Net Zero Carbon Potential of Bio-based Building Materials

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Abstract. This research paper explores the net zero carbon potential offered by bio-based building materials in South Africa, specifically, mass timber and two bio-based concretes, hempcrete and nonCrete. As the construction industry grapples with the urgent need to reduce its carbon footprint, bio-based materials offer a promising path toward sustainability. Hempcrete, known for its excellent insulation properties and carbon sequestration capabilities; nonCrete, making use of alien invasive species, thereby restoring natural systems; and mass timber, lauded for its strength and renewability, are analysed for their environmental benefits and practicality in modern construction. The study examines the cradle to gate carbon emissions of these materials, as well as fitness for purpose. Findings suggest that bio-based materials not only contribute to significant carbon savings during their production and usage phases but also enhance building performance. The study methodology compares the embodied carbon of a comparable section of wall of each material. Calculations are based on data available in embodied carbon databases, case studies and environmental product declarations. The paper finds that despite limited standardised data, the selected materials have net negative embodied carbon and concludes with recommendations for integrating these materials into mainstream construction practices to drive the industry towards a more sustainable future.

Keywords: Bio-based concrete · Embodied carbon · Mass timber

1 Introduction

The construction industry is facing the challenge of reducing its carbon footprint. Traditional building materials, such as concrete and steel, contribute significantly to global carbon emissions due to their energy-intensive production processes [1]. As sustainability becomes more critical, bio-based building materials offer a promising alternative, advancing climate resilience, low emissions, and better lives in line with South Africa's just transition goals. This article examines the net zero carbon potential of bio-based materials, particularly focusing on mass timber and bio-based concretes.

Bio-based materials can potentially lower the embodied carbon and energy demand of buildings relative to conventional materials [2]. Bio-based materials are partially or fully derived from renewable biological products or by-products [3]. In this study, materials that are produced using vegetative biomass in part or in whole are considered. The carbon

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that is sequestered by vegetation through photosynthesis is permanently stored in the building material, only being released if the material is burned or decomposed—even when this happens, the biomass is considered to be emissions neutral. There are various types of bio-based construction materials that are used for structural elements, envelope materials, insulation and other components. This study focusses on selected building envelope materials that are available in South Africa, specifically, mass timber and two types of bio-concrete—hempcrete and nonCrete (see Fig. 1).

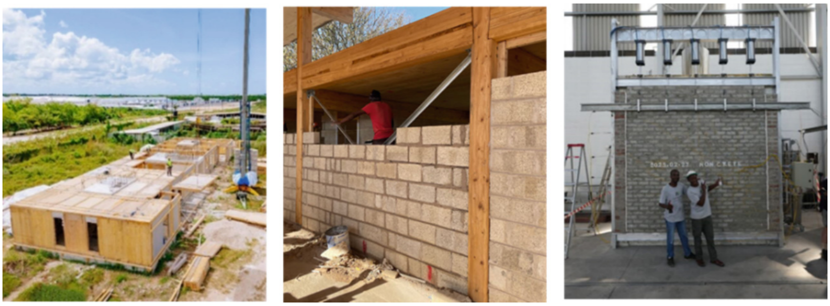

Fig. 1. Images of mass timber construction, Hempblock infill walls, and nonCrete test wall (from left to right).

2 Literature Review

To provide a global backdrop for this study within the South African context, the literature was reviewed to understand the status of the use of biobased building materials globally. Ten key papers were identified that examined bio-based building materials, of which two were studies relating to residential buildings, two were on office buildings, and two were on multi-storey buildings, reflecting the potential broad application of bio-based materials in buildings.

The selected papers included a diverse range of bio-based products, such as CLT, bamboo, bio-concrete, lime hempcrete composites, hemp shiv, straw, bio-mass based insulation and general wood products. The studies covered a range of locations and climates, indicating that bio-materials are diverse in type and application and are finding some uptake all over. Eight of the ten studies reported reductions in net embodied carbon impact compared to conventional materials and two reported net negative embodied carbon.

None of the literature in this exercise referenced the use of bio-materials in Africa or South Africa. A further search for literature referencing the use of bio-materials specifically in South Africa identified papers about wood, hemp, bamboo, straw, cork, nonCrete and salvaged timber. The findings reveal that timber is widely used in South Africa [4, 5], however, this refers to the common practice of using timber for roof trusses, while the interest of the current study is the use of mass timber for the building envelope. The references to hemp [6], bamboo [7], and nonCrete [8] indicate that these materials are emerging technologies, while straw, cork, and salvaged timber lack documented use. Furthermore, straw and cork are only mentioned as insulation materials and not structural or envelope materials; hemp is mentioned as masonry infill and insulation. According to da Silva [9], the production of bio-based building materials in South Africa is not mainstreamed, despite an abundance of renewable raw materials from timber plantations, agricultural crops and Invasive Alien Plants (IAPs).

