Assessing the sustainability of bio-based materials in construction: a literature review of the life-cycle assessment results

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Abstract: The construction industry is undergoing a transformation towards sustainability, driven by growing concerns about greenhouse gas emissions. One promising innovation in this context is bio-based materials. These materials have been shown to have specific properties that make them suitable for practical applications. As a result, many stakeholders in the construction industry are exploring the possibility of replacing the traditional and environmentally harmful materials such as concrete, steel, and polymers, with bio-based materials. However, despite their favorable properties, these materials have limited use in practical applications. One of the barriers to their uptake is the lack of shared knowledge on the real sustainability impact resulting from the use of these materials. In addition, research results on this topic are rather scattered. Therefore, the aim of this paper is to synthesize the results of existing studies, while applying life-cycle assessment methodologies to bio-based materials in construction in the European context. Overall, bio-based materials have a lower environmental impact than traditional materials, especially in the production phase. However, in addition to production, other criteria should be considered in the assessment, in particular the required function, for which the material will be used, and the lifetime of the building. This underlines the importance of using different LCAs methods and implementing a case by case approach, in order to reduce the environmental impact of the building sector.

Keywords: bio-based materials, construction industry, life cycle assessment, LCA methodology

I. Introduction

The construction sector in Europe is a major contributor to environmental degradation and resource depletion. Construction activities generate large amounts of waste, which may contain hazardous materials that pose risks to both the environment and human health, such as asbestos, lead, and mercury (UNEP, 2021). According to the European Environment Agency (EEA, 2019) the construction and demolition sector generated approximately 871 million tons of waste in 2016, representing 36% of the total waste generated in the European Union (EU) that year. Soil erosion and sedimentation caused by construction activities can lead to water pollution. In addition, the construction industry uses up to 40% of the materials produced globally and generates approximately 35% of the world's waste (Leising et al., 2018). In 2014, the construction sector in the EU consumed 42% of the total extracted materials, including 50% of all fossil fuels consumed (EEA, 2016). This high level of resource consumption can lead to depletion of non-renewable resources and contribute to climate change.

Among other things, construction materials, including paints, solvents, and adhesives, can contain hazardous substances that can leach into the environment if not handled properly. Furthermore, the production of more traditional materials such as cement and steel, requires energy and generates greenhouse gas emissions, contributing to climate change (Dhakal et al., 2015). Moreover, the extraction and use of these materials can have negative impacts on ecosystems, in terms of deforestation and habitat destruction (UNEP, 2019).

Various approaches have been proposed to reduce the environmental impact of the construction industry, e.g., reuse of parts of the buildings, use of waste from other industries as material for construction. One of these approaches is to replace traditional materials with bio-based materials. Indeed, more widespread use of bio-based materials in the construction sector could promote more sustainable construction methods and practices by reducing waste and emissions and minimizing the use of non-renewable resources, as well as more sustainable built environment.

However, despite their potential, bio-based materials are currently still underutilized due to several factors, including a lack of knowledge about existing sustainable alternatives to traditional materials and resistance to the introduction of innovative solutions by the construction industry (Dams et al., 2023). Recent studies have demonstrated the potential of these materials such as the use of fungi to create fully functional partitions in modern buildings (Carcassi et al., 2022), and the assessment of the impact of bio-based materials on the building sector can serve as a driver to overcome potential barriers to their increased adoption. Life-cycle assessment (LCA) techniques have proven powerful to assess the impact of construction materials. Therefore, the objective of this study is to consolidate and analyze the existing literature on the application of LCA methodology to bio-based materials used in construction in the European context. The primary focus of this review is to assess the potential of these materials from both environmental and social perspectives.

As the demand for sustainable building solutions grows, assessing the impacts of these materials throughout their product life cycle becomes relevant in order to understand how they can be used to improve the sustainability of construction and achieve a more widespread use.

This work aims to contribute to the debate on the feasibility and sustainability of incorporating bio-based materials in the construction industry, by encompassing the advantages and disadvantages of their applications.

