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Fast-Growing Bio-Based Construction Materials as an Approach to Accelerate United Nations Sustainable Development Goals

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Abstract: The United Nations Sustainable Development Goals (UN SDGs) ensure future human well-being. However, they face challenges due to the pressing need to reduce carbon emissions, with nearly 40% originating from the construction sector. With the current global environmental and energy crisis, there is a pressing need to address building carbon emissions and prioritise investments in passive strategies for improving indoor thermal comfort. Exploring fast-growing bio-based materials like bamboo, straw, hemp, and flax directly addresses these concerns, fostering environmental sustainability. Material selection in construction is crucial for advancing the SDGs, for example, promoting sustainable cities and communities (SDG11) and responsible consumption and production (SDG12). This paper proposes a comparative analysis of conventional and bio-based construction materials, focusing on their production stages through life cycle analysis. Tools such as Building Emissions Accounting for Materials (BEAM) and the Methodology for Relative Assessment of Sustainability (MARS) enable a detailed comparison. The results highlight the benefits of bio-based materials in storing carbon more rapidly and their lower environmental impact compared to conventional alternatives. Moreover, bio-based materials contribute to indoor moisture regulation and a healthier indoor environment, underscoring their potential to accelerate progress towards the UN SDGs through informed material choices in design practices.

Keywords: fast-growing bio-based materials; material choice; building emissions; SDGs achieving; BEAM; MARS

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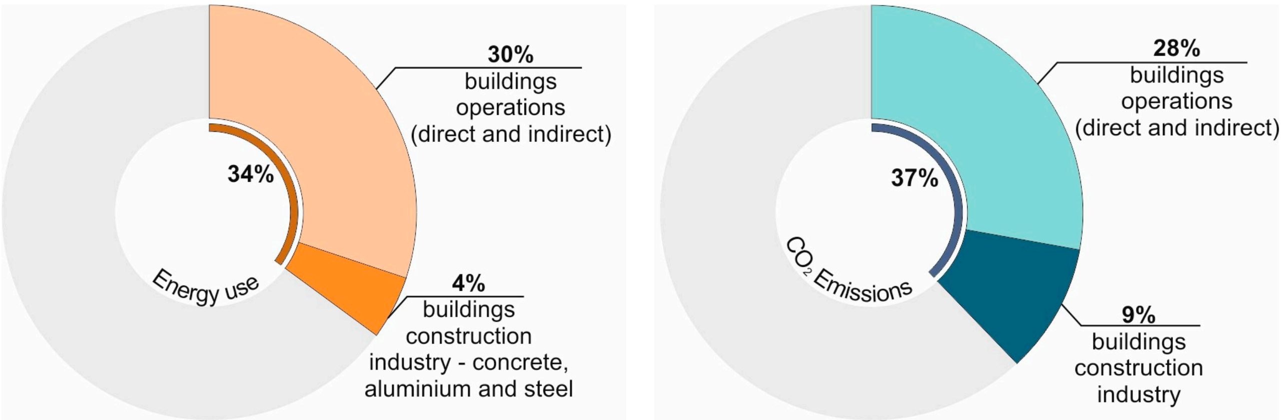
1. Introduction

The United Nations Sustainable Development Goals (UN SDGs) emerged as an initiative to promote economic growth and fulfil social needs, such as education, health, and job opportunities while dealing with climate change. Intended as a roadmap for sustainable development, the SDGs address interconnected global challenges, such as poverty, hunger, health, education, gender equality, clean water, sanitation, and others. This initiative recognises the importance of an integrated approach, promoting economic growth, social inclusivity, and environmental sustainability. Additionally, the SDGs highlight the need to address climate change and its widespread impact on ecosystems, economies, and societies.

The United Nations 2030 agenda serves as a timeline for achieving these goals by proposing 17 goals and 169 related targets, in which multidisciplinary approaches at a global level are considered.

In general, the construction value chain through new buildings and renovations is essential to meet the UN SDGs, for example, by including safe and affordable housing (SDG 11), providing transportation and energy infrastructure (SDGs 7 and 9), and water and sanitation (SDG 6) [1]. Through a conceptual framework of building materials, Omer and Noguchi [2] concluded that building materials can help achieve 13 goals, namely SDGs 1, 3, 4, 6, 7, 8, 9, 11, 12, 13, 14, 15 and 17, and 25 targets of the UN 2030 Agenda. The authors provided a state-of-the-art review of the SDGs, focusing on the connections to buildings and materials. They illustrated how building materials play a role in accelerating the SDGs despite highlighting the lack of research in this field [2]. In summary, material choice is recognised as having a significant impact on the UN SDGs, which shows how important they are for creating a better and more equitable future.

The construction industry is one of the most polluting activities, accounting for 37% of global operational energy and process-related CO_2 emissions and 34% of total energy use (Figure 1) [3,4]. It is also a strategic sector that can impact climate change, living conditions, economic growth, and city resilience. Building materials and construction activities also account for 10% of greenhouse gas emissions and 50% of all resource extraction [4].



(a) (b)

Figure 1. (**a**) Building's energy use. (**b**) Building's emissions. Adapted from [3].

According to the International Energy Agency report [5], global energy-related CO_2 emissions grew 0.9% in 2022, or 321 Mt, of which 60 Mt CO_2 is associated with heating and cooling demand in extreme weather. During the operational phase of a building, 80% of household energy is related to thermal comfort [6], emphasising the importance of effective envelope and insulation to reduce energy demand. However, embodied carbon on conventional thermal insulation products can have a high environmental impact. In this context, the IPCC's sixth report [7] proposes the adoption of low-carbon materials and nature-based solutions to diminish the long-term embodied carbon in buildings. Additionally, recent publications show that passive strategies and proper choice and use of materials can reduce significant HVAC systems employment in buildings [8].

