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How much upfront-embodied GHG emissions can wooden buildings save—displacement factors for wooden buildings

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Abstract

Wood can be a reasonable building material replacement for major greenhouse gas (GHG)-emission sources, such as concrete, steel, and masonry. Here, we conduct a detailed evaluation of the upfront-embodied GHG (UE-GHG) emissions benefits of wood compared with the other construction materials. By using lifecycle assessment (LCA) data from 92 case buildings in the literature, we provide an extensive synthesis of the displacement factor (DF) for wooden buildings. We use DF as a reference number for comparable building LCA studies to understand the GHG-emission benefits of wooden buildings. A pattern of lower UE-GHG emissions was found in our study; on average, the wooden buildings showed approximately 23% lower UE-GHG emissions than their non-wooden counterparts. Generally, low-rise (especially detached) buildings were found to have better DF values compared to mid-to-high-rise buildings. In addition, the process-specific LCA study found higher DF values for wooden buildings compared with input–output LCA studies that mostly base their calculations on average material manufacturing data. Finally, it is important to note that the DF values of different case buildings ranged from −0.15 to 0.69, which highlights the importance of careful technical considerations and efficient design of wooden buildings in order to maximize their DF benefits. We highlight the emergence of hybrid (structure) wooden buildings, especially for mid- to high-rise buildings, in recent years and emphasize the urgent need for a hybrid building definition because current practice allows the branding of low-wood-content buildings as wooden buildings.

1. Introduction

Buildings are responsible for one third of greenhouse gas (GHG) emissions globally when both operational and embodied emissions are considered [1, 2]. Accordingly, a number researchers have examined how to decrease the GHG emissions of buildings [3–5]. For example, Hertwich *et al* [6] recommended a 20% reduction of space utilization per person as a strategy for reducing construction emissions by 2050. They also proposed an extension to building lifespans. Other researchers have compared the effects of lightweight design on GHG emissions, using reduced amounts of aluminum and concrete [7, 8], or have recommended material substitution [9], higher recovery [10–12], and greater production efficiency [13–15] as ways to reduce building construction GHG emissions.

As a construction material, wood has several key benefits. Based on lifecycle assessment (LCA), it has lower pre-use GHG emissions (embodied) compared to other materials, such as concrete and steel [16–25]. A more recently acknowledged benefit is its potential to store carbon [4, 26–28]. Churkina *et al* [9] estimated the cumulative carbon capture as 45–484 Mt for a 50% wooden building scenario and 88–885 Mt for a 90% wooden building scenario for future building construction in Europe from 2020 to 2050. In addition, Amiri *et al* [29] conducted a carbon storage study for Europe for a period of 20 years and estimated the cumulative value as 22–67 Mt for a 5% scenario, 44–133 Mt for a 10% scenario, 20–600 Mt for a 45% scenario, and

356–1067 Mt for an 80% scenario. It is necessary to guarantee the long-term storage of carbon, otherwise the stored carbon might be released back to the atmosphere.

In addition to its lower embodied GHG emissions, wood has a lower density compared to materials such as concrete and steel, resulting in 30%–50% reduced dead loads on the lower floors and foundations [30]. This can lead to additional material savings and structural design efficiencies, especially in multistory buildings. Furthermore, wood offers several practical and health-related benefits. It is a lightweight material relative to its strength, making it easier to transport and handle during construction, which can reduce labor costs and construction timelines [31]. Wood is also easier to cut, fasten, and modify on-site, offering design flexibility and adaptability. From a human health perspective, studies have shown that exposure to wood in interior spaces can have positive psychological and physiological effects, including reduced stress and improved indoor air quality [32]. These attributes contribute to wood's appeal not only in residential architecture but also in schools, offices, and public buildings where occupant well-being is prioritized.

Despite these benefits, wooden buildings face significant challenges that must be addressed in order to ensure their long-term sustainability and safety. A key concern is fire resistance. While engineered wood products such as cross-laminated timber (CLT) are designed to meet fire safety standards, wood remains a combustible material, and additional fire-protection systems (e.g. sprinklers, fire-resistant coatings) are often required [33]. Furthermore, wood is highly susceptible to moisture, which can lead to swelling, warping, rot, and fungal decay if the wood is not properly protected and maintained [34]. These issues are particularly important in humid or wet climates, where wood's vulnerability to moisture can shorten its lifespan and increase maintenance costs.

Compared to steel and concrete, wooden buildings may have a shorter functional lifespan, especially if maintenance is inadequate or if the building is exposed to harsh environmental conditions. Wood structures are also more prone to damage from termites, insects, and biological degradation over time [35]. Although protective treatments and building envelope designs can mitigate some of these issues, they often require ongoing investment and care. These factors may reduce the overall cost-effectiveness and environmental advantage of wood when assessed over the entire building lifecycle.

On the environmental side, the large-scale use of wood for construction raises concerns about deforestation, habitat loss, and competition for land. If not sourced from certified sustainable forests, increased timber demand can lead to the depletion of natural ecosystems and threaten biodiversity [36]. The expansion of fast-growing plantations to meet construction needs may also displace land used for food production or conservation purposes [37]. Moreover, not all harvested wood is efficiently used in buildings—a significant portion becomes waste during processing, which limits the carbon storage potential of timber construction [38].

Wooden buildings often require more frequent maintenance than those made of more durable materials, especially in exposed conditions. Protective coatings, ventilation strategies, and insect treatments must be regularly applied to maintain performance over time. Additionally, although wood performs well in low- to mid-rise buildings, its use in tall buildings is structurally constrained by strength and fire codes in many regions [39]. This limits its applicability in high-density urban contexts. Furthermore, LCAs of wood are often highly sensitive to assumptions about end-of-life scenarios, forest regrowth, and substitution effects—making results highly variable across studies [40].

Regarding the environmental benefits of wooden buildings, particularly their lower pre-use GHG emissions (i.e. embodied carbon), it is essential to estimate their carbon mitigation potential. This can be achieved by calculating the avoided emissions from using wood instead of other building materials for the same function, using the displacement factor (DF) approach (explained in Subsection 2.4; see, e.g. [41, 42]). Despite studies focusing on wood-based material at a product level [40, 43], a large-scale synthesis study providing comparative DFs at a building level is still missing from the literature. To date, studies comparing GHG emissions and/or calculating DF values have various limitations that make it difficult for decision-makers to apply the results when evaluating the large-scale effects, for example, at a regional or global scale. Typical study limitations include a tendency to focus on one single type of wooden product, such as roundwood, CLT, or glued laminated timber (glulam), one building type (low-rise, mid-rise or high-rise), or one specific country. With large-scale comparative studies, an even bigger problem is the methodological differences in the included case studies, which is an important issue causing major variations when comparing outcomes [43, 44].

