construction and operation, renovation and demolition, reuse, recycling, or energy recovery. Their findings are supported by the results of this literature review (see Table 7).

Table 7. Studies on the potential reduction of GHG/CO_2 emissions by increased use of wood in the building sector.

Phase	Findings	References
Raw material extraction	Timber has to be extracted from sustainably managed forests and certified	[41,44,132–137]
The design/pre-construction phase	Design has to ensure flexible building use, adaptive reuse, long-term durability, and the optimization of material recovery	[53,57,78,89,131,138,139]
	Effective timber waste management plan should be developed before the construction phase	[131,140–144]
The construction phase	The prefabrication of timber elements and modular construction contribute to waste reduction on site	[131,145–148]
	Waste management on site (monitoring, sorting, collection, and storing) is essential for waste reduction, recycling, and reuse	[131,149]
The renovation phase	Timber can be used as a retrofitting system to reduce the carbon footprint of more traditional existing structures	[150–154]
The demolition phase	Demolition planning, selective demolition, sorting, and labelling of waste can help to recover wood for reuse or recycling	[42,131,149]
Reuse and recycling	Wood-based products, e.g., pallets, beams, wood-frame structures, can be reused in new constructions	[131,149,155]
	Wood wastes can be used for the production of new materials	[7,42,64,66,67,69,70,72,79,80]
Energy recovery	By-products from wood production processes can be used for energy production	[39,53,65,71,131]

Timber extraction is an important phase for achieving a circular economy in further stages of the building life cycle. To achieve sustainability, timber building materials have to be produced from wood that is certified and sourced from replanted/sustainably managed forests [132–134]. Certification and eco-labelling confirm that the management of a specific forest area is in line with sustainability principles [135].

Based on circular economy principles, design has to ensure flexible building use, adaptive reuse, long-term durability, and the optimization of material recovery. Some studies note that carbon stored in wooden structures is released into the atmosphere at the end-of-life of the building. Therefore, it is important to ensure the long-time durability of timber buildings and reuse structural timber elements [53,78,89,90]. The more efficient use of wood resources is beneficial for climate change mitigation [57]. It is also important to develop an effective timber waste management plan in the pre-construction phase [131]. BIM can be used to calculate the detailed composition of waste materials [131,141–144].

In the construction phase, it is important to reduce waste as much as possible. One of the solutions is the prefabrication of timber elements and modular construction [131,145–148]. On the other hand, waste management on site, including monitoring, sorting, collection, and storing, is essential for waste reduction, recycling, and reuse [131].

The renovation of existing timber buildings leads to energy savings and decarbonization of the building stock [150]. On the other hand, studies show that timber can be used as a retrofitting system to reduce the carbon footprint of more traditional existing structures [151–154].

Demolition at the end of the building's lifetime has to be carefully planned to recover wood, which can be used for further reuse and recycling [42,131,149].

Recycling wood, as one of the waste components, reduces the need for new raw materials [68]. Some of the wood-based products, e.g., pallets, beams, and wood-frame structures, can be reused in new construction [131]. Other authors investigated how local urban and industrial wastes could be recycled and transformed into sustainable building materials, e.g., [7,42,64,66,67,69,70,72,79,80]. Various recycling and reuse options were proposed, such as the reuse of wood wastes into the production of particleboard [7], the production of mycelium insulation material for CLT production residue recycling [79]; the use of recycled wood shavings for wood bio-concretes [66,67]; and the use of waste wood materials in cement mortars [72].

Other studies, e.g., [39,53,65,71], emphasized that by-products from wood production processes can be used for energy products, such as pellets, and that heating power can be used to reduce carbon footprints.

3.2.4. Future Research Directions

Despite the fact that a vast number of articles analyze timber construction and its potential effects on climate change, some research gaps still exist. Based on the literature review and personal knowledge of authors obtained in practice and international projects such as "Sustainable Public Buildings Designed and Constructed in Wood", "Circular Economy in Wooden Construction", "Sustainable High-Rise Buildings Designed and Constructed in Timber", "Knowledge Alliance for Sustainable Mid-Rise and Tall Wooden Buildings", "Design and Construction of Environmental High Performance Hybrid Engineered Timber Buildings", and "Back to the Future—Building with Sustainable Local Traditional Materials", the main research gaps and future directions are distinguished and summarized in Figure 6.

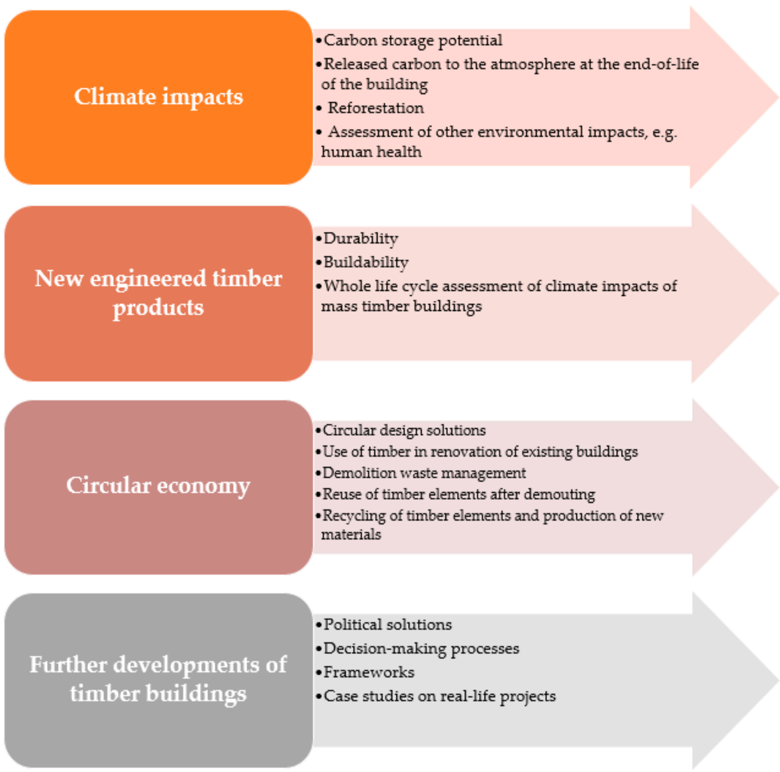

Figure 6. Future research directions.

Climate impacts

Existing research on the LCA of timber elements still has some limitations. The storage potential of carbon released to the atmosphere at the end-of-life of the building should be more extensively researched in the future. In addition, increased timber use, reforestation, and sustainable forest management have to be estimated to see real climate effects. Besides carbon sequestration, a reduction in GHG/CO_2 emissions, and an assessment of other environmental impacts of timber construction (such as human health), ecosystem quality is still limited in the scientific literature.

Research on new engineered timber products

Some new engineered mass timber products, e.g., CLT and glulam, were not deeply investigated as traditional building materials, such as concrete or steel. Therefore, additional research on the durability, buildability, and whole life cycle assessment of climate impacts of mass timber buildings is needed.

Circular economy

Only some studies investigate the application of circular economy principles in the whole building life cycle. More extensive research is required in design solutions to ensure flexible building use, adaptive reuse, long-term durability, and the optimization of material recovery.

Some studies show that timber can be used as a retrofitting system to reduce the carbon footprint of more existing traditional structures. More investigations are needed in this field.

Timber waste management, research on wood utilization, possible recycling and reuse options of timber elements, cascading principles, and the production of new materials should be investigated further in the future.

Further developments of timber buildings

Appropriate legal frameworks and real-life business applications are important to enhance a wider application of timber materials. An integral long-term strategic approach is needed to develop efficient forest and wood management strategies [45] and bioeconomy transition pathways towards sustainability [138] to have impacts on climate change. Thus, it can be assumed that more extensive research on possible political solutions, decision-making processes, frameworks, and the provision of examples from case studies on real-life projects may promote the selection of timber as a building material. Furthermore, the extension of education on alternative construction materials may significantly increase interest in sustainable timber construction.

4. Conclusions

Literature analysis revealed that the first article on climate change and timber construction was published in 2006, just after the approval of the Kyoto Protocol. The number of publications significantly increased from the year 2018. The majority of publications were published in journals such as *Sustainability*, *the Journal of Cleaner Production*, *Energy and Buildings*, *and Building and Environment*, which cover topics on sustainability, energy efficiency, and environmental issues in the built environment. The top authors in terms of the number of publications and citations who analyzed timber construction concerning climate change are Sathre, R.; Gustavsson, L.; Skog, K. E.; Heath, L. S.; Balasbaneh, A. T.; and Bin Marsono, A. K. The greatest number of articles was produced by the authors from USA, Finland, Sweden, and Canada.

An in-depth content analysis of the articles has helped to distinguish three thematic areas of research: (1) timber as a sustainable material, (2) the carbon storage of and reduction in GHG/CO_2 emissions, and (3) the circular economy. Many authors emphasize the benefits of timber as a sustainable building material, i.e., timber is a natural, ecological, renewable, durable, recyclable, and reusable material that facilitates the bioeconomy in construction, absorbs and stores carbon, and contributes to reductions in GHG/CO_2 emissions and waste in construction. Existing research highlights timber construction as the lower-carbon option compared to traditional industrial building materials, such as steel or concrete. Most commonly, environmental impacts are modeled through life cycle assessment (LCA) or similar techniques. In addition, it is estimated that timber construction can contribute to a circular economy, e.g., timber structures can be reused and wood waste can be recycled and used for the production of other materials or heating power.

It can be concluded that authors from different countries across the globe agree that the increase in timber construction has a significant potential impact on the achievement of carbon reduction targets and therefore in dealing with climate change issues.

Indeed, some research gaps still exist. From this review and based on author's experience obtained in practice and through international timber-construction-related projects, in the future, research could cover carbon storage potential, the timing of carbon emissions, land allocation, and released carbon at the end-of-life of the building. Additional research is needed in terms of the durability, buildability, and whole life cycle assessment of climate impacts of engineered timber products, such as glulam or CLT. Another research direction is the circular economy in timber construction with regards to wood utilization, demolition waste management, the possible recycling and reuse options of timber elements, cascading principles, and the manufacturing of new materials from recycled products. More studies are still needed on possible political solutions, decision-making processes, frameworks, and examples from case studies to promote the selection of timber as a building material.

This study can be beneficial to both academics and practitioners because it provides an overview of relevant research works on timber construction and its impacts on climate change from both textual visual and perspectives, summarizes the main research results, and distinguishes research gaps. However, it should be considered that the literature sample is limited to WoS English journal articles, as of October 2022.

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