II. Background

A. Life-cycle assessment in construction

The construction sector is a major contributor to global environmental impacts, which have been widely quantified in the literature using Global Warming Potential (GWP) and Cumulative Energy Demand (CED) indicators. However, LCA is the most comprehensive method to have a complete overview on the impacts over the entire life cycle of materials. LCA is a widely accepted methodology used to evaluate the environmental impacts of products or services throughout their life cycle, from raw material extraction, to production, transportation, use, and disposal. LCAs have also been used to assess the environmental performance of buildings, infrastructure, and construction materials. LCAs in the construction sector typically follow the ISO 14040 and 14044 standards, which provide a framework for conducting a comprehensive and transparent assessment of environmental impacts. The assessment includes several stages, such as goal and scope definition, inventory analysis, impact assessment, and interpretation. The interpretation phase helps to understand and communicate the results of the LCA, including identifying opportunities for improvement and making recommendations for reducing environmental impacts.

Generally, LCA methodologies may consider a single product/material a comparison between two or more (comparative LCAs). Moreover, they may focus on a specific range of phases, e.g. production phase (A1-A3, cradle-to-gate LCAs), or on the overall life-cycle (cradle-to-cradle or cradle-to-grave).

Several studies have used LCA methods, mainly to assess the environmental impacts of construction projects, building materials, and infrastructure, although some of them also investigate economic and social impacts. For example, a study by Cabeza et al. (2015) applied LCA to assess the environmental impacts of different insulation materials used in buildings. The study found that natural insulation materials, such as cork and cellulose, had lower environmental impacts than synthetic materials, such as polyurethane foam. In fact, some materials reduce the overall impact of the building throughout its life cycle (Vilches et al., 2017), while taking in consideration also other aspects such as local availability and occupant wellbeing (Liu et al., 2017).

B. Bio-based materials in construction

Bio-based materials are made from renewable biological resources such as crops, wood, and waste materials. The term bio-based refers to materials "completely or partially derived from biomass" (EN 16575: 2014). Bio-based materials can be used in a variety of applications, including insulation, flooring, and building components. For example, hemp-based insulation is made from the inner fibers of the hemp plant and has excellent insulation properties. It is also an effective air purifier, making it an environmentally friendly choice for building insulation (Heidari et al., 2019).

Bio-based materials offer a sustainable and environmentally friendly alternative to traditional construction materials due to their reduced carbon footprint (Carcassi et al., 2022a). In addition to their reduced environmental impact, they also have improved performance characteristics such as insulation and fire resistance. Bio-based materials can also be cost-effective in certain applications, especially when compared to traditional materials that have high manufacturing and transportation costs (Carcassi et al., 2022b). However, it is important to ensure that bio-based materials are produced sustainably and do not contribute to deforestation or other environmental problems

III. METHODOLOGY

As previously mentioned, this research aims to synthetize the current body of research on the life cycle assessment technique when implemented on bio-based materials in construction in the European context. Therefore, the methodology chosen is systematic literature review. To collect the data, the Scopus engine has been used and the research query was structured as follows: TITLE-ABS-KEY ("life-cycle assessment" OR "LCA" OR "LC assessment") AND TITLE-ABS-KEY ("bio-based material*" OR "bbm" OR "bb material*" OR "bio material*") AND TITLE-ABS-KEY ("construction"). The search led to 41 articles, which were then filtered taking into account the reference context of the studies and the relevance to the topic with respect to the one investigated here. Consequently, after analyzing abstract and key words, 17 articles are identified as not relevant for the purpose of this research. Then, the remaining 24 articles were examined. 10 articles have been removed from our sample. Three articles focused exclusively on data collection for life cycle inventory and the description of different ways of constructing LCAs; one article focuses on other methodologies, which are complementary to LCA methods; and six articles are related to a context that goes beyond Europe. Overall, 14 papers have been retained for the final sample and analysed.

IV. FINDINGS

From the analysis of the papers, common patterns emerged. Table 1 describes the main features emerged from the papers in respect to the aim of the review.

TABLE I. COMPARISON AND ANALYSIS OF STUDIES

Paper	*Type of LCA*	*Type of material*	*Type of constr. product*	*Building lifespan*	*Area considered*	*Measured impact*
Bošković and Radivojević (2023)	*Cradle to grave LCA*	*hemp-lime concrete*	*wall*	*100 years*	*Serbia*	*Environmental GWP, $kgCO_2eq/m^2$*
Mouton et al., (2023b)	*Cradle to cradle comparative LCA: A1-C4*	*bio-based building elements (such as timber, straw, hemp) vs. conventional solutions*	*Multi-story building*	*60 years*	*Belgian building sector*	*Environmental GWP, $kgCO_2eq/m^2$ UFA, and 18 other indicators*
Mouton et al., (2023a)	*Cradle to cradle comparative LCA: A1-C4*	*bio-based building element variants – assessing timber-, straw- