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To cite this article: Alessio Mastrucci *et al* 2026 *Environ. Res. Lett.* **21** 184015

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OPEN ACCESS

RECEIVED
1 April 2026

REVISED
14 July 2026

ACCEPTED FOR PUBLICATION
27 August 2026

PUBLISHED
17 September 2026

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LETTER

Carbon storage and mitigation potential of structural wood and biochar-based concrete in global urban building scenarios

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Keywords: carbon sequestration, cities, building sector modeling, bio-based materials, material efficiency, climate change mitigation, scenario analysis

Supplementary material for this article is available online

Abstract

Urbanization is accelerating globally, increasing material demand and associated greenhouse gas (GHG) emissions. Bio-based construction materials can store biogenic carbon within buildings over long periods, yet their net climate change mitigation potential, interaction with circular strategies, and feasibility remain uncertain. Here, we assess biogenic carbon storage and net embodied GHG emissions in global urban building stocks between 2020 and 2100 under material substitution scenarios including structural wood and biochar-based concrete at substitution levels of 10%, 30% and 50%. We further explore the mitigation potential of combining these substitution scenarios with sufficiency and circular economy strategies that reduce floor space demand and material flows. We account for biogenic carbon inflows and outflows, embodied emissions, and feasibility considerations. We find that substituting conventional construction systems with structural wood results in cumulative net carbon storage of 11.0–24.8 $GtCO_2eq$ by 2100. These scenarios reduce cumulative net embodied GHG emissions by 20–100 $GtCO_2eq$ (−8% to −40%) compared to current construction practices, due to both lower embodied emissions and higher net carbon storage associated. In contrast, substituting with biochar-based concrete achieves more limited cumulative net carbon storage of 7.9–14.5 $GtCO_2eq$ and reduces cumulative net embodied emissions by up to 8 $GtCO_2eq$ (−4%), constrained by feasible substitution rates in cement needed to maintain structural performance. Combining material substitutions with sufficiency and circular strategies delivers the greatest mitigation potential, lowering cumulative net embodied emissions by up to 64% for wood and 41% for biochar by 2100. Achieving the full carbon storage potential without complementary sufficiency and circular strategies would require substantial

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expansion of biochar supply, while the feasibility of wood-based storage depends strongly on the level of material substitution. These findings clarify the potential, limits, and feasibility of biogenic carbon storage in urban buildings worldwide.

1. Introduction

Urban areas are responsible for approximately 70% of global greenhouse gas (GHG) emissions (Ge and Friedrich 2024, Rhodium Group 2024); the building and land transport sectors alone accounting for roughly 6%–13% and 12%–16% of global emissions respectively, depending on whether indirect electricity-related emissions are included (Ge and Friedrich 2024, Rhodium Group 2024). Ongoing urbanization adds pressure: the global urban population is projected to grow by over two billion by 2050, predominantly in cities of the Global South, which in turn translates into new construction and transport infrastructure expansion (UN 2022). The long lifespans of buildings (>40 years) and transport infrastructure (often exceeding a century) mean that investment and planning decisions made today will lock in emissions trajectories for decades (Creutzig *et al* 2016). Yet, urbanization in many rapidly growing regions continues to follow material intensive patterns leading to high GHG emissions (IPCC 2022b). Material-related strategies are therefore critical to reduce or compensate emissions arising from the urbanization wave (Dunant *et al* 2025).

Buildings are responsible for 21% of global GHG emissions due to their operation and construction (Cabeza *et al* 2022), requiring urgent mitigation action. Global life cycle emissions from the buildings and construction sector could increase by ∼50% to nearly twofold by mid-century if no further action is taken (Zhong *et al* 2021, Li *et al* 2025). More than half of these emissions are expected to originate from the life cycle of materials (embodied emissions), including material extraction, manufacturing, transportation, construction, maintenance, and end-of-life disposal (Röck *et al* 2020, UNEP 2023). Although supply-side decarbonization of materials has been thoroughly investigated, sufficiency and circular strategies can significantly reduce embodied emissions and improve the feasibility of meeting climate goals (Zhong *et al* 2021, Alaux *et al* 2026).

Buildings play an important role for carbon dioxide removal and storage (CDR) strategies (Arehart *et al* 2021, Kuittinen *et al* 2023), due to their relatively long lifetime. Previous studies estimate that switching to wood-based construction could result in a storage potential of buildings up to 1.32 Gt CO_2 yr^{-1} globally (Mishra *et al* 2022). A broader set of construction-related materials, including biochar-based concrete and bricks with bio-fibers, hold a storage potential of up to 16.6 Gt CO_2 yr^{-1} globally, based on current production levels (Van Roijen *et al* 2025). This study focuses on structural wood and biochar-based concrete as decision-relevant and materially significant carbon storage technologies in the building sector (Edwards *et al* 2026). Together, they provide a meaningful contrast in carbon storage routes, material properties, and technology maturity, with structural wood already well established in many world regions while biochar-based concrete is in a development stage.

Biogenic carbon storage is a key characteristic of bio-based construction materials, enabling the retention of carbon within buildings over extended periods (Edwards *et al* 2026). Both wood- and biochar-based materials store biogenic carbon that was removed from the atmosphere during biomass growth, as long as the material remains intact (Abed *et al* 2022, Zhou *et al* 2025). Structural wood does not actively sequester carbon after processing; however, bio-based residues from production and construction, as well as deadstock and end-of-life material, can serve as feedstock for biochar production (Abed *et al* 2022, Zhou *et al* 2025). The biogenic carbon stored in construction materials should be distinguished from the carbon sink function of forests, as attributing forest carbon uptake directly to harvested materials could result in double counting between product and land-use carbon pools (Johnston and Radeloff 2019, Sato and Nojiri 2019). Sustainable forest management and reforestation following harvest are important conditions for maintaining forest carbon stocks and realizing the long-term climate benefit of biogenic carbon storage (Rodríguez-Veiga *et al* 2025, Curasi *et al* 2026). Compared with short-lived biomass uses such as bioenergy, long-lived construction products can prolong the retention of biogenic carbon and delay its return to the atmosphere (Rüter *et al* 2019). In addition to biogenic carbon storage, buildings can also contribute to CDR through active CO_2 uptake processes, such as carbonation of cementitious materials. However, although carbonation can reabsorb part of cement-related process emissions, its contribution is generally a smaller fraction, making these materials net carbon emitters (Pomponi *et al* 2020, Steinberger-Maierhofer *et al* 2026).

Beyond direct carbon storage, reducing embodied emissions through sufficiency and circular economy strategies can further enhance the climate mitigation potential of construction materials (Xue *et al* 2024). Sufficiency strategies aim to design, construct, and use buildings in ways that meet the needs of users while reducing the consumption of materials, energy, and other resources (Zell-Ziegler *et al* 2021, Baumgartner *et al* 2022, Lage 2022).

