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TOPICAL REVIEW

Carbon storage in the built environment: a review

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Abstract

With a rapidly decreasing carbon budget, the urgency of deep greenhouse gas reductions becomes increasingly necessary. This accentuates the need for the emerging paradigm shift, transforming the built environment from a major source of CO_2 emissions to a carbon sink. Biogenic carbon sequestration and storage (CSS) has the potential to play a pivotal role as it offers multiple pathways for cities to improve their carbon sink capacity. There are various methods used to quantify the carbon storage potential of the built environment, and there is a lack of consensus on how biogenic carbon should be treated. This review aims to elucidate the ways in which scientific literature has considered carbon storage in the built environment by drawing a picture of the existing mechanism for CSS in the urban built environment with the focus on the existing mechanism of biogenic CSS materials. Limitations and challenges of using biogenic CSS materials are identified to point out future research directions. In addition, barriers hindering wider utilization of CSS in the built environment are discussed.

Definition List

Aboveground carbon storage	Carbon storage that occurs at or above ground level
Belowground carbon storage	Carbon storage that occurs below the surface of the ground
Biogenic carbon	Carbon absorbed from the atmosphere during biomass growth
Carbon content	Carbon contained within a material
Carbon sequestration	The process of removing carbon from the atmosphere
Carbon sink	Something that absorbs more carbon than it releases
Carbon storage	The containment of carbon for a period of time
Carbon uptake	The amount of carbon removed from the atmosphere during the growth process of biogenic material
Climate change impact	Radiative forcing impact of different GHGs, relative to CO_2
Global Warming Potential (GWP)	A Metric to compare the climate impact of different GHGs, relative to CO_2
Gross carbon sequestration	Total amount of carbon removed from the atmosphere
Gross carbon storage	Total carbon contained for a period of time
Gross CO2 uptake	Total amount of CO2 removed from the atmosphere during the growth process of biogenic material

Net carbon sequestration	The amount of carbon removed from the atmosphere accounting for all carbon uptake and release
Net carbon storage	Total carbon contained for a period of time when accounting for all carbon uptake and release
Net lifetime emissions	Total lifetime emissions when accounting for all carbon uptake and release

1. Introduction

The idea of making cities more sustainable has been around for decades (Satterthwaite 1997), though the conversation has shifted from low-carbon to net-zero, and more recently, to beyond net-zero through carbon sequestration and storage (CSS). The paradigm in which cities are considered a carbon sink is a response to limit global temperature rise and the need for humanity to go beyond reducing greenhouse gas (GHG) emissions to negative emissions (Arehart *et al* 2021, IPCC 2023). According to the Intergovernmental Panel on Climate Change (IPCC) (2023) we only have a small remaining carbon budget, around 500 $GtCO_2$ from the beginning of 2020, referring to the amount of carbon that can be emitted to stay within the target of 1.5 °C. Friedlingstein *et al* (2022) estimate the situation to be even more dire, reporting the remaining global carbon budget to be only 380 $GtCO_2$ from the beginning of 2023 for a 50% likelihood of limiting global warming to 1.5 °C. Assuming 2022 emissions levels, this budget would be used up in less than 10 years (Friedlingstein *et al* 2022).

With a rapidly decreasing carbon budget, the urgency of deep GHG reductions becomes increasingly necessary. Moreover, even with rapid decarbonization, the only option to remain under 1.5 degrees warming seems to be to reach below zero emissions in just a couple short decades (IPCC 2023). Today, more than 1000 cities (UNFCCC (UN Framework Convention on Climate Change) 2020) and over 130 countries (Net Zero Tracker 2023) around the globe are considering or have committed to reducing emissions to net-zero by 2050 at the latest. While this is an important step forward, the likelihood of achieving these goals has been questioned (Climate Action Tracker 2023). This accentuates the need for the emerging paradigm shift, transforming the built environment from a major source of CO_2 emissions to a carbon sink (e.g. Cao *et al* 2020, Churkina *et al* 2020, Pomponi *et al* 2020), meaning that the built environment would absorb more carbon than is released driven by it.

While the built environment is currently a major source of emissions with a staggering share of 40% of the annual global emissions, it is possible to transform this source of emissions into a carbon sink and storage (Amiri *et al* 2020, Churkina *et al* 2020, Talvitie *et al* 2023). Biogenic CSS has the potential to play a pivotal role as it offers multiple pathways for cities to improve their carbon sink capacity. For example, Kuittinen *et al* (2023) identified the following biogenic methods to improve carbon storage rates in the built environment: i) utilization of biobased construction materials ii) biochar utilization in soils iii) enhancing natural photosynthesis and iv) uptake of carbon into soils. The first two methods represent indirect biogenic methods, where the initial CSS is converted into a long-term storage in the built environment by secondary processes, often outside the urban boundary. Amiri *et al* (2020) and Talvitie *et al* (2023) have demonstrated the potential efficiency of these methods, up to net positivity. The latter two represent direct methods, which improve the resulting carbon sink and storage within the cityscape *in-situ*. Multiple researchers have demonstrated the potential of this direct carbon sink to mitigate production-based emissions of cities as well as its influence on regional-level CSS capacity (e.g. Zhao *et al* 2010, Nowak *et al* 2013, Berglihn and Gomes-Baggethun 2021). As such, biogenic carbon sinks can manifest in the cityscape and should thus be accordingly accounted for in the urban carbon balance.

There are various methods used to quantify the carbon storage potential for the built environment, though life cycle assessment (LCA) is the most common approach. Global warming potential (GWP) is widely used in LCA. It is recognized by the IPCC and expresses the cumulative radiative forcing over a specified time horizon in CO_2 equivalent (CO_2eq) (IPCC 1990). Despite being widely employed, there is a lack of consensus on how biogenic carbon should be treated in LCA (Breton *et al* 2018). There are several approaches to address the temporal aspect of biogenic carbon. First, is a static approach 0/0, referred to as the 'carbon neutral approach', where the biogenic carbon uptake during the growth process (0) is equal to the biogenic carbon released at the end-of-life (EoL) (0), essentially disregarding biogenic carbon. A second static approach, −1/+1, considers the biogenic carbon uptake to be negative (−1) and release to be positive (+1). One benefit of this approach is that it gives an overview of the biogenic carbon flows (Hoxha *et al* 2020). According to Galimshina *et al* (2022), the main drawback of both of these approaches is that they do not consider the time biogenic carbon is stored in the built environment or the biogenic material regrowth time. To better account for the timing aspect, dynamic approaches have been developed (Hoxha *et al* 2020). Levasseur *et al* (2010) first proposed a dynamic LCA (DLCA) approach using time-dependent characterization factors to account for the effects of delayed emissions. Cherubini *et al* (2011) developed characterization factors for biogenic CO_2, including the biomass regrowth period, to calculate the biogenic GWP (GWP bio), which was later extended by Guest *et al* (2013) to also consider the length of time the biogenic carbon is stored. When comparing these three approaches in a review of 58 literature sources, Hoxha *et al* (2020) found that the 0/0 approach is mainly followed in environmental product declarations, the $-1/+1$ approach is recommended by most current standards, and the dynamic approach is recommended in scientific literature. They suggest employing a dynamic approach when assessing biogenic construction materials, as the static approaches do not accurately reflect the impact to the climate (Hoxha *et al* 2020).

This review aims to elucidate the ways in which scientific literature has considered carbon storage in the built environment. Cities as a carbon sink paradigm is evaluated through multiple domains: buildings, infrastructure, and urban modified green spaces. A wealth of research has explored the ways in which biogenic CSS can improve carbon storage rates of the built environment and how carbon storage should be accounted for. Compared to the review by Kuittinen *et al* (2023), our work covers the mentioned three built environment entities together which has not been done before. The findings of this review present CSS ranges for various biogenic materials and mechanisms that can enable comparison across the built environment domains. Through this perspective, we aim to give a more wholistic view of the built environment's potential to contribute to a carbon sink and storage future.

There is an ongoing discussion about whether existing mechanisms for CSS in the urban built environment can successfully contribute to cities as carbon sinks. Many studies have tried to quantify and compare the CSS rates of different materials with contrasting methods which have led to different outcomes. Therefore, a systematic review of the current development is needed to comprehensively explore their limitations and identify the existing research gaps so that future studies can better address them.

By conducting this review, this work aims to fulfill three objectives: draw a picture of the existing mechanism for CSS in the urban built environment, to identify the limitations and challenges of using biogenic CSS materials, and to point out future research directions.
The review focuses on the following research questions:

1. What are the existing mechanisms for carbon sequestration and storage in the urban built environment?
2. What is the contribution of distinct components to carbon sequestration and storage within the urban environment?

