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Carbon Mitigation Potential in Building Design: A Region-Specific LCA Approach for Nature-Based Construction

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Abstract. The construction sector is responsible for more than a third of global greenhouse gas emissions. Nature-based materials have emerged as a promising solution for alternative building design. A key research gap lies in understanding the carbon mitigation potential of nature-based building design in local contexts, given the highly region-specific building designs and applicability. Here we adopt a transparent life cycle assessment (LCA) approach to compare housing typologies specific to three different world regions: Germany, Indonesia, and Bhutan. With first hand data from local partners, we developed whole building life cycle inventories that account for the influences of local building cultures and climatic conditions on design, material selection and implementation. Our results indicate a marked and consistent carbon mitigation potential across three regions, reaching a net carbon reduction potential of 52-66% compared to conventional mineral-based building design, despite varied regional heterogeneity. Materials like timber, hemp, and straw can additionally store carbon and thus through efficient and long-term use can act as carbon sinks. We demonstrate that both the carbon storage capacity and the substitution effect of replacing traditional materials can contribute significantly to carbon reduction when adopting nature-based building designs. The findings demonstrate that utilizing local materials and context-specific approaches, is a viable and regionally adaptable alternative. The evaluated building types reflect realistic construction practices across diverse contexts, highlighting a substantial potential for climate change mitigation.

1. Introduction

Currently, the building sector is responsible for 37% of global energy and process-related emissions [1], making it a critical intervention area for achieving climate change mitigation goals. The projected doubling of the global building stock by 2050, driven by population growth and urban sprawl [2] further underscores the urgency for adopting sustainable practices in the built environment. The switch from conventional carbon-intensive to nature-based building materials offers a powerful way to reduce embodied emissions and potentially turn the built environment from a carbon source to a carbon sink [3,4]. For example, engineered timber systems serve as

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promising alternatives to mineral-based materials [5]. Fast-growing bio-based materials such as straw and hemp offer even greater greenhouse gas (GHG) mitigation potentials through rapid carbon sequestration during their growth [6]. Unlike timber, which requires decades to regenerate, these materials complete their cycles within a year (e.g. hemp, straw) or a few years (bamboo), providing such opportunities already in the short run [7–9]. Earth-based materials, with their high thermal mass and low processing energy, enhance bio-based materials by improving fire resistance, acoustic insulation and heat protection while further reducing buildings' carbon footprints [10,11]. In literature a range of terms for categorizing these lower-carbon materials is used [12–14]. Here we adopt the term "nature-based materials" to include both bio-based and earth-based materials. Although they have been recognized as a promising solution for construction and have attracted considerable attention for their carbon mitigation potential, existing studies rarely examine region-specific typologies or assess the feasibility of such designs in diverse local contexts. Moreover, the local context such as culture, climate, and architectural heterogeneity is often overlooked in life cycle assessments (LCA). This neglects the difference in regional construction practices due to material availability, building techniques, historical lineage, and environmental conditions. In this study, we present region-specific LCA results for three case studies in Europe and Asia. We aim to enable a level comparison of environmental performance across diverse geographical and socioeconomic contexts. We accommodate region-specific housing typologies while ensuring consistency in assessment criteria, promoting progress towards regenerative building practices. By comparing nature-based (NB) and conventional (CV) constructions, we address key gaps in current literature, which typically focus on single case studies or individual building components [15]. Our approach exemplifies its applicability through the analysis of different mid-rise residential housing typologies, providing insights into comparative LCA of housing types across different regions.

2. Methods and Materials

2.1. Goal and Scope

The goal of the study is to enable both a local and cross regional comparison of the life cycle emissions of each housing type to inform local design and policy decisions on mitigation efforts. It comprises a whole building LCA for representative midrise housing types for three countries, exemplified by the urban agglomerations of Berlin (Germany), Denpasar (Indonesia), and Thimphu (Bhutan). For each typology, we model two cases: A CV version with a structural system and materials representative of status-quo building practices, and a NB version composed of bio- and earth-based materials wherever feasible, while maintaining comparable architectural, structural and environmental performance such as the U-value. While the appearance and scale of each housing type reflects regional characteristics, all models are composed of a consistent set of building components. We base our methodology on the internationally recognized EN 15978 standard, which offers an adaptable framework for conducting building LCAs across diverse contexts. Despite such standards, literature reviews have identified methodological opacity – especially regarding system boundaries and functional unit definitions [6,16–19]. To address this, we explicitly define all included modules and a set of selection criteria (see Annex). We report environmental impact results both at component level and for the whole building, referenced to multiple functional units to enhance comparability across studies. We present a comparative LCA of NB and CV construction, reflecting local material availability and supported by collaboration with local partners to ensure regionally grounded construction practices. The primary functional unit is calculated in kg CO_2-equivalents (kg CO_2-eq.) reported per m^2 of building component at

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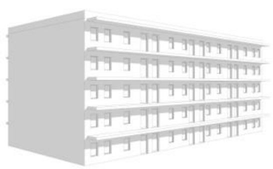
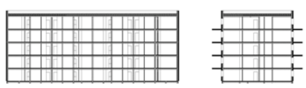
component level and per m^2 of gross floor area (GFA) at building level. For comparability, we also include results per m^2 usable floor area (UFA) and per capita in the Annex. Since most studies adopt 1 m^2 of net or GFA as the functional unit [6,17] we follow this convention for consistency. Impact calculations assume a lifespan of 50 years, which aligns with standard LCA studies [6,20].

2.2. Case Study Regions and Building Types

The research project explores three regions with distinct climatic conditions influencing local building practices. (Table 1)

Table 1. Key data for the three case studies and corresponding housing typologies. For details on the material layers see Annex. The climate is classified after Beck et al. [24] for the years 1991-2020.

	Berlin, Germany	**Thimphu, Bhutan**	**Denpasar, Indonesia**
Local climate conditions	Temperate climate, humid, warm summer (Cfb)	Temperate climate, dry winter, warm summer (Cwb)	Tropical monsoon climate (Am)
Nature-based material availability	Timber, loam, hemp, reed, straw	Timber, bamboo, loam, hemp	Bamboo, loam, reed
Local architectural characteristics	Typical multi-family-building, top-floor below 13m (“GK4”)[25]	Traditional windows *Rabsel*, traditional attic design *Jamthog* [26]	Traditional shop-house typology with courtyard [27]
Storeys	5	4	3
Building height	15.5m	16.7m	11.2m
Gross floor area (GFA)	3818 m^2	778 m^2	392 m^2
Usable floor area (UFA)	2573 m^2 (CV), 2606 m^2 (NB)	487 m^2 (CV), 491m^2 (NB)	252 m^2 (CV), 250 m^2 (NB)
Building structure CV	Reinforced concrete (RC), sand-lime-bricks, mineral wool, fired tiles	Reinforced concrete (RC), Terracotta bricks, timber roof, corrugated metal	Reinforced concrete (RC), concrete blocks, steel roof, corrugated metal
Building structure NB	RC, timber frame, hemp-fiber, earth blocks, wooden floor, timber roof	RC, timber frame, hempcrete, earth blocks, wooden floor, timber roof	RC, laminated/round bamboo frame, reedcrete, bamboo floor, bamboo roof
Axonometry			
Building Section			

The nine building components studied are floor slab, exterior walls, interior walls, core walls, floors, roof, exterior windows and doors, columns and beams and balcony elements. For each we compile the typical CV material composition and an appropriate NB alternative. To validate their performance, we use the Ubakus calculator and the dataholz.eu database. In order to minimise the ecological footprint, regional availability and efficient value chains for building materials are important. We therefore select the materials based on existing or potential regional availability, climatic suitability and vernacular building practices, with expertise from local partners. Within some NB components, such as for the ground floors and core walls, CV materials are included to maintain the same structural standard.

2.3. System Boundary

We cover the LCA modules A1-A3 (extraction, processing, manufacturing), A4 (transportation), A5 (installation), B4 (replacement), C2-C4 (transportation to end-of-life, waste processing, and disposal). Operational energy and beyond building life-cycle stages are out of the scope of this paper. More information on the included LCA modules can be found in the Annex.

The environmental impacts are measured using two key indicators: Global Warming Potential (GWP) and Carbon Storage Potential (CSP). We apply the +1/-1 approach for biogenic carbon accounting, calculating CSP based on the A1-3 value of biogenic GWP (GWP_{bio}), as defined in EN 15804:2019. In this study, NB materials are assumed to be harvested from managed ecosystems, and their CSP reflects the sequestration of atmospheric CO_2. There is currently no consensus in the literature on how to report the CSP of buildings using NB materials due to uncertainty about carbon release at the end-of-life [18,21,22]. We address this by reporting CSP separately from GWP results, reflecting two perspectives: Taken alone, the GWP result represents the linear scenario in which materials are burned or landfilled at end-of-life (C3-C4). The CSP value represents a potential circular scenario in which materials remain in continuous use, and thus full sequestration potential (GWP_{bio} A1-3) is allocated to NB materials. It is also important to note that CSP scales proportionally with the volume of NB materials used. For practical application, balancing carbon storage goals with efficient use and sustainable harvesting of bio-based resources is essential.

2.4. Life Cycle Inventory (LCI) and Data Assessment

The workflow, as illustrated in Figure 1, follows the Type 1 integration method as defined by Teng et al. [23] in their systematic review of BIM-LCA integration studies. For the LCI phase we employ a BIM-integrated approach, where volumetric and surface area quantities for each building component are extracted from BIM models of each typology and multiplied by material-specific impact intensity factors from OneClickLCA, using the Level(s) life-cycle carbon calculation tool (EN15804+A1/+A2). We use Graphisoft ArchiCAD for BIM modelling, and Microsoft Excel for calculations. The modelling is conducted at Level of Development (LOD) 300, which Teng et al. [23] identified as the most common in reviewed studies. In collaboration with local partners, we first explore the regional architectural and material contexts in the three locations. Based on this, we develop representative building typologies and component assemblies, incorporating region-specific materials. At building level, the total material quantities extracted from the BIM models are normalized by GFA to yield impacts per m^2.

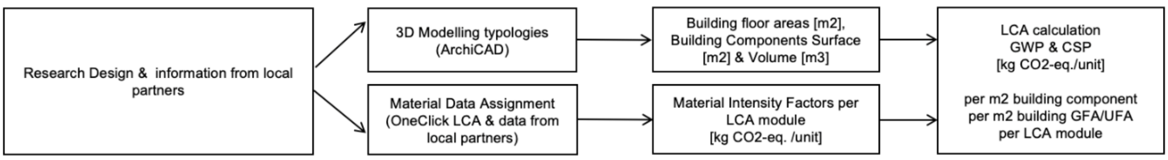


Figure 1. Diagram of the BIM integrated LCA Workflow

Once the material list is compiled for each component, impact intensity factors are sourced from OneClickLCA using the Level(s) life-cycle carbon (EN15804 +A1/+A2) calculation tool (2024), which draws on a range of international databases, environmental product declarations (EPDs) and literature. These factors are aligned with EN15804:2019+A2 (Cradle to Gate with options). For Germany, data primarily comes from national ÖKOBAUDAT database. For Bhutan and Indonesia, OneClick's generic material EPDs are used, due to the lack of publicly available national databases or EN 15804-compliant commercial EPDs. These generic EPDs are compiled and adjusted by OneClick based on upstream data and tailored national energy mixes. To improve regional accuracy, we customize transportation distances for module A4 for the volumetrically significant materials, based on estimates provided by our local collaborators. For steel, concrete, and fired bricks, transport emissions are calculated using exact distances between specific factories and the target city: steel travelled 200 km to Berlin, 370 km to Thimphu, and 1,295 km to Denpasar; concrete 60 km to both Berlin and Thimphu, and 35 km to Denpasar; and fired bricks 160 km to Berlin, 155 km to Thimphu, and 80 km to Denpasar. Timber and bamboo are assumed to be sourced regionally, with transport distances of 72 km (Berlin), 100 km (Thimphu), and 23 km (Denpasar). For all other materials, OneClick's default A4 assumptions remain unchanged. To define the replacement cycles per material (module B4), we refer to the lifespan table published by BBSR, Germany [28]. When density values are missing in OneClick, we use data from IBO, Austria. A summary of the input data can be found in the Annex.

3. Results and discussion

The LCA results at building-component level show which parts of a building are associated with the highest GWP and CSP. This is then followed by results at whole-building level.

3.1. Building-component-level results

The component scale results are calculated per m² of the respective surface. They reflect the emission intensity of the component compositions, independent of their total quantity required in each building. This enables a clear comparison to identify the components with the highest environmental impact and opportunities for GWP reduction and material optimization.

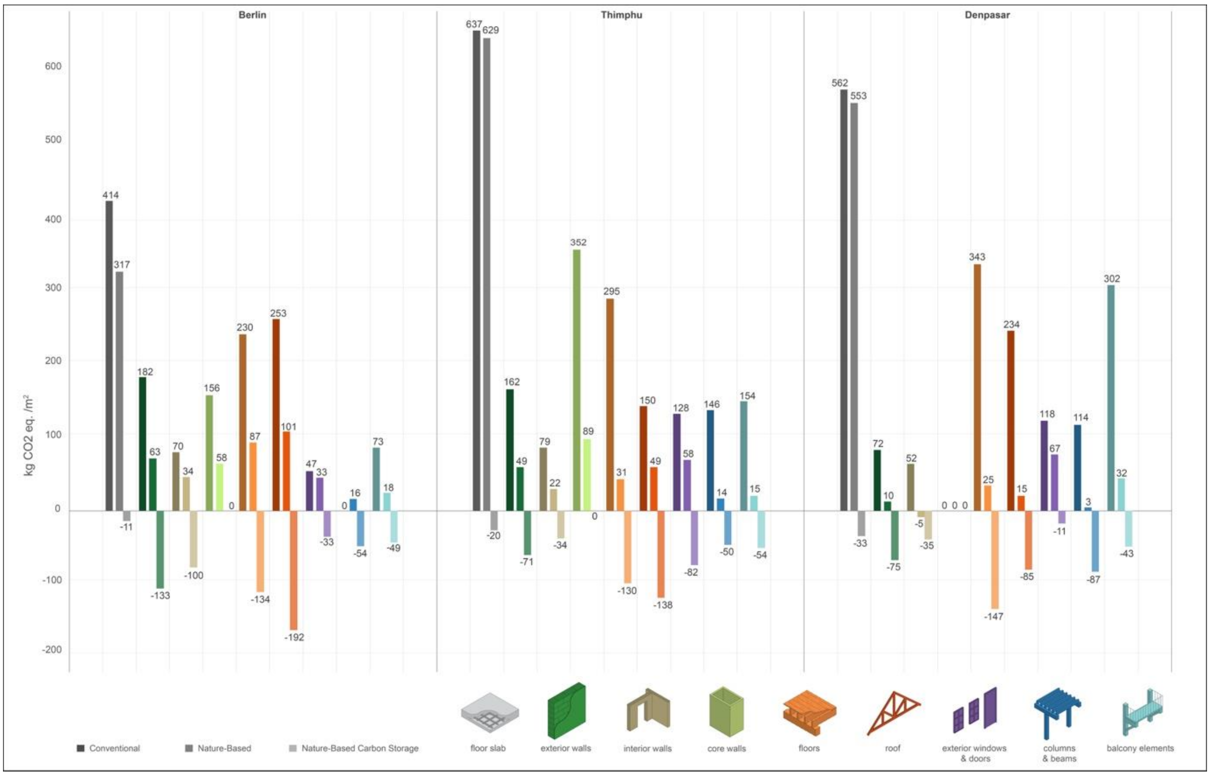


Figure 2. Impact in CO_2-eq/m² building component showing the CV-component GWP (left bar), NB-component GWP (center) and NB-component CSP (right) per regional type. All values are based on a calculation scope of 50-years. For details on component-results see Annex.

In all cases, the ground floor slab exhibits the highest GWP per m² component for CV and NB versions. This stems from the use of reinforced concrete in all types, driven by the structural and environmental performance requirements. Small emissions reductions were achieved by replacing synthetic insulation and finishing layers with NB alternatives. Differences in results between regions arise from variations in material layer thicknesses as well as the influence of recycled content in rebar and different energy-mixes in production. NB ground floor slab results are lowest for Germany, where recycled content exceeds 90% [30] and the energy mix used in production is comparatively cleaner; higher for Bhutan, where steel imported from India contains around 20% recycled content [31]; and highest for Indonesia, where the steel manufacturer's EPD indicates a national average of 15% recycled content. In all three regions, the CV floors show high GWP due to the use of CO_2-intensive materials like screed and synthetic or mineral insulation. By substituting these with a wood-earth floor in Thimphu and a bamboo-earth floor in Denpasar, the GWP can be reduced by 89%–93%. The Berlin NB case utilizes CLT floor slabs, achieving a 62% reduction. All NB floors show a comparably high CSP. The CV roof versions in Berlin and Denpasar show high GWP due to the use of reinforced concrete in Berlin and a steel structure in Denpasar. In contrast, Bhutan's traditional Jamthog roof design (Table 1), constructed with timber, results in a significantly lower GWP. Additional layers, such as corrugated metal sheets in Thimphu and Denpasar and aluminum foil in Berlin, increase CO_2 intensity. The Berlin CV exterior walls have a high GWP due to Germany's stringent insulation requirements for new buildings. The use of mineral-wool and an additional thermal insulating plaster contributes to this. The NB version shows a large CSP using hemp as infill. In Thimphu, the CV core walls have the second highest GWP as due to Bhutan's seismic conditions, this component is made of reinforced concrete causing high production emissions. Therefore, the NB version remains stabilized by concrete framework but is filled with compressed earth blocks reducing the GWP but not significantly increasing the CSP, as earth has low emissions but does not store carbon. Denpasar's balcony elements are also marked by a high GWP, built with reinforced concrete. Switching to NB for balconies can achieve reductions of 75% in Berlin, 90% in Thimphu, and 89% in Denpasar.

3.2. Whole-building-level results

This section presents the overall environmental impact of the building per m² GFA, broken down by components and phases. These results do not only depend on material choices but also on the quantity of materials used within the whole building. Our analysis reveals that the global warming reduction potential from CV to NB construction consistently ranges from 52% to 66% (Figure 3), despite variations in building components influenced by architectural traditions, construction practices, and climate conditions. This demonstrates that NB approaches are effective in reducing environmental impact across a wide range of building components.

Floors are a key lever for emission reduction and CSP at the whole-building level. Their high material volume and complex layering significantly impact total environmental performance, making them a priority for optimization. The floor slab, however, remains a major challenge, as all cases rely on reinforced concrete due to moisture constrains, limiting decarbonization potential. In the CV Berlin case, load-bearing walls are used as the primary structural system, in contrast to the NB cases, which employ skeletal frames. Columns and beams exhibit low emissions across all NB cases, thereby enhancing the potential for adaptive reuse and providing long-term benefits (e.g. flexibility) that extend beyond the defined LCA boundaries. Exterior walls offer substantial potential for GWP reduction and increase the CSP due to their large surface area, which enhances insulation and structural performance. Roof impacts vary with geometry and materials. High-pitched roofs require more material, increasing both GWP and CSP, but they align well with NB construction, offering ventilation and drainage advantages. Flat roofs have a lower relative impact but require careful moisture protection [32] when optimized with NB insulation. While the NB interior walls contribute less to total emissions, they offer strong CSP, particularly in typologies with extensive internal partitioning. Their lower structural and regulatory demands compared to exterior walls make them an ideal application for NB materials, significantly contributing to the building-level CSP without proportionally increasing the GWP. This aligns with Van Roijen et al. [33] emphasizing the importance of assessing CSP not just per material but per actual application volumes. While interior walls exhibit a comparably low GWP (Figure 2), their contribution to the whole-building GWP is substantial, demonstrating the importance of evaluating impact at both component and building levels. For Berlin, switching from CV to NB interior walls cuts their GWP by half, aligning with Churkina et al. [34], who report a 40% GWP reduction for generalised NB construction types. Thinley et al. [26] show a 72% reduction in embodied emissions shifting from CV to mass timber in a comparable Bhutanese mid-rise building (assuming carbon neutrality for timber), although their analysis is limited to A1-A5. Our findings are based on broader system boundaries and therefore indicate a smaller reduction potential with further potential through full CV material substitution, as applied in Thinley et al. [26]. For Bhutan and Bali, the CV cases with load-bearing skeleton plus load-bearing infill (e.g. bricks) increase the GWP, as duplicated structural elements raise material use and emissions.

