Geo and Bio Based Materials as Circular Solutions Towards a Regenerative Built Environment

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Abstract. Global environmental awareness pushes the building sector to achieve carbon neutrality and nd low embodied impact solutions. The European Union has set a 2050 goal and is regulating the whole carbon life cycle (embodied and operational) as part of the Energy Performance of Buildings Directive (EPBD). In this scope, low-tech geo-bio-based materials can have an important role in reducing the embodied environmental impacts and carbon in buildings. Due to their low processing production, these materials t in a circular approach since they can be easily recycled or returned to the natural environment at a minimal environmental cost. However, the lack of quantitative data on the life cycle environmental performance of some non-conventional techniques can hinder their use since professionals cannot compare the bene ts of such versus conventional practice and comply with future EPBD requirements. This paper aims to contribute to the topic by presenting results on the life cycle environmental performance of earthen materials and bio-based insulation products versus conventional solutions based on data from Environmental Product Declarations or studies following the EN15804 standard. The results show that earthen materials can reduce the potential environmental impacts by about 50% versus conventional mansory walls. At the same time, bio-based insulation solutions offer the advantage of lowering operational carbon emissions and stocking carbon (e.g. straw has a Global Warming Potential performance about three times better than Expanded Polystyrene). The bene ts of using earthen and bio-based materials are also discussed for the different building life-cycle stages, focusing on the possibility of reusing/recycling these materials in a closed-loop approach.

Keywords: Earthen materials · Bio-based materials · Low-carbon materials · Circular materials · Life cycle assessment

1 Introduction

Regarding the current climate change scenario, the struggle to limit global warming to a 1,5 ºC rise in temperature comes up against the high level of CO_2 emissions over the last decades. According to the International Panel on Climate Change (IPCC), all sectors have options to at least halve emissions by 2030 [1]. For the built environment-related sectors

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(cities, buildings, and industry), there are substantial emissions reduction opportunities through measures such as lower energy consumption, carbon storage in natural solutions, ef cient use of materials, reusing and recycling products and minimising waste [1].

The built environment is a key sector to intervene since it is responsible for almost 40% of CO_2 emissions [2]. In 2022, about 9% of those emissions were related to building materials [3]. Among building materials, concrete and steel are the most important contributors to the embodied carbon of all building types, representing more than 60% of it [4]. The OECD report on global resources stated that the use of materials will rise from 79Gt in 2011 to 167Gt in 2060 [5]. At the same time, materials management emissions related will grow from 28Gt to 50Gt of CO_2 eq. by 2060 [5].

Adopting circular solutions could reverse the trend and avoid exceeding several planetary boundaries. According to the most recent Circularity Gap Report, such adoption could lead to a signi cant 145% decrease in climate change and an even more substantial 190% reduction in land system change [6]. However, according to this report, nowadays, just 7,2% of the total material comes from circular inputs, known as secondary materials. The report explains that it is not only due to our incapacity to recycle but also because we are building more. The circularity metrics have fallen since the rst report (2018), which stated 9,1%. Material choice becomes a key point for a circular economy and a regenerative built environment. The growing environmental awareness will increase the demand for more sustainable solutions, therefore forcing the construction industry to follow the path towards a circular economy, sustainable resource management and environmental protection [7, 8].

Concerning the European context, strategies such as the European Green Deal address decarbonisation, aiming to reduce greenhouse gas emissions by 55% by 2030 and making Europe the rst climate-neutral continent by 2050 [9]. To achieve this goal, the Energy Performance Building Directive (EPBD) recast 2022 [10] demands for new buildings from 2030 onwards, the calculation of the life cycle Global Warming Potential (GWP), as well as predicts at least double renovation rates from 2020 to 2030. Northern European countries, such as Denmark and Sweden, have even more ambitious plans to deal with the environmental impact of buildings. Denmark targets to reduce new housing emissions from 482 to 20 $kgCO_2$ eq/m^2, while life cycle emissions would be reduced from 9,6 in 2020 to 0,4 $kgCO_2$ eq/m^2 in 2029 on a most optimist scenario, on a 50—year reference period [11]. The Danish Reduction roadmap also intends to reduce the number of new buildings by limiting the permitted square meters per year and reducing the square meters per person [11]. In the case of Sweden, it aims to bring greenhouse gases emissions to zero by 2045, becoming the rst fossil-free country in the world [12]. Among the Swedish actions is a signi cant reduction in emissions from heating, which includes combined heat and power production plants and district heating systems for buildings [12].