To control the scope, the review focuses on the Nordic context. However, building materials and infrastructure are less restricted to geographic location, as materials that are not natural in the Nordic context could be imported and utilized in the Nordic region. For the urban green infrastructure domain, location was narrowed down to the Nordics. This focus was imposed to account for the variations in physical conditions across different regions, which pose challenges in achieving a univocal quantification of CSS potential.

The structure of this review is as follows: section 2 presents the methods and research design. Section 3 showcases the results. Finally in section 4, we conclude with the discussion and implications.

2. Method

2.1. Research design

First, a screening of the literature in the field of carbon sink cities was conducted. Based on this review, the urban built environment was divided into three domains: buildings, infrastructure, and human-modified urban green spaces, referred to as urban green infrastructure. A new round of literature search was then conducted in each domain and systematically reviewed as explained in the following section.

2.2. Selection of studies

Two methods were used to select studies for the literature review: (1) the snowball method was used to collect 15 papers based initially on the knowledge of the authors and accumulated based on their references and the next references and so on. (2) a search was conducted in Google Scholar, the Scopus database, and the Web of Science database between September 3rd and December 20th, 2021 using a combination of search terms connected with Boolean operators 'AND' and 'OR' where relevant. Table 1 lists the primary and secondary search terms used to identify articles of interest. The search began broadly with 'carbon sink cities' and was narrowed down to select articles relevant to each of the three domains. New papers were added to the collection with them coming out and reaching the recognition of the authors.

Table 1. Primary and secondary search strings used for literature search.

Domain	Substance
Buildings	Carbon storage
Building materials	Sequestration
Wood	Carbon sink
Harvested wood products	Biogenic carbon
Timber	LCA
Glulam	
Bamboo	
Cement	
Hempcrete	
Cork	
Green roofs	
Green walls	
Living walls	
Infrastructure	
Bridges	Carbon storage
Timber	Sequestration
Roads	Carbon sink
Asphalt	Biogenic carbon
Retaining walls	LCA
Utility poles	Sustainable
Urban green infrastructure	
Urban vegetation	Carbon
Urban forest	Negative emissions
Urban soil	Ecosystem services

Based on this search, 151 articles were initially identified. These 151 articles were then screened for relevance based on (1) title, (2) abstract, and (3) full-text using the following criteria:

1) Focus on the urban built environment
2) Relates to one of the three domains: buildings, infrastructure, urban green infrastructure
   a. In the urban green infrastructure domain, focuses on the Nordic context
4) Addresses carbon storage
5) Peer reviewed, excluding literature review studies and conference papers
6) This screening led to a final collection of 40 papers for the review. Included papers are listed in table 2.

2.3. Review methodology

In the review process, an article was subjected to a comprehensive read through, where its methodology, results and main conclusions were documented and critically evaluated. The reported CSS rates were documented with notation whether the numbers referred to net or gross rates. Data were initially collected as presented in each paper. Due to significant differences among reported units, the reported CSS rates were converted to equivalent units, uniform across the different reviewed domains where possible.

3. Results

Based on the papers collected during the review process, the urban built environment was organized into the mentioned three main domains. These domains were further divided into sub-domains i.e. buildings were categorized as foundation & structure and insulation & finishes following the focus areas of the reviewed literature. Within these sub-domains, various materials and biogenic structures are discussed in the next subsections. Figure 1 shows the breakdown of the three domains used to frame the results including the identified gaps in research. Table 3 summarizes the calculated or reported CSS based on biogenic structure and mechanism, with relevant literature. Each biogenic structure is categorized into sub-domain and domain.

3.1. Buildings

The existing literature divides buildings into three key entities in terms of research on carbon storing materials: foundation & structure, insulation, and finishes, though some studies address buildings as a whole. For example, Dabaieh *et al* (2020) assessed a complete refugee house utilizing primarily bio-based

Table 2. Lists literature included in this review, sorted into the three domains (buildings=Bldgs, infrastructure=Infra, urban green infrastructure=UGI), including keywords and geographic area.

	Study	Year	Domain	Keywords	Geographic area
1	Arehart *et al*	2020	Bldgs	Hempcrete, carbonation, LCA, embodied carbon, carbon storage, carbon sequestration	N/A
2	Arrigoni *et al*	2017	Bldgs	LCA, hempcrete, natural building material, CO_2 uptake, carbonation	Italy
3	Azzi *et al*	2019	Bldgs	N/A	Sweden
4	Chang *et al*	2018	Bldgs	Carbon emissions, environmental benefit, plybamboo, bamboo utilization, LCA	Taiwan
5	Chen *et al*	2022	Bldgs	N/A	China
6	Dabaieh *et al*	2020	Bldgs	LCA, minus carbon, GHG, refugee housing, urban living lab	Sweden
7	Demertzi *et al*	2017	Bldgs	Biogenic carbon, building materials, environmental impact, expanded cork granules, expanded cork slab, LCA	Portugal
8	Galimshina *et al*	2022	Bldgs	LCA, life cycle cost analysis, uncertainty quantification, building renovation	Switzerland
9	Geß *et al*	2021	Bldgs	LCA, insulation material, renewable resources	Germany
10	Gu *et al*	2019	Bldgs	Climate change, carbon emission reduction, bamboo floor, green-level, carbon storage	China
11	Hafner & Schäfer	2018	Bldgs	N/A	Germany, Austria
12	Hawkins *et al*	2021	Bldgs	LCA, building design, embodied carbon, timber, climate emergency	UK
13	Head *et al*	2020	Bldgs	Wood products, buildings, dynamic LCA, climate change, biogenic carbon	Canada
14	Hepburn *et al*	2019	Bldgs	N/A	Global
15	Mattila *et al*	2012	Bldgs	Carbon storage, straw, pyrolysis, natural building, LCA	Finland
16	Peñaloza *et al*	2016	Bldgs	LCA, dynamic LCA, wood construction, biogenic CO_2, climate impact assessment	Sweden
17	Pittau *et al*	2018	Bldgs	Carbon storage, wall, fast-growing materials, biogenic materials, dynamic LCA, LCA	Switzerland
18	Pittau *et al*	2019	Bldgs	N/A	EU-28
19	Resch *et al*	2021	Bldgs	Buildings, LCA, embodied emissions, dynamic, biogenic, carbonation	N/A
20	Scrucca *et al*	2020	Bldgs	Agriculture, buildings, hemp hurds, LCA, energy consumption, GHG emission	France
21	Sierra-Perez *et al*	2016	Bldgs	Insulation materials, LCA, cork, renewable material, sustainable construction, building energy	Spain
22	Xi *et al*	2016	Bldgs	N/A	Global
23	Xu *et al*	2022b	Bldgs	Bamboo building materials, carbon emissions, carbon storage, carbon reduction potential, construction industry	China
24	AzariJafari *et al*	2021	Infra	Carbonation, data science, concrete mix design, EoL, pavement use, abatement cost	US
25	Bergman *et al*	2014	Infra	N/A	US

(Continued.)

Table 2. (Continued.)

26	Bouhaya *et al*	2009	Infra	N/A	France
27	Cherian & Siddiqua	2021	Infra	Wood ash recycling, pulp and paper industry, subgrade stabilization, mechanical properties, microstructural evolution, environmental impact	Canada
28	Hou *et al*	2021	Infra	Recycled aggregates, compacted recycled sand, carbonation CO_2 uptake, road construction	France
29	Hung *et al*	2009	Infra	Kyoto Protocol, carbon sink CO_2 sequestration, wooden leisure facilities, eco-technology, green materials	Taiwan
30	O'Born	2018	Infra	Timber bridge, LCA, road infrastructure	Norway
31	Peñaloza *et al*	2018a	Infra	Life cycles, wooden bridges, concrete bridges, environmental engineering, climate change, biogenic carbon storage, concrete carbonation	Sweden
32	von der Thannen *et al*	von der Thannen *et al* 2020	Infra	Soil bioengineering, LCA, openLCA, Ecoinvent, civil engineering	Austria
33	Ariluoma *et al*	2021	UGI	Biochar, carbon sink, green infrastructure, LCA, urban trees, urban yards	Finland
34	Berglihn & Gomez-Baggethun	2021	UGI	Ecosystem services, urban forest, Oslomarka, Oslo, green infrastructure, nature-based solutions, Norway	Norway
35	Linden *et al*	2020	UGI	CO_2, ecosystem services, hemi-boreal climate, park management, Urban green space, urban soils	Finland
36	Lu *et al*	2020	UGI	Impervious surfaces, top soil removal, construction layer	Finland
37	Poeplau *et al*	2016	UGI	N/A	Sweden
38	Riikonen *et al*	2017	UGI	Carbon sequestration, tree soil carbon, tree biomass equations, urban trees	Finland
39	Setälä *et al*	2016	UGI	Plant functional groups, soil carbon, nitrogen and organic matter concentration, soil ecosystem services, urban park age, soil depth	Finland
40	Tarvainen *et al*	2019	UGI	Urban geochemistry, compositional data, heatmap, soil, Finland	Finland
41	Tidaker *et al*	2017	UGI	Carbon footprint, golf, LCA, life cycle assessment, turf maintenance	Sweden