Yan *et al* [45] calculated the DF values for two typical residential building types (single/two family buildings and apartment buildings) with different material selection scenarios in Germany. The wooden options were timber frame or CLT, while the concrete options were reinforced concrete or porous concrete and the masonry options were perforated brick or sand-lime brick. The results showed DF values of 0.35–0.56 for single/two family houses and 0.09–0.48 for multistory buildings, but their study included a limited number of case buildings.

Therefore, there is a need for a study that includes the majority of building types with different wood technology options and covering wide geographical areas with comparable methodological choices. The present study aimed to evaluate the carbon mitigation potential (i.e. the DF values) of comparable wooden vs. non-wooden (concrete, steel, and masonry) buildings, including a variety of building types, wooden product technologies, and geographical areas. To avoid direct building comparisons with different methodological choices (i.e. inventory analysis, scoping, functional unit, etc.), only multiple-case studies with both wooden and non-wooden buildings were included in this study.

The study is divided into three main phases. First, we surveyed the literature and collected a database from the literature to cover a large number of multiple-case studies of buildings with different types and structures in a variety of locations around the world. Second, we conducted a detailed analysis of the identified studies considering the wood types, building types, and building sizes, using different methods of evaluation. In the final phase, we used the GHG emissions values in each of the studies to calculate the DF values and utilized these to evaluate the typical upfront embodied carbon mitigation potential of a wooden building compared to non-wooden buildings.

2. Methods

This study was conducted in three stages and several substages. In the first stage, a total of 175 case studies on buildings constructed from wood, concrete, steel, or masonry were selected from the literature. These case buildings included low-, mid-, and high-rise buildings. From the case studies, we selected those that compared a wooden building with a non-wooden one, which resulted in 92 case buildings. In addition, the components and lifecycle stages of the case buildings included in the studies were assessed. Next, the studies using LCA as a sustainability evaluation tool were selected, and the case data and findings on GHG emissions were collected. Only studies that directly compared GHG emissions of wooden to non-wooden buildings were included in order to have the same methodological choices for the DF calculations. Finally, we used the GHG values to calculate the DF values (explained in subsection 2.2) of wooden buildings and conducted an analysis of wooden buildings based on wood use.

2.1. Selection of case buildings from the literature

Studies were selected based on the search strategy and the author's knowledge. In the first step, the phrases 'GHG emissions of timber buildings' and 'GHG emissions of timber buildings' were searched using Scopus on 14 January 2024; these searches yielded 221 and 93 results, respectively (a total of 314 results). After limiting the results to journal articles and excluding conference papers, reports, and book chapters, 221 (151 + 70) papers remained. At this stage, we added 16 papers based on our knowledge that were not found by the search, while also removing duplicates, which brought the total number of papers to 237. Then, we conducted a screening exercise and removed 88 papers that were outside of the scope of this study. In the final step, 90 papers were excluded through full-text assessment, leaving 56 papers. From these studies, we selected only the ones in which at least one timber building was compared to non-wooden ones; this resulted in 92 case buildings (see supplementary information for further details).

2.2. Calculation of DF

To calculate the DF, we used equation (1), below, which comes from the study by Hafner *et al* [45]. Originally, the DF was introduced by Sathre and O'Conner [40], and this version is used extensively in the literature (see, e.g. [46, 47]). In order to avoid confusion, we have named the DF used in this study as $\mathrm{DF}_{\mathrm{H\&S}}$. In the equation, the GHG emissions of wooden buildings are deducted from the GHG emissions of non-wooden buildings and then divided by the GHG emissions of non-wooden buildings,

$$\mathrm{DF}_{\mathrm{H\&S}} = \frac{\mathrm{GHG}_{\mathrm{Building\_other}} - \mathrm{GHG}_{\mathrm{Building\_timber}}}{\mathrm{GHG}_{\mathrm{Building\_other}}} \tag{1}$$

where $\mathrm{GHG}_{\mathrm{Building\_timber}}$ is the GHG emissions of a timber building and $\mathrm{GHG}_{\mathrm{Building\_other}}$ is the GHG emissions of other (i.e. non-wooden) buildings, including steel, concrete, and masonry. The value of DF varies between −1 and 1, where a positive (negative) value shows a reduction (increase) in GHG emissions when constructing buildings with wood instead of steel, concrete, or masonry. A higher DF value indicates greater potential for reducing upfront-embodied GHGs (UE-GHGs) through material substitution.

2.3. Typology of case buildings

For more detailed data analysis, we categorized the studies by author, year, and location of the study; building type and area; number of floors; material used; and the LCA method applied in the study (process, IO, or hybrid LCA). The buildings were classified as low-rise (1–3 floors), mid-rise (4–9 floors), and high-rise

(10+ floors); in this study we use the phrase mid-to-high-rise in places where we include both mid- and high-rise buildings. The study cases come from different locations, showcasing the comprehensiveness of the present study.

While the material used for the construction of the case buildings was concrete, steel, masonry, or wood, the types of wood used included logwood, CLT, and glulam. In some cases, the type of wood was mixed (e.g. CLT and glulam). The trend of wood use in building construction showed that wooden products with less processing, such as logwood, have been used for lower rise buildings, but the option of engineered wood, such as CLT, has been applied more during recent years.

2.4. The GHG emissions of the case buildings

The GHG emissions evaluations in the selected studies were mainly conducted (by their authors) by performing an LCA for the entire lifecycle of a building. Overall, there are three types of LCAs, namely the process LCA, the input–output (IO) LCA, and the hybrid LCA, which is a combination of the process and IO LCAs (see, e.g. [48–50] for detailed information). The process LCA is one of the most widely used LCAs, although there are some limitations with this method because of its dependency on the results of the incorporated system [51, 52]. The IO LCA uses a broader scope and is performed by tracing the energy use and emissions production of different industries, but this type of LCA has lower granularity [53–55]. The hybrid LCA combines the IO and process LCAs in order to minimize the errors of the individual methods [56, 57]. All three types of LCAs were found in the reviewed studies.

We acknowledge that process-based, IO, and hybrid LCAs differ in terms of their system boundaries, with IO LCAs often yielding higher GHG emission values due to their broader scope. However, since our DF values were calculated based on within-study comparisons—where both wooden and non-wooden buildings were assessed using the same LCA approach and in a single study—the influence of these boundary differences on DF outcomes was minimized.

While LCA studies can include pre-use (construction), use (operation), and end of life (EoL) phases, we only considered the pre-use phase (A1–A5) values from the reviewed studies for our comparison (A1: raw material extraction and supply, A2: transport to manufacturer, A3: manufacturing, A4: transport to construction site, A5: construction and installation). In order to consider biogenic carbon accounting, there are two main LCA approaches, namely 0/0 and $-1/+1$. Note that in some countries, these approaches may be used but with modifications for specific considerations (mainly based on EoL scenarios) [58]. In the 0/0 approach, biogenic carbon is counted as 0 in module A, while in the $-1/+1$ approach, carbon is counted as stored in module A (negative emissions) and released in module C (EoL). This study used the 0/0 approach, which assumes a neutral balance (no credit or debit) in both the construction and EoL phases. This approach is widely accepted as a robust method for evaluating UE-GHGs, particularly in comparative studies where EoL scenarios may vary significantly.