As buildings become more energy-ef cient, attention turns to the increasing relevance of embodied emissions in materials [4]. In this framework, geo and bio-sourced materials have the most negligible impact as they tend to be locally available for construction. These kinds of materials have been present in the construction community for a long time, as vernacular construction is based on them. In the scope of sustainability, vernacular architecture holds signi cant importance, as this type of construction carries the notion of being built to meet the needs in which its strategies and materials are the basis of sustainable construction. Research conducted globally has demonstrated that its features play a crucial role in ensuring comfortable living environments, lowering environmental impact, reducing energy consumption and consequently mitigating CO2 emissions [13–18]. Contemporary construction needs to adapt vernacular materials to current projects.

In order to reduce energy and materials demand, it is essential to prioritise energy-efficient systems through passive strategies and incorporate circular materials whenever possible, as emphasised in the Circularity Gap Report 2023 [6]. Natural materials used in vernacular architecture, such as earth and fibres, have considerably lower embodied energy and carbon dioxide emissions than conventional materials and can reduce environmental impacts associated with buildings [8, 18, 19].

The transition from a linear to a circular production model, characterised by an ongoing cycle of recycling, production, use, and recycling, is imperative. The transition from a linear to a circular production model, characterised by an endless cycle of recycling, production/transformation, use, and recycling, is imperative. Therefore, it is important to predict the use of low-carbon impact materials, such as geo and bio-based materials with a high recyclability rate. Materials can transform buildings into carbon sinks and, at the same time, be guaranteed to be reused or recycled. Low-processed materials do not require significant effort to be reused since they can be disassembled and transformed for reapplication. The recycling processes must guarantee the original level of quality of materials rather than downcycle them [20].

However, there is a lack of quantitative data on the benefits regarding environmental performance and recyclability rate of geo- and bio-based materials, which hinders professionals from comparing and specifying these products. In this context, this work discusses their environmental performance and contribution towards a construction based on natural building materials.

2 Geo and Bio Based Construction Materials

Geo-based materials are the ones from mineral-origin resources, such as raw earth and dry stone. On the other hand, bio-based materials are partially or entirely from biomass, such as wood, hemp, straw, cork, sheep's wool, etc. Both, when minimally processed, tend to have a low environmental impact, and when reused or in the form of by-products or co-products, such as recycled textiles or wooden boards, they enter into a circular economy logic.

Humanity has used geo- and bio-based construction materials for as long as shelter was needed, relying on renewable resources or abundant reserves, leading to easy recyclability and economically efficient products [20]. However, many of these natural materials are hardly associated with progress and even rejected for connotation to sub-development. Regardless, in some contexts, using these materials is related to a luxury lifestyle, and their value is overpriced.

Pricing of building materials often ignores the fair labour and environmental costs of conventional materials, potentially distorting their true affordability. Regenerative materials may appear more expensive initially due to low demand and skilled labour.

However, recognising their true costs, including environmental factors, could position them as more cost-effective in the long term. Berge [20] argues that current prices, influenced by green taxes, obscure true environmental expenses. A shift towards a more realistic assessment of material costs is crucial to promoting sustainability and equity in the construction industry.

Developing and improving geo and bio-based materials is an asset for new buildings but mainly for the renovation market, reducing the embodied environmental impacts of interventions. Additionally, as these materials are natural, low processed and do not contain chemical content, they also contribute to a better indoor air quality than in conventional buildings. In some cases, as earth and natural bres, their vapour-free and hygroscopic inertia properties also allow them to self-regulate moisture passively.

2.1 Earthen Construction

Earthen construction has deep historical roots and has been used for centuries, with many examples found across diverse cultures globally. Nowadays, it is gaining renewed attention due to its inherent ecological features and being used and adapted to contemporary buildings and needs.