materials, including straw, clay, lime, timber, reeds and wood fiber insulation. Their assessment included two options: the pre-use phase emissions without inclusion of the carbon content of the materials, and with the carbon content accounted for. The GWP was shown to be −226.2 kg CO_2eq /m^2 when the carbon content was accounted for, compared to 257.7 kg CO_2eq /m^2 without the carbon content. Through DLCA, Peñaloza *et al* (2016) compared a concrete structure, a cross laminated timber (CLT) structure, and a structure with 69% biobased material, under four different scenarios with different time horizons, timing of forest regrowth, building lifetime, and EoL scenarios. The biobased material consisted of CLT, cellulose fiber insulation, glue laminated timber (glulam), sawn timber, and plywood. When including forest regrowth during the service life of the building, they found the GWP assessed in the 100 year time perspective to be −188 kg CO_2eq /m^2 of living area for the biobased building. Under the same parameters, the CLT building

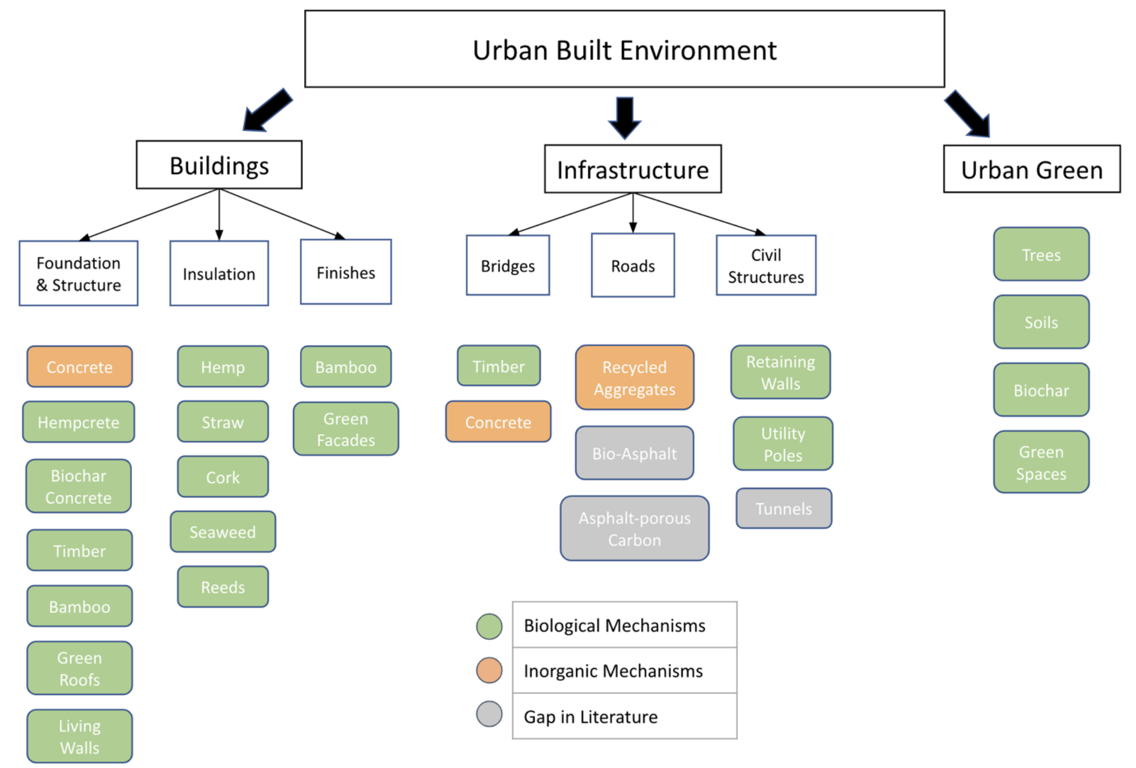

Figure 1. Shows the breakdown of the three domains in the urban built environment: buildings, infrastructure, and urban green infrastructure.

was shown to temporarily sequester carbon, though the net-lifetime GWP was positive (5 kg CO_2eq /m^2 of living area). This was still a significant reduction compared to the concrete building that resulted in 462 kg CO_2eq /m^2 of living area. Hafner and Schafer (2018) analyzed 12 large multi-story residential buildings constructed with frame materials of CLT, timber, reinforced concrete, brick, and a hybrid of these materials. The CLT frame building was found to have the highest stored CO_2, −209.8 kg CO_2eq /m^2 of gross external area, over the 50 year lifetime, despite demonstrating net-positive lifetime emissions. Moreover, Amiri *et al* (2020) showed in their review how several wooden building case studies found the carbon storage in the wooden materials to exceed the pre-use phase emissions. These results emphasize the potential of the various plant-based construction materials utilized in building construction in converting the built environment into a means of carbon storage. Next, each one of the three key sub-domains is covered.

3.1.1. Foundation and structure

Traditional materials for the foundation and structure of buildings include concrete, steel, and wood. For steel and concrete production, technological carbon capture and storage (CCS) can significantly reduce the embodied emissions (e.g. IEA 2019, Paltsev *et al* 2021), though this paper is focused on the material itself as a storage mechanism rather than using CCS to decarbonize the upstream production process.

3.1.1.1. Concrete

Traditional concrete can store carbon through two primary methods: cement carbonation and CO_2 cured concrete. The first method occurs naturally when CO_2 in the air chemically reacts with calcium hydroxide and hydrated calcium silicate, resulting in stable carbonates. In a 2016 study, Xi *et al* estimated that 1.4 Gt, or 43% of CO_2 emissions from the production of cement over the period of 1930–2013 have been offset through cement carbonation, excluding the emissions associated with fossil fuel use during cement production. Cumulative emissions from cement production over the same period were estimated to be 38.2 Gt CO_2 (Xi *et al* 2016). While lime-based products do absorb carbon over their lifetime, Pittau *et al* (2018) found this reduction in emissions does not compensate for the high initial emissions associated with the production of these materials. The carbonation process is also very slow (Possan *et al* 2016), meaning that the production-phase emissions remain in the atmosphere for a considerable period even for the share sequestered in the carbonation process. The natural carbonation process could be enhanced in the EoL phase. If the concrete from demolished buildings was crushed, increasing the surface area exposed to air, the

Table 3. Presents the biogenic structures, categorized into sub-domains where relevant, and domain. The carbon sequestration mechanism is shown with CSS values. In most cases, the CSS values were calculated from results presented in the reviewed literature to enable comparability within and across the domains.

Biogenic structure	Sub-domain	Domain	Mechanism	CSS values	Relevant literature (running numbers from table 2)
Concrete	F&S	Bldgs	Hempcrete	0.04–0.72 kg CO_2eq /kg*	1, 2, 17
			Biochar concrete	0.60–0.78 kg CO_2eq /kg*	5
	Roads	Infra	Demolition concrete	30–60 kg CO_2eq /m^3	28
			Recycled binders	Not reported	27
Timber	F&S	Bldgs	Timber	1.7–2.8 kg CO_2eq /kg*	13
			CLT	1.6 kg CO_2eq /kg*	12
			Glulam	1.41 kg CO_2eq /kg*	12
	Bridges	Infra	Lumber, plywood, particle board	1.84 kg CO_2 /kg*	26, 29, 30, 31
	Other—Utility pole	Infra	Timber	1.9 kg CO_2eq /kg*	25
Bamboo	F&S	Bldgs	Plybamboo	1.5–1.9 kg CO_2eq /kg*	4
			LBL	2.2 kg CO_2 /kg*	23
	I&F	Bldgs	Scrimber flooring	0.3 kg CO_2 eq /kg	10
Green roofs & living walls	F&S	Bldgs		Not reported	
Straw	I&F	Bldgs	Straw insulation	1–1.63 kg CO_2eq /kg*	8, 15, 17,
Hemp	I&F	Bldgs	Hemp insulation	1.68–1.9 kg CO_2eq /kg	8, 19
Cork	I&F	Bldgs	Cork board	2.08–2.33 kg CO_2eq /kg*	7, 20
			Cork granulates	1.49 kg CO_2eq /kg*	21
Seaweed	I&F	Bldgs	Seaweed insulation	−1.23 kg CO_2eq /kg	9
Reed	I&F	Bldgs	Reed insulation	−2.18 kg CO_2eq /kg	9
	Other	Infra	Retaining walls	Not reported	32
Trees		UGI	Aboveground carbon storage	8.11–41.8 kg CO_2eq /m^2	33, 34, 35 38
Soil		UGI	Belowground carbon storage	4.04–130.3 kg CO_2eq /m^2	33, 35, 36, 37, 39, 40, 41

*calculated from presented results based on reported density of material for Buildings and Infrastructure domains. Results reported in hectares were converted to square meters for the urban green infrastructure (UGI) domain. Results presented in kg C were converted to kg CO_2 using a conversion factor of 3.67 based on atomic weight.

carbonation process could be greatly enhanced compared to the natural carbonation speed during the building lifetime (Maia Pederneiras *et al* 2022).