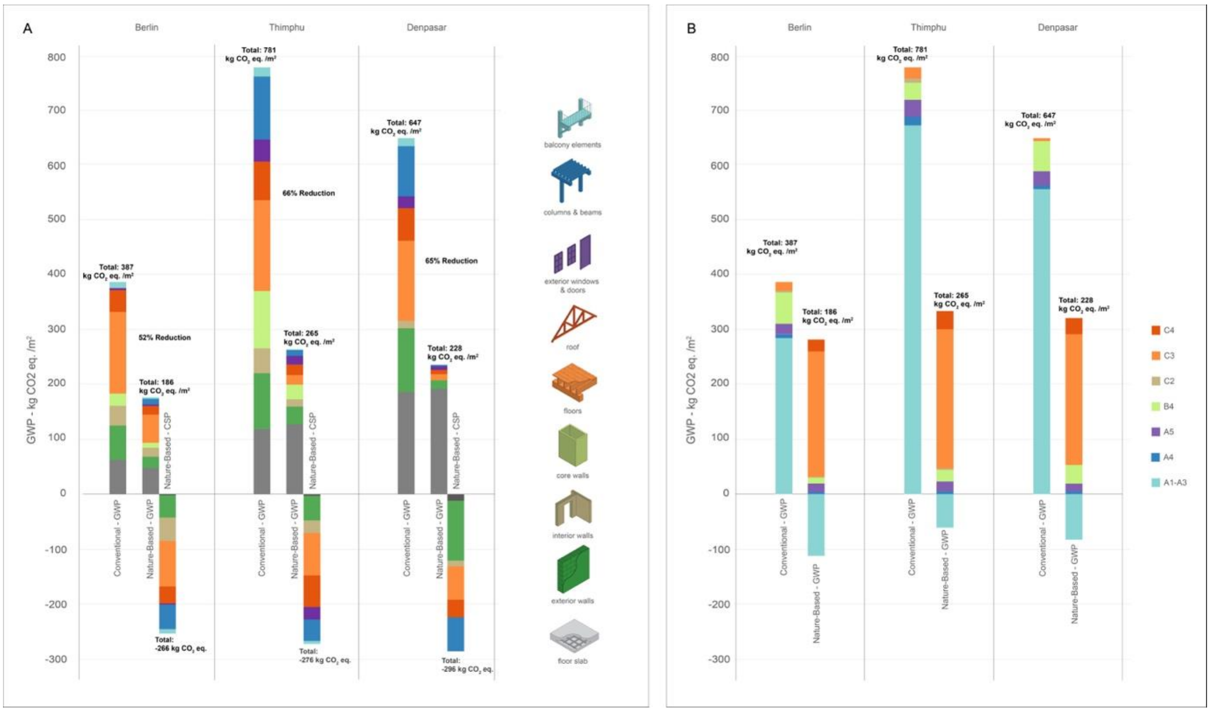


Figure 3. a) GWP and CSP per m^2 GFA and share of building components. The first bar per region represents CV-type GWP, the second bar NB-type GWP, the third bar NB-type CSP. **b)** GWP per m^2 GFA and share of LCA-modules. All values are based on a calculation scope of 50-years. For details on building-results see Annex.

Breaking down whole-building results by LCA modules (Figure 3b) shows that A1-A3 is largest emission contributor in the CV cases. NB components have a low GWP in these early phases due to the stored carbon. However, assuming a linear construction practice, these materials release CO_2 at the end of life (C3-C4) through decomposition or combustion, leading to higher emissions than CV materials in this stage. This aligns with Rinne et al. [35], who find that, compared to hybrid and CV structures, timber has the lowest A1-A3 emissions (-28%), and lower A4 emissions (-19% timber, -55% hybrid) but higher C1-C4 emissions.

Thus, to emphasize the benefits of a circular construction practice, we present the NB CSP separately to the GWP. Our results show that higher NB material use strengthens CSP, underscoring the potential of cascading materials and thereby extending the lifespan of stored carbon. Beyond A1-A3 and C3-C4, module B4 can significantly contribute to whole-building GWP due to multiplication of emissions due to replacement of materials. B4 impacts, evident in both NB and CV, highlight the importance of material longevity and a construction that minimizes environmental exposure.