Reducing floor area demand through downsizing, higher occupancy, and space sharing has been identified as one of the most effective sufficiency measures in the building sector, and has been associated with embodied emission reductions of approximately 10% to 40% across different building types and geographical contexts (Hertwich *et al* 2019, Pauliuk *et al* 2021, Zhong *et al* 2021, Mastrucci *et al* 2024). Circular strategies in the built environment reduce virgin resource demand and associated environmental impacts by narrowing, slowing, and closing material flows (Bocken *et al* 2016, Pomponi and Moncaster 2017). Representative strategies include material lightweighting (narrow), lifetime extension and building reuse or repurposing (slow), and material reuse and recycling (close) (Hertwich *et al* 2019, Pauliuk *et al* 2021, van Engelenburg *et al* 2026). At the global scale, implementing circular economy strategies could reduce material-related building emissions by nearly 50% relative to a baseline scenario (Zhong *et al* 2021).

Despite recent assessments of the carbon storage potential in the global building sector, significant limitations remain. Existing assessments focus primarily on structural wood (Churkina *et al* 2020, Mishra *et al* 2022, Gingrich *et al* 2025, Yayla *et al* 2025), whereas information on other materials is limited. Current estimates of storage potential for a broader set of materials largely rely on present-day production volumes of conventional materials (Van Roijen *et al* 2025), with limited consideration of future material demand, interactions with the supply-side, and feasibility constraints. Many assessments of biogenic carbon storage in buildings quantify gross additions of stored carbon to the building stock without accounting for subsequent carbon outflows at the end of life, leaving uncertainty regarding the net climate benefits over the full life cycle (Hoxha *et al* 2020, Pomponi *et al* 2020). Moreover, interactions between carbon storage strategies and other sufficiency and circular strategies remain insufficiently explored (Gingrich *et al* 2025, Vélez-Henao and Pauliuk 2025). On the other hand, integrated assessment models (IAMs) used to assess long-term mitigation scenarios generally represent the building sector at insufficient technological and material resolution to capture these strategies explicitly and often rely on critical simplifications and assumptions (Pauliuk *et al* 2017, Wiedenhofer *et al* 2024). Enhancing the representation of carbon storage and circular strategies in the global building sector is essential to more accurately assess their realistic potential in future mitigation efforts.

We address these research gaps by exploring scenarios that implement structural wood and biochar-based concrete as biogenic carbon storage strategies in the global urban building sector. Our analysis accounts for associated carbon emissions and biogenic carbon storage potential, synergies and trade-offs with sufficiency and circular strategies, and feasibility considerations by comparison with current production levels of different materials. We use the detailed global IAM-based building stock model MESSAGEix-Buildings (Mastrucci *et al* 2021), combined with Life Cycle Assessment (LCA), to generate projections of future material demand and material outflows, carbon storage flows, and embodied emissions associated with building construction and end of life. We adopt the $-1/+1$ approach, which accounts for biogenic carbon inflows and outflows by assigning a negative emission to CO_2 uptake associated with biomass growth and an equivalent positive emission upon carbon release at the end of life (Ouellet-Plamondon *et al* 2023, Steinberger-Maierhofer *et al* 2026). These scenarios aim to inform more realistic mitigation and sustainability scenarios for urban buildings worldwide.

2. Methods

Our modeling framework to assess global urban scenarios integrates the building stock model MESSAGEix-Buildings, sectoral extension to the MESSAGEix-GLOBIOM IAM, and LCA for biogenic carbon storage and embodied emission estimations accounting for material supply chains. The following sections describe building stock modeling, carbon storage potential and emission accounting, and scenario setup.

2.1. Building stock modeling

MESSAGEix-Buildings (Mastrucci *et al* 2021), openly available in a public repository (https://github.com/iiasa/message-ix-buildings), is a building stock model that assesses buildings-related energy and material flows in future scenarios, embedding a stock-turnover model based on dynamic material flow analysis (MFA). The model covers both residential and non-residential buildings globally and has high granularity in representing heterogeneous building characteristics across geographical regions and locations. The model runs for 61 regions globally, aggregated here to 6 regions (see supplementary information, section 1) for results reporting, with five-year timesteps until 2060, and ten-year timesteps until 2100. At every time step, the model calculates the size of the stock, number of demolitions based on building type-specific survival curves, and number of new constructions to replace demolished buildings and meet population-driven demand (Mastrucci *et al* 2021). First, we project urban population by multiplying the total population by the projected level of urbanization, based on the available socio-demographic projections for the Shared Socio-economic Pathway SSP2 (Jiang and O'Neill 2017, Kc and Lutz 2017, Riahi *et al* 2017). Second, we calculate the total floor space in the building stock by multiplying the urban population projections by floor space per capita values differentiated

by region, sector, and building type. For residential buildings, floor space per capita is projected based on a series of logistic curves and accounts for differences between housing types (single-family housing and multi-family housing), their share in the stock, as well as household size and number of housing units (Mastrucci *et al* 2021). For non-residential buildings, floor space per capita is GDP-dependent (Harvey 2014), and estimated using GDP projections for SSP2 (Dellink *et al* 2017) (see supplementary information, sections 3.2 and 5.2 for more information). We calculate material demand and material outflows by multiplying newly constructed and demolished floor area by material intensity coefficients representing different building types, construction types, and regions from the RASMI database (Fishman *et al* 2024). The set of materials in this study include aluminum, bricks, concrete, copper, glass, steel, and wood. In addition, we consider material variants for structural wood and biochar-based concrete representing new construction technologies in the material substitution scenarios. While the adoption of biochar-based concrete is still in its infancy, regional differences in current wood construction practices are captured through differentiated material intensity coefficients. More details on model implementation and input data are provided in the supplementary information, sections 2 and 3.

2.2. Carbon storage potential and emission accounting

We use the biogenic carbon content of structural wood materials and biochar-based concrete to assess changes in carbon stocks within the global urban building stock through 2100 and compare them with embodied emissions from the product stage and end-of-life waste processing and disposal stages (CEN 2026). The analysis focuses on biogenic carbon storage in building materials; carbonation of cementitious materials is not included in the assessment. We adopt a $-1/+1$ biogenic carbon approach, supported by the building stock turnover model described above, which tracks carbon inflows and outflows over time (Ouellet-Plamondon *et al* 2023, Steinberger-Maierhofer *et al* 2026). In this framework, carbon inflows are accounted for when materials are incorporated into the building stock (-1), while carbon outflows associated with end-of-life processes are accounted for when materials leave the stock ($+1$). This approach ensures consistency within the building stock system boundaries and tracks biogenic carbon flows separately from embodied emissions. In this study, net biogenic carbon storage refers to the physical accumulation of biogenic carbon within the building stock, defined as the difference between biogenic carbon inflows and outflows from the stock.

For biochar-based concrete, we explore three different biochar contents for structural applications: a conservative biochar content of 2% by mass of cement (Low) to ensure optimal structural performance (Maljaee *et al* 2021, Lin *et al* 2023, Zhao *et al* 2024); biochar content of 5% by mass of cement (Medium), balancing mechanical integrity and carbon benefits (Murali and Wong 2024, Kang *et al* 2026); and biochar content of 10% by mass of cement (High), representing the upper structural feasibility threshold with optimized mix design and innovative technologies (Hylton *et al* 2024, Zou *et al* 2025, Wang *et al* 2026). Considering a carbon storage intensity of 2.93 kg CO_2/kg for biochar (Zhou *et al* 2026) and 15% cement content in concrete in mass terms, the carbon storage intensity of biochar-based concrete amounts to 0.009 kg CO_2/kg, 0.022 kg CO_2/kg, and 0.044 kg CO_2/kg with Low, Medium, and High biochar content (see also supplementary information, section 4). The carbon storage intensity of sawnwood is assumed as 1.833 kg CO_2/kg (Rüter *et al* 2019) and the dry mass as 85% of total mass (Sathre and O'Connor 2010). We run additional sensitivity analyses to account for the range of values for carbon storage potential in biochar and wood based on the literature (see supplementary information, section 4).

We quantify embodied emission intensity coefficients (kg CO_2eq/kg material) for the set of seven construction materials above using prospective LCA data based on Zhong *et al* (2021) for the product stage and additional data for the end-of-life stage. Embodied emissions are evaluated using the global warming potential (GWP-fossil) indicator, based on the ecoinvent 3.6 database (Wernet *et al* 2016), and exclude biogenic carbon uptake and release, which are accounted for separately as described above. For the product stage, the emission intensity coefficients account for shifts in energy mixes and technologies aligned with a reference SSP2 current policy scenario (Zhong *et al* 2021) (see supplementary information, section 3.4 for more information). We calculate total embodied emissions over time by multiplying the timeseries of emission intensity coefficients with projected demand and outflows of construction materials from the building stock model. We finally compute net embodied emissions over time as embodied emissions minus net biogenic carbon storage, as defined above, reported in CO_2eq units to facilitate comparison with embodied GHG emissions.

2.3. Scenarios

The scenario framing combines two sets of strategies, namely material substitution and material efficiency (table 1), for a total of nine combined scenarios (table 2). We explore two material substitution strategies for new urban buildings considering materials with high carbon storage potential (Van Roijen *et al* 2025). In the *Biochar* scenario, we consider the substitution of conventional concrete with biochar-based concrete. In the *Wood* scenario, we explore the substitution of conventional, region-specific construction practices with suitable structural wood

Table 1. Description of the material substitution and material efficiency strategies.

Strategy name	Description
Material substitution strategies	
Current practice	Continuation of current construction practice
Biochar	Gradual (linear) substitution of concrete with biochar-based concrete in all urban building types reaching target substitution levels by 2050. Three target substitution levels are considered: - Low: 10% substitution of concrete with biochar-based concrete and a conservative biochar content of 2% by mass of cement to ensure optimal structural performance (Maljaee *et al* 2021, Lin *et al* 2023, Zhao *et al* 2024). - Medium: 30% substitution of concrete with biochar-based concrete and biochar content of 5% by mass of cement, balancing mechanical integrity and carbon benefits (Murali and Wong 2024, Kang *et al* 2026). - High: 50% substitution of concrete with biochar-based concrete and biochar content of 10% by mass of cement, representing the upper structural feasibility threshold with optimized mix design and innovative technologies (Hylton *et al* 2024, Zou *et al* 2025, Wang *et al* 2026).
Wood	Gradual (linear) substitution of current construction systems with structural wood in all urban building types. Three target substitution levels are considered: - Low: 10% substitution, similar to other low scenario in previous studies (Mishra *et al* 2022) - Medium: 30% substitution, an intermediate level of ambition. - High: 50% substitution, representing high ambition (Mishra *et al* 2022, Mastrucci *et al* 2024).
Material efficiency strategies	
Reference	Continuation of current trends and practices
Sufficiency	Gradual reduction of floorspace per capita in new construction of all urban types up to 20% by 2050 relative to projected levels (Zhong *et al* 2021, Pauliuk *et al* 2021), by increased occupation and sharing of space consistent with decent living standards.
Circular	Gradual implementation of the following material efficiency strategies in all urban building types: - Floorspace per capita reduction in new buildings (same as in the Sufficiency scenario). - Extension of expected lifetime by 90% for new buildings through improved design and durability and by 50% in existing buildings through improved reuse and maintenance (Zhong *et al* 2021, Pauliuk *et al* 2021, Mastrucci *et al* 2024). - Lightweighting to reduce material intensity in new construction up to 19% for aluminum and steel and 10% for concrete by 2050 (Zhong *et al* 2021, Pauliuk *et al* 2021). - Increase the share of recycling up to 90% for steel, 95% for aluminum, and 92% for copper by 2050 (Zhong *et al* 2021).

Table 2. Overview of scenarios combining material substitution and material efficiency strategies.

Scenario number	Material substitution strategy	Substitution levels	Material efficiency strategy
1	Current practice	—	Reference
2	Biochar	Low, Medium, High	Reference
3	Wood	Low, Medium, High	Reference
4	Current practice	—	Sufficiency
5	Biochar	Low, Medium, High	Sufficiency
6	Wood	Low, Medium, High	Sufficiency
7	Current practice	—	Circular
8	Biochar	Low, Medium, High	Circular
9	Wood	Low, Medium, High	Circular

systems, specifically wood-framed single-family homes and cross-laminated timber (CLT) multi-family homes and commercial buildingsstitution levels of conventional te (see supplementary information, section 3.3). For each substitution strategy, we assume three different target substitution levels

of conventional technologies, namely 10% (Low), 30% (Medium), and 50% (High) by 2050, following a linear growth trajectory, consistent with existing studies on wood substitution (Mishra *et al* 2022, Mastrucci *et al* 2024). The material substitution scenarios are contrasted with a scenario assuming continuation of current construction practice (*Current practice* scenario).

We combine these material substitution strategies with a set of material efficiency strategies to investigate their trade-offs and synergies with floorspace per capita reduction in new buildings (*Sufficiency* scenario) and a range of circular strategies (*Circular* scenario), including lifetime extension, lightweighting, and increased use of recycled materials, besides floorspace per capita reduction. These two scenarios are considered alongside a scenario assuming continuation of current trends and practices (*Reference* scenario). All scenarios share the same socio-demographic development consistent with the SSP2 storyline 'Middle of the road' representing continuation of current trends (O'Neill *et al* 2017).

3. Results

3.1. Material demand and material outflows

The global demand for construction materials in urban buildings sharply increases globally under growing population and floorspace levels in the *Current practice* scenario, peaking around mid-century and then gradually declining through 2100 (figure 1(a)). Material outflows follow this trend with a lag determined by the building's lifetime, peaking and stabilizing in the second half of the century. Asia experiences the highest material demand and material outflow levels in 2050, but material demand grows particularly rapidly in Africa and South America (figure 1(b)), becoming dominant after 2050. Conversely, material demand is stable or declining in Europe and Australasia, while only slightly increasing in North America, and material outflows keep increasing due to the progressive demolition of existing buildings. In terms of material mass (figure 1(b)), concrete, bricks, and steel represent the largest portion of material demand and material outflows across the different world regions, with some differences in the relative share of bricks and concrete reflecting diverse construction practices and building types. Material demand and material outflow levels in the *Biochar* scenarios are similar to the Current Practice scenario, with part of the concrete demand being substituted by biochar-based concrete. In contrast, the adoption of structural wood solutions in the *Wood* scenarios reduces material demand globally, up to 9%, 23%, and 39% with Low, Medium and High substitution levels in 2050, as well as material outflows, due to lighter-weight building structures compared to the prevailing construction practice relying on concrete, steel, and bricks. Results for 2100 are reported in the supplementary information, section 5.2.