The literature cites several advantages of bio-based materials, including low embodied carbon [10], superior strength of some [11, 12], and superior thermal insulation [13]. However, no single product is suitable for all contexts and uses [8].

The review of literature produced two key findings, specifically in the South African context. Firstly, there is a low uptake of bio-based construction materials in South Africa, as evidenced by the low number of research papers available. Secondly, there is a lack of knowledge regarding the true environmental implications of bio-based materials and the carbon risk impacts of sustainable construction materials in general [14].

3 Research Objectives and Methodology

The goal of this study is to establish whether the lower embodied carbon of emerging bio-based construction materials in South Africa justifies their use instead of conventional methods. The objective was to compare the embodied carbon of three bio-based building envelope materials that are available in South Africa—hempcrete, nonCrete, and mass timber—to establish which has the greatest potential to reduce embodied carbon in buildings.

The exercise only considers the cradle to gate life cycle assessment (LCA) data (stages A1 to A3, as defined by EN 15978). Although this represents a limitation, this scope was set to eliminate variables associated with transport and construction emissions, which could not be established. In each scenario, 1 m^2 of the installed wall was considered, including any joining and structural elements required to constitute the wall.

As far as possible, emissions data from the South African manufacturers were used. However, only one of the manufacturers (non-Crete) of the three products analysed was able to provide embodied carbon data. The data for mass timber and hempcrete was sourced from literature and international manufacturers. Data sourced was in most cases not verified by a third party and the LCA scope is not always clear—for example, in some cases, Stage A1 to A3 data is given and in other cases Stage A1 to A5 figures are used. This research attempts to account for these factors to present a fair comparison between the three local products. The lack of actual and reliable embodied carbon data for local products was a limitation, however, the study examines the theoretical case for each bio-material, formulating a methodology for application in future studies when actual data becomes available, and discussing other considerations for each material.

4 Understanding Bio-based Building Materials

The three selected materials are considered here in terms of their embodied carbon, as well as other qualities. A square meter of walling of mass timber, hempcrete blocks and nonCrete blocks is considered, using standard available elements to establish the respective wall thicknesses of 165, 300 and 230 mm.

4.1 Mass Timber

Mass timber (MT) products are engineered for strength and durability. These products include cross-laminated timber (CLT), laminated veneer lumber (LVL), and glue-laminated timber (glulam), creating massive timber planes or framing elements for constructing walls, floors, roofs, partitions and other elements [12], as shown in Fig. 1.

MT displays similar structural properties as concrete and steel, while requiring less energy to be produced [15] and can be manufactured in larger and longer sections than conventional construction timber [11]. Elements are typically manufactured off site in a factory where precise measurement and cutting reduces material waste and enables rapid erection on site [12]. Prefabrication results in less noise, dust and construction waste on site [11]. This also means that much of the emissions normally associated with construction occur off site and fall into Stage A3 of a life cycle assessment. This could potentially skew a comparative LCA with other products, depending on the scope of the assessment.

Embodied Carbon of Mass Timber. MT is considered renewable, since trees can be re-grown; carbon sequestered during their growth offsets the emissions generated during production, with studies showing a reduction in embodied emissions of up to 90.8% relative to conventional steel structure construction, considering cradle to site emissions [15]. Such claims, however, are inconsistent across different studies and are highly dependent on the accuracy and scope of emissions assessments, and the context and location [16]. Data varies across different studies and little to no data is available for South African products.

An online search for mass timber manufacturers in South Africa yielded three main manufacturers, one of which makes no claims regarding emissions, another claiming 0.9 tonnes of carbon dioxide (CO_2) sequestered per cubic metre, and the third similarly claiming a 1:1 ratio of stored carbon per volume of timber. However, these figures appear to only refer to sequestered carbon and do not account for production emissions. According to the ICE database (version 4.0)[1], CLT has embodied carbon of 0.25 $kgCO_2e/kg$ (for scoped boundaries A1 to A3), or -1.39 $kgCO_2e/kg$ if sequestered carbon is accounted for. However, the ICE database notes that this could vary depending on the timber species, density, moisture content and several other variables; these variables make definitive claims based on the ICE data impossible. It is not clear in the literature whether the off-site cutting and preparation of prefabricated elements is included in this, however, it is assumed that it is not.

In the context of this study, solid elements used for exterior wall panels are considered, assuming load-bearing CLT wall elements with a thickness of 165 mm. The characteristic density of South African (SA) Pine is stated to be 360 kg/m^3 (for S5 timber), according to the local manufacturer's data [17], which means that 1 m^2 of wall weighs 59.4 kg, resulting in embodied carbon of -82.566 $kgCO_2e$, if using the ICE database value of -1.39 $kgCO_2e/kg$.

[1] https://circularecology.com/embodied-carbon-footprint-database.html.

4.2 Hempcrete

Hempcrete is a bio-composite material made from the inner woody core (hemp hurds or shiv) of the hemp plant mixed with a lime-based binder to make a concrete-like compound. It has good insulation properties and possesses significant carbon sequestration capabilities. Hempcrete can be used in various ways in construction, such as in-situ casting, precast blocks, plaster or spray [18, 19]. In this study, hempcrete blocks (600 mm × 300 mm × 308 mm) are considered, based on products available in South Africa.

Hempcrete has low compressive strength and is often used as infill material within timber columns [19]. The strength and density of hempcrete varies depending on the exact mix and method of application, which is also true of the thermal conductivity properties [18, 19].

Embodied Carbon of Hempcrete. Hemp grows quickly and has a high yield, making it a rapidly renewable resource with high carbon sequestration potential [20]. The hemp plant absorbs CO_2 during its growth, and the lime binder continues to absorb CO_2 from the atmosphere after production in a process known as carbonation [18, 20]. This dual carbon sequestration process makes hempcrete a highly attractive option for sustainable, low-carbon buildings.

The energy embodied in the field production of hemp is low relative to other crops [21], however the process of manufacturing lime requires heating of calcium carbonate to high temperatures and about 41% of the volume is emitted as CO_2, resulting in an initial high embodied carbon as the product it leaves the gate (LCA stage A3); this is off-set by the CO_2 that is absorbed through carbonation over a 100-year lifetime [21] but technically falls out of the scope of cradle to gate.

Only two local suppliers of hempcrete blocks were found, neither of which were able to provide embodied carbon data for their products. Data obtained directly from a manufacturer in the United States of America[2] suggest that 1 m^2 of a Hempblock wall holds −56 $kgCO_2e$ of embodied carbon, including lime render and perlite cement; it is unclear whether this includes the structural timber framing, and the size of the blocks and thickness of the wall is not given.

Ip and Miller [21] calculate that 1 m^2 of hempcrete wall installed (cast in-situ with timber framing) has a carbon footprint of −36.08 $kgCO_2e$ for a 300 mm thick non-load bearing wall, including the timber frame. This considers the case for the installed product over a 100-year lifetime and thus accounts for carbon sequestered by the lime beyond the construction phase. If the sequestration through carbonation of lime (−28.55 $kgCO_2e$) and construction and haulage (3.76 $kgCO_2e$) are excluded, the resultant carbon footprint of the product at LCA stage A3 calculates to −11.29 $kgCO_2e$. A similar case for a load-bearing wall is presented by Ip and Miller [21], showing emissions of −35.53, or −22.8 $kgCO_2e$ if lime carbonation (−13.6 $kgCO_2e$) and construction and haulage (0.87 $kgCO_2e$) are excluded.

Emanuele et al. [22] demonstrate that an in-situ cast hempcrete wall has lower carbon emissions associated with its production (as per IPCC method) than hempcrete blocks (excluding the impact of carbonation) due to the energy required for the manufacture of

[2] https://hempblockinternational.com/.

the blocks. However, the CO_2 emissions cited for the manufacture of the blocks is very similar to that of the in-situ wall cited by Ip and Miller.

These examples demonstrate the complexities of calculating the embodied carbon, which is dependent on the interpretation of the scope and factors such as varying agricultural practices, transport distances, lime processing methods and mix design [23].

For the sake of this exercise, the data provided by Ip and Miller [21] for a non-load-bearing wall will be assumed, which is in the range cited by various studies [23].

4.3 NonCrete

NonCrete is an innovative biomass concrete developed in South Africa. It uses chipped biomass from IAPs, such as Eucalyptus, as a supplementary ingredient in the concrete mix. The volume of ordinary Portland cement (OPC) in the mix is reduced by the inclusion of a proprietary binder, and the mix is specifically designed, considering the size and moisture content of the wood chips.

The concrete mix can be used for various precast elements; in this paper the load-bearing bricks are considered, which are the same size as conventional clay bricks and have properties at least equivalent to conventional masonry construction.

Embodied Carbon of NonCrete. The carbon sequestered during the growth of the trees is retained in the wood chips within the concrete mix for bricks, resulting in a net negative embodied carbon emission intensity. Furthermore, the control of IAPs contributes to the restoration of indigenous ecosystems [24], supporting a circular economy.

According to the manufacturer, the load-bearing bricks considered for this study have an embodied carbon value of -96 $kgCO_2e/m^3$ or -21 $kgCO_2/m^2$ (for Stages A1 to A3) for a double skin load-bearing wall. If conventional cement mortar with a 1:4 cement to sand ratio is used for building the wall (using a carbon emission intensity factor of 0.146 $kgCO_2e/kg$, as per ICE v4), the resulting overall embodied carbon of 1 m^2 wall is -15.7 $kgCO_2e$.

4.4 Comparative Analysis Discussion

The above theoretical calculations of the embodied carbon associated with construction of 1 m^2 of wall using each of the materials is summarised in Table 1, considering only LCA stages A1 to A3. The results show that MT has the lowest embodied carbon and that all products have net negative emissions, with potential to reduce the overall carbon footprint of a building.

Table 1. Summary of embodied carbon associated with each construction material.

Material	Embodied carbon per m^2 constructed
Mass timber	-82.566 $kgCO_2e$
Hemp blocks	-11.29 $kgCO_2e$ (including lime carbonation) -36.08 $kgCO_2e$ (excluding lime carbonation)
NonCrete bricks with mortar	-15.7 $kgCO_2e$

However, there are several limitations with these values, in particular the fact that in all cases, the cited emissions data are not clear and transparent, and rigorously calculated local data is lacking.

Apart from embodied carbon, other characteristics of the materials are also relevant to consider when selecting materials. These are discussed below and summarised in Table 2. Some key metrics (based on Agrément SA fitness for purpose requirements for alternative building systems) are used to evaluate further qualities of each of the three materials, including thermal performance (insulation properties), acoustic performance (sound transmission), compressive strength, and fire resistance.

Table 2. Characteristics of materials.

Metric	Mass timber	Hempcrete block	NonCrete brick[3]
Thermal performance (U-value)	0.12 W/mK [17]	0.23 [25]	TBC
Acoustic performance (sound transmission)	35 dB [26]	51 dB [27]	TBC
Compressive strength	16–18 MPa [17]	1 MPa [27]	10 MPa
Fire rating (minutes)	60 min [17]	120 min [27]	180 min

Since these are emerging technologies, much of the data is not yet published, limiting the ability to rigorously compare these products. NonCrete demonstrates the longest fire resistance (tested in accordance with SABS 10177-2), although the other two products may have stopped testing and only reported on the minimum requirements for fire resistance. All three products demonstrate at least a 60-min fire resistance.

Hempcrete is porous, giving it unique attributes of thermal and acoustic insulation; it has a high noise reduction coefficient [19] and hygrometric properties, enabling it to control humidity [28]. Of the products with known acoustic performance, hempcrete shows superior performance, outperforming standard brick wall performance, which is typically has sound transmission index of about 40 dB, and meeting most requirements set by Agrément SA, which varies between 33 and 52 dB, depending on the use case. The acoustic performance of CLT walls alone (i.e., without additional insulation layers) is not well-documented. Literature seems to indicate a weighted sound reduction index (R_w) of 33–35 dB for a 100 mm thick panel [26, 29]. For the current study, we accept the R_w of 35 dB for the 165 mm panel, and highlight that further research is needed regarding this aspect. The sound reduction index of nonCrete was not available at the time of writing.

The nonCrete manufacturer claims that their bricks have good thermal insulation properties, although specific data could not be sourced; both CLT and hempcrete show good thermal insulation, meeting the minimum requirements for thermal insulation specified by the National Building Regulations through SANS 10400-XA:2021.

Although no data on the durability of all three materials could be sourced, it was found that hempcrete is susceptible to freeze-thaw degradation, resulting in a weakening

[3] https://noncrete.com/.

of the material [18]. Hempcrete has a low compressive strength and is suitable for infill walls only, while the nonCrete load-bearing bricks have a compressive strength of 10 MPa. MT is noted for its strength and durability, making it suitable for a variety of construction applications, including high-rise buildings, and is relatively light weight, reducing transportation and installation costs, further enhancing its practicality. The load-bearing capacity of each material is based on data from the manufacturers or literature and could not be verified against specific local test requirements.