3.3. Scenario and Sensitivity Analysis

Material choices and data sources significantly affect emission outcomes. OneClick LCA generic data tends to overestimate impacts compared to manufacturer or regional EPDs - with emission intensity values ranging from 67%–105% for concrete/steel and up to 188% for bamboo and 120% for timber (compared to the results above, for CV and NB construction).

A higher proportion of recycled concrete leads to 4%-36% lower GWP in all three regions (compared to results above, for CV and NB). When using recycled steel (15% and 60% recycled content), total emissions can be reduced by 27%-41% in Indonesia and 8%-19% in Bhutan (with 60%-90% recycled content), across NB and CV construction. Testing alternative material data of recycled steel for Germany leads to higher impacts compared to the initial ÖKOBAUDAT data which already includes a high share of metal scrap and electric arc furnace steelmaking.

Building lifespan also significantly affects results. In Germany, stricter regulations lead to more complex material layers that increase maintenance demands over time. Bhutan and Indonesia have fewer high-maintenance layers, so replacement rates are lower, even though structural materials are assumed to last equally across regions. For Germany the CV emissions rise from 89% (25 years) to 146% (75 years), while NB emissions increase from 94% to 134%. Similar patterns are seen in Bhutan (CV: 96–102%, NB: 92–122%) and Indonesia (CV: 92–128%, NB: 92–113%). The total emissions of all NB scenarios are considerably lower than for CV. More information can be found in the Annex.

3.4. Limitations and further outlook

This study analyses mid-rise housing typologies with regional differentiation in terms of design and materials. We assess embodied emissions, excluding use-phase impacts and emissions related to the sourcing of NB materials, e.g. forestry management. To evaluate local material availability, partnering with local research groups provided valuable insight to refine our assessments. Given significant differences in embodied carbon [5], we incorporated locally specific data (transport distances, recycling quotas, specific EPDs) to reduce uncertainties from generalized defaults. Due to the lack of data, for round bamboo, emission intensity values for laminated bamboo are applied.

Our results show that NB materials can reduce and store carbon, aligning with numerous studies who emphasize the benefits of bio-based substitutes for energy-intensive materials [7,8,15]. However, maximizing NB materials for carbon storage alone is not the solution. A whole life carbon perspective prioritizes material efficiency and sufficiency, ensuring that only the necessary material-amount is used to meet structural and functional needs while minimizing embodied emissions. This balanced approach optimizes both resource use and emission reduction. While NB materials can support storing carbon in buildings, their impact depends on sustainable forest management, circular lifecycle strategies, and efficient value chains to ensure responsible sourcing, reuse, and recycling while minimizing ecosystem harm. For instance, sustainable forestry reduces GHG emissions from timber [17], thus including timber harvesting emissions would enhance the assessment.

Future research could further expand LCA studies to include retrofit, building extensions, material reuse, design for disassembly, operational energy, and additional impact indicators like raw material consumption and waste generation. Ultimately, to become relevant for national policy making, such assessments should be scaled up to the city, regional, or national level, and wood supply assessments and carbon accounting should be linked to actual forest carbon dynamics.

4. Conclusion

This study is the first to systematically compare conventional and nature-based construction across multiple regional typologies, providing a comprehensive life cycle assessment (LCA) that reflects both current practices and future-oriented material choices and practices. By modelling each typology with conventional methods and nature-based alternatives, we highlight the potential impact of material shifts, ensuring regionally viable solutions. Our approach offers a transferable framework for sustainable construction by focusing on detailed building component modelling supported by local expertise and plausible material substitutions. Despite variations in architectural traditions and cultural influences, our findings show a consistent reduction potential in whole-building emissions from 52-66%. This indicates that implementing NB approaches across a wide range of building components presents an effective strategy for reducing environmental impact. The transparent, modular approach used here enables straightforward application and comparison to other regions, contributing to CO_2 declarations, benchmarks, and policy development.

Ultimately, this study underscores the critical role of efficient material use and long-term carbon management in optimizing sustainable architecture. By embracing nature-based solutions, we can achieve transformative, regionally applicable strategies that drive meaningful progress toward a carbon-neutral built environment.

5. Annex

Supplementary data and results can be found here:
https://doi.org/10.6084/m9.figshare.28512464.v3

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