3.2. Additional carbon storage potential from material substitution

Material substitution strategies increase biogenic carbon storage in global newly constructed urban buildings. The additional carbon storage potential, representing carbon inflows into the building stock beyond those under the *Current practice* scenario, significantly depends on the assumed substitution level, reaching 0.005, 0.03, and 0.12 Gt CO_2eq yr^{-1} in the *Biochar* scenario and 0.08, 0.23, and 0.38 Gt CO_2eq yr^{-1} in the *Wood* scenario under Low, Medium, and High substitution levels in 2050 (figure 2(a)). Structural wood strategies entail the largest additional carbon storage potential due both to high storage potential per unit of material and larger amounts of bio-based materials embedded in construction. Conversely, carbon storage potential is relatively lower with biochar-based concrete, despite the large amount of concrete demand, due to small biochar content to ensure structural resistance and relatively lower carbon storage potential per unit of material. In the first half of the century, more than half of the global additional storage potential is achieved in Asia (figure 2(b)). After 2050, the potential shifts towards Africa due to continued increase in construction activities under population growth, while decreasing in Asia. Other regions have smaller shares and, except for South America, mostly show a declining trend over time. Residential buildings detain over 80% of the total carbon storage potential (figure 2(c)), reflecting a larger share of the newly built stock relative to non-residential buildings.

3.3. System-level carbon flows and net carbon storage

At the building stock level, carbon storage evolves dynamically over time as the balance between carbon inflows from new construction and carbon outflows associated with the end-of-life stage of buildings. Carbon inflows increase and peak around mid-century (figure 3(a)), reflecting trends in material demand (figure 1). Under Medium substitution levels, peak inflows increase from 0.23 $GtCO_2$eq yr^{-1} under Current practice to 0.26 $GtCO_2$eq yr^{-1} in the *Biochar* scenario and 0.46 $GtCO_2$eq yr^{-1} in the *Wood* scenario. Carbon outflows are initially smaller than inflows but gradually increase, following projected demolition trends and narrowing the gap with carbon inflows. Different substitution levels primarily affect carbon inflows, whereas their impact on carbon outflows is smaller and delayed due to building service lives.

The net carbon storage potential, reflecting the distribution of construction materials and the balance

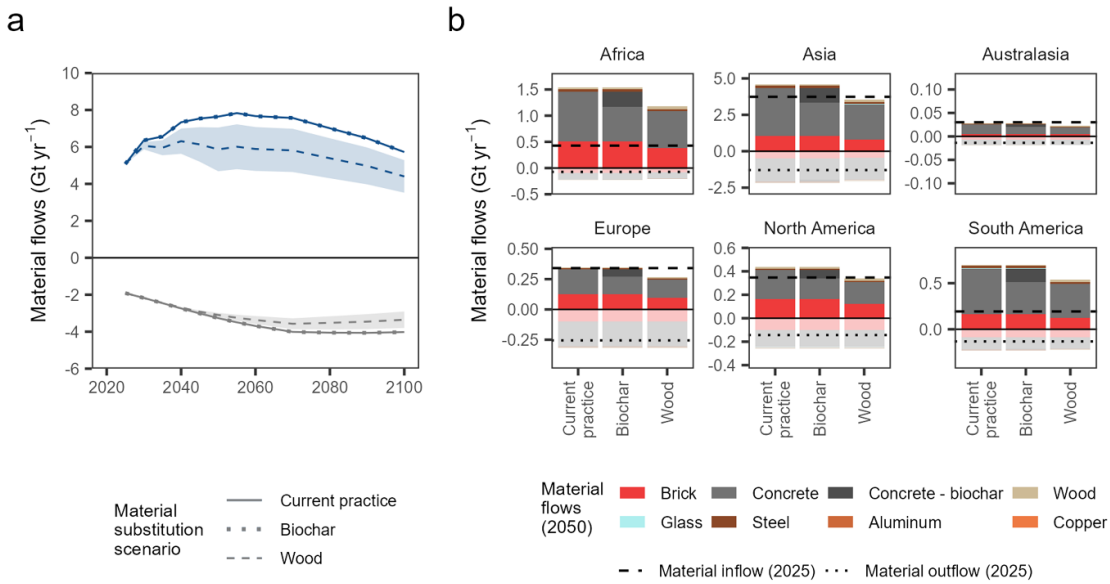

Figure 1. Material demand and outflows for urban buildings globally under different material substitution scenarios. Panel a: material demand (positive) and outflows (negative). Areas in light blue represent ranges between Low and High substitution levels. Panel b: material demand and outflows in different world regions in 2050 under different material substitution scenarios (Medium substitution level) and comparison with 2025 levels (dashed lines). Note that unit scales differ by region.

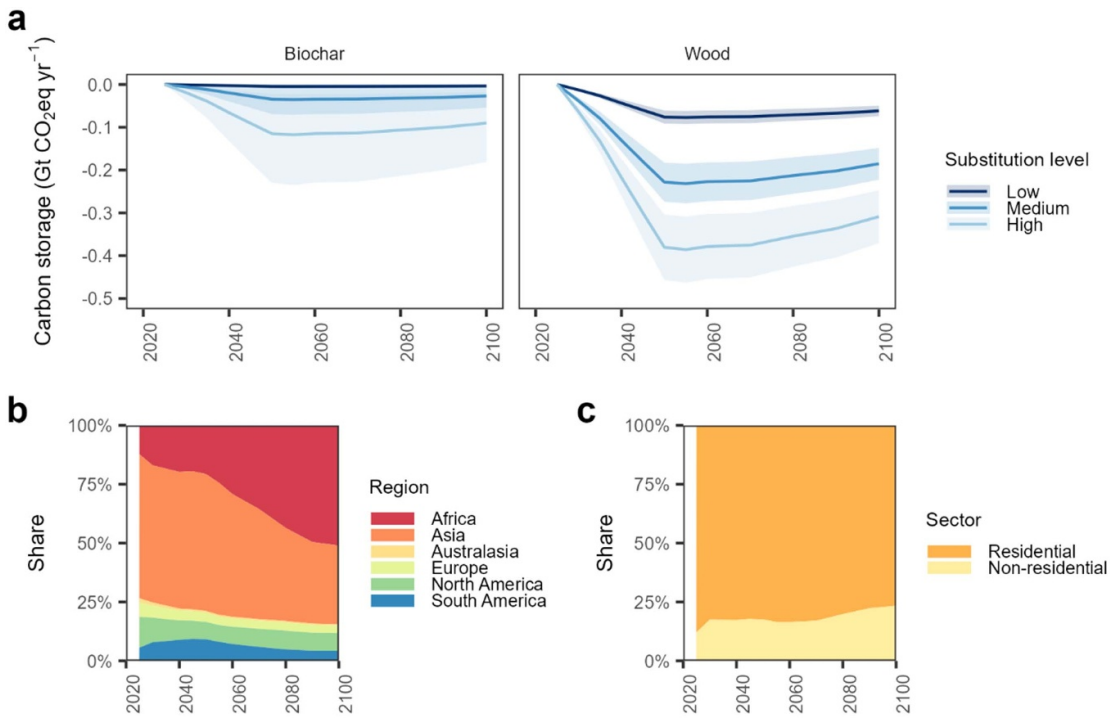

Figure 2. Additional biogenic carbon storage potential in new urban buildings worldwide under different material substitution scenarios relative to the *Current practice* scenario. Panel a: Global potential under different levels of material substitution with biochar-based concrete (*Biochar* scenario) and structural wood (*Wood* scenario). Areas in light blue indicate ranges of carbon storage potential for biochar and wood, based on the literature. Panel b: average share of carbon storage potential across different world regions. Panel c: average share of carbon storage potential across residential and non-residential sectors.