The second method intentionally injects CO_2 to cure concrete, though this reduces the natural cement carbonation (Liu 2021). Hepburn *et al* (2019) reported the storage potential for this method is estimated to store between 0.1 and 1.4 Gt CO_2 /yr over the long term on the global scale—with the CO_2 sequestered well beyond the lifespan of the infrastructure itself. Alternative concrete mixes have been discussed in a sustainability context, including recycling and replacing aggregates to reduce the use of cement and potentially sequester carbon (Kazemian and Shafei 2023). Hempcrete is a bio-based composite which is a mixture of hemp shives and a lime binder. The compressive strength of hempcrete reported in the academic literature ranges from 0.125–4.74 MPa (Jami *et al* 2019), compared to structural concrete which must have a minimum compressive strength of 20.7 MPa according to International Building Code (IBC 2021). It is not a replacement for traditional concrete due to its low strength properties, though it has become popular as an insulation material alternative, demonstrating negative lifetime emissions (Arrigoni *et al* 2017). Through

LCA, Arrigoni *et al* (2017) found that a hempcrete wall absorbed a net 12.09 kg CO_2eq /m^2 or 0.14 kg CO_2eq /kg of hempcrete material, when accounting for the CO_2 uptake in the growth of the hemp and short-term CO_2 absorption from the binder after 240 d. The CO_2 uptake was reported to be 0.72 kg CO_2eq /kg of hempcrete and 1.84 kg CO_2eq /kg of hemp shives. This resulted in a carbon sink, with net-negative lifetime emissions. The authors estimate the overall emissions balance would be −26.01 kg CO_2eq /m^2 of hempcrete wall, or −0.31 CO_2eq /kg of material, if the binder was completely carbonated. Arehart *et al* (2020) assessed 36 hempcrete formulations using a theoretical carbon storage mathematical model based on DLCA. When accounting for biogenic carbon storage and carbonation, they determined hempcrete can have net-negative lifetime emissions, depending on the density and binder type. The CO_2 uptake from different hempcrete formulations ranged from 1 kg CO_2eq /m^2 of wall assembly, or 0.04 kg CO_2eq /kg of hempcrete, for the very light density hempcrete, up to above 60 kg CO_2eq /m^2 of wall assembly, or 0.28 kg CO_2eq /kg of hempcrete, for the heavy density hempcrete. Another concrete alternative that is widely studied is biochar concrete (Gupta *et al* 2018). Biochar is a material produced by burning biogenic material in the absence of oxygen. Reports for the carbon storage potential vary, depending on the feedstock and use, though gross ranges fall between 2.0 kg to 2.6 kg of CO_2eq /kg (Azzi *et al* 2019). Biochar can be used for many applications in construction materials to achieve carbon neutrality or carbon negativity, including as a filler in cement, aggregates in concrete, and in composites such as asphalt (Zhang *et al* 2022). Chen *et al* (2022) found that concrete with 30 wt% biochar as an aggregate and 9 wt% metakaolin, a supplementary cementitious material, as a binder can sequester a net 0.059 kg CO_2 /kg of concrete block. This mix was found to have the best mechanical properties, with a compressive strength of 10.3 MPa. The authors found that increased use of biochar negatively affected the compressive strength of the biochar concrete blocks. Supplementary cementitious materials, such as the metakaolin, in turn enhanced the strength, so all mixtures they tested fulfilled the strength requirement of 7 MPa.

3.1.1.2. Timber

Timber as a building material has been studied most extensively in the context of CSS. Timber building materials are often referred to under the umbrella term harvested wood products (HWP) (Geng *et al* 2017) but can further be broken down into specific products referred to as glulam (Issa *et al* 2005) and CLT (Brandner *et al* 2016). It is important to keep in mind that accounting for the carbon storage potential of timber products is greatly influenced by the underlying assumptions such as EoL treatment, time horizon, and forestry practices (e.g. Røyne *et al* 2016, Head *et al* 2020, Hawkins *et al* 2021, Morris *et al* 2021, Resch *et al* 2021), discussed further in section 4.

Hawkins *et al* (2021) compared concrete, steel, and timber building materials using DLCA. For timber, they considered CLT and glulam, reporting each material has a gross sequestration of −1.6 kg CO_2 /kg and −1.41 kg CO_2 /kg respectively. The sequestration is assumed to occur between the harvest (year 0) and the rotation (year 50), though the authors highlight the assumed timing of carbon sequestration in a DLCA model can lead to highly variable results. They found that when accounting for sequestration under an optimistic scenario with bioenergy with carbon capture and storage capturing all EoL emissions, timber can provide a net-negative impact to global warming. They do highlight the influence that assumptions in the model have in the results but report the climate benefit from timber components improves the longer the biogenic carbon stays contained in the built environment.

Head *et al* (2020) developed life cycle inventories and dynamic climate change impacts of Canadian wood products, accounting for temporary carbon storage, EoL emissions of wood products used in buildings, and GHG emission profiles of forest impact from wood harvest with temporal differences. The CO_2 uptake from the various species considered ranged between around 1.7 kg CO_2eq /kg of wood product, up to 2.8 kg CO_2eq /kg of wood product. They found that the dynamic life cycle of wood products in buildings has an overall net-negative climate change impact in the 100 year time horizon for most wood products. They reported the climate change impact ranging from −1263 to −388 kg CO_2eq /m^3 of wood product or −0.93 to −3.02 CO_2eq /kg of wood product. These differences are mainly attributed to the wood products lifespan. In a case study of 20 timber buildings using DLCA, Resch *et al* (2021) found that wood products in buildings can have mitigation effects through biogenic CO_2 uptake, particularly during longer time horizons. Specifically, the CLT and timber materials resulted in net-negative lifetime emissions when the building life was assumed to be 80 years, assessed in the 100 year time perspective.

3.1.1.3. Bamboo

Also an alternative to steel, bamboo has been considered useful in structural components of a building, particularly in place of rebar in traditional reinforced concrete. Commonly used applications include laminated bamboo lumber (LBL) (Chen *et al* 2020), glue laminated bamboo (Xiao *et al* 2017), bamboo plywood (plybamboo), and bamboo scrimber (Huang *et al* 2019). In general, bamboo grows best in the tropical climates of Asia, Africa, America, and Oceania, though there is the potential for some species to be grown in Europe (Depuydt *et al* 2019). China is the world's largest grower of bamboo and largest exporter of bamboo products, so most of the academic literature is focused on this region (Gan *et al* 2022). Despite this, there is potential to import this material for use in the Nordic region. Chang *et al* (2018) used LCA to access bamboo production in Taiwan and found that plybamboo had net-negative lifetime emissions when accounting for the CO_2 uptake occurring during the growth process. Bleached plybamboo and heat treated plybamboo were found to have 1.9 kg CO_2eq gross CO_2 uptake, with net lifetime emissions of −1 kg CO_2eq /kg and −0.6 kg CO_2eq /kg, respectively. Standard plybamboo was reported to have around 1.5 kg CO_2eq gross CO_2 uptake /kg, with net lifetime emissions of −1.2 kg CO_2eq /kg. Xu *et al* (2022b) quantified the carbon emissions and storage of bamboo components and found that bamboo building materials has the highest carbon storage potential compared to lumber, engineered lumber, concrete, steel, timber, and hempcrete. The carbon uptake of LBL was reported to be 0.6 kg C/kg of material, or 2.2 kg CO_2 /kg of material.