The 2020 Global Status Report for Building and Construction [4] highlights that building is a domain that lacks mitigation policies on CO_2 emissions despite its impact. As environmental awareness becomes more relevant, driven by the consequences of climate change, some initiatives arise from global governments. In Europe, the Energy Performance of Buildings Directive (EPBD) recast of 2022 [9] stipulates the life cycle assessment of the Global Warming Potential (GWP) for new buildings starting in 2030. This directive will significantly impact future thermal regulations, aligning with the European Green Deal [6] goal to decarbonise the EU's building stock by 2050, positioning Europe to lead as the first climate-neutral continent.

Material choice becomes essential to lowering the environmental impact of building materials. Features such as being a renewable resource with a reduced carbon footprint, biodegradability, recyclability, and preserving biodiversity in ecosystems lead to bio- and geo-based materials. According to Carcassi et al. [10], climate-neutral energy efficiency construction is feasible when using timber- and bamboo-based building materials. However, a comprehensive life cycle assessment (LCA) is needed to evaluate the real environmental cost of a material use.

Life cycle assessment (LCA) is the basis of environmental product declarations (EPDs), providing a structured approach to evaluating products' environmental impacts throughout their life cycle. EPDs rely on LCA data to offer stakeholders standardised documentation on environmental performance. This provides a deeper understanding of a product's environmental footprint and facilitates comparisons between products and construction solutions.

In this context, fast-growing materials derived from rapidly renewable sources such as bamboo, hemp, reed, or trees like eucalyptus stand out as the stored carbon during their lifetime can be greater than released carbon when the building material is manufactured (Figure 2). Conventional construction materials, such as bricks and cast concrete, contribute significantly to climate change. Despite some claims, high initial emissions cannot be compensated for by carbon uptake in lime-based alternatives [11]. Regardless of the emissions from manufacturing and use, carbon-storing materials offer a significant advantage that might be the key point for future post-carbon construction. Using fast-growing bio-based materials for construction products can create carbon-neutral or even carbon-negative products [12].

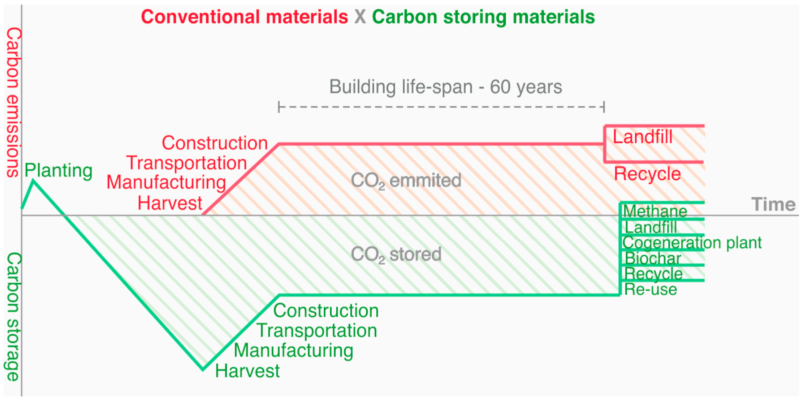


Figure 2. Influence of carbon sequestration of bio-based materials over conventional materials emissions. Adapted from [13].

Fast-growing materials are natural resources or crops that have rapid growth, making them readily available for harvest and use in a short period. They reduce pressure on ecosystems and support environmentally friendly practices. Examples already used in construction worldwide are bamboo, hemp, straw, flax, kenaf, and several species of reed.

According to Pittau et al. [11], storing carbon in fast-growing biogenic materials is more efficient than storing it in timber elements. Once these materials capture the stored carbon fully within one year after construction, forest products take longer due to the required long rotation period for regrowth [11,12,14].

In the Global North, retrofitting existing buildings with agricultural waste products, such as straw, presents an opportunity for bio-based thermal insulation [12]. In this context, while fast-growing materials are mostly known for their insulation properties due to their fibrous composition, their applications extend far beyond insulation. They are versatile components in various construction projects, from structural components crafted from bamboo to finishing materials like plaster, flooring, siding, roofing shingles, and acoustic panels, which are aesthetically pleasing. In Brazil, the implementation of bio-concrete solutions using bamboo had the potential to reduce up to 65% of carbon emissions [15].

In this sense, this study aims to analyse the potential of fast-growing bio-based construction materials, thanks to their high biogenic carbon, to accelerate the achievement of SDGs.

2. Materials and Methods

The comparison proposed in this paper is based on sustainability assessment tools based on life cycle assessment (LCA) methods and environmental product declarations (EPDs) to compare construction solutions and materials. Two approaches were selected to enable the use of multiple comparative methods for construction solutions that involve both conventional and bio-based materials, particularly those derived from fast-growing species.

The first approach chosen is the open-access tool Building Emissions Accounting for Materials (BEAM) [16], developed by the organisation Builders for Climate Action to account for the carbon stored in bio-based materials.

BEAM only considers the product stage of the building life cycle, i.e., the production phases from extraction to manufacturing, including transportation (modules A1–A3 on a life cycle assessment method). This explains the importance of this stage for carbon emissions that represent 65 to 85% of total life cycle emissions from building materials [16]. Other life cycle phases, such as transportation, construction, maintenance, and end-of-life scenarios, are not considered due to the assumptions that need to be made, which often lack accuracy, and can reduce assessment precision. This is a pragmatic choice to maintain the precision of results by avoiding including uncertain and variable factors. These activities depend on location, technology, and practices, introducing a high degree of variability. Estimating future activities, such as maintenance and end-of-life scenarios, involves predicting future practices, which is inherently uncertain.