2.5. Wooden building classification

While our analysis primarily focused on DF values derived from comparative LCAs, we have also proposed a conceptual classification of timber buildings based on qualitative assessments. This categorization includes fully wooden buildings as well as varying degrees of hybrid structures (e.g. Hybrid25, Hybrid50, Hybrid75), as presented in table 2 in the Results section. However, due to the limited availability of detailed material data (e.g. bills of materials or exact volumes of wood used), we were not able to apply this classification systematically across all case studies.

In a number of cases, we made qualitative assessments of likely wood content levels based on multiple contextual indicators, including building type, height classification (e.g. detached house vs. mid-rise apartment), year of construction, regional context, the presence of engineered wood products (e.g. CLT, glulam), textual descriptions, and building images. These assessments were also supported by the professional experience of the authors, particularly in identifying material systems and structural typologies in LCA documentation. While informative, these evaluations were not used as a formal basis for analysis. Instead, they are presented as a conceptual framework intended to support more consistent classification and reporting in future research where more detailed data is available.

3. Results

3.1. The CO_2-eq emissions of wooden and non-wooden buildings

The results indicate that the UE-GHG emissions of wooden building construction options ranged from 40 to 1170 kg CO_2-eq/m^2, depending on the method and scoping of a particular study (table 1). This observation rationalizes our research design—it is not sensible to compare wooden building emissions across case studies but rather to focus on building comparisons within studies then calculate the DF in each reviewed study, and

Table 1. The 81 case buildings and their UE-GHG emissions (kg CO_2-eq/m^2).

No.	Author	Year	Building type	GA (m^2)	Floors	Location	Structural	Non structural	Products	LCA method	Material	UE-GHG emissions (kg CO_2-eq/m^2)
1	Cole and Kernan	1996	Office	4620	3	Canada	a	a		Process	Timber (a)	320
2	Cole and Kernan	1996	Office	4620	3	Canada	a	a		Process	Concrete (a)	330
3	Cole and Kernan	1996	Office	4620	3	Canada	a	a		Process	Timber (b)	340
4	Cole and Kernan	1996	Office	4620	3	Canada	a	a		Process	Concrete (b)	350
5	Cole and Kernan	1996	Office	4620	3	Canada	a	a		Process	Steel (b)	360
6	Cole and Kernan	1996	Office	4620	3	Canada	a	a		Process	Steel (b)	380
7	Trusty and Meil	1999	Detached res.	223	1 or 2	Canada	a			Process	Lumber	280
8	Trusty and Meil	1999	Detached res.	223	1 or 2	Canada	a			Process	Steel	340
9	Trusty and Meil	1999	Detached res.	223	1 or 2	Canada	a			Process	Concrete	420
10	Borjesson and Gustavsson	2000	Apartment res.	1679	4	Sweden	a			Process	Timber	50
11	Borjesson and Gustavsson	2000	Apartment res.	1679	4	Sweden	a			Process	Concrete	80
12	Fay *et al*	2000	Detached res.	183	2	Austria	a	a	a	Hybrid	Timber	730
13	Fay *et al*	2000	Detached res.	183	2	Austria	a	a	a	Hybrid	Masonry (Brick)	790
14	Saari	2001	Detached res.	135	1 or 2	Finland	a	a	a	Process	Wood	200
15	Saari	2001	Detached res.	2447	1 or 2	Finland	a	a	a	Process	Concrete	220
16	Lenzen and Treloar	2002	Apartment res.	1679	4	Sweden	a			Hybrid	Timber (a)	90
17	Lenzen and Treloar	2002	Apartment res.	1679	4	Sweden	a			Hybrid	Concrete (a)	110
18	Lenzen and Treloar	2002	Apartment res.	1679	4	Sweden	a			Hybrid	Timber (b)	110
19	Lenzen and Treloar	2002	Apartment res.	1679	4	Sweden	a			Hybrid	Concrete (b)	130
20	Lenzen and Treloar	2002	Apartment res.	1679	4	Sweden	a			Hybrid	Timber (c)	160
21	Lenzen and Treloar	2002	Apartment res.	1679	4	Sweden	a			Hybrid	Concrete (c)	170
22	Häkkinen and Virtanen	2006	Public	7600	3	Finland	a			Process	Timber	40
23	Häkkinen and Virtanen	2006	Public	7600	3	Finland	a			Process	Concrete	120
24	Gustavvson *et al*	2006	Apartment res.	1700	4	Sweden	a	a		Process	Lumber (a)	220

(Continued.)

Table 1. (Continued.)

No.	Author	Year	Building type	GA (m^2)	Floors	Location	Structural	Non structural	Products	LCA method	Material	UE-GHG emissions (kg CO_2-eq/m^2)
25	Gustavvson *et al*	2006	Apartment res.	1700	4	Finland	a	a		Process	Concrete (a)	260
26	Gustavvson *et al*	2006	Apartment res.	1679	4	Sweden	a	a		Process	Lumber (b)	300
27	Gustavvson *et al*	2006	Apartment res.	1679	4	Finland	a	a		Process	Concrete (b)	260
28	Pasanen *et al*	2011	Apartment res.	2065	4	Finland				Process	Wood type	190
29	Pasanen *et al*	2011	Apartment res.	2066	4	Finland				Process	Concrete	270
30	Fuller and Crawford	2011	Detached res.	84	1	Australia	a	a		Input–output	Logwood	1000
31	Fuller and Crawford	2011	Detached res.	101	1	Australia	a	a		Input–output	Masonry (Brick)	1010
32	Fuller and Crawford	2011	Detached res.	130	1	Australia	a	a		Input–output	Masonry (Brick)	1030
33	Fuller and Crawford	2011	Detached res.	149	1	Australia	a	a		Input–output	Masonry (Brick)	1120
34	Fuller and Crawford	2011	Detached res.	170	1	Australia	a	a		Input–output	Masonry (Brick)	1120
35	Fuller and Crawford	2011	Detached res.	195	1	Australia	a	a		Input–output	Masonry (Brick)	1140
36	Fuller and Crawford	2011	Detached res.	214	1	Australia	a	a		Input–output	Masonry (Brick)	1170
37	Gong *et al*	2012	Apartment res.	5590	3	China	a	a		Process	Lumber	190
38	Gong *et al*	2012	Apartment res.	5590	3	China	a	a		Process	Concrete	190
39	Passer *et al*	2012	Apartment res.	1609	3	Austria	a	a	a	Process	Timber (a)	490
40	Passer *et al*	2012	Apartment res.	1980	3	Austria	a	a	a	Process	Concrete (a)	540
41	Passer *et al*	2012	Apartment res.	1381	3	Austria	a	a	a	Process	Timber (b)	660
42	Passer *et al*	2012	Apartment res.	970	3	Austria	a	a	a	Process	Concrete (b)	670
43	Passer *et al*	2012	Apartment res.	1150	3	Austria	a	a	a	Process	Concrete (b)	770
44	Takano *et al*	2014	Apartment res.	1243	3	Finland	a	a		Process	Timber (a)	100
45	Takano *et al*	2014	Apartment res.	1243	3	Finland	a	a		Process	Steel (a)	130
46	Takano *et al*	2014	Apartment res.	1243	3	Finland	a	a		Process	CLT (b)	150
47	Takano *et al*	2014	Apartment res.	1243	3	Finland	a	a		Process	Concrete (b)	180
48	Takano *et al*	2014	Apartment res.	1243	3	Finland	a	a		Process	Concrete (b)	200

(Continued.)

Table 1. (Continued.)

49	Takano *et al*	2014	Apartment res.	1243	3	Finland	a	a	Process	Masonry (Brick) (b)	210
50	Ajayi *et al*	2015	Public	2100	2	Canada	a	a	Process	Timber	120
51	Ajayi *et al*	2015	Public	2100	2	Canada	a	a	Process	Steel	350
52	Ajayi *et al*	2015	Public	2100	2	Canada	a	a	Process	Masonry (Brick)	380
53	Ajayi *et al*	2015	Public	2100	2	Canada	a	a	Process	Masonry (Brick)	390
54	Hafner and Schäfer	2017	Apartment res.	723	4	Germany	a	a	Input–output	CLT (a)	157
55	Hafner and Schäfer	2017	Apartment res.	723	4	Germany	a	a	Input–output	Masonry (a) (b)	257
56	Hafner and Schäfer	2017	Apartment res.	723	8	Germany	a	a	Input–output	CLT (b)	168
55*	Hafner and Schäfer	2017	Apartment res.	723	4	Germany	a	a	Input–output	Masonry (a) (b)	257
57	Hafner and Schäfer	2017	Apartment res.	3847	5	Germany	a	a	Input–output	CLT + Timber (c)	181
58	Hafner and Schäfer	2017	Apartment res.	1478	4	Germany	a	a	Input–output	Masonry (c) (d) (f)	341
59	Hafner and Schäfer	2017	Apartment res.	1257	4	Germany	a	a	Input–output	Timber (d)	182
58*	Hafner and Schäfer	2017	Apartment res.	1478	4	Germany	a	a	Input–output	Masonry (c) (d) (f)	341
60	Hafner and Schäfer	2017	Apartment res.	1172	5	Germany	a	a	Input–output	Timber (f)	214
58*	Hafner and Schäfer	2017	Apartment res.	1478	4	Germany	a	a	Input–output	Masonry (c) (d) (f)	341
61	Hafner and Schäfer	2017	Apartment res.	2717	4	Germany	a	a	Input–output	Timber (e)	196
62	Hafner and Schäfer	2017	Apartment res.	2717	4	Germany	a	a	Input–output	Masonry (e) (g)	217
63	Hafner and Schäfer	2017	Apartment res.	6152	3	Germany	a	a	Input–output	Timber (g)	239
62*	Hafner and Schäfer	2017	Apartment res.	2717	4	Germany	a	a	Input–output	Masonry (e) (g)	217
64	Hafner and Schäfer	2017	Apartment res.	1394	6	Germany	a	a	Input–output	Timber (h)	248
65	Hafner and Schäfer	2017	Apartment res.	1394	6	Germany	a	a	Input–output	Masonry (h)	316
66	Pierobon *et al*	2019	Office	14 715	11	US	a		Process	CLT + Glulam (a)	334
67	Pierobon *et al*	2019	Office	14 715	11	US	a		Process	Concrete (a) (b)	450
68	Pierobon *et al*	2019	Office	14 715	11	US	a		Process	CLT + Glulam (b)	328
67*	Pierobon *et al*	2019	Office	14 715	11	US	a		Process	Concrete (a) (b)	450
69	Liang *et al*	2020	Office	8360	12	US (Portland)	a	a	Process	CLT + Glulam	193
70	Liang *et al*	2020	Office	8360	12	US (Portland)	a	a	Process	Concrete	237

(Continued.)

Table 1. (Continued.)

No.	Author	Year	Building type	GA (m^2)	Floors	Location	Structural	Non structural	Products	LCA method	Material	UE-GHG emissions (kg CO_2-eq/m^2)
71	Jayalath *et al*	2020	Apartment res.	1248	8	Australia	a			Hybrid	CLT	550
72	Jayalath *et al*	2020	Apartment res.	1248	8	Australia	a			Hybrid	Concrete	1111
73	Jayalath *et al*	2020	Apartment res.	1248	8	Australia	a			Hybrid	CLT	544
74	Jayalath *et al*	2020	Apartment res.	1248	8	Australia	a			Hybrid	Concrete	1098
75	Jayalath *et al*	2020	Apartment res.	1248	8	Australia	a			Hybrid	CLT	557
76	Jayalath *et al*	2020	Apartment res.	1248	8	Australia	a			Hybrid	Concrete	1099
77	Li *et al*	2021	Detached res.	111	1	China	a	a		Hybrid	Timber	309
78	Li *et al*	2021	Detached res.	137	2	China	a	a		Hybrid	Steel	310
79	Li *et al*	2021	Detached res.	140	2	China	a	a		Hybrid	Steel	407
80	Li *et al*	2021	Detached res.	177	2	China	a	a		Hybrid	Masonry	556
81	Li *et al*	2021	Detached res.	120	1	China	a	a		Hybrid	Masonry (clay brick)	631
82	Amiri *et al*	2021	Office	4013	4	Iceland	a	a		Process	CLT (a)	379
83	Amiri *et al*	2021	Office	4013	4	Iceland	a	a		Process	Concrete (a) (b)	664
84	Amiri *et al*	2021	Office	4013	4	Iceland	a	a		Process	Concrete (a) (b)	672
85	Amiri *et al*	2021	Office	4013	4	Iceland	a	a		Process	Timber (hybrid) (b)	562
83*	Amiri *et al*	2021	Office	4013	4	Iceland	a	a		Process	Concrete (a) (b)	664
84*	Amiri *et al*	2021	Office	4013	4	Iceland	a	a		Process	Concrete (a) (b)	672
86	Rinne *et al*	2022	Apartment res.	2000	5	Finland	a	a		Process	CLT (a)	168
87	Rinne *et al*	2022	Apartment res.	2000	5	Finland	a	a		Process	Concrete (a) (b)	230
88	Rinne *et al*	2022	Apartment res.	2000	5	Finland	a	a		Process	Timber (hybrid) (b)	226
87*	Rinne *et al*	2022	Apartment res.	2000	5	Finland	a	a		Process	Concrete (a) (b)	230
89	Robati and Oldfield	2022	Office	43 229	13	Australia	a	a		Process	Timber	417
90	Robati and Oldfield	2022	Office	43 229	13	Australia	a	a		Process	Concrete	465
91	Zhang *et al*	2023	Office	10 000	10	China	a	a		Process	Timber (hybrid)	132
92	Zhang *et al*	2023	Office	10 000	10	China	a	a		Process	Concrete	192

Note: See the supplementary file for comprehensive information on the table.

* The case buildings that have been used for comparison for more that one time in a study.

only after that compare the DF values across case studies. While the within-study results were reasonable due to the same scoping (e.g. included and excluded components) and same assumptions, this was not the case when comparing UE-GHG emission results across studies. Notwithstanding this condition, our analysis revealed a pattern in UE-GHG emission comparisons within each study, namely that UE-GHG emissions from wooden buildings were systematically lower than from other comparable buildings. On average, UE-GHG emissions from wooden buildings were 23% lower than from non-wooden buildings, while the median difference was 18%.

In order to visualize the wooden buildings, we separated the studies that included comparisons between wooden buildings and other options (within each study). In the event of multiple wooden or non-wooden case buildings, we used symbols (a) or (b), respectively, in front of the case name and compared these with cases with the same symbol (figure 1). After the exclusion of non-comparative case studies, 92 case buildings were left in the data, as mentioned in the Methods section. On average, wooden buildings were found to have the lowest UE-GHG emissions, followed by masonry, steel, and finally concrete buildings. The range of minimum to maximum values for steel buildings was the narrowest, while all other building types (wooden, concrete, and masonry buildings) had roughly the same ranges in terms of values.

3.2. DF values for wooden buildings

Applying equation (1) from Subsection 2.2, the DF values were found to be positive for wooden buildings, showcasing a potential to reduce UE-GHG emissions. The average DF value for studies published before 2014 was 0.13 and, interestingly, substantially higher (0.33) for more recent studies (i.e. studies less than 10 years old). As wooden buildings have attracted increasing interest in recent years as a climate change mitigation option, it seems that the low-carbon design has gained more attention in practice as well. This trend may also reflect improvements in LCA practices, material efficiency, and a greater emphasis on sustainability in the built environment.

In one specific study, from 2006, the DF value was negative (−0.15; see figure 2) due to limited use of wood in the wooden building structure, which supports calls for a clear definition of a wooden building: some buildings are classed as wooden when only a few of the building components are wood. In another study, from 2017, the DF value for wooden buildings was also negative (−0.10).

For further evaluation, we analyzed the DF values based on the LCA method used in the studies, the height and type of the building, and the scope of the inventory. Only the LCA method selection and low-rise (especially detached houses) vs high-to-mid-rise comparison produced interesting differences between the groups, so only figures for these two categorizations are presented here (figures 3 and 4), and the other two are provided in the supplementary information (SI).

Figure 3 shows that the average DF value for process LCA was 0.24 (range −0.15 to 0.69), and 0.20 (range −0.10–0.5) for IO and hybrid LCA. The process-based LCA studies found higher DF values for wooden buildings compared with IO and hybrid LCA studies; this is likely to be because the IO and hybrid LCA studies based their calculations mostly on average industry data, while the process LCA studies utilized more project-specific LCA data.

Figure 4 shows the average DF values for low-rise buildings as 0.22 (range 0–0.69) and 0.24 (range −0.15 to 0.5) for mid-to-high-rise ones. Some low-rise buildings had higher DF values, which is mainly due to using less processed or natural wood for their construction, resulting in lower UE-GHG emissions. This observed trend highlights the need for further research into the influence of material processing on DFs.

3.3. Fully wood and hybrid wooden buildings

Wooden buildings are considered to have less UE-GHG emissions compared to other buildings made from materials such as concrete, steel, or masonry. However, in practice, all wooden buildings contain other building materials, such as concrete for foundations, metal for HVAC, and so on. Due to this, the definition of wooden buildings appears to be arbitrary in the reviewed articles. The issue here is that any building with some wooden components might be called a ‘wooden building.’ Our study shows that a non-wooden building can have lower UE-GHG emissions compared to a wooden one. This is the case when a building is classed as ‘wooden’ but has a limited number of wooden components or the wood for its construction is substantially processed. In this case, the DF value may be negative. On the other hand, it is possible to construct a masonry building with local materials and minimum processing, which results in low emissions.

Based on the findings of our review study, we suggest that the ‘wooden building’ definition would benefit from a broader understanding of the wooden building concept, accepting the fact that all wooden buildings are hybrid buildings in the real world. The wooden building definition might work similarly to the green certification of buildings. As a comparison, there are several studies confirming that green-certified buildings, especially at the lower levels of certification (e.g. Certification in Leadership in Energy and Environmental Design—this certificate system has four levels of Certified, Silver, Gold, and Platinum), will