3.1.1.4. Green roofs and living walls

Green roofs and living walls refers to roof and wall structural components of a building that consist of several layers of vegetative material including a plant layer, soil layer, drainage, and root barrier layer (Shafique *et al* 2020). Living walls differ from green walls in that living walls are composed of embedded layers instead of relying on climbing or hanging plants (Manso and Castro-Gomes 2015). Both green roofs and living walls provide direct and indirect benefits to carbon emissions, with direct carbon sequestration through vegetation growth and indirect carbon sequestration through reduced building energy consumption (Shafique *et al* 2020). In the context of cities, green roofs and living walls provide a promising solution to improve green coverage in urban areas where space is limited (Manso and Castro-Gomes 2015). Carbon sequestration of green roofs and living walls have been studied extensively (e.g. Charoenkit and Yiemwattana 2016, Shafique *et al* 2020), though most studies focus on warm or tropical climates. The carbon sequestration potential for these structural components is highly dependent on the plant species, along with other considerations such as climate (Charoenkit and Yiemwattana 2016, Seyedabadi *et al* 2021). Despite a lack of research in the Nordic context, green roofs in Scandinavia are traditionally constructed with turf (Lonnqvist *et al* 2021), so it can be assumed the carbon sequestration potential would be similar to Nordic soils and lawns, discussed in section 3.3.

3.1.2. Insulation & finishes

Fast-growing bio-based materials have been shown to have a significant potential of capturing and storing carbon when used as thermal insulation in buildings (Pittau *et al* 2018, 2019). Particularly hemp and straw have received attention, and are therefore covered in the next section, followed by other materials and finishes.

3.1.2.1. Hemp and straw

Pittau *et al* (2018) compared different exterior wall structures using DLCA to demonstrate long-lived carbon storage in buildings. They compared hemp and straw as fast-growing biogenic materials, to timber, bricks, and cast concrete. The results of this study show that fast-growing bio-based materials have the potential to rapidly decrease the carbon footprint of buildings due to their uptake of carbon and short rotation time. The biogenic carbon stored in these fast-growing materials was shown to be restored in the crop fields after only 1 year after harvesting. For pressed straw, the CO_2 uptake was reported to be around 140 kg CO_2eq /m^2 of wall, or 1.4 kg CO_2eq/kg of material. Pittau *et al* 2018). When assessing the carbon storage potential of the EU housing stock, Pittau *et al* (2019) found that fast-growing biogenic materials have a higher carbon sink potential compared to timber and consider these materials as an insulation alternative to be an effective instrument to meet European climate goals. In a LCA study of hemp cultivation in France, Scrucca *et al* (2020) found that hemp as a building material can sequester 1.29 kg CO_2eq/kg of hemp hurds. This study showed that the carbon sink occurring during plant growth is greater than the total emissions from upstream activities, processing, and waste treatment, resulting in net-negative lifetime emissions.

Straw bale is bio-based material that is commonly utilized and widely studied in academic literature as a thermal insulation material with additional carbon storage benefits (e.g. Koh and Kraniotis 2020, Tlaiji *et al* 2022). In a 2012 study, Mattila *et al* found that straw bale construction has the potential to sequester and temporarily store around 1 kg CO_2eq/kg of straw when accounting for the sequestered carbon from the growth of straw. They conclude this material is a low-tech and promising method for CSS. Galimshina *et al* (2022) used dynamic carbon storage to see the effect of emissions offset from renovation with bio-based materials including hemp mat, straw bale, wood fiber, and hempcrete for a case building in Western Switzerland. For the scenarios including hemp mat and straw bale in the exterior wall and ceiling, they report the GWP bio to be between −0.04 and −0.28 kg CO_2eq /m^2 floor area, depending on the thickness and material used. They report the carbon content to be 45.7% for hemp mat and 44.3% for straw, which equates to a gross carbon sequestration of 1.68 kg CO_2eq/kg of hemp mat and 1.63 kg CO_2eq/kg of straw bale. Hemp and straw and are considered to be optimal insulations materials in most scenarios discussed, which the authors attribute to the short regrowth period.

3.1.2.2. Other natural materials

Other innovative insulation materials are not well studied but have carbon sequestration potential. Cork is a bio-based material that can be used as an insulation material in buildings. Using LCA, Sierra-Perez *et al* (2016) demonstrated cork insulation boards can result in net-negative lifetime emissions, depending on the EoL scenario. They report the biogenic carbon storage of the cork board to be 15 kg CO_2eq /m^2, or 2.08 kg CO_2eq /kg of cork board. The net lifetime emissions were found to be −2.80 kg CO_2eq /m^2 or 0.39 kg CO_2eq per, excluding EoL. Assuming the EoL treatment was landfill where 98% of the biogenic carbon remained contained, the net lifetime emissions were found to be −2.06 kg CO_2eq /m^2 or −0.29 kg CO_2eq /kg of cork board. With incineration as EoL treatment, all biogenic carbon was assumed to be re-emitted, resulting in net lifetime emissions of 4.07 kg CO_2eq /m^2 or 0.57 kg CO_2eq /kg of cork board. Demertzi used LCA to assess the environmental impacts from expanded cork slab and granules. The net-lifetime GWP was calculated to be between −2.183 and −9.315 kg CO_2eq /m^2 of material for the cork slab or between −0.5 and −2.08 kg CO_2eq /kg of material and between −1.362 and −5.901 kg CO_2eq /m^2 of cork granulates, or between −0.31 and −1.34 kg CO_2eq /kg of material. The results were dependent on the EoL scenario and lifetime (30 or 50 years). They report the biogenic CO_2 uptake to be 2.33 kg CO_2eq /kg of expanded cork slab and 1.49 kg CO_2eq /kg of cork granules (Demertzi *et al* 2017). Natural materials, such as seaweed, have also been historically used as building materials (Widera 2014), and have reemerged in the sustainable building context. Geß *et al* (2021) compared four different renewable insulation materials using LCA. They found that seaweed insulation resulted in negative lifetime GHG emissions, along with insulation made from reed. Seaweed insulation was found to have net-lifetime emissions of −0.32 kg CO_2eq /kg of insulation material, with the gross CO_2 uptake accounting for −1.23 kg CO_2eq /kg of insulation material. For the reed insulation, the gross CO_2 uptake was shown to be −2.18 kg CO_2eq /kg of insulation material with net-lifetime emissions of −3.55 kg CO_2eq /kg of insulation material

Cellulose fiber insulation is made of plant fibers, often recycled paper or waste materials from HWP processing, though it is not commonly used in place of traditional insulation materials due to lack of experience (Hurtado *et al* 2016). Because it originates from biomass, it sequesters carbon and can provide lasting carbon storage during the lifetime of the building. Sheep wool has been more widely studied as an insulation alternative e.g. (Parlato and Porto 2020), though most research is focused on the physical and insulation properties of this material. Korjenic *et al* (2015) found that sheep wool had the lowest lifetime CO_2 emissions compared to traditional mineral wool, though this study did not account for the carbon sequestration potential of sheep wool. Mycelium composites, grown from fungi, are emerging as a novel building material that have the potential to be used as foams, finishes, plastics (Jones *et al* 2020) and insulation (Xing *et al* 2018). According to Jones *et al* (2020), the carbon sequestration resulting from the natural growth process of this material is one its key advantages.

3.1.2.3. Finishes

Hafner and Özdemir (2023) emphasize the importance of timber finishing elements for GHG reduction due to their ability to be installed in any type of building regardless of building type. Gu *et al* (2019) discuss carbon storage in bamboo scrimber flooring with connection to carbon sequestration in fast-growing bamboo forests. They found that 1 m^3 of bamboo scrimber flooring had a net-negative lifetime emissions of −14.89 kg CO_2eq, or −0.02 kg CO_2eq /kg of flooring. The CO_2 uptake accounted for 0.3 kg CO_2eq /kg of flooring, which is significantly lower compared to the structural bamboo material discussed in section 3.1.1. They applied a weighted factor in their calculated method to account for the service life which could explain this difference. Additionally, green facades can be added to new or existing buildings through a variety of methods including direct greening, with traditional climbing plants, and indirect greening with trellis support (Manso and Casrto-Gomes 2015). This can increase green coverage and resulting carbon sequestration, particularly in urban areas.

3.2. Infrastructure

The literature on carbon storage in infrastructure is much more limited, though the materials that have carbon storage potential used in the building domain can also be utilized in infrastructure to some extent. The limited number of studies focus on mostly bridges, road pavements, with very few studies addressing other infrastructure, like utility poles and retaining walls. Other infrastructure components such as tunnels, utility services, and other civil structures are excluded due to lack of literature.