Additionally, accurate data for these activities might not be available or may be highly context-specific. The BEAM tool also considers carbon storage. The mass of biogenic material is calculated according to the EPD or LCA, and the mass of carbon on the biogenic material is based on the chemical composition from the Phyllis database [17]. It is important to note that only a determined list of materials, which are structure, enclosures, and partitions, is included in BEAM, as they represent most of the material mass and usually last more than 25 years. For this work, six exterior wall solutions were selected for comparison. Comparisons were made considering 100 m^2 of an external wall, and all insulations have the same thermal performance with a thermal resistance of 3 (m^2 K)/W, deemed sufficient for effective insulation.

The materials for the solutions are chosen based on the items available in the tool database, considering both traditional and alternative options, as well as commonly used materials in the market. Concrete masonry and compressed earth blocks are chosen for the support wall, while extruded polystyrene (XPS), wood fibre, and hempcrete are chosen for insulation. Furthermore, a structured panel made of straw bale is also under consideration due to its innovative nature.

The second approach involves applying the Methodology for Relative Assessment of the Sustainability of Construction Solutions (MARS-SC), a multicriteria tool developed by Mateus [18,19]. The methodology encompasses three dimensions: environmental, functional, and economical. Based on the performance of each dimension, the tool indicates the most sustainable options for specific requirements, allowing construction solutions to be chosen with the best balance between lower environmental impact, improved functional performance, and better economic feasibility. By highlighting gaps in available construction solutions for achieving specific sustainability goals, MARS-SC offers insights to guide research and development efforts towards creating new and innovative materials, technologies, and processes. Its utilization of life cycle assessment (LCA) data brings an evidence-based perspective to its analysis. Although it does not directly offer construction solutions, it guides informed decision-making and drives sustainable development within the construction industry. This critical perspective promotes a necessary reassessment of existing practices, leading to advancements in the broader construction sector and fostering the adoption of more sustainable and circular building practices.

For the present work, only the environmental dimension is assessed, as functional performance among the solutions was equalised to allow a fair comparison. All insulation materials of the solutions proposed presented a thermal resistance (R-value) of 3 (m^2K)/W, as it is the thermal resistance for the commercialised 10 cm thickness of the most common thermal insulation products used in construction, namely extruded polystyrene (XPS). All environmental impacts of insulation material were taken from valid EPDs that followed the EN 15804 version 2 standard [20], as it has been the recommended procedure since 2022.

The chosen solutions involve an external wall base composed of double ceramic hollow brick with 10 mm cement brick laying mortar and 15 mm cement plaster mortar, coated with three layers of water-based plastic paint on both sides. Within this framework, eight insulation options were selected for evaluation: XPS, EPS, rock wool, glass wool, cork, hemp and flax mixture, hemp, and straw. This insulation selection compasses from highly processed to almost raw materials, reaching both widely used products in the market and innovative options derived from fast-growing materials.

3. Results and Discussion

3.1. Building Emissions Accounting for Materials (BEAM) Approach

Considering the BEAM approach, some simulations were carried out using the tool.

Two types of wall closures were selected: concrete blocks and compressed earth blocks. Additionally, three types of insulation materials were chosen as follows: XPS, wood fibre, and hempcrete. The structural solution of straw bale panels complemented these selections. Figure 3 illustrates the combined results and outcomes obtained from the tool.