between carbon inflows and outflows at the global building stock level, peaks at 0.13 $GtCO_2eq\ yr^{-1}$ by 2055 under *Current practice*, driven by the continued uptake of wood construction (figure 3(b)). Under Low, Medium, and High substitution levels, peak net carbon storage amounts to 0.13, 0.16, and 0.24 $GtCO_2eq\ yr^{-1}$ in the *Biochar* scenario and to 0.19, 0.32, and 0.46 $GtCO_2eq\ yr^{-1}$ in the *Wood* scenario. Even in the *Biochar* scenario, most net carbon storage is attributable to wood, with biochar contributing a comparatively smaller share. Cumulative net carbon storage potential between

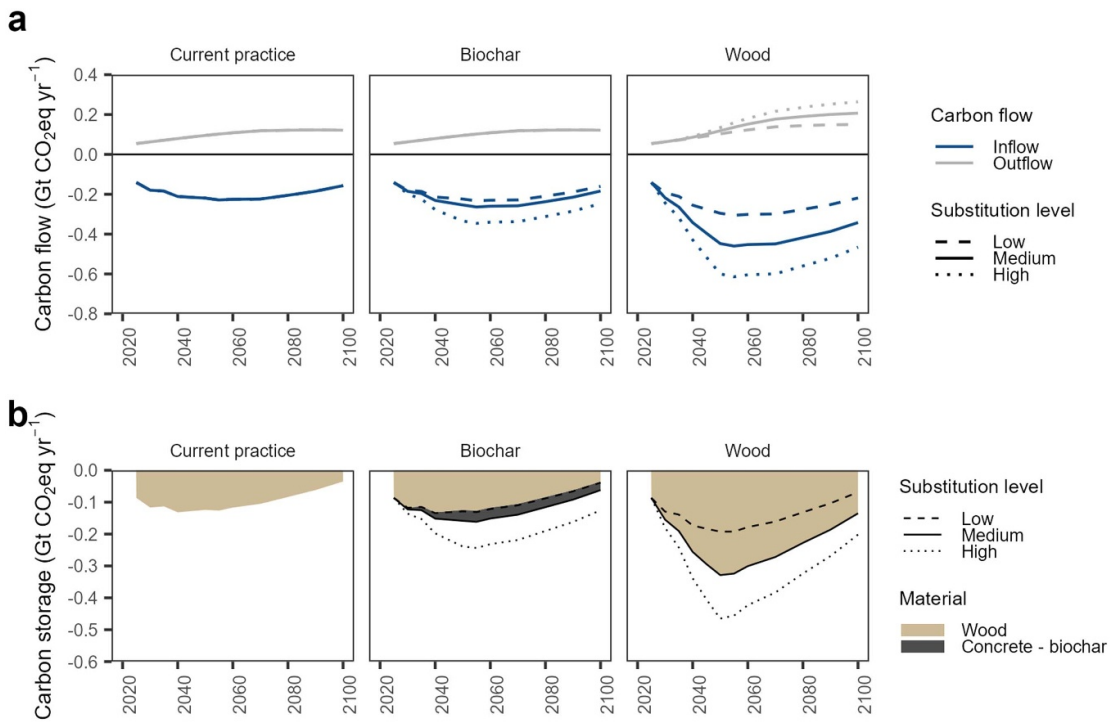

Figure 3. Biogenic carbon inflows and outflows and net carbon storage potential in the global urban building stock under different material substitution scenarios. Panel a: Carbon inflows and outflows. Panel b: Net carbon storage.

2020 and 2100 amounts to 7.6 $GtCO_2eq$ in the *Current practice* scenario. Under Low, Medium, and High substitution levels, this increases to 7.9, 9.7, and 14.5 $GtCO_2eq$ in the *Biochar* scenario and to 11.0, 17.9, and 24.8 $GtCO_2eq$ in the *Wood* scenario, respectively.

3.4. GHG emission pathways

Under *Current practice*, global embodied emissions for new urban buildings keep increasing through mid-century and then decline alongside material demand (figure 4(a)). The biogenic carbon stored in wood-based materials used in current practices contributes to the net carbon balance of the building stock, resulting in lower net embodied emissions. The *Biochar* scenario only minimally reduces embodied emissions as an effect of cement substitution with biochar, while storing additional carbon through biochar. Switching to structural wood in the *Wood* scenario has higher potential driven by simultaneous reduction of embodied emissions, due to lightweight and less energy-intensive construction systems, and higher storage capacity. As a result, the peak emission levels are shaved around mid-century, and net-embodied emissions are overall much lower compared to the other two scenarios. Cumulative net embodied emissions between 2020 and 2100 (figure 4(b)) amount to 249 $GtCO_2eq$ under *Current practice*. Under Low, Medium, and High substitution levels cumulative net embodied emissions decrease to 249, 246, and 241 $GtCO_2eq$ (0%, −1%, and −4%) in the *Biochar* scenario, and to 229, 189, and 149 $GtCO_2eq$ (−8%,-24%, and −40%) in the *Wood* scenario.

3.5. Integration of material substitution with sufficiency and circular strategies

The adoption of sufficiency and circular strategies significantly lowers material demand by reducing new floorspace (*Sufficiency* scenario), narrowing material demand, delaying new construction, and enhancing material efficiency (*Circular* scenario). Total reductions in material demand compared to the *Reference* scenario amount to 28% in the *Sufficiency* scenario and 46% in the *Circular* scenario in 2050 under *Current practice* (figure 5(a)).

These material demand reductions affect both embodied emissions and carbon storage potential in the *Biochar* and *Wood* material substitution scenarios (figure 5(b)). While associated with lower storage potential under reduced material demand levels, the *Circular* scenario results in the lowest values of cumulative net embodied emissions, highlighting the importance of reducing embodied emissions in the first place. Combing such embodied emission reductions with carbon storage strategies drives the largest reduction in cumulative net embodied emissions (figure 5(c)). Reductions amount to 40%–41% with biochar-based concrete and 44%–64% with structural wood across different substitution levels, compared to the *Reference* material efficiency scenario under *Current practice* (figure 5(c)).

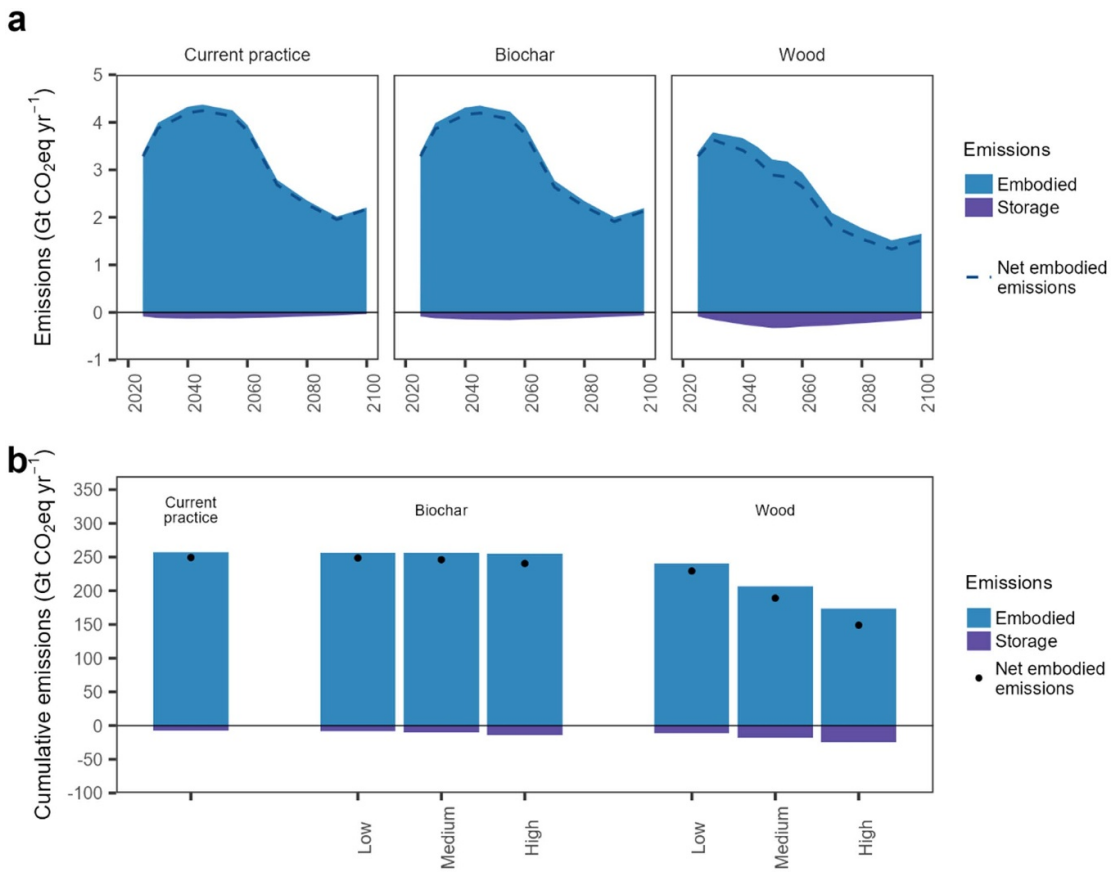

Figure 4. Projections of embodied greenhouse gas (GHG) emissions and biogenic carbon storage potential for the global building stock under different material substitution scenarios. Panel a: projections over time under Medium substitution level. Panel b: Cumulative GHG emissions and storage potentials between 2020 and 2100.

3.6. Feasibility of switching construction practice

We compare the projected biochar demand (*Biochar* scenario) and wood demand (*Wood* scenario) with available statistical data on current production levels to provide initial insights into upscaling implications and feasibility (figure 6). In the *Biochar* scenario with Medium substitution, biochar demand reaches 12 Mt yr^{-1} by mid-century, representing a 34-fold increase compared to current production level, estimated at 0.35 Mt yr^{-1} (International Biochar Initiative 2024). Peak biochar demand varies substantially across substitution levels, ranging from 2 Mt yr^{-1} (Low substitution) to 40 Mt yr^{-1} (High substitution). Demand can be further reduced in the *Sufficiency* and *Circular* scenarios, but would still require substantial production scale-up in all cases. While existing studies suggest that such scale-ups are technically feasible (Karan *et al* 2023, Sirén 2024), competition with other uses should be further considered.

Wood provision in the *Wood* scenario with Medium substitution would need to increase by a factor of 1.3 compared to current global production of sawnwood of 445 Mm^3 yr^{-1} (FAO 2026) to meet peak demand. In the High substitution scenario, production would need to scale up by a factor of 1.8, while the Low substitution scenario remains below the current production level. The implementation of sufficiency and circular strategies enables a reduction in wood material demand of over 40% by 2050, significantly improving feasibility. While in the case of biochar substantial upscaling would still be needed in the *Circular* scenario, wood peak demand would be only slightly above current production levels under High substitution and below current production levels under Medium substitution. Also in the case of wood, other uses beyond building construction should be further considered alongside the projected demands.

4. Discussion and conclusions

This study investigated the potential for biogenic carbon storage in future urban building scenarios using structural wood and biochar-based concrete. Our results indicate that implementing structural wood in new urban buildings is effective both in reducing embodied emissions and in storing carbon, leading to up to 40% lower net cumulative GHG emissions under 50% substitution by 2050 compared to a reference scenario. Biochar-based concrete exhibits a more limited potential of up to 4%, primarily due to the constrained share