3.2.1. Bridges

Timber, discussed previously as a building structural material, also has the potential to be used for bridge construction. In a review study of lifecycle assessment on modern timber bridges, Niu and Fink (2019) found that out of the ten studies included in their review, only one included carbon storage (Bouhaya *et al* 2009), while most considered timber to be carbon neutral. Bouhaya *et al* (2009) conducted one of the few LCA studies an LCA on a timber bridge, specifically a two-lane wood beam bridge. They demonstrate the EoL assumptions have a significant impact on the results, with recycling and landfill resulting in net-negative lifetime emissions due to carbon storage in timber. Incineration at the EoL canceled out the carbon uptake in the timber growth and resulted in net-positive lifetime emissions (Bouhaya *et al* 2009). Peñaloza *et al* (2018a) compared two similar bridge designs constructed with concrete and timber. They found the timber bridge demonstrated lower lifetime emissions compared to the concrete alternative. When including concrete carbonation, and biogenic carbon storage in the timber is accounted for, the timber bridge demonstrates additional benefits to GWP, though the actual benefit is strongly influenced by the time horizon chosen in the analysis and the EoL assumption. They recommend using a long time horizon to assess both concrete carbonation and biogenic carbon storage, given these processes occur over long periods of time (Peñaloza *et al* 2018a). O'Born (2018) used LCA to compare a timber bridge to a concrete alternative and found the timber bridge has significantly lower emissions compared to the concrete bridge. Additional benefits from the timber bridge came from the EoL assumption that the timber was incinerated and energy was recovered. They assume CO_2 uptake from the growth process is released again at EoL and do not account for carbonation of concrete due to uncertainty. They conclude that timber should be implemented on a wider scale for infrastructure. On a smaller scale, Hung *et al* (2009) report a significant reduction in CO_2 emissions when replacing concrete with wooden bridges, pedestrian trails, platforms, and check dams in eco-engineered recreational facilities in Taiwan. They report the net carbon sequestration of the various wood materials used, finding that lumber ranged between −0.44 to −0.47 kg C/kg, plywood was −0.28 kg C/kg, and particle board was −0.19 kg C/kg. This equates to −1.61 to −1.71 kg CO_2 /kg lumber, 1.93 kg CO_2 /kg plywood and 0.7 kg CO_2 /kg particle board. Considering gross carbon sequestration, all materials were assumed to be 1.84 kg CO_2eq /kg, calculated by the carbon content.

3.2.2. Roads

Another important component of infrastructure is roads. Concrete and asphalt are the most common materials used in modern road construction, both associated with high GHG emissions. Using recycled and alternative materials, such as waste products for road construction have demonstrated benefits of avoided emissions by reducing the need for new material production and waste sent to landfill (Ciampa *et al* 2020, Jahanbakhsh *et al* 2020). Hou *et al* (2021) found significant carbon storage potential when using recycled aggregates from demolition concrete in sub-base layers of pavement construction. Due to natural carbonation, this material can store up to 30 kg CO_2 /m^3 of compacted recycled aggregate under normal conditions and up to 53 kg CO_2 /m^3 under accelerated conditions, though the authors report the carbonation process for this type of road construction would be slow. They recommend instead carbonating the recycled aggregate before using it in construction (Hou *et al* 2021). In a study of the US pavement network, AzariJafari *et al* (2021) found the carbon potential to be 5.8 million tonnes of CO_2 by 2050 due to carbonation. Over an extended time period of 30 years, this demonstrates significant potential for carbonation in pavement surfaces. In a 2021 study, Cherian and Siddiqua evaluated recycled pulp mill fly ash from Canada's pulp and paper industry as a binder in road construction material. They found this material has the potential to significantly reduce environmental impacts from road construction by reducing landfill waste volume from a by-product that otherwise would have been sent to landfill. They report high-carbon biochar particles in this fly ash waste product, which could serve both as carbon storage and enhance early-stage strength of this material in road construction. Bio-asphalt can serve as a replacement for traditional asphalt as a road material made with bio-based binders, such as plant-based oils or manures (Al-Sabaeei *et al* 2020) and modifiers, such as biochar (Rondón-Quintana *et al* 2022, Yaro *et al* 2023). Despite growing popularity in recent years (Rondón-Quintana *et al* 2022), there is still a significant gap in literature addressing the carbon storage potential of these bio-based alternatives.

3.2.3. Other infrastructure

Retaining walls play an important role in cities that experience significant land use changes. Soil bioengineering refers to a construction technique that utilizes biological material for civil engineering needs. This solution can include living materials such as plants, in combination with stone, soil, logs, or other non-living material (von der Thannen *et al* 2020). In a traditional LCA study, von der Thannen *et al* (2020) compare three soil bioengineering construction types in Vienne, Austria. The study only includes the construction phase and does not calculate the carbon uptake of the biogenic material, though the authors recognize including the use phase and EoL would give a more comprehensive view of the lifetime emissions (von der Thannen *et al* 2020). Utility poles are another infrastructure component that can utilize wood products. In a 2014 study, Bergman *et al* used LCA to assess the life cycle emissions from wood products, including utility poles constructed with pentachlorophenol-treated wood. They found that wooden utility poles have a net-negative lifetime emissions of −2.5 kg CO_2eq /pole or −0.004 kg CO_2eq /kg. The biogenic carbon content was assumed to be 50%, or 1.9 kg CO_2eq /kg.

3.3. Urban green infrastructure

Cities in the Nordics tend to have relatively high green land cover rates compared to many other European countries (Fuller and Gaston 2009, Kabisch *et al* 2016). This translates to relatively high importance of urban green infrastructure and related carbon pools of vegetation and soil for the city-wide carbon storage, which has received attention in the recent literature as well. The existing literature focuses on urban trees, soil storage capacity and urban green spaces, of which the first two are covered in the next sub-sections, whereas the last one is covered in the discussion section due to it largely consisting of the first two.

3.3.1. Urban trees

Berglihn and Gomez-Baggethun (2021) estimated the average gross carbon storage of trees in urban fringe forest of Oslomarka in Norway at 10.3 kg C/m^2, with annual gross sequestration of 0.1 kg C/m^2, though they note that their estimates are subject to high uncertainty. Linden *et al* (2020) estimated the aboveground gross carbon storage of urban parks in Helsinki at 2.21–2.81 kg C/m^2, highlighting the impact of coarser tree cover compared to urban remnant and fringe forests. Ariluoma *et al* (2021) estimated an average gross tree sequestration of 0.12 kg C/m^2/a which could be amplified to 0.23 kg C/m^2/a with biochar amendment in semi-public residential yards, resulting in average gross tree carbon storages of 5.94 kg C/m^2 and 11.4 kg C/m^2 during the 50 year study period, respectively. Finally, Riikonen *et al* (2017) highlighted that the emissions from the growing medium need to be accounted for when estimating the life cycle CSS impact of tree planting, as the planted street trees acted as emissions sources rather than carbon sinks during the early years after their establishment, resulting in average annual emissions or negative net sequestration of 1.3 kg C/m^2/a.

3.3.2. Soil

Soil forms the greatest terrestrial organic carbon storage globally and multiple studies have aimed at quantifying their carbon content in the Nordic urban context. Linden *et al* (2020) estimated average park soil gross carbon storage at 10.4 kg C/m^2 in Helsinki, Finland and a much higher average rate of 15.5 kg C/m^2 specifically for soils under pervious surfaces. Similarly, Setälä *et al* (2016) estimated average soil gross carbon densities of 14.9 kg C/m^2, 21.4 kg C/m^2 and 18.9 kg C/m^2 at young parks and 22.02 kg C/m^2, 23.4 kg C/m^2 and 35.5 kg C/m^2 at old parks under lawn grass, deciduous trees and evergreen trees, respectively.

Poeplau *et al* (2016) studied the impact management intensity of lawn had on the soil carbon content. Their results showed that intensive management via high frequency mowing can substantially increase soil gross carbon storage capacity, from an estimated average of 6.64 kg C/m to 7.43 kg C/m provided that the clippings are left to decay at the site. Similarly, Tidaker *et al* (2017) estimated an average gross soil carbon storage of 8 kg C/m^2 for an intensively managed golf course and an average gross sequestration of 1.6 kg C/m^2/a or an average net sequestration of 0.03 kg C/m^2 when compared to maintenance related emissions. Anthropogenic impact on soil carbon storage capacity has been studied further by Lu *et al* (2020) who demonstrated that soil sealing is extremely detrimental in cold climate environments, on average reducing surface soil gross carbon storage to 1.2 kg C/m^2, compared to an estimated 28.8 kg C/m^2 under pervious surfaces. Finally, Ariluoma *et al* (2021) demonstrated how biochar can be applied to soil to enhance soil gross carbon storage by up to 7.6 kg C/m^2.