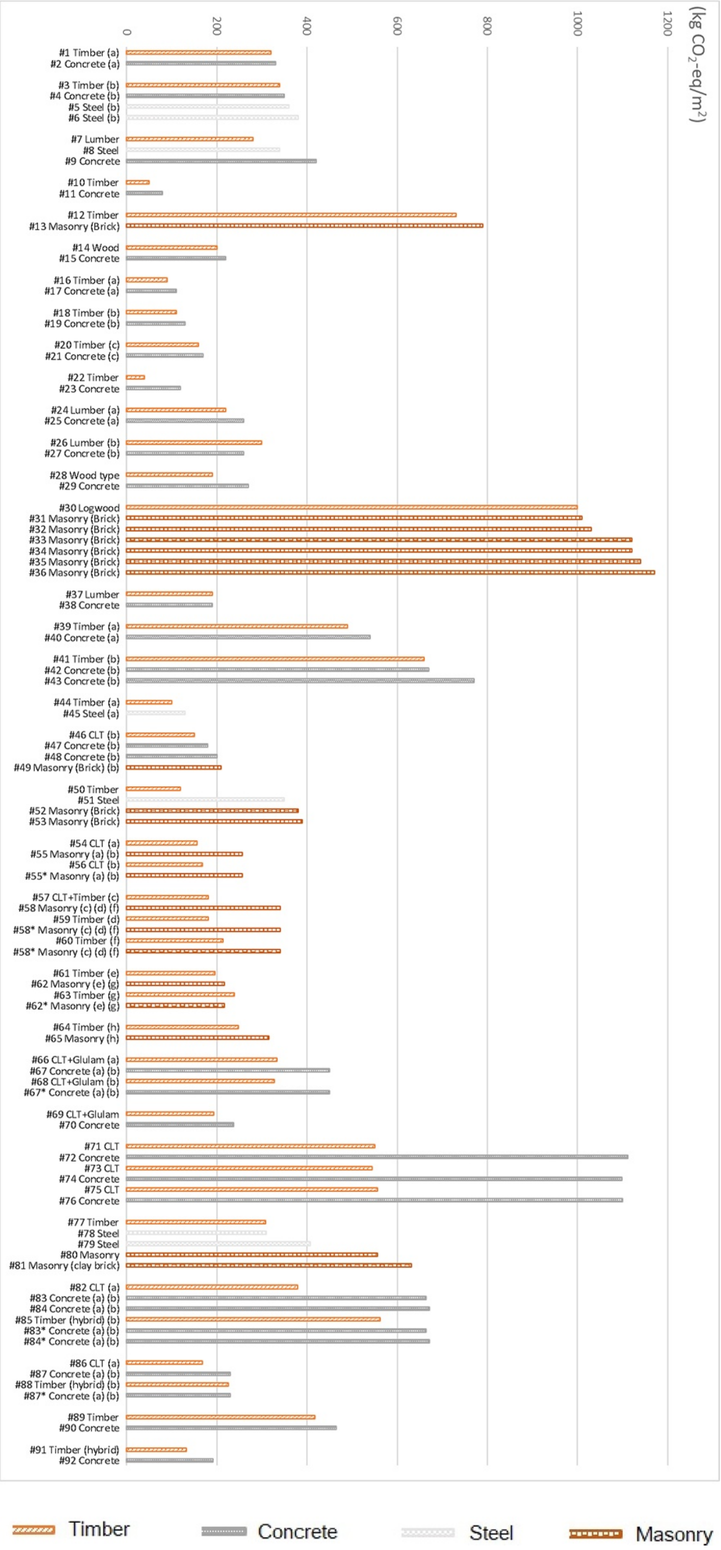

Figure 1. Comparison of UE-GHG emissions for wooden and non-wooden buildings in each study (kg CO_2-eq/m^2). *Please check the supplementary information (SI) for higher resolution and detailed information on this figure 3

not save energy or produce lower emissions [3]. It is inappropriate to classify a building with only a few wooden components, such as a façade or finishing, as wooden; hence, clearer categorization is needed.

Building components can typically be divided into structural and nonstructural components. If a building's structural and nonstructural components are made of wood, they can be classed as fully wooden buildings. In cases where the structure is non-wooden and the nonstructural components, such as floors, ceilings, or nonstructural walls, are made of wood, they can be classed as semi-wooden buildings.

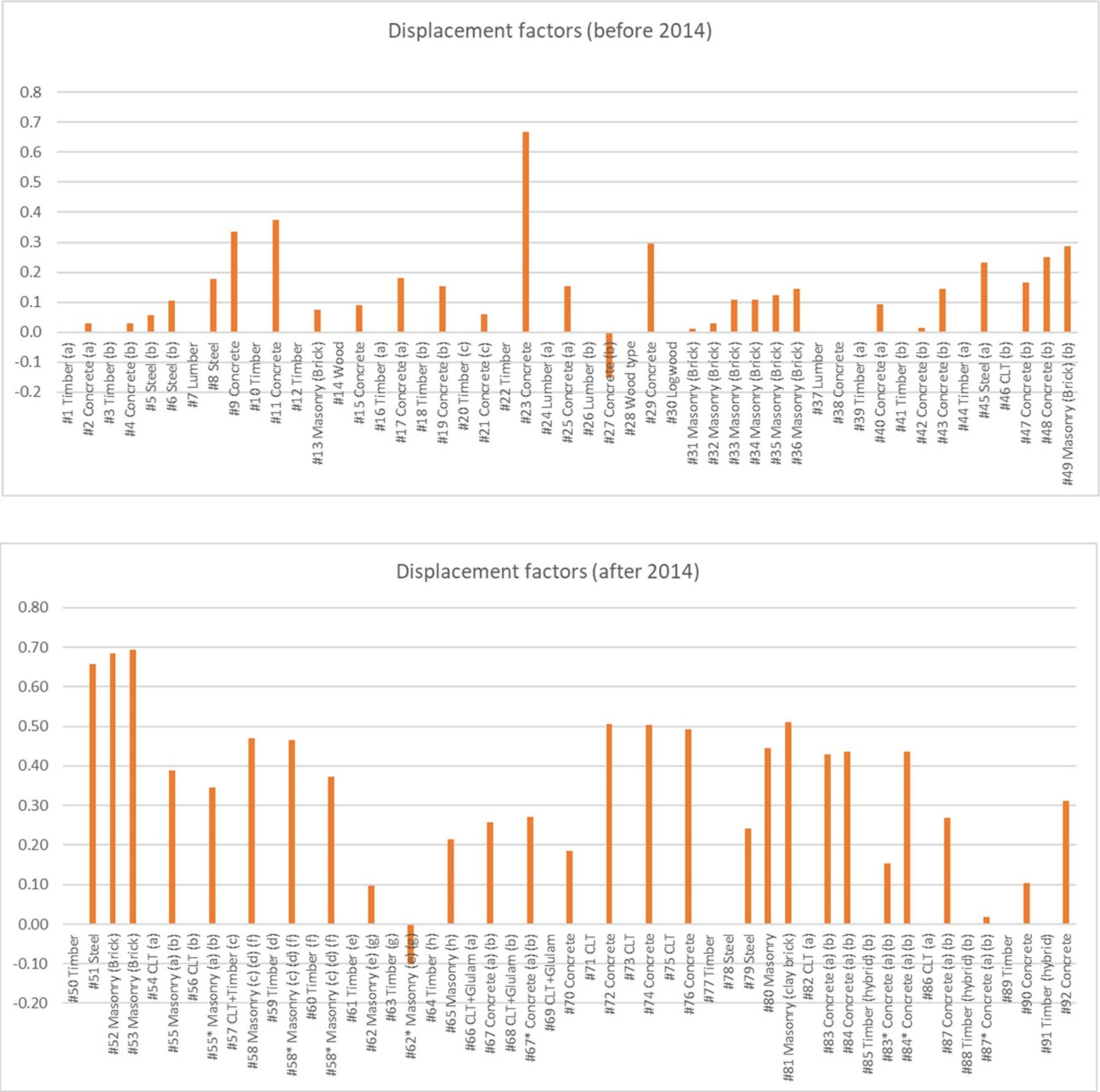

Figure 2. DF values (wooden buildings compared to steel, concrete, and masonry buildings).
Note: Boxplot format figure is available in the SI.