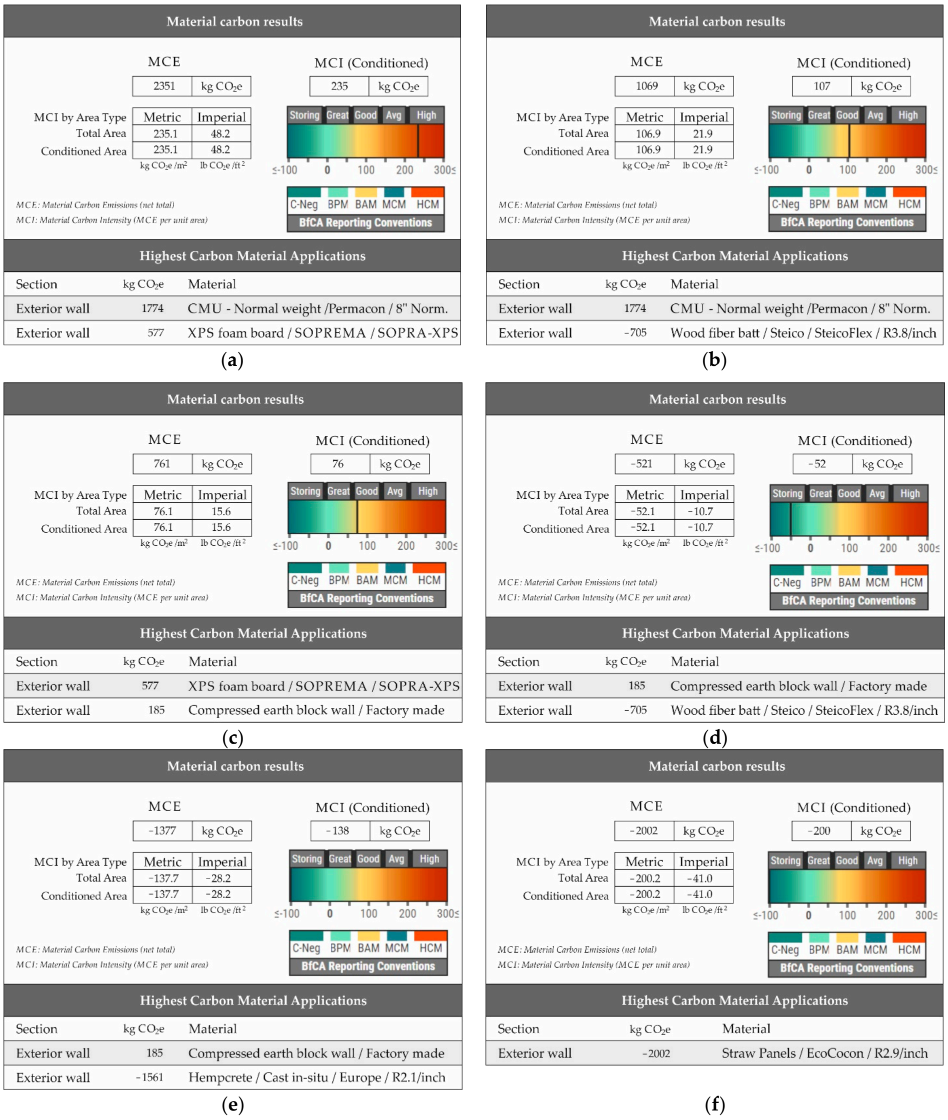


Figure 3. BEAM material carbon results. (**a**) Concrete masonry with XPS foam board insulation. (**b**) Concrete masonry with wood fibre batt insulation. (**c**) Compressed earth block with XPS foam board insulation. (**d**) Compressed earth block with wood fibre batt insulation. (**e**) Compressed earth block with hempcrete insulation. (**f**) Structural insulated straw bale panel.

Table 1 summarises each simplified wall assembly's Material Carbon Intensity (MCI).

Table 1. The material's carbon intensity according to the constructive solution based on BEAM results.

Constructive Solution	Material Description	Material Carbon Intensity (MCI) (kg CO_2e/m^2)
Concrete masonry unit with insulation	Permacon concrete masonry of 20 cm and XPS foam board	235
Concrete masonry unit with insulation	Permacon concrete masonry of 20 cm and wood fibre board	107
Compressed earth blocks with insulation	Compressed earth block wall with XPS foam board	76
Compressed earth blocks with insulation	Compressed earth block wall with STEICO wood fibre batt	−52
Compressed earth blocks with insulation	Compressed earth block wall with cast in situ hempcrete	−138
Structural insulated panel	EcoCocon straw panel	−200

Assemblies using fast-growing bio-based insulation products resulted in carbon-negative solutions. On the other hand, solutions that included highly processed insulation materials, such as XPS or concrete-based products, were ranked with a considerably higher environmental impact.

While the BEAM tool is user-friendly, its reliance on an internal database of EPDs inaccessible to external users makes conducting comprehensive analyses for all impact categories impractical. Negative results typically indicate materials with a high rate of biogenic carbon.

3.2. Methodology for Relative Assessment of Sustainability of Construction Solutions (MARS-SC)

Concerning the MARS-SC, the same external wall base was selected for all solutions: a double ceramic hollow brick wall with a 10 mm cement brick laying mortar and 15 mm cement plaster mortar, finished with three coats of water-based plastic paint on both sides. Within this structure, eight different types of insulation, from commonly used materials to unconventional bio-based materials, were chosen for evaluation.

Table 2 summarises the data for the density and thermal conductivity of materials, along with the necessary thickness to achieve a thermal resistance of 3 (m^2 K)/W for insulation materials and the mass per square meter of each material, tailored to suit the requirements of the MARS-SC tool. Table 3 presents the required mass per square meter of materials for the external wall base.

Table 2. The technical information and quantity required for insulation material.

Material	Density (kg/m^3)	Thermal Conductivity (W/(mK))	Thermal Resistance ((m^2 K)/W)	Thickness (m)	kg/m^2
Conventional material—XPS	25.95	0.033	3.00	0.10	2.595
Conventional material—EPS	18.50	0.030	3.00	0.09	1.665
Conventional material—Rock wool	95	0.037	3.00	0.11	10.545
Conventional material—Glass wool	16	0.037	3.00	0.11	1.776
Bio-based material—Corkboard	110	0.039	3.00	0.12	13.455
Bio-based material—Hemp and flax board	37	0.040	3.00	0.12	4.320
Bio-based material—Hemp fibre	35	0.040	3.00	0.12	4.200
Bio-based material—Straw	100	0.052	3.00	0.16	15.600

Table 3. External wall base materials quantity required.

Material	Density (kg/m^3)	kg/m^2
Ceramic hollow brick (30 × 20 × 15 cm)	625 kg/m^3 or 5.2 kg/un (15.36 un/m^2)	159.74
Cement plaster mortar—15 mm	1900	57
Cement brick laying mortar—10 mm	1900	44.65
Water-based plastic paint—3 coats	1.56 kg/L	0.75

After quantifying all materials outlined in the proposed solutions, environmental impact data were obtained from the LCA database and specific EPDs. Table 4 summarises the impacts per kilogram of material.

Table 4. Database of the impacts of the material used per kg—life cycle phase: cradle-to-gate (A1–A3).