4. Discussion

This study aimed to review the existing mechanisms for CSS potential in the urban built environment. To achieve this, a systematic review of 41 peer-reviewed published articles encompassing the CSS potential was conducted. Based on this review the urban built environment was divided into three domains: buildings, infrastructure, and urban green infrastructure. Although these studies differ in approach, system boundaries, and scope, they all demonstrate that bio-based materials have advantages over non-bio-based from an environmental perspective, like GWP over the life cycle and CSS potential.

Based on the reviewed literature, the most prominent existing mechanisms available for CSS in the urban built environment include the widespread utilization of HWP and fast-growing bio-based materials in buildings and infrastructure structures, as well as enhancing the natural photosynthesis rates and carbon storage of soil and vegetation in the urban fringe.

Storing carbon in long-lasting building elements is an important strategy for a zero-carbon society (Pittau *et al* 2019) with the potential to make the built environment a carbon storage beyond the upfront development emissions (Amiri *et al* 2020, Talvitie *et al* 2023). However, fast-growing biobased materials such as straw and hempcrete blocks are the most promising materials with high CSS potential combined with rapid carbon re-absorbtion by the new crops (Pittau *et al* 2019). They have a higher potential to act as carbon sinks compared to timber and can therefore play an important role in mitigation of climate change impacts (Pittau *et al* 2019). Temporary carbon storage in the building stock can contribute to reducing net carbon emissions and slowing climate change, which would effectively buy more time for advancements to be made in climate technologies (Morris *et al* 2021, Andersen *et al* 2022). Moreover, the EoL, which often is considered to cause high emissions in the case of biogenic materials due to the common treatment by incinerating, is a highly uncertain life cycle phase for newly built and future buildings due to the long life time of buildings and developing treatment technologies, including re-use which can significantly improve the emissions profile (Joensuu *et al* 2022). Overall, due to the uncertainty related to the emissions potentially occurring in the future, usage of a compounding factor would be advisable in assessments over longer time-periods. This would also be supported by the fact that the warming impact of any future emissions by any selected future year is lower than those emitted earlier. The incineration related EoL emissions also should not be estimated using the common static, or attributional, approach since incineration typically replaces other combustion, making the setting inherently consequential.

In the case of green infrastructure, the potential to improve CSS rates in the cityscape varies across the urban gradient. In central areas where the land value is high, less space is allocable to green spaces whereas this proportion grows towards the urban fringe. This is especially true in the Nordic cities of low average population density, where vast green areas and remnant forests are common in the suburbs and can thus greatly improve the city-wide CSS rate (Kabisch *et al* 2016, Berglihn and Gómez-Baggethun 2021). The preservation of these existing biogenic carbon sinks is crucial in transforming the cities towards carbon negative future, as urban vegetation typically takes long to recover after initial construction disturbance and transform into a net negative carbon sink, pronounced in the short growing season conditions of the Nordics (Bae and Ryu 2015, Riikonen *et al* 2017, Havu *et al* 2022). In addition, in the case of new construction solutions to increase the green infrastructures proportion of the surrounding land cover could prove beneficial, as soil sealing has been estimated to result in carbon storage losses and the increased green coverage could translate to substantial increases in the city-wide CSS rate via bottom-up scalability (Tahvonen and Airaksinen 2018, Lu *et al* 2020). Furthermore, novel solutions such as biochar additions could prevent biogenic carbon storage depletion and recover faster towards the equilibrium level after a construction disturbance (Ariluoma *et al* 2021, Kuittinen *et al* 2023).

Previous syntheses of research have demonstrated the importance of different forms of ownership, functionality and associated management practices as well as underlying physical and temporal drivers in establishing the CSS potential of urban green infrastructure (e.g. Pataki *et al* 2006, Lorenz and Lal 2015, Ignatieva *et al* 2020). In the Nordic context, the natural remnant and fringe environments are extremely important for regional CSS as demonstrated by Berglihn and Gómez-Baggethun (2021) who estimated that the annual carbon sequestration by Oslomarka trees may contribute up to 35% of the total regional forest carbon sequestration, despite only hosting approximately 0.1% of the total urban population in the Oslo area. Furthermore, Linden *et al* (2020) and Setälä *et al* (2016) highlight the importance of public green spaces amidst the city, presenting similar or slightly lower average carbon densities for urban parks compared to natural forests of the same region. The carbon storage rates of public green spaces are likely emphasized by intensive maintenance and management practices and relatively low soil respiration rates in cold environments, which increase ecosystem productivity and carbon residence times (Poeplau *et al* 2016, Setälä *et al* 2016, Tidaker *et al* 2017).

Carbon storage of semi-public and private green spaces has been studied far less compared to public green spaces in the selected study period, limited to one study which more so focused on the impact biochar could have in enhancing both above- and belowground CSS rates (Ariluoma *et al* 2021). However, past studies have shown that semi-public and private green spaces can have substantial influence on city-wide amount of urban green infrastructure and ecosystem services (e.g. Cameron *et al* 2012, Mitchell *et al* 2018, Tahvonen and Airaksinen 2018). Thus, their carbon storage qualities could present opportunities for cities to integrate them as part of the employed climate change mitigation strategies, a subject that would deserve more scientific scrutiny in the future.

Based on Linden *et al* (2020), a substantial opportunity to enhance the CSS potential of public and semi-public/private green spaces would lie in improving their tree coverage. However, this would require long-term planning of related maintenance. Riikonen *et al* (2017) estimated that it could take planted street trees up to 30–55 years to achieve net positive ecosystem exchange rates after the initial carbon losses from growing medium. This effect is subject to variation depending on vegetation and soil typology among other environmental factors, but the required life-cycle length for urban trees to reach carbon neutrality seems to be longer than for those growing in natural areas. Hence planning for longevity is crucial for tree planting to result in net positive CSS impact in the urban setting, accounting for the diverse disturbance mechanisms involved (Riikonen *et al* 2017, Tammeorg *et al* 2021).

Green and grey infrastructure interact closely to establish the city-wide carbon pool and some structural limitations specific to Nordic conditions could restrict this potential. For example, cryogenic processes characteristic of the arctic-boreal climate of Nordic cities requires the removal and replacement of soil surface layer by sand or gravel under impervious surfaces to prevent damage by freezing processes, subsequently causing carbon losses and reduced storage potential (Lu *et al* 2020).On the other hand, anthropogenic activities can also improve green space's CSS capacity, provided that they do not deplete soil C and subsequently seal the soil from further sequestration. For example, Tarvainen *et al* (2019) observed the highest total carbon contents in human induced soil layers rich in organic carbon and Ariluoma *et al* (2021) highlighted the potential of biochar treatment for increasing the long-term soil gross carbon storage rates.

While the present discourse around considering cities as a possible carbon sink has shown that there exists a significant potential, implementing the full potential of CSS in the urban built environment is extremely complex and requires efforts from various stakeholders and policymakers. Wider adoption of bio-based materials is further impeded by several barriers like market and policy barriers, lack of knowledge, and the resilience of the current technological system (Hildebrandt *et al* 2017). The potential of using wood, bio-based materials, and green infrastructure is also dependent on numerous factors which need to be considered when deciding on the most suitable material to be used within a built environment project (Morris *et al* 2021).

In the following section, we further discuss the existing barriers for implementing the full potential of CSS and research gaps based on the reviewed literature.

4.1. Market and policy barriers

In a marketplace demanding predictability and uniformity of structural products, fossil-based industries are more effective than engineered wood products in playing out their competitive advantages (Hildebrandt *et al* 2017). Therefore, a more level playing field needs to be put in place and unpredictable defects of raw materials monetized through regulatory protocols (Organschi *et al* 2016). Furthermore, the market for some wooden products does not yet exist because modern technologies cannot immediately compete against established technologies (Hildebrandt *et al* 2017). Urban governors have a primary role in managing cities and planning future developments by setting efficient policies (Stocchero *et al* 2017) and taking a lead in encouraging the use of bio-based materials by demanding their use more widely through planning and land use policies (Hildebrandt *et al* 2017, Nakano *et al* 2020, Piccardo *et al* 2021). The current climate policy is too weak and therefore it´s important to intensify efforts to identify and manage both soft (organization) and hard (technology) barriers (Karlsson *et al* 2020).