There are many earthen-building techniques, developed and adapted to speci c geographic contexts. Some of the most common earthen construction techniques include: i) adobe bricks, made from a mixture of earth, water, and sometimes straw, moulded and sun-dried; ii) rammed earth, entails compressing layers of earth within a formwork to build massive solid walls; iii) cob consists of blending clay, sand, and straw, and it is often used to build robust walls and sculptural structures; iv) compressed earth blocks can be considered a modern and improved version of adobe bricks, created by compacting a mixture of earth, water and sometimes stabilising agents, and has become one of the most versatile techniques for contemporary use. This technique is known for its durability and thermal mass properties, making it suitable for sustainable and energy-ef cient construction.

These techniques are known for their durability and thermal mass properties, particularly rammed earth. Their high thermal and hygroscopic inertia helps to regulate indoor temperature and relative humidity, reducing the dependence on active heating or cooling systems. This not only enhances energy ef ciency but also creates a comfortable living environment. Ongoing research and technological innovations aim to enhance the durability and stability of earthen structures [21]. These actions promote sustainable building practices, such as the circularity of the process. The circularity inherent in earthen construction, coupled with its deep historical heritage, positions it as a guiding force for future sustainable and innovative building solutions.

2.2 Bio Based Insulation Materials

Bio-based insulation materials are usually sourced from plants/trees, including hemp, straw, cork, or wood. Additionally, they can be sourced from animals, such as sheep wool insulation, or from recycled materials like textiles or paper. Moreover, experimental natural insulation materials, such as mycelium-based ones, are gaining prominence in research [22].

As climate change increases extreme temperatures frequency, building's indoor comfort by passive means becomes a challenge. Despite insulation appearing to offer a proper solution for reducing energy demand for heating and cooling, most conventional insulation materials have complex industrial processes and pose significant harm to the environment, including high global warming potential. In this scenario, bio-based materials have the highest potential of lowering embodied carbon emissions in buildings due to their ability to stock carbon and contribute to mitigating climate change [23].

Nevertheless, the performance of these materials should not be evaluated based on a single factor but on the combination of various factors such as energy performance (thermal conductivity), environmental impact, carbon stocking and potential for end-of-life valorisation. Additionally, beyond energy-efficiency performance, when compared to conventional materials, bio-based materials offer advantages such as renewability, biodegradability, and a lower carbon footprint.

3 Environmental Performance of Natural Materials

Life Cycle Assessment (LCA) plays an important role in understanding and improving the environmental performance of a building through material choice. It is essential to assess their entire life cycle, from raw material extraction to end-of-life disposal or recycling. LCA provides a systematic and comprehensive framework for evaluating the environmental impacts associated with each stage of a material's life.

LCA methods are essential for manufacturers to identify areas for improvement within the life cycle of a material. This approach can contribute to minimise adverse environmental effects, improve resource efficiency, and promoting the adoption of more sustainable alternatives.

This work focuses on presenting the life cycle analysis results during the product stage (modules from A1 to A3), except for rammed earth, which includes the construction stage (A4-A5). Additionally, the potential benefits beyond the system boundary are also discussed.

Regarding earthen construction, many research studies emphasise the potential of earthen materials to reduce the environmental impact of buildings. However, the use of stabilisers in earthen solutions may differ in performance. Cement-stabilised rammed earth studies show that total embodied energy rises proportionally with cement content [24, 25]. For both earth blocks and rammed earth, the addition of lime, even in small amounts, emerged as a significant contributor to environmental impacts and embodied energy [18]. Thus, Arrigoni et al. [25] affirmed that creating durable mixes without stabilisers is possible. The study carried out by Fernandes et al. [18] also confirmed that adding hydraulic lime contributes to more than 60% of the value of all impact categories in module A3 (Manufacturing).

When assessing the global warming potential and embodied energy of conventional and earth-based solutions, noticeable reductions in values can be observed (see Fig. 1). Compressed earth blocks exhibit less than half the global warming potential of both ceramic and concrete blocks, a trend similarly observed in the case of rammed earth walls compared to alternative conventional solutions [26]. In terms of embodied energy, a similar trend is evident. Ceramic and concrete blocks possess 2.5 and 1.5

times more embodied energy than compressed earth blocks, respectively. Lightweight concrete blocks exhibit twice as much embodied energy, whereas ceramic blocks have approximately 0.45 times more embodied energy than rammed earth.

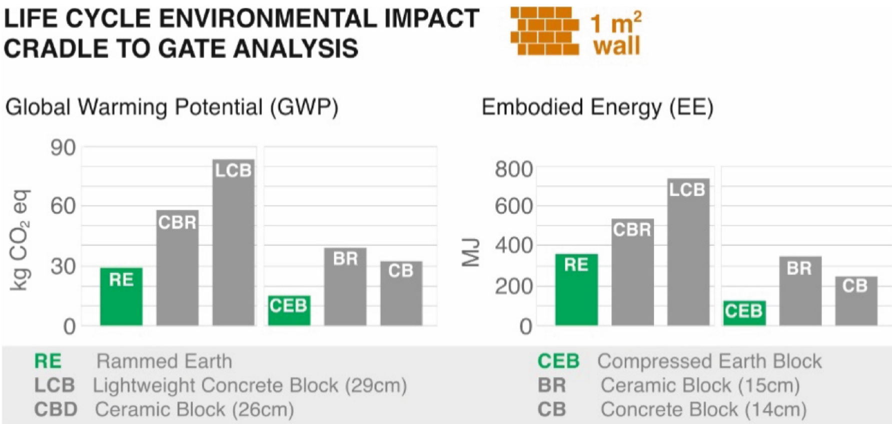

Fig. 1. Life cycle environmental impact comparison between earthen buildings and conventional solutions. Adapted from [26].

Regarding the life cycle analysis of bio-based insulation materials, the most significant advantage lies in their ability to store carbon during growth. In this sense, fast-growing plant-based materials, such as reed and straw, have proven to be particularly advantageous. The carbon sequestration during growth contributes to a reduction of overall carbon emissions, and along with their potential for recycling at the end of their life cycle, they are excellent choices for environmentally responsible insulation solutions.

A significant concern may be related to the thermal performance of bio-based insulation, yet only a greater thickness can match the performance of conventional materials while ensuring a considerably lower impact. The figure below (see Fig. 2) compares the thickness and emissions of known insulation products with the same thermal performance. While bio-based products require the same thickness or more than conventional products, their emissions are considerably lower or even "negative", i.e. stocking carbon.

Despite XPS foam and mineral wool requiring the same thickness to provide a thermal resistance of 5 (m^2K)/W, the global warming potential of XPS is more than ten times higher than that of mineral wool. While straw bale insulation is the thickest among the analysed materials, its rapid growth characteristic contributes significantly to a highly negative environmental impact and is about three times better than EPS foam board.

Among other advantages, it can be highlighted the renewable nature of bio-based materials, the low processing needed, which leads to energy efficiency in production, and biodegradability contribute to the end-of-life scenarios and circularity of the construction processes (Fig. 3).

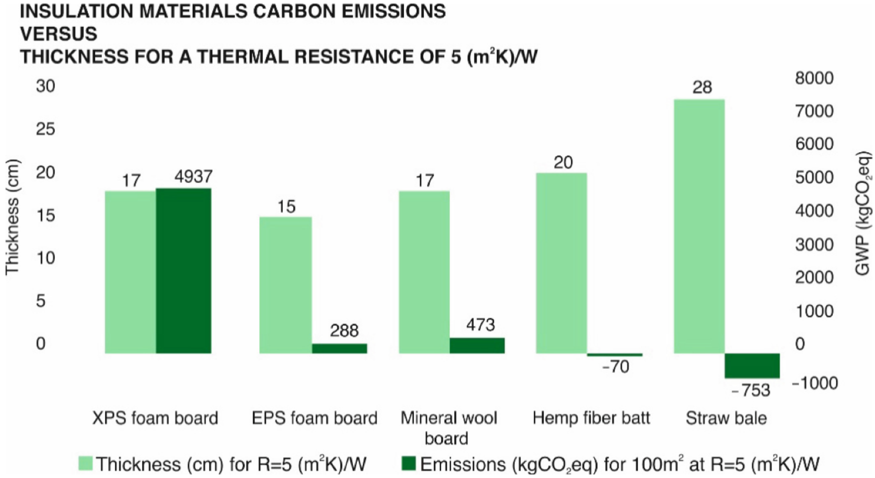

Fig. 2. Comparison between insulation material thickness and carbon dioxide emissions for a 5 (m^2K)/W thermal resistance, considering product stage (A1-A3). Adapted from [23, 27].