Material	GWP [1]	ODP [2]	AP [3]	POCP [4]	EP [5]	NRE [6]	Ref.
XPS	3.25×10^{0}	2.57×10^{-8}	6.54×10^{-3}	4.93×10^{-3}	4.48×10^{-2}	8.72×10^{1}	[21]
EPS	4.54×10^{0}	8.43×10^{-8}	1.49×10^{-2}	1.15×10^{-2}	7.79×10^{-2}	9.08×10^{1}	[22]
Rock wool	1.01×10^{0}	2.10×10^{-12}	1.12×10^{-2}	2.57×10^{-3}	2.24×10^{-2}	1.55×10^{1}	[23]
Glass wool	2.36×10^{0}	2.34×10^{-7}	2.75×10^{-2}	4.97×10^{-2}	3.03×10^{-1}	2.36×10^{1}	[24]
Corkboard	-1.77×10^{1}	7.83×10^{-8}	1.23×10^{-2}	1.57×10^{-2}	1.64×10^{-1}	9.13×10^{0}	[25]
Hemp and flax board	-5.64×10^{-1}	3.06×10^{-8}	4.39×10^{-3}	2.81×10^{-3}	4.79×10^{-2}	1.23×10^{1}	[26]
Hemp fibre	-1.77×10^{0}	1.19×10^{-8}	1.54×10^{-3}	1.14×10^{-3}	1.69×10^{-2}	5.89×10^{0}	[27]
Straw	-1.16×10^{0}	1.05×10^{-8}	1.43×10^{-3}	4.48×10^{-4}	1.65×10^{-2}	9.38×10^{-1}	[28]
Ceramic hollow brick (30 × 20 × 15 cm)	2.20×10^{-1}	1.58×10^{-8}	5.48×10^{-4}	4.00×10^{-5}	6.71×10^{-5}	2.58×10^{0}	[29]
Cement plaster mortar—15 mm	1.95×10^{-1}	8.00×10^{-9}	3.15×10^{-4}	1.29×10^{-5}	4.87×10^{-5}	1.31×10^{0}	[29]
Cement brick laying mortar—10 mm	1.95×10^{-1}	8.00×10^{-9}	3.15×10^{-4}	1.29×10^{-5}	4.87×10^{-5}	1.31×10^{0}	[29]
Water-based plastic paint—3 coats	2.46×10^{0}	3.69×10^{-7}	1.69×10^{-2}	7.72×10^{-4}	4.23×10^{-3}	4.78×10^{1}	[29]

[1] Global Warming Potential (kg CO_2eq); [2] Ozone Depletion Potential (kgCFC-11eq); [3] Acidification Potential (mol H^+ eq); [4] Photochemical Ozone Creation Potential (kg NMVOC eq); [5] Eutrophication Potential (kg P eq); [6] Use of non-renewable primary energy (excluding those used as raw materials) (MJ).

Environmental impacts were adjusted based on the quantity used when considering one sq. meter of each solution. Table 5 illustrates the environmental impact of the base solution and Tables 6–13 illustrate the sum of the environmental impact of the base solution with the specific insulation and the total impact per category. The calculation was performed by multiplying the impact of 1 kg of the material, as shown in Table 4, by the kilograms per square meter, as presented in Tables 2 and 3.

Table 5. Impacts of materials used in base solution.

Material	kg/m²	GWP	ODP	AP	POCP	EP	NRE
Ceramic hollow brick (30 × 20 × 15 cm)	159.74	3.51×10^{1}	2.52×10^{-6}	8.75×10^{-2}	6.39×10^{-3}	1.07×10^{-2}	4.12×10^{2}
Cement plaster mortar—15 mm thickness	57	1.11×10^{1}	4.56×10^{-7}	1.80×10^{-2}	7.35×10^{-4}	2.78×10^{-3}	7.47×10^{1}
Cement brick laying mortar—10 mm thickness	44.65	8.71×10^{0}	3.57×10^{-7}	1.41×10^{-2}	5.76×10^{-4}	2.17×10^{-3}	5.85×10^{1}
Water-based plastic paint—3 coats	0.75	1.85×10^{0}	2.77×10^{-7}	1.27×10^{-2}	5.79×10^{-4}	3.17×10^{-3}	3.59×10^{1}
TOTAL		5.68×10^{1}	3.61×10^{-6}	1.32×10^{-1}	8.28×10^{-3}	1.88×10^{-2}	5.81×10^{2}

Table 6. Impacts of materials used in solution 01—XPS insulation.

Material	kg/m²	GWP	ODP	AP	POCP	EP	NRE
XPS insulation	2.59	8.44×10^{0}	6.66×10^{-8}	1.70×10^{-2}	1.28×10^{-2}	1.16×10^{-1}	2.26×10^{2}
Base solution	262.14	5.68×10^{1}	3.61×10^{-6}	1.32×10^{-1}	8.28×10^{-3}	1.88×10^{-2}	5.81×10^{2}
TOTAL		6.52×10^{1}	3.68×10^{-6}	1.49×10^{-1}	2.11×10^{-2}	1.35×10^{-1}	8.07×10^{2}

Table 7. Impacts of materials used in solution 02—EPS insulation.

Material	kg/m²	GWP	ODP	AP	POCP	EP	NRE
EPS	1.665	7.56×10^{0}	1.40×10^{-7}	2.48×10^{-2}	1.91×10^{-2}	1.30×10^{-1}	1.51×10^{2}
Base solution	262.14	5.68×10^{1}	3.61×10^{-6}	1.32×10^{-1}	8.28×10^{-3}	1.88×10^{-2}	5.81×10^{2}
TOTAL		6.44×10^{1}	3.75×10^{-6}	1.57×10^{-1}	2.74×10^{-2}	1.48×10^{-1}	7.32×10^{2}

Table 8. Impacts of materials used in solution 03—rock wool insulation.

Material	kg/m²	GWP	ODP	AP	POCP	EP	NRE
Rock wool	10.54	1.06×10^{1}	2.22×10^{-11}	1.18×10^{-1}	2.71×10^{-2}	2.37×10^{-1}	1.63×10^{2}
Base solution	262.14	5.68×10^{1}	3.61×10^{-6}	1.32×10^{-1}	8.28×10^{-3}	1.88×10^{-2}	5.81×10^{2}
TOTAL		6.74×10^{1}	3.61×10^{-6}	2.51×10^{-1}	3.54×10^{-2}	2.55×10^{-1}	7.45×10^{2}

Table 9. Impacts of materials used in solution 04—glass wool insulation.

