Journal of Physics:
Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: A Schneider *et al* 2025 *J. Phys.: Conf. Ser.* **3140** 142001 doi:10.1088/1742-6596/3140/14/142001

Evaluating nature-based material choices for structural and envelope components of buildings

A Schneider[1*], E-M Friedel [1], A Holsten [1,2], C Li [1,2], F Exton-Smith [1,3], B K Reck [1,4]

[1] Bauhaus der Erde gGmbH, Berlin, Germany
[2] Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany
[3] Technische Universität, Berlin, Germany
[4] Yale School of the Environment, New Heaven, CT, USA

* Corresponding author: schneider@bauhauserde.org

Abstract. Shifting from conventional to nature-based construction materials is a key strategy for reducing greenhouse gas (GHG) emissions in the built environment. While bio-based materials like timber have gained attention for their carbon storage potential, a broader understanding of nature-based materials is needed to support a truly regenerative approach. This study compares three bio-based building materials (timber, hemp, straw) and one geo-based material (earth) with conventional materials in structural and envelope building components in the context of Berlin. Functional equivalence is ensured through German building performance standards. We assess material intensity and environmental impacts by evaluating global warming potential (GWP) and carbon storage potential (CSP) using Life Cycle Assessment (LCA). Findings indicate that all nature-based systems substantially reduce lifecycle emissions compared to the conventional with bio-based materials offering notable carbon storage. However, material choices are accompanied with trade-offs, for example structural timber use may require higher resource demands, while straw and hemp stand out for their insulation properties and rapid renewability. These insights underscore the importance of material selection in optimizing sustainability outcomes, balancing carbon storage, resource efficiency, and ecosystem impacts. The study highlights the potential of diverse nature-based materials in advancing climate goals and fostering a regenerative built environment.

1. Introduction

The building sector accounts for 37% of global energy and process-related CO_2-emissions [1], making it a key lever for climate change mitigation. Operational energy accounts for around two thirds of these emissions, while a third stems from embodied energy. Conventional building materials like concrete [2] and steel [3] are particularly energy-intensive, and while decarbonization pathways exist [4–6], they face scaling challenges [7]. A key strategy for reducing embodied energy is shifting to sustainably sourced, low-carbon materials. Bio-based materials store carbon over their lifetime, potentially transforming buildings from net carbon emitters to carbon sinks [8–10]. This storage occurs in wood products, fast-growing bio-based materials like hemp or bamboo, and agricultural residues like straw [11]. These materials have shorter rotation periods than timber, enabling faster carbon mitigation

[10,12,13]. Earth-based materials further enhance sustainability, offering high thermal mass, low processing energy requirements, and improved fire resistance [14–16]. We use the term "nature-based" to describe the combination of bio- and earth-based materials, acknowledging that various terms exist in literature [17–19]. While many studies assess building components, fewer address whole-building integration. Carcassi et al. [20], for instance, found that bio-based insulation can achieve climate neutrality while meeting regulatory standards and maintaining feasible wall thicknesses. Others compare bio-based and conventional insulations [21,22] or assess specific components [13,23]. Few researchers, including Ben-Alon et al. [24], also consider earthen materials in specific assemblies such as walls. Despite the recognized potential of nature-based materials for construction and carbon mitigation, most research remains component-specific, limiting insights into whole-building impacts. For example, Mouton et al. [25] analyzed several bio-based materials across multiple construction projects but did not assess full-building integration. Expanding research to include material and component combinations in whole-building structures would significantly improve understanding carbon mitigation potential and clarify performance impacts. We therefore compare a range of nature-based materials in structural and envelope components, assessing environmental impacts across the life cycle to highlight trade-offs and inform material selection.

2. Methods

2.1 Life Cycle Assessment

Using Life Cycle Assessment (LCA), we evaluate the environmental impact of the materials in various component compositions for a five-story apartment building in the urban context of Berlin. One conventional (CV) scenario is compared to four different nature-based (NB) ones, covering key components: Floor slabs with foundation, exterior walls, bearing interior walls, floors, roofs, columns and beams. This selection has a high potential to replace conventional building techniques and address about 80% of embodied emissions [26]. The system boundary is defined according to the modules outlined in EN 15804:2012+A2:2019, focusing on the lifecycle phases (i.e. excluding operational emissions): A1-A3 (extraction, processing, manufacturing), B4 (replacement), and C2-C4 (transport to end-of-life, waste processing, disposal). The assumed calculation period is 50 years. Lifecycle inventory data from the German ÖKOBAUDAT version OBD 2024 A2 is used to calculate the impact values for the emission indicators Global Warming Potential (GWP) and Carbon Storage Potential (CSP). Results are reported in kg CO_2 equivalents (kg CO_2-eq.) per m^2 component and per m^2 of gross floor area (GFA) for each scenario. The study applies the +1/-1 approach for biogenic carbon accounting, calculating CSP based on the A1-3 value of GWP biogenic (GWP_{bio}) as defined in EN15804:2019. NB materials are assumed to be sourced from managed ecosystems, capturing atmospheric CO_2 given different approaches to carbon release at end-of-life [27–29]. GWP and CSP are presented separately, offering two perspectives: The GWP reflects a linear approach where materials are disposed of at end-of-life (C3-C4), while the CSP reflects a circular approach in which materials remain in the cycle, retaining their full carbon sequestration potential (GWP_{bio} A1-3).

For the life cycle inventory phase, a BIM-integrated approach was utilized to quantify the surface areas of building components for both the CV and NB model. The quantities were extracted from a representative BIM model and combined with material impact intensity factors using the German tool eLCA to assess environmental impacts. The modeling was conducted in Graphisoft ArchiCAD. The building typology and associated components were based on research from TABULA [30]. At building level, material-specific impacts were aggregated according to BIM-derived quantities and normalized by the gross floor area (GFA) to calculate overall environmental impacts per unit of floor space. The total GFA amounts to 3818 m^2.

2.2 Building Components and Combination-Scenarios

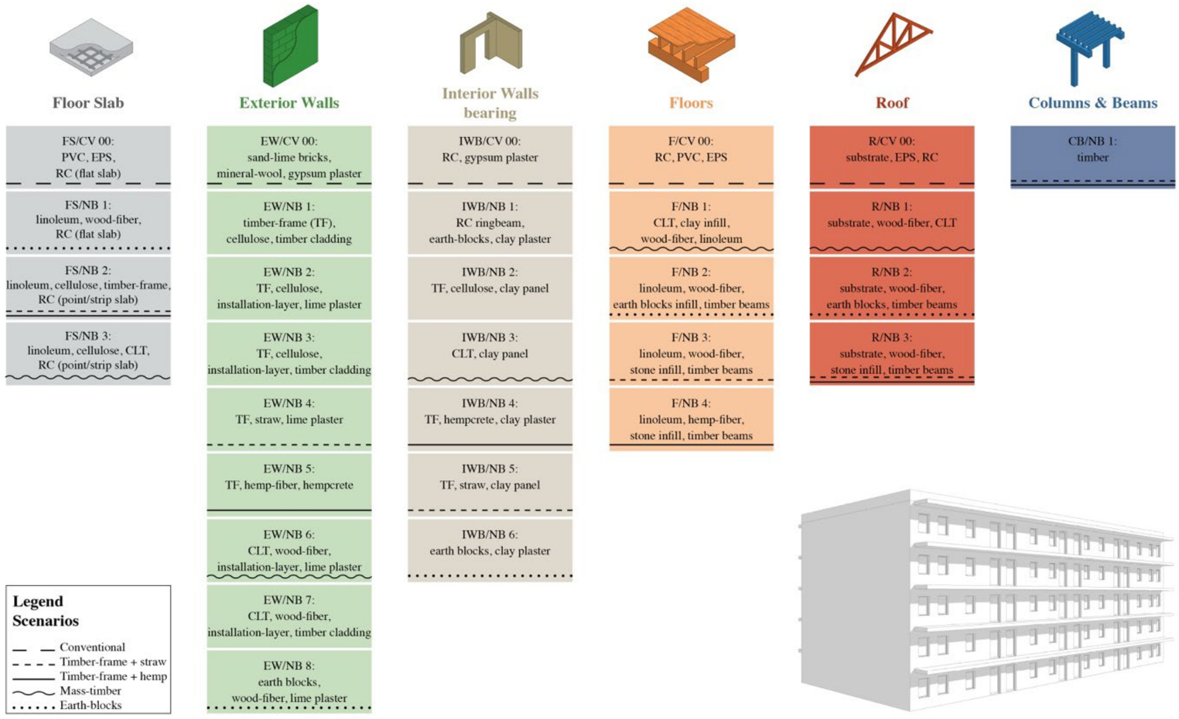

Figure 1. Building component details, combination scenarios and the axonometric mid-rise model. For details on component-layers see Annex.

Each building component is qualitatively assessed for performance indicators such as thermal and acoustic insulation, humidity regulation and fire safety. German Building Class 4 standards are applied to ensure fire protection, as the components are based on research from dataholz.eu [31] and general experience with similar built examples and assembly types. Thermal insulation and heat protection are validated using the Ubakus calculation tool [32], applying the German EH40 standard for thermal performance. All assessed constructions were assumed to meet the minimum requirements for sound insulation as defined in DIN 4109-1. However, verifying the performance of each component is essential for project-specific applications, particularly when higher sound insulation standards are required like in the DIN 4109-5.

The GWP and CSP values resulting from the LCA are used to compare the environmental impacts of different building types. For each component, one CV and 1-8 NB versions are considered (see Figure 1). Columns and beams only apply in the two timber-frame (TF) NB versions as primary load-bearing structure in which the exterior walls are non-bearing. Figure 1 presents a range of potential combination-scenarios from which five combination-scenarios are selected: Reinforced concrete with sand-lime bricks (CV), timber-frame with straw infill (TFS), timber-frame with hemp-fibre infill and hempcrete (TFH), mass-timber (MT) and earth block masonry (EB).

3. Results & Discussion

3.1 Emission indicator evaluation

The findings reveal that all nature-based building scenarios result in significantly lower life cycle emissions than the conventional scenario. Reductions in GWP range from 53% in the mass timber (MT) scenario to 65% in the timber frame with straw (TFS) scenario (see Table 1).

Table 1. Results for Global Warming Potential (GWP) and Carbon Storage Potential (CSP) for all five the combination scenarios (CV, TFS, TFH, MT, EB). NB relative GWP is compared to CV.

	CV (RC + bricks)	**TFS (TF + straw infill)**	**TFH (TF + hemp infill)**	**MT (Mass timber)**	**EB (Earth-blocks)**
GWP* (kg CO2/total)	918802	320373	408786	435842	400715
GWP* (kg CO2/m2 GFA)	241	84	107	114	105
GWP (kg CO2/m2 GFA x a)	4,81	1,68	2,14	2,28	2,10
Relative GWP (%)	100%	35%	44%	47%	44%
CSP* (kg CO2/total)	-8475	-676024	-580535	-900790	-555927
CSP* (kg CO2/m2 GFA)	-2	-177	-152	-236	-146

* calculation period: 50 years

Among the scenarios, TFS achieves the lowest embodied emissions, delivering a 65% reduction per square meter of gross floor area compared to the conventional building. This is primarily due to its high proportion of natural fibre insulation and minimal use of high-emission materials such as cement or lime-based binders. Therefore, also the CSP is comparably high, benefitting from straw as a low-processed and fast-growing material. The timber frame with hemp (TFH) scenario has higher embodied emissions than TFS, despite both using timber-frame-systems. This impact difference occurs due to lime as composite in implemented hempcrete layers. However, it still achieves a substantial 56% reduction in embodied emissions per square meter relative to the CV scenario, while storing a moderate amount of biogenic carbon. Since columns and beams are specific to timber-frame systems, they are not considered in the other scenarios. The earth-based (EB) scenario also reduces GWP by 56%, despite having a lower proportion of bio-based materials compared to the TF scenarios. This is largely due to the low emissions associated with earth-based products through minimal processing and regional sourcing. However, EB has the lowest CSP among the nature-based options, since the earth blocks in this case do not store carbon. Here, highest carbon storage occurs in floors, roof and exterior walls, primarily due to bio-based insulation. The relatively high floor slab emissions in the EB scenario can be attributed to the use of recycled reinforced concrete. This underscores that, even with NB insulation and flooring, the inclusion of recycled concrete results in higher emissions compared to designs excluding concrete. The Mass Timber (MT) scenario exhibits the highest GWP among the nature-based options due to its high material demand and associated production emissions. This is an interesting finding, as the inclusion of columns and beams as a separate system still leads to lower emissions at the whole-building scale for both TF scenarios. However, it achieves a 53% GWP-reduction compared to CV while offering the highest CSP, driven by the substantial timber volume required to meet regulatory standards. While this carbon storage potential is beneficial, the sustainability of mass timber applications ultimately depends on responsible wood sourcing. This underscores the need for LCAs to extend beyond building system boundaries to capture broader environmental impacts.

The most interesting finding at component level (Figure 2) reveals that floors exhibit the highest GWP across all scenarios yet also have the highest CSP in all NB versions. This makes them the most promising building component for both emission reductions and carbon storage due to their high mass in buildings and the use of thick insulation to meet performance requirements. Also, the exterior walls show major potential in terms of GWP reduction, which was also proven by Ben-Alon [24] who found that NB wall assemblies can save 60-82% CO_2 compared to conventional.

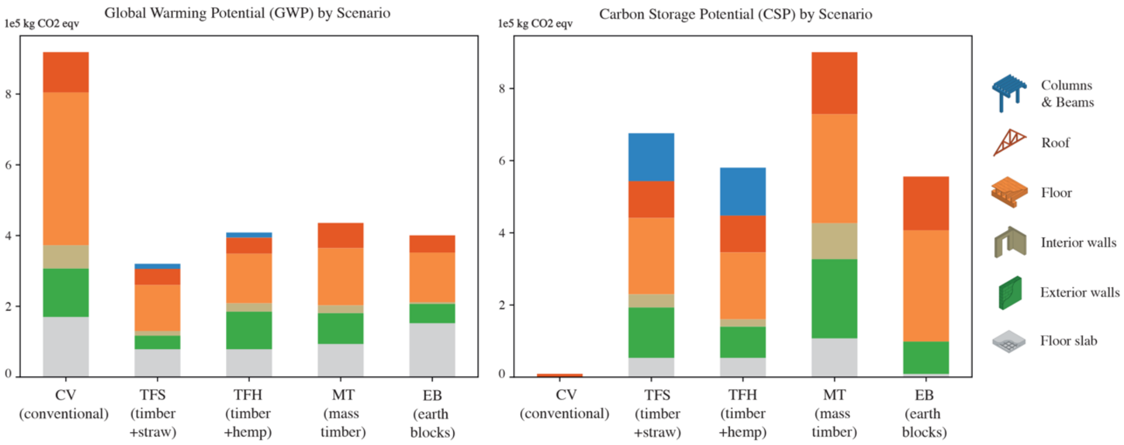

Figure 2: Total GWP and total CSP for all scenarios, split by building component shares. Results for the GWP normalized per m^2 GFA and building lifespan can be found in Table 1 and in the Annex.

3.2 Building performance indicator evaluation

The lightweight TFS-construction would require additional dense mass for summer heat protection. The TFH scenario benefits from the higher mass of lime, improving heat protection, while its hemp-fiber insulation has a density comparable to straw, resulting in similar U-values. In the MT scenario, loose clay infill in the floors enhances thermal performance, particularly in summer. The EB scenario, with its high-mass compressed earth block floors, excels in summer heat insulation but requires additional insulation layers for exterior walls, increasing wall thickness. For both TF scenarios the columns and beams are the load-bearing structure and therefore the non-bearing exterior wall can meet lower fire protection requirements. With TFH benefiting from the non-flammable lime in hempcrete, TFS and MT utilize earth-based cladding to meet fire safety standards. Overall, optimizing U-values in NB scenarios involves balancing mass and insulation strategies while addressing material-specific fire safety requirements.

Summarizing emission and performance indicators, the results demonstrate that NB building components show strong potential to reduce and store carbon if they are being kept within a circular system. This aligns with numerous studies who emphasize the benefits of plant-based [10,12,20] and earth-based substitutes [24] for energy-intensive materials. Our results demonstrate that each construction presents trade-offs between environmental impact, carbon storage, and building performance. The TFS scenario achieves the lowest GWP but requires additional mineral layers containing earth, lime or stone for improved acoustic insulation, heat- and fire protection. MT stores the most carbon although showing the highest GWP due to intensive resource use. While having the lowest CSP, the EB scenario maintains a relatively low GWP, benefitting from inherent fire resistance and acoustic properties of earth-based materials, though additional insulation is needed for thermal performance. Overall, all NB scenarios emit less than the CV scenario.

3.2 Outlook and limitations

This study examines a mid-rise housing typology with a focus on nature-based materials such as hemp and straw, representing fast-growing and renewable options [11]. Future research could explore additional nature-based materials (e.g. reed), which may offer comparable performance. Expanding the analysis to include a broader range of material and component combinations as well as additional evaluation indicators (e.g. raw material consumption) could deepen the understanding of sustainable construction. Although this work focuses on material impacts and excludes use-phase calculations, insulation performance was standardized using EH40 requirements. In the German context, strict comfort and regulatory standards can pose challenges for nature-based solutions, raising the broader question: Should increasing regulatory demands continue to take precedence or should policy shift towards enabling more sustainable, simplified construction methods? These systemic trade-offs warrant further investigation.

4. Conclusion

This study shows that nature-based materials offer substantial benefits in terms of reduced GWP and increased CSP when compared to conventional materials. Construction system choice influences material consumption and impacts from extraction, processing, and further effects on ecosystems. Straw and hemp are particularly promising due to good thermal insulation, enabling slender building envelope profiles. Additionally, these materials are fast-growing, with straw serving as an agricultural byproduct. This makes them valuable alternatives to timber, potentially helping to preserve forests and protect vital ecosystems. All nature-based scenarios result in lower embodied emissions than the conventional reference while still meeting key building requirements. There is no single optimal solution - architectural choices should rather be tailored to local conditions, material availability and specific needs, balancing carbon reduction with functional performance. The findings contribute to meeting climate targets and sustainability benchmarks as part of a transition towards a regenerative built environment.

5. Annex

Supplementary data and results can be found here: https://doi.org/10.6084/m9.figshare.28696811.v2

Acknowledgements

This research was carried out within the ReBuilt project, funded by the Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety (BMUKN) based on a resolution of the German Bundestag. ArchiCAD was provided for free by Graphisoft.

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