For green infrastructure, most of the market and policy barriers relate more so to the planning and zoning practices of cities. For example, many of the Nordic capital regions are currently seeking to density their urban structure, emphasizing infill construction in existing low- to mid-population density areas (e.g. City of Reykjavik 2014, City of Helsinki 2021). This drives up land value and could lead to zoning and development of high floor area ratio areas with little permeable surfaces, leaving less space for green infrastructure to act as a carbon sink. However, the practice could also lead to lower land development pressure in the urban fringe and may thus preserve the high carbon sink areas there, at least in the short run. In the end, even along with the emergence of high-density development focus, the carbon storage capacity of urban green infrastructure could be enhanced by focusing on improving the carbon capacity/land unit.

The barriers limiting progress in lowering emissions from infrastructure construction include supply chain interaction and institutional factors (Rootzén *et al* 2020). Infrastructure projects can vary in terms of culture, policies, and capabilities in the national and local context (Karlsson *et al* 2020). The central and local governments and public agencies have the power to decide how much and what kind of transport infrastructure will be built and therefore have the responsibility to reduce the CO_2 emissions from infrastructure construction (Rootzén *et al* 2020).

4.2. LCA—DLCA—time horizon

Due to varying system boundaries, assumptions, lack of completeness, time-dependent effects, and lack of transparency in methodological choices, the validity of building LCAs has been questioned (Resch *et al* 2021). The lack of comparability across standards and studies on bio-based constructions undermines the trust in LCA results due to the result depending on the approach selected by the practitioner (Andersen *et al* 2022). Due to this inconsistency of LCA practice in the building sector, additional approaches are needed to support decision-making (Peñaloza *et al* 2018b). There also needs to be a standardized approach to exclude further confusion and inconsistency (Morris *et al* 2021). A harmonization process within the development of LCA methods could be a way forward (Andersen *et al* 2022).

Conventional LCA practices have been criticized for favoring the use of single metric GWP to assess climate impacts and not looking further to consider the climate‘s response and subsequent impacts on the human and ecological system (Hawkins *et al* 2021). Using only single impact metrics risks promoting sub-optimal or counterproductive strategies (Hawkins *et al* 2021). Studies limited to assessing impacts related to climate change without considering the importance of other environmental impacts can lead to unintentional shifting of environmental burdens or trade-offs (Andersen *et al* 2022).

There remains significant uncertainty around EoL scenarios and the timing of emissions (Hawkins *et al* 2021), which bio-based products are sensitive to (Morris *et al* 2021). The assumption of carbon neutrality when bio-based materials are harvested from sustainable forests has been criticized by several authors (Pittau *et al* 2018, Morris *et al* 2021, Andersen *et al* 2022). LCAs involving forestry products should address the time dependence of CO_2 fluxes as forestry activity highly affects the timing of CO_2 uptake and emissions (Head *et al* 2020). Accounting for delayed emissions has been shown to have a notable effect on results (Morris *et al* 2021). However, very few studies consider timing (Morris *et al* 2021). Present, future, and past emissions are treated equally in traditional LCA which means the environmental impacts are irrespective of the moment at which they occur (Pittau *et al* 2018).

The real effect of an emissions/uptake cycle in a selected time horizon can be observed in terms of radiative forcing when the timing is considered, the real effect of an emissions/uptake cycle in a selected time horizon can be observed in terms of radiative forcing when time is considered (Pittau *et al* 2018). With a shorter time horizon and the use of consistent time horizon, the uncertainty of future impacts can be reduced (Resch *et al* 2021).

The effects of technological change in GHG emissions from the manufacturing processes should not be underestimated as they can affect the results of long-term climate impact assessment (Peñaloza *et al* 2018b). Not assuming any improvement in the GHG intensities of future building materials, or in their EoL treatment options can lead to a biased result. A recent study by Joensuu *et al* (2022) suggested utilizing a discount factor in LCA buildings or objects with long service lives as one solution to uncertainty related to the emissions intensity of any building materials.

DLCA aims to provide greater consistency in the accounting of impacts associated with all carbon fluxes by including timing in LCA, which is particularly relevant for bio-based materials (Pittau *et al* 2018, 2019, Morris *et al* 2021). It also allows for comprehensive, graphical, and climate-focused comparison which helps with effective decision-making in the climate emergency (Hawkins *et al* 2021). One of the main obstacles to a wider adoption of DLCA in the building design practice is the increased complexity which requires specialist knowledge (Hawkins *et al* 2021).

4.3. Carbon cycle

It‘s important to consider the overall carbon balance of the evaluated system as the potential for the removal and storage of carbon (Andersen *et al* 2022). Andersen *et al* (2022) found that if the storage period is sufficiently long in the building, biogenic carbon results in a negative carbon emission during the building lifetime due to additional carbon being absorbed by a new forest growth. The carbon dynamics in the short- to medium term of the growth rate in trees therefore needs to be considered to gain an overall climate benefit from the use of timber in constructions (Andersen *et al* 2022).

The longer a wooden product is used, the longer the carbon storage can be preserved (Hafner and Schäfer 2018). Due to the extended period of use stage, operational carbon plays a vital role in total carbon emissions during a building´s full life cycle (Xu *et al* 2022a). When compared to timber, fast growing biogenic materials such as straw and hemp have an increased potential to act as carbon sink because they do not require long rotation periods and the rapid CO_2 uptake in plantation (Pittau *et al* 2019). The long rotation period of the forest is the main cause, where the carbon capture during regrowth cannot compensate the effect from the emissions (Pittau *et al* 2019). By eliminating the re-emission of biogenic carbon at the EoL by re using timber elements over multiple service lives the cooling effects could persist indefinitely regardless of building’s lifespan (Hawkins *et al* 2021).

4.4. Sustainable forestry

Andersen *et al* (2022) found that 3% of global forest area is needed for the construction of future building floor area in 2060, which is a large share given that deforestation is a concern (Andersen *et al* 2022). Therefore timber´s potential as a lower-impact alternative to concrete and steel is dependent on sustainable forest management (Hawkins *et al* 2021). Wood can be used sustainably if it does not exceed the rate of forest regeneration (Nakano *et al* 2020). Material efficiency and carbon storage capacity should always be considered when using wood material (Hafner and Schäfer 2018).

Reducing the global biomass stock due to timber production would not result in carbon neutrality (Skullestad *et al* 2016). Therefore it´s important to consider the current pool of forest and that the increased demand and production of bio-based materials is done in a sustainable manner to ensure the long-term availability of material (Hafner and Schäfer 2018, Andersen *et al* 2022). Wood materials should be certified by internationally recognized forest management certification schemes or other third party approved certification schemes (Piccardo *et al* 2021).

4.5. Implications for future research

To enable an approach towards net zero emissions by 2045, it´s important to further investigate the extent to which the built environment can store carbon (Arehart *et al* 2021). This review intended to present ranges for different carbon storing mechanisms, through the units across the three domains varied widely. Different methods, units, and ranges made it impossible to present a meaningful comparison. This became evident even in the buildings domain on which the majority of the existing studies had focused. Particularly biogenic materials other than wood have so far received less attention than they deserve. With the infrastructure domain, very few studies were even found, and more would be urgently needed. With green infrastructure the focus of this review was on the Nordic countries, with some generalizability to other northern locations, but evidently there is no consensus yet about the carbon storage capacity of different types of urban green structures even in this context, and many other geographic areas and climate zones have received much less attention.

Improving the consistency across LCA studies would allow for cross-study comparability and conclusiveness. Better treatment of the time factor would also be urgently needed to improve comparability between the conventional non-biogenic and biogenic materials when used in long-lasting structures like in the built environment. Finally, while LCA is a commonly employed method, it is not the only method available for quantifying carbon storage potential. Other methods should simultaneously be developed in such a way that results are comparable across domains.

5. Conclusion

The current carbon storage in the built environment is only a fraction of global carbon emissions and the built environment directly or indirectly causes a significant share of the global emissions. To be able to decarbonize the built environment and turn it into a continuous carbon sink, it is not enough to maximize carbon storage but also requires reducing the life cycle emissions of buildings and infrastructure (Arehart *et al* 2021). This review has identified various ways carbon can be stored in the urban built environment through the lens of buildings, infrastructure, and urban green infrastructure. Despite a clear opportunity for the urban built environment to contribute to global emissions reduction, significant market and policy barriers exist today. Uncertainty in methodologies further complicates the research required to drive high-impact policy decisions.

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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