Material	kg/m²	GWP	ODP	AP	POCP	EP	NRE
Glass wool	1.776	4.19×10^{0}	4.16×10^{-7}	4.88×10^{-2}	8.82×10^{-2}	5.38×10^{-1}	4.19×10^{1}
Base solution	262.14	5.68×10^{1}	3.61×10^{-6}	1.32×10^{-1}	8.28×10^{-3}	1.88×10^{-2}	5.81×10^{2}
TOTAL		6.10×10^{1}	4.03×10^{-6}	1.81×10^{-1}	9.65×10^{-2}	5.57×10^{-1}	6.23×10^{2}

Table 10. Impacts of materials used in solution 05—corkboard insulation.

Material	kg/m²	GWP	ODP	AP	POCP	EP	NRE
Corkboard insulation	13.455	-2.39×10^{2}	1.05×10^{-6}	1.66×10^{-1}	2.12×10^{-1}	2.20×10^{0}	1.23×10^{2}
Base solution	262.14	5.68×10^{1}	3.61×10^{-6}	1.32×10^{-1}	8.28×10^{-3}	1.88×10^{-2}	5.81×10^{2}
TOTAL		-1.82×10^{2}	4.67×10^{-6}	2.98×10^{-1}	2.20×10^{-1}	2.22×10^{0}	7.04×10^{2}

Table 11. Impacts of materials used in solution 06—hemp and flax insulation.

Material	kg/m²	GWP	ODP	AP	POCP	EP	NRE
Hemp and flax insulation	4.320	-2.44×10^{0}	1.32×10^{-7}	1.90×10^{-2}	1.21×10^{-2}	2.07×10^{-1}	5.32×10^{1}
Base solution	262.14	5.68×10^{1}	3.61×10^{-6}	1.32×10^{-1}	8.28×10^{-3}	1.88×10^{-2}	5.81×10^{2}
TOTAL		5.44×10^{1}	3.75×10^{-6}	1.51×10^{-1}	2.04×10^{-2}	2.26×10^{-1}	6.34×10^{2}

Table 12. Impacts of materials used in solution 07—hemp fibre insulation.

Material	kg/m²	GWP	ODP	AP	POCP	EP	NRE
Hemp fibre insulation	4.200	-7.42×10^{0}	4.99×10^{-8}	6.47×10^{-3}	4.78×10^{-3}	7.10×10^{-2}	2.47×10^{1}
Base solution	262.14	5.68×10^{1}	3.61×10^{-6}	1.32×10^{-1}	8.28×10^{-3}	1.88×10^{-2}	5.81×10^{2}
TOTAL		4.94×10^{1}	3.66×10^{-6}	1.39×10^{-1}	1.31×10^{-2}	8.99×10^{-2}	6.06×10^{2}

Table 13. Impacts of materials used in solution 08—straw insulation.

Material	kg/m²	GWP	ODP	AP	POCP	EP	NRE
Straw insulation	15.600	-1.81×10^{1}	1.63×10^{-7}	2.22×10^{-2}	6.99×10^{-3}	2.58×10^{-1}	1.46×10^{1}
Base solution	262.14	5.68×10^{1}	3.61×10^{-6}	1.32×10^{-1}	8.28×10^{-3}	1.88×10^{-2}	5.81×10^{2}
TOTAL		3.87×10^{1}	3.78×10^{-6}	1.54×10^{-1}	1.53×10^{-2}	2.77×10^{-1}	5.96×10^{2}

Afterwards, an analysis of the impact of each category in the proposed solution becomes feasible. Unexpectedly, the biogenic carbon from hemp and straw solutions fails to offset the processes involved. Thus, it is not reflected in the total GWP as initially predicted, as it is noticed for the cork insulation solution, which is the only one having a negative GWP value. Despite being among the least environmentally friendly solutions, solutions with commonly used materials like XPS and EPS do not reveal the highest impacts.

Table 14 shows the sum and comparison of the environmental impact categories among the proposed solutions.

Table 14. A summary of the environmental impact of the construction solutions.

Construction Solutions	GWP	ODP	AP	POCP	EP	NRE
Solution 01—XPS insulation	6.52×10^1	3.68×10^{-6}	1.49×10^{-1}	2.11×10^{-2}	1.35×10^{-1}	8.07×10^2
Solution 02—EPS insulation	6.44×10^1	3.75×10^{-6}	1.57×10^{-1}	2.74×10^{-2}	1.48×10^{-1}	7.32×10^2
Solution 03—Rock wool insulation	6.74×10^1	3.61×10^{-6}	2.51×10^{-1}	3.54×10^{-2}	2.55×10^{-1}	7.45×10^2
Solution 04—Glass wool insulation	6.10×10^1	4.03×10^{-6}	1.81×10^{-1}	9.65×10^{-2}	5.57×10^{-1}	6.23×10^2
Solution 05—Corkboard insulation	-1.82×10^2	4.67×10^{-6}	2.98×10^{-1}	2.20×10^{-1}	2.22×10^0	7.04×10^2
Solution 06—Hemp and flax insulation	5.44×10^1	3.75×10^{-6}	1.51×10^{-1}	2.04×10^{-2}	2.26×10^{-1}	6.34×10^2
Solution 07—Hemp fibre insulation	4.94×10^1	3.66×10^{-6}	1.39×10^{-1}	1.31×10^{-2}	8.99×10^{-2}	6.06×10^2
Solution 08—Straw insulation	3.87×10^1	3.78×10^{-6}	1.54×10^{-1}	1.53×10^{-2}	2.77×10^{-1}	5.96×10^2
Best Value (lower impact)	-1.82×10^2	3.61×10^{-6}	1.39×10^{-1}	1.31×10^{-2}	8.99×10^{-2}	5.96×10^2
Worst Value (higher impact)	6.74×10^1	4.67×10^{-6}	2.98×10^{-1}	2.20×10^{-1}	2.22×10^0	8.07×10^2

As each category exerts distinct impacts on the overall environmental footprint, applying a system of weights is essential. The weight coefficients for each category in MARS-SC were referenced from the Environmental Protection Agency (EPA) [30,31] and are reflected in Table 15. The following weights were considered as follows:

- GWP = 38%;
- ODP = 12%;
- AP = 12%;
- POCP = 14%;
- EP = 12%;
- NRE = 12%.