An important consideration in terms of the environmental impact associated with each product is the renewability and recyclability of each product. The growth period for the bio-based components of each product is a factor of how quickly the resource can be replenished. The growth period for South African (SA) Pine used in locally produced CLT is 25 years [30], compared to the four-month growth period of hemp. According to Ip and Miller [21], 30 kg of hemp is used in 1 m^2 of 300 mm thick wall and 45.82 $kgCO_2e$ is effectively stored over the lifetime of the plant—this means that hemp sequesters more carbon per weight than SA Pine used in CLT (which is a 1:1 ratio). However, further factors that are beyond the scope of this study need to be considered, such as the carbon that is released from the soil during the frequent ploughing for re-planting of hemp.

Studies show that Eucalyptus stores more carbon over a typical plantation tree life span than Pine trees [31], although this depends on the region and specific sub-species. A review of literature did not yield data specific to South African plantation pines (*Pinus radiata*) and non-plantation alien invasive species used by nonCrete (*Eucalyptus camaldulensis*). A direct comparison between these two species, used in mass timber and nonCrete respectively, is not truly possible because the growth period of the wild invasive Eucalyptus tree is not fixed. A further consideration is the renewability of the bio-mass, which is not directly applicable in the case or IAPs; although the Eucalyptus is preferably not re-grown because it is considered invasive, the production of nonCrete has the advantage of addressing circularity in the restoration of natural ecosystems rather than renewability.

All three products claim to be recyclable at end of life. Hempcrete can be broken down and worked into the soil and is biodegradable and recyclable [18] leaving behind a nutrient rich compos or waste-to-energy incineration; nonCrete can be crushed and reused as aggregate in new nonCrete products; mass timber can be reused or chipped and recycled in composite wood products.

5 Findings and Discussion

The findings suggest that bio-based materials contribute to significant carbon savings, demonstrating net negative embodied carbon. However, embodied carbon data is limited, and several other critical factors need to be considered when evaluating the suitability of each material for a particular project.

In terms of environmental impact and renewability, hemp grows rapidly enabling rapid replenishment, supporting frequent manufacturing cycles, and sequestering more carbon per weight than SA Pine used in CLT, which has a much longer growth cycle and requires heavy harvesting and processing equipment. To ensure environmental sustainability, plantations must be managed responsibly and support biodiversity. Eucalyptus is an invasive species and its use in nonCrete results in environmental benefits associated with the restoration of natural ecosystems.

All three bio-based materials considered claim recyclability: hempcrete is biodegradable, nonCrete can be crushed and reused as aggregate, and mass timber can be reused or recycled in composite products.

Selecting the optimal bio-based material for a construction project involves weighing a series of trade-offs based on project-specific needs and the unique characteristics of hempcrete, nonCrete, and MT. Local accessibility of the products may ultimately be a key factor in selecting a material, which impacts delivery time, costs, and transport emissions. Project teams should conduct a holistic assessment, considering performance, environmental impact, durability, cost, and regulatory context to make an informed selection. The development of a decision-matrix that considers the various factors is recommended.

An important observation in this study is the lack of standardised and verified data on each product, making a rigorous comparison impossible. Even though standards exist for establishing the embodied carbon of materials (such as ISO 14067, EN 15978, and PAS2050), the data is not presented in a uniform way in literature and product data sheets. Further research and standardisation will enhance the comparability of these promising bio-based materials, supporting their broader adoption in sustainable construction.

5.1 Recommendations for Integrating Bio-based Materials

While the environmental benefits of the bio-based materials discussed here are evident, the products and market are at a low readiness level. To integrate bio-based materials into mainstream construction practices, the following recommendations are proposed.

Evidence-based policies and regulations should be developed and implemented in South Africa to enforce transparent environmental product declarations, disclosing the embodied carbon of products in a standardised metric.

Continued research and development is essential to improve the performance and cost-effectiveness of bio-based materials. This is possible through collaborative efforts between manufacturers, research bodies and regulators.

6 Conclusion

The goal of this study is to establish whether the lower embodied carbon of bio-based construction materials justifies their use instead of conventional methods. Despite inconsistent and non-standardised data, it can be concluded that bio-based building materials, such as mass timber, hempcrete and nonCrete, offer a promising path toward achieving net zero carbon targets in the construction industry. The integration of bio-based materials into mainstream construction practices can drive the industry towards a more sustainable future, reducing its carbon footprint and contributing to global efforts to combat climate change.

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