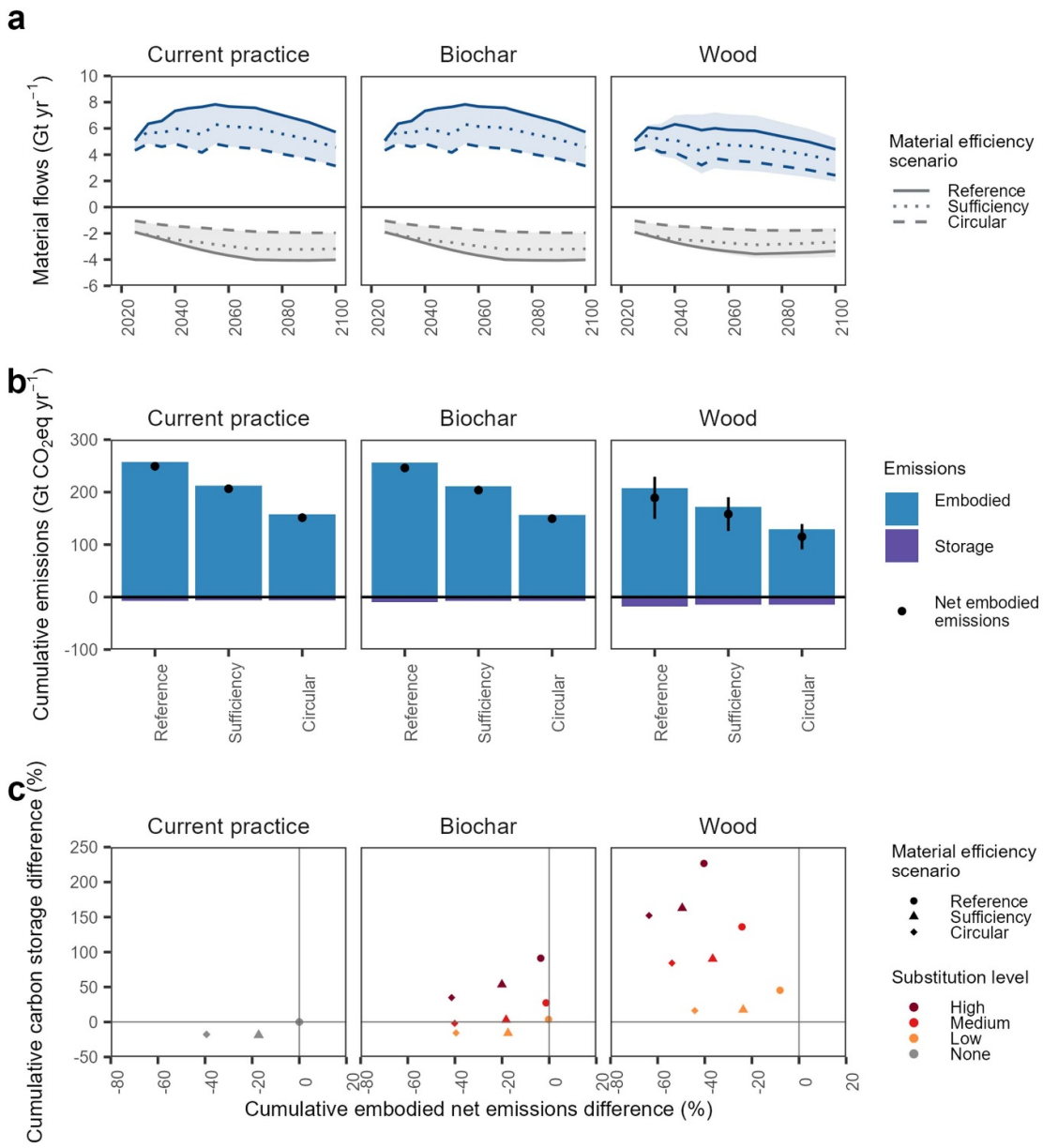

Figure 5. Projections of material flows, global embodied greenhouse gas (GHG) emissions, and biogenic carbon storage potential for the global building stock under different material substitution and material efficiency scenarios. Panel a: Material demand (positive) and outflows (negative). Lines represent flows under medium substitution level, areas in light blue represent ranges between High and Low substitution levels. Panel b: Cumulative global GHG emissions and storage potential between 2020 and 2100. Dots represent net embodied GHG emissions under Medium substitution level, whiskers represent ranges of net embodied GHG emissions between high and low substitution levels. Panel c: Difference in cumulative carbon storage and cumulative embodied net emissions between 2020 and 2100 relative to the *Reference—Current practice* scenario.

of biochar in concrete to ensure structural performance. Sufficiency and circular strategies substantially lower material demand and material outflows across all scenarios and, despite trade-offs with storage potential, result in the largest reductions in net cumulative GHG emissions until 2100, up to 64% with structural wood and 48% with biochar-based concrete.

Overall, these findings are in line with existing research on carbon storage in the built environment, while highlighting some important differences. The additional carbon storage potential of switching construction practice to structural wood in new urban buildings ranges between 0.08 and 0.38 $GtCO_2eq\ yr^{-1}$ by 2050, consistent with the range 0.1–0.3 $GtCO_2eq\ yr^{-1}$ provided in Rodriguez Mendez *et al* (2024). The cumulative biogenic storage additions in our *Wood* scenario ($-39\ GtCO_2eq$) are similar to those reported by Mishra *et al* (2022) for a comparable scenario assuming wood implementation in 50% of new urban buildings worldwide ($-37\ GtCO_2eq$). A major difference between the two studies lies in the projected trends of carbon storage through wood construction. While the study by Mishra *et al* (2022) projects a continuous growth in the storage potential driven

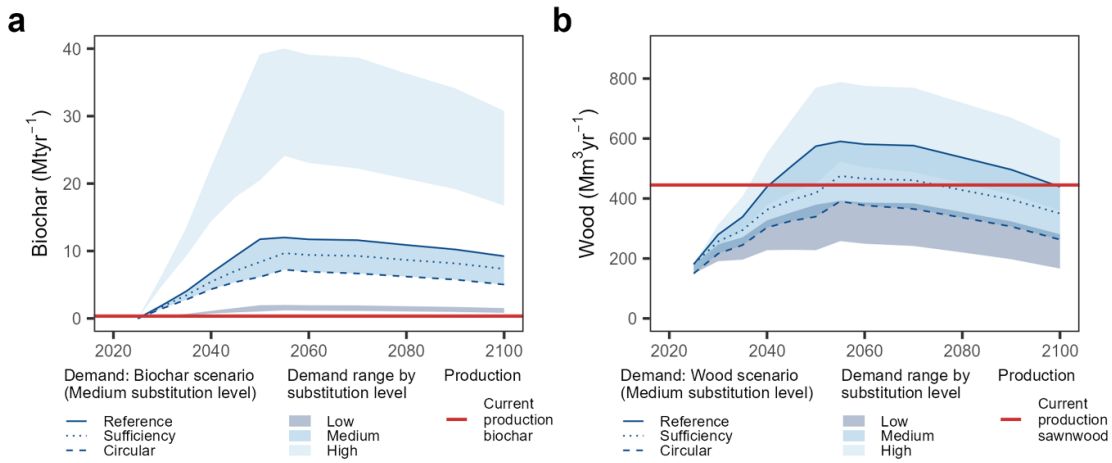

Figure 6. Comparison of projected global material demands in new urban buildings under different material substitution and material efficiency scenarios and current total material production levels. Panel a: Projection of biochar demand in the Biochar scenarios and current production level (International Biochar Initiative 2024). Panel b: Projection of wood demand in the wood scenarios and current production levels of sawnwood (FAO 2026).

by wood implementation, our study presents a peak around mid-century and subsequent decline, reflecting slower global population growth, which reduces demand for new construction and construction materials in the second half of the century. This trend is consistent with other studies of global wood demand (Gingrich *et al* 2025). Moreover, this study shows that the stock-level net cumulative carbon storage is notably lower than the carbon storage potential accounting for new construction only (25 $GtCO_2eq$ versus 39 $GtCO_2eq$ in the *Wood* scenario under High substitution), because it accounts for carbon outflows associated with the end-of-life stage, which are not captured when only new construction is considered.

Given that the literature on biochar-based carbon storage potential in buildings is very sparse, only limited comparisons are possible. Previous studies (Rodriguez Mendez *et al* 2024) report a storage potential of 0.2–0.3 $GtCO_2eq\,yr^{-1}$ through biochar-based cement in buildings construction. We found a lower carbon storage potential of up to 0.12 $GtCO_2eq\,yr^{-1}$, likely due to the limitations in embedding biochar in concrete to ensure minimum structural resistance. On the other hand, this is likely a conservative value as we only consider biochar-based concrete, while not accounting for other non-structural cement-based materials, such as plaster and mortar, where biochar could be embedded.

This study advances global research on carbon storage potential in buildings in several ways. While previous research has primarily focused on carbon storage in wood (Mishra *et al* 2022, Gingrich *et al* 2025), we expand the scope by including biochar-based concrete, an alternative, yet highly debated, structural material. We further extend earlier assessments of storage potentials (Van Roijen *et al* 2025) by incorporating future urbanization dynamics, building stock evolution, and accounting for biogenic carbon flows, including end-of-life carbon releases, and embodied emissions, enabling a more complete assessment of the climate change mitigation potential of building-based storage strategies. By explicitly accounting for building stock turnover, we provide an internally consistent assessment of material inflows and outflows, embodied emissions, and carbon storage, complemented by considerations of sufficiency and circularity. These advances enable a more comprehensive evaluation of future GHG emission trajectories of embodied carbon reduction and storage strategies associated with future urbanization pathways.