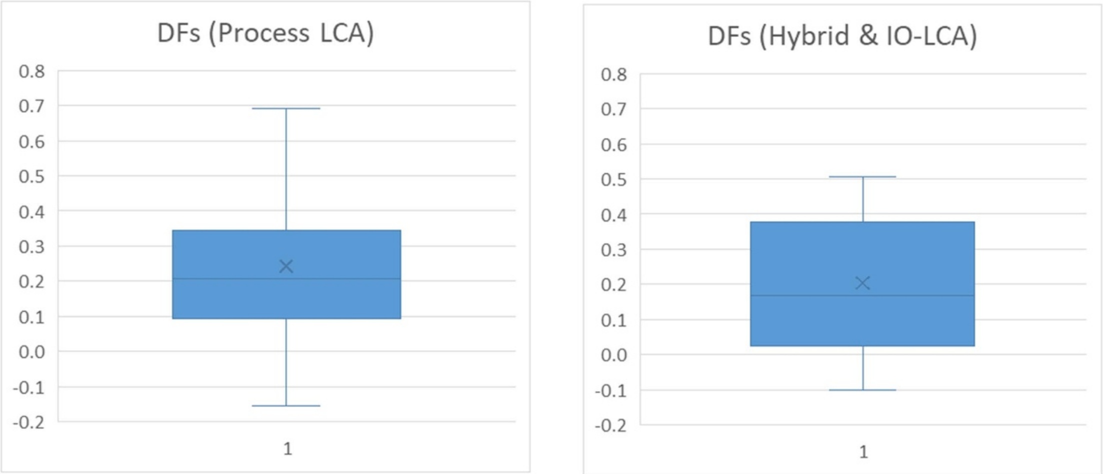

Figure 3. DF values based on LCA method.

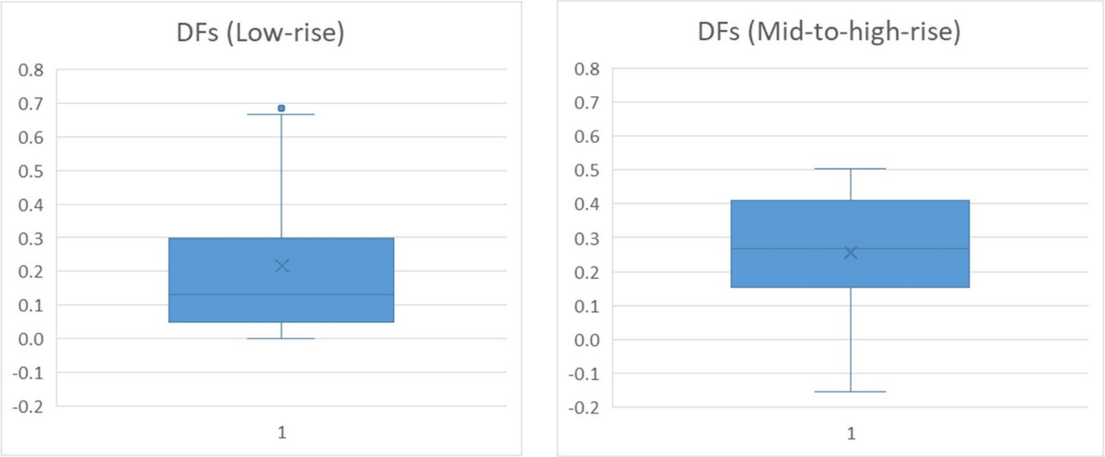

Figure 4. DF values based on the height of the case buildings.

Table 2. The definition of a hybrid wooden building, based on wood use.

Share of wood use	Wooden (structural + nonstructural components)	Semi-wooden (nonstructural components)
>95%	Wooden building	Not possible
>75%	Hybrid75 wooden building	Hybrid75 semi-wooden building
>50%	Hybrid50 wooden building	Hybrid50 semi-wooden building
>25%	Hybrid25 wooden building	Hybrid25 semi-wooden building

Many real-world projects involve hybrid wooden structures that combine wood with other materials, such as reinforced concrete. To help improve transparency and comparability in future studies, we propose a framework for describing the wood content of both structural and nonstructural components. For instance, buildings could be qualitatively rated as having approximately 50%, 75%, or over 95% wood content based on the proportion of materials such as CLT, glulam, or solid lumber used in their construction (table 2). This categorization is not used to systematically classify the reviewed studies in this paper but is recommended as a guiding approach for future work to support more precise comparison and policy alignment.

Table 1 showed that, in practice, some of our research cases could be considered as Hybrid50 or less (i.e. hybrid wooden buildings with other construction materials than wood used in bearing structures). In those studies, the structure of the building is made of a combination of wood with concrete or steel.

One option used is to construct any underground floors and the ground floor using concrete and the upper floors using wood. Another option is when a hybrid wooden building needs to be constructed in a location susceptible to earthquakes. These buildings can be designed to fulfill the earthquake impact requirements, for example, a CLT structure with a reinforced concrete stem (such as a staircase) for a mid-to-high-rise building. Different options for hybrid wooden buildings exist, which highlight the need for classification, as they might present quite different emissions savings. For example, a hybrid wooden case building in Finland saved near zero emissions compared to a concrete one [59], while another study in China showcased an almost 30% emissions saving by a hybrid wooden building compared to a concrete building [60].

While a focus on types of wooden or hybrid wooden buildings is necessary, the other factor for wooden building construction improvement is their share compared to non-wooden ones at a city level. In fact, there are two variables for future scenarios of wooden construction: one is the number of wooden buildings compared to non-wooden ones (concrete, steel, and masonry), and the other is the different UE-GHG emission values for wooden buildings compared to non-wooden ones. Both of these variables need to be considered by decision-makers.

4. Discussion

This study synthesized existing comparative LCAs to evaluate the GHG emissions performance of wooden buildings relative to non-wooden alternatives. Drawing on a systematically selected set of case studies from different global regions, building types, and height categories, we focused on embodied emissions from the pre-use phase (A1–A5) to calculate DFs. The DF serves as an indicator of the potential GHG emissions savings when replacing conventional building materials—such as concrete, steel, or masonry—with wood. The results showed a predominance of positive DF values, confirming that wooden buildings generally produce lower UE-GHG emissions compared to their counterparts.

The overall range of DF values in our dataset was from −0.154 to 0.692, with recent studies suggesting an average GHG emissions benefit of around 30% for wooden buildings. However, DF values varied significantly depending on building characteristics. In particular, low-rise wooden buildings, such as single-family homes, consistently exhibited higher DF values, a trend that aligns with findings from previous studies (e.g. [45, 61]). These buildings are often constructed with minimally processed or natural wood, which contributes to lower emissions. In contrast, mid- and high-rise buildings often rely on engineered wood products, such as CLT, which require more processing and may result in reduced GHG emission benefits. While the sample of high-rise cases was limited, their DF values were generally in line with those of mid-rise buildings.

The DF is a useful tool for comparative analysis, particularly within studies that examine multiple building designs under consistent assumptions. Our findings suggest that DF should be applied with caution in cross-study comparisons, as methodological differences—including system boundaries, material inclusion, case building location, and LCA methods—can introduce substantial variability. This is evident in table 1 and supported by prior research by Leskinen *et al* [43], highlighting the challenges of comparing absolute GHG values across studies using different LCA approaches. Moreover, interpreting DF values near 1 or −1 requires careful attention, as extreme differences in emissions between buildings can lead to similar DF values despite very different contexts. These variations reinforce the importance of using DF within clearly defined and comparable study settings.