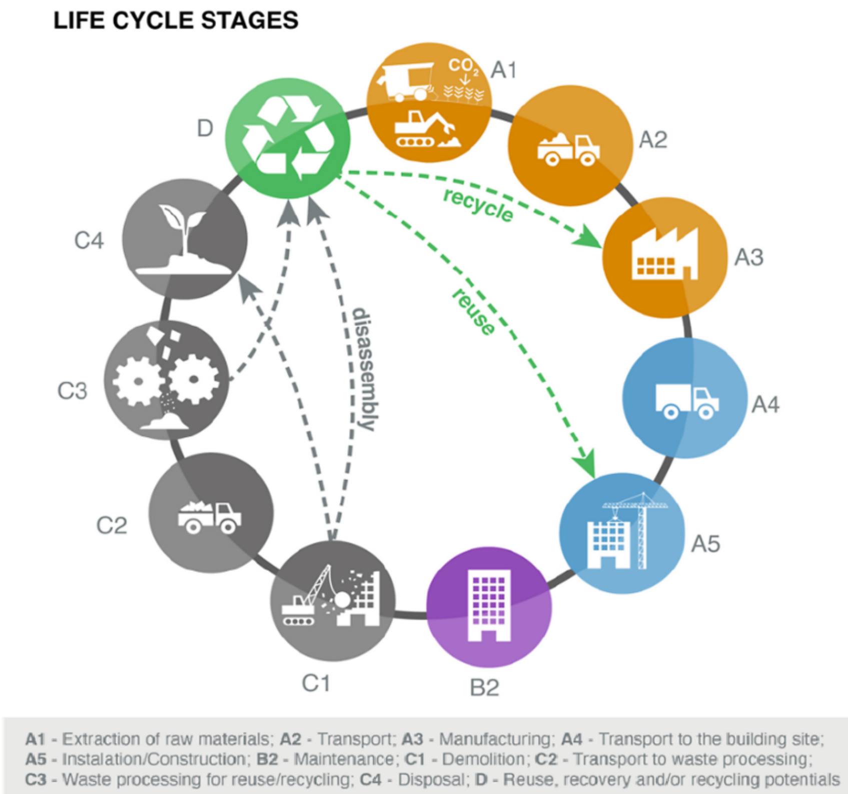

Fig. 3. Life cycle stages framework for building materials [18, 28].

It must be highlighted that geo- and bio-based materials can be easily recycled/reused into a new cycle, in some conditions with the same function as the previous. If not, disposing of the earth to the environment at a minimal environmental cost is possible since no harmful products were incorporated. As for other organic materials, such as plant-based, they can maintain their stocked carbon when in good condition and reused in construction or can serve as nutrients for further plant growth. Emphasising the proper disposal of these materials is crucial, as burning or depositing them in landfills releases the carbon accumulated throughout their life cycle.

4 Conclusions

Exploring geo- and bio-based materials in the context of a circular economy presents a transformative journey towards achieving a regenerative built environment.

These materials offer multiple benefits, from reducing carbon footprints to harnessing renewable resources, presenting a transformative trajectory for the industry that aligns perfectly with circularity and resource efficiency principles. Geo-bio-based materials can have a relevant role in the implementation of a truly circular economy in the building sector since they can be easily recycled/reused into new cycles, in some cases with the same function as the previous without downgraded quality, and by minimising waste and optimising the use of resources. When this is not possible, disposing of the soil has minimal environmental cost once it has no harmful products incorporated (e.g. non-cement stabilised soil). As for bio-based materials, they maintain their stocked carbon during proper reuse in construction, or they can be disposed of and serve as nutrients for further plants or even used for energy valorisation.

However, natural materials come with a set of challenges that need to be addressed for widespread adoption. Material consistency, regulatory intricacies, and the need for standardised practices are critical hurdles that demand strategic solutions. By better understanding its characteristics and continually developing actions to promote the use of these materials, it is possible to lead to a more resilient and regenerative built environment.

Due to the advantages mentioned in this paper, geo- and bio-based building materials have the potential to reduce the embodied environmental impacts of buildings, contribute to a truly circular construction economy and create healthy living environments.

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