Comparisons with current material production levels highlight the need for significant upscaling to meet projected demand to a factor of 34 for biochar and 1.3 for wood under Medium substitution levels. The limited availability of bio-based materials for use in construction is a widely discussed concern in the literature (IPCC 2022a). A marked increase in forest harvests driven by expanding wood markets has raised concerns about potentially undermining future forest-based climate mitigation and biodiversity conservation (Ceccherini *et al* 2020). Demand-side sufficiency and circular strategies can further improve the feasibility of material substitutions by reducing material demand and slowing material cycles through extended product lifetimes, as illustrated in our analysis. On the supply side, improved supply-chain management, reducing carbon leakage, wood cascading and closing bio-based material loops are equally important (Jarre *et al* 2020). Management approaches that enable the production of construction timber alongside biomass for energy and other uses could be developed within the agriculture and forestry sectors,

potentially providing multiple co-benefits (Nabuurs *et al* 2017).

Future modeling efforts should better account for these cross-sectoral interactions, competitions and synergies across different biomass uses, including construction, energy, and food systems, as well as impacts on forest ecosystems to ensure that increased use of bio-based materials does not exceed ecological limits (IPCC 2022a). At present, however, building and land-use models remain largely disconnected and tend to overlook these interactions, with only a limited number of studies explicitly linking wood-based construction and land-use dynamics (Mishra *et al* 2022, Gingrich *et al* 2025). Biochar, for example, is also applied to cropland to enhance soil fertility and crop yields (Joseph *et al* 2021, Javadi *et al* 2024, Li *et al* 2024), highlighting a competing demand between its use in the agricultural sector and emerging applications in building materials. At the same time, natural disturbances (van Lierop *et al* 2015, Grünig *et al* 2026), such as wildfires and insect outbreaks, introduce additional uncertainty into the supply of construction wood. Furthermore, studies that account for all relevant carbon pools associated with wood utilization, i.e. forest carbon pools linked with product carbon pools, including substitution effects, show that increased harvest rates may also lead to increases in atmospheric carbon dioxide stocks. This can result from unconsidered processing offcuts in the supply chain and reduced forest sink capacities due to intensified harvesting (Soimakallio *et al* 2021). Additional efforts are therefore required to better integrate land-use, energy system, and building sector modeling within a comprehensive carbon accounting framework, in order to capture cross-sectoral interactions and system-wide implications (Churkina *et al* 2020, Mastrucci *et al* 2023). Greater attention is needed to land-use implications, including biodiversity and nature conservation, alongside land-use change, biogenic emissions, and other environmental impacts such as water use, to fully capture the broader consequences of shifting construction practices. Economic feasibility is also critical, given competing uses of biomass and other resources (Muscat *et al* 2020), and should be systematically incorporated into future analyses, along with socio-economic implications, such as employment and distributional effects (Howard *et al* 2021). Key barriers to scaling biochar-based concrete and wood construction include technical uncertainties, fragmented regulatory frameworks, economic and market constraints, supply chains, workforce and industry capability gaps, public and stakeholder acceptance challenges, and governance issues, all of which warrant further investigation in future feasibility studies. Despite sharing several common barriers, the two technologies require distinct analytical approaches due to differing levels of technological and market maturity. Finally, stronger integration with the energy supply sector is necessary to position construction material strategies within broader decarbonization pathways (Pauliuk *et al* 2017).

In this study, we focused on a limited set of bio-based structural materials to investigate biogenic carbon storage potential in global urban buildings. Future assessments should encompass a broader range of materials with a whole life-cycle approach. Non-structural bio-based construction materials, including bio-based panels and insulation, should be included for more comprehensive analysis. Use of local fast-growing bio-based materials is promising both in building renovation, e.g. straw and cork, and new building construction, e.g. bamboo, across different world locations (Carcassi *et al* 2022, Göswein *et al* 2026), requiring region-specific analysis. While our results on biochar-based concrete show relatively limited carbon storage potential, non-structural applications, such as partition walls, panels, plasters, and mortars could result in significant additional potential (Tang and Qiu 2024, Zhang *et al* 2025, AlSieedi *et al* 2026). Each material has been widely studied in isolation, but the trade-offs and synergies arising from the joint use of biochar-based concrete, timber, and other bio-based construction materials remain insufficiently understood (Ramage *et al* 2017, Zhang *et al* 2022). A limitation of this study is the exclusion of carbonation of cementitious materials, which represents a secondary but non-negligible pathway of long-term carbon uptake in buildings (Xi *et al* 2016, Van Roijen *et al* 2025, Steinberger-Maierhofer *et al* 2026). Reasons for its exclusion include the strong dependence on exposure conditions and end-of-life pathways, which would be challenging to quantify at the global scale and would introduce additional uncertainty. This assumption may lead to some overestimation of the relative carbon storage benefit of alternative materials. However, given the relatively limited magnitude of carbonation compared to embodied emissions, its overall effect is expected to be minor and not to affect the main conclusions of this study. Carbonation of cementitious materials should be further explored and compared with bio-based solutions in future building sector scenarios. While we focused here on exogenous uptake rates for material substitution, future scenario work should also account for more realistic adoption dynamics, including the relevant scale-up constraints and barriers, and considering competition across sectors, market and price dynamics, and constraints on forestry and land-use side, e.g. nature conservation. Despite these limitations, the scenarios developed in this study can provide a strong starting point for more integrated assessments on the carbon storage potential in the global urban building sector to effectively support sustainability and climate mitigation strategies.

Acknowledgments

The authors would like to thank Keywan Riahi, Yoga Pratama, Alexander Passer, and Shuhaib Nawawi for helpful discussion and feedback on the manuscript. MJG is also affiliated with Pacific Northwest National Laboratory, which did not provide specific support for this paper.

Data availability statement

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

Supplementary Data 1 available at: https://doi.org/10.1088/1748-9326/ae9f73/data1.

Supplementary Data 2 available at: https://doi.org/10.1088/1748-9326/ae9f73/data2.

Funding

This work has received funding from the Horizon Europe Research and Innovative Action Programme under Grant Agreement No. 101056810 (CircEUlar Project) and Grant Agreement No. 101081604 (PRISMA project). We also acknowledge and appreciate funding under the European Union's ERC-2020-SyG 'GENIE' Grant, Grant ID 951542. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them. The work by TU Graz was partly funded by the BIOCHARm project [funding number FO999923195], funded under the programme 'Mission Klimaneutrale Stadt—Technologien und Innovationen für die klimaneutrale Stadt 2024' by the Federal Ministry of Innovation, Mobility and Infrastructure (BMIMI) of Austria. We acknowledge the support by the Energy Demand changes Induced by Technological and Social innovations (EDITS) project, which is an initiative coordinated by the Research Institute of Innovative Technology for the Earth (RITE) and the International Institute for Applied Systems Analysis (IIASA), and funded by the Ministry of Economy, Trade, and Industry (METI), Japan.

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