Another factor influencing emissions performance is the degree of wood processing. Wooden buildings that use minimally processed or natural wood, such as small-diameter roundwood, tend to have lower embodied GHG emissions [61]. Although design limitations can arise from using such materials, these can be addressed through innovations in material processing, prefabrication, and structural connection systems [62–65]. Engineered wood products, such as CLT, are becoming more common, especially in multistory buildings, due to their favorable mechanical properties, standardization, and speed of construction. Improved CLT production methods could also allow for reduced material use through lower safety factors, provided that mechanical performance improves. However, it is important to note that CLT manufacturing contributes to GHG emissions, and the carbon benefits are dependent on the type and quantity of wood used, as well as the overall building design.

Additionally, combining timber with low-carbon concrete, especially in hybrid structures or foundations, offers further opportunities to reduce emissions. For example, using wood can reduce the foundation size by 30%–50%, which can be even more beneficial when low-emission cement alternatives are used [30] Studies also show that hybrid buildings made from wood and concrete can outperform fully concrete buildings in terms of GHG emissions [18, 61]. These strategies suggest that a combined material approach, along with technical improvements and policy support, can help to advance low-carbon construction practices in urban settings.

Our analysis focused on the pre-use phase (Stages A1–A5), which represents the UE-GHG emissions of building materials. While this scope aligns with the early decision-making stage of building design, we recognize the importance of considering the full lifecycle, including Stage B (the use phase) and Stage C (the end-of-life phase). In particular, Stage C—although often contributing a smaller share of total emissions—is poorly defined in many studies, especially regarding demolition and material reuse strategies. This is a gap that future research should address, especially for hybrid timber buildings. Furthermore, our findings are based on the 0/0 biogenic carbon accounting approach, which assumes that carbon is neither credited nor debited in modules A or C. Under alternative approaches, such as the −1/+1 method, the role of stored carbon becomes much more significant, potentially altering the perceived climate benefits of timber buildings.

Although our findings suggest that wooden buildings emit less upfront GHGs compared to non-wooden alternatives, it is important to acknowledge the potential role of publication bias. Studies that report favorable environmental outcomes for timber are more likely to be published, especially in journals focused on sustainability. This may lead to an overrepresentation of positive findings in the literature and should be considered when interpreting the overall trends. To address this, future reviews could incorporate gray literature or unpublished studies to provide a more balanced view of DFs and embodied emissions.

Another important consideration is the treatment of carbon storage and forest impacts in LCA. While many attributional LCAs, including those reviewed in this study, focus on the direct emissions from materials and construction processes, consequential LCAs explore the broader system effects of increased timber demand. These effects may include deforestation, changes in land use, and competition with biodiversity or food production. For instance, Hurmekoski *et al* [48] showed that expanding timber harvests to support decarbonization goals may delay carbon payback periods, while warned that excessive harvesting could undermine forest ecosystems. Similarly, Mishra *et al* [66] projected that rising global demand for wood could have significant land use impacts by 2100. However, they also suggested that these risks can be mitigated through careful planning and strong forest governance. These broader sustainability dimensions are not fully captured in most building LCAs and should be further explored in future research.

As countries pursue carbon neutrality goals under the Paris Agreement, the role of the built environment in climate mitigation becomes increasingly important. The European Union, for example, has committed to carbon neutrality, while countries such as Singapore, Finland, and Sweden have announced even more ambitious targets for 2030–2045. One way to contribute to these targets is through long-term carbon storage in wooden buildings. When properly maintained, wood products in buildings can retain stored carbon for decades. Extending the lifecycle of buildings, promoting reuse and recycling after demolition, and incorporating timber into circular construction models can further prolong this carbon storage. However, it is also important to distinguish between carbon sequestration and offsetting, as offsetting merely reduces or avoids emissions elsewhere without directly removing CO_2 from the atmosphere.

A key issue in scaling up timber construction is the availability and sourcing of wood. Global wood demand is already high, with annual roundwood use reaching 2028 million m^3 and wood used as fuel accounting for 1943 million m^3 in 2018, according to the FAO [67]. As timber is redirected from short-lived uses (such as fuel) to long-lived uses (such as buildings), it can contribute to climate change mitigation. This shift, however, requires careful planning and innovation, especially in the production of engineered wood products. Additionally, reduced demand for carbon-intensive materials such as cement and steel may further lower emissions across the supply chain. Importantly, timber used in construction does not need to originate solely from natural forests. Planted forests and agroforestry systems, particularly those that are intensively managed, can offer higher wood yields with lower environmental impact [67].

Despite these opportunities, the widespread use of wood in construction raises concerns that must be addressed through responsible forest management. Unsustainable harvesting practices and monoculture plantations may lead to biodiversity loss and ecosystem degradation, potentially undermining the climate benefits of timber construction. Therefore, using wood from sustainably managed forests that also support forest biodiversity is essential. In addition, wooden buildings face durability challenges, such as vulnerability to fire, moisture, insect damage, and decay. These risks require context-specific design solutions and adherence to strict building codes. As Östman *et al* [33] emphasized, fire safety in wooden buildings can be improved through measures such as structural fire resistance, fire space separation, and ensuring sufficient evacuation time for occupants. These technical and ecological concerns should be central to future research and policy strategies aimed at promoting responsible timber construction.

5. Conclusions

This study provides a comprehensive evaluation of DFs to assess the UE-GHG emissions savings achieved by using wood instead of conventional building materials such as concrete, steel, and masonry. By analyzing 92 case buildings selected through a systematic literature review, we found that wooden buildings generally have lower UE-GHG emissions during the pre-use phase (A1–A5). Most notably, low-rise wooden buildings, particularly those using minimally processed wood, demonstrated higher DF values—highlighting their strong carbon-saving potential. However, the wide range of DF values across studies, from −0.15 to 0.69, underscores the importance of factors such as building height, wood processing level, and LCA methodology.

Our findings suggest that while wood can serve as a low-carbon alternative, its carbon benefits are not uniform and depend heavily on design choices, material sourcing, and construction practices. To ensure consistency in future research and policy, we recommend a clearer definition of what constitutes a 'wooden building,' including a classification system based on the share and structural role of wood in the building. Additionally, hybrid construction methods, the use of engineered wood, and improvements in recycling practices offer promising pathways for further reducing emissions. However, the broader application of wood in construction also requires careful attention to forest sustainability, biodiversity impacts, durability challenges, and fire safety. Addressing these factors through regulation, innovation, and responsible sourcing is essential to ensure that timber buildings contribute effectively to climate goals. This research contributes to more informed decision-making for sustainable construction and supports the integration of timber in carbon mitigation strategies within the building sector.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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