The environmental performance of each solution in all impact categories, presented in Table 15, was determined using the following normalisation equation:

$$\overline{P_i} = \frac{P_i - P*_i}{P_i^* - P*_i} \; \forall_i, \quad (1)$$

where $\overline{P_i}$ is the result of the normalising parameter i, P_i is the value of the i parameter to normalise and $P*_i$ and P_i^* serve as benchmarks for parameter i, representing the levels of the best and worst values, respectively. The equation converts the value of each parameter into a dimensionless scale, where zero corresponds to the level of worst practice and one corresponds to the level of best practice.

Then, the overall environmental performance (EI) was calculated by the sum of each normalised value multiplied by the weights presented above.

When considering the normalised values, the hemp fibre solution is consolidated as the option with the lowest environmental performance, closely followed by the straw insulation solution. Unexpectedly, corkboard and rock wool insulation solutions ranked lowest in environmental performance, as shown in Table 15.

Table 15. A summary of the environmental performance level of the construction solutions.

Construction Solutions	$\overline{GWP}$	$\overline{ODP}$	$\overline{AP}$	$\overline{POCP}$	$\overline{EP}$	$\overline{NRE}$	EI
Solution 01—XPS insulation	0.009	0.937	0.934	0.961	0.979	0.000	0.480
Solution 02—EPS insulation	0.012	0.867	0.885	0.931	0.972	0.354	0.504
Solution 03—Rock wool insulation	0.000	1.000	0.298	0.892	0.922	0.297	0.427
Solution 04—Glass wool insulation	0.026	0.605	0.735	0.597	0.781	0.871	0.452
Solution 05—Corkboard insulation	1.000	0.000	0.000	0.000	0.000	0.488	0.439
Solution 06—Hemp and flax insulation	0.052	0.875	0.922	0.965	0.936	0.818	0.581
Solution 07—Hemp fibre insulation	0.072	0.953	1.000	1.000	1.000	0.952	0.636
Solution 08—Straw insulation	0.115	0.845	0.901	0.989	0.912	1.000	0.621

Although the analysis shows that the cork insulation solution is worse than the XPS insulation solution, it does not mean XPS is better for the environment than cork as a material; as cork requires a greater thickness to the same thermal performance, this could have influenced the values for higher impact. Additionally, the better performance in the GWP category does not compensate for the worst performance at the level of the ODP, AP, POCP, and EP impact categories, which led to this solution having final values similar to those of conventional solutions.

The MARS-SC tool enables the comparison of several solutions and allows for a more detailed analysis since it is based on EPDs, and each environmental impact category can be individually assessed. Despite some adversities, solutions with fast-growing bio-based insulation materials are consistently among the more sustainable solutions, considering only the environmental dimension.

4. Conclusions

Fast-growing bio-based materials are expected to have lower environmental impacts in construction solutions, primarily due to their biogenic carbon content. The chosen tools for this investigation facilitated a comprehensive comparison of various solutions, encompassing both traditional and widely used materials and bio-based alternatives, including those with rapid growth rates.

While the BEAM tool provided a rapid analysis system for selecting materials and solutions, the specific features of the MARS-SC tool enable the identification of the impact category that has the highest influence on overall environmental performance.

This study highlighted the potential of fast-growing bio-based materials to enhance the sustainability of construction practices and correlate with sustainable development goals. However, it also emphasizes the need to evaluate extraction and production processes to ensure a genuinely sustainable product.

In addition to the direct environmental impacts analysed in this study, using bio-based materials in construction contributes to the valorisation of local resources and fosters the creation of value chains that promote economic growth and well-being, thereby facilitating responsible production practices. Using bio-based materials also helps protect biodiversity and natural environments by reducing the need for material processing infrastructure and decreasing pollution associated with conventional materials. The data obtained from the methods indicate that straw insulation and hemp-based solutions, namely bio-based solutions, consistently have a lower environmental impact. According to the BEAM approach, the optimal solution was the structured insulated panel of straw, which exhibited an environmental impact 185% lower than the worst-performing solution among those selected. The second-best option was the hempcrete-based solution, with an impact of 158% lower. The hemp fibre-based solution emerged as the best in the MARS-SC approach, showing a 49% lower impact than the worst solution. The second-best solution on MARS-SC was the straw-based option, still achieving a 45% lower impact than the worst solution.

In addition to their environmental benefits, bio-based materials also offer notable functional performance. This is exemplified by Lehner et al. [32], who discuss the mechanical characterisation of straw bales.

Regarding the limitations of this work, it is limited by the availability of Environmental Product Declarations (EPDs) for bio-based materials. This is due to the heterogeneous nature and the ongoing regulatory development of these materials for such products worldwide. Further research is recommended in the field of biomass characterisation and production processes to enhance sustainability metrics for unconventional materials, thus promoting market competitiveness. Despite the evidence supporting the use of fast-growing bio-based materials, uncertainties remain regarding factors such as carbon removal, as stated by Pittau et al. [11], highlighting the need for additional research to measure their impact on climate change, especially with the prospect of scaling up their usage.

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References

1. Linde, L.; Nilsson Lewis, A.; Sanchez, F. *Towards a Sustainable Global Construction and Buildings Value Chain*; Leadership Group for Industry Transition: Stockholm, Sweden, 2022.
2. Omer, M.A.B.; Noguchi, T. A conceptual framework for understanding the contribution of building materials in the achievement of Sustainable Development Goals (SDGs). *Sustain. Cities Soc.* **2020**, *52*, 101869. [CrossRef]
3. United Nations Environmental Programme. *2022 Global Status Report for Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector*; United Nations Environmental Programme: Nairobi, Kenya, 2022; Volume 224.
4. UNEP. *2020 Global Status Report for Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector*; United Nations Environmental Programme: Nairobi, Kenya, 2020.
5. IEA. *CO_2 Emissions in 2022*; IEA: Paris, France, 2023.
6. European Commission. European Green Deal: Commission Proposes to Boost Renovation and Decarbonisation of Buildings. Available online: https://ec.europa.eu/commission/presscorner/detail/en/ip_21_6683 (accessed on 20 October 2022).
7. IPCC. *Climate Change 2022—Mitigation of Climate Change—Working Group III Contribution to the IPCC Sexth Assessment Report (AR6)*; IPCC: Geneva, Switzerland, 2022.
8. Fernandes, J.; Mateus, R.; Gervásio, H.; Silva, S.M.; Bragança, L. Passive strategies used in Southern Portugal vernacular rammed earth buildings and their influence in thermal performance. *Renew. Energy* **2019**, *142*, 345–363. [CrossRef]
9. European Parliament. *Revision of the Energy Performance of Buildings Directive: Fit for 55 Package*; European Parliament: Strasbourg, France, 2022.
10. Carcassi, O.B.; Habert, G.; Malighetti, L.E.; Pittau, F. Material Diets for Climate-Neutral Construction. *Environ. Sci. Technol.* **2022**, *56*, 5213–5223. [CrossRef] [PubMed]
11. Pittau, F.; Krause, F.; Lumia, G.; Habert, G. Fast-growing bio-based materials as an opportunity for storing carbon in exterior walls. *Build. Environ.* **2018**, *129*, 117–129. [CrossRef]
12. Göswein, V.; Arehart, J.; Phan-huy, C.; Pomponi, F.; Habert, G. Barriers and opportunities of fast-growing biobased material use in buildings. *Build. Cities* **2022**, *3*, 745–755. [CrossRef]
13. Builders for Climate Action. Making Real Zero Carbon Buildings with Carbon Storing Materials (What is Embodied Carbon?). Available online: https://www.youtube.com/watch?v=RSstTiuuj-Y&ab_channel=BuildersforClimateAction (accessed on 5 March 2024).
14. Pittau, F.; Lumia, G.; Heeren, N.; Iannaccone, G.; Habert, G. Retrofit as a carbon sink: The carbon storage potentials of the EU housing stock. *J. Clean. Prod.* **2019**, *214*, 365–376. [CrossRef]
15. Correa de Melo, P.; Rosse Caldas, L.; Masera, G.; Pittau, F. The potential of carbon storage in bio-based solutions to mitigate the climate impact of social housing development in Brazil. *J. Clean. Prod.* **2023**, *433*, 139862. [CrossRef]
16. Builders for Climate Action. BEAM Users Guide. Available online: https://www.buildersforclimateaction.org/beam-estimator.html (accessed on 15 February 2024).
17. European Comission. Phyllis Database. Available online: https://knowledge4policy.ec.europa.eu/dataset/beo-ecnphyllis_en (accessed on 20 February 2024).

18. Mateus, R.; Bragança, L. Avaliação da Construção Sustentável: Propostas para o Desenvolvimento de Edifícios Mais Sustentáveis. Ph.D. Thesis, Universidade do Minho, Braga, Portugal, 2009.
19. Mateus, R.; Bragança, L. Sustainability assessment and rating of buildings: Developing the methodology SBToolPT-H. *Build. Environ.* **2011**, *46*, 1962–1971. [CrossRef]
20. *EN 15804:2012+A2:2019*; Sustainability of Construction Works—Environmental Product Declarations—Core Rules for the Product Category of Construction Products. European Committee for Standardization: Brussels, Belgium, 2019.
21. The International EPD. *Environmental Product Declaration: XPS Styropan*; The International EPD: Stockholm, Sweden, 2023.
22. The International EPD. *Environmental Product Declaration: EPS Kauno Silas UAB*; The International EPD: Stockholm, Sweden, 2023.
23. The International EPD. *Environmental Product Declaration: Rock Wool Knauf Insulation*; The International EPD: Stockholm, Sweden, 2023.
24. The International EPD. *Environmental Product Declaration: Glass Wool Ursa*; The International EPD: Stockholm, Sweden, 2023.
25. EPD Hub. *Environmental Product Declaration: Cork Board Insulation Amorim*; EPD Hub: Dublin, Ireland, 2023.
26. Bau EPD GmbH. *Environmental Product Declaration: HEMP COMBI JUTE*; Bau EPD GmbH: Wien, Austria, 2022.
27. The International EPD. *Environmental Product Declaration: Hemp Fibre Insulation Ekolution AB*; The International EPD: Stockholm, Sweden, 2023.
28. The International EPD. *Environmental Product Declaration: Straw, School of Natural Building (SNaB)*; The International EPD: Stockholm, Sweden, 2022.
29. Bragança, L.; Mateus, R. *Life-Cycle Analysis of Buildings: Envirnonmental Impact of Building Elements*; Associação iiSBE Portugal: Guimarães, Portugal, 2012; ISBN 978-989-96543-3-4.
30. United States Environmental Protection Agency. *Reducing Risk: Priorities and Strategies for Environmental Protection*; United States Environmental Protection Agency: Washington, DC, USA, 1990.
31. United States Environmental Protection Agency. *Toward Integrated Environmental Decision-Making*; United States Environmental Protection Agency: Washington, DC, USA, 2000.
32. Lehner, P.; Horňáková, M.; Vlček, P.; Teslík, J. Experimental investigation of two test setups on straw bales used as load-bearing elements of buildings. *Buildings* **2021**, *11*, 539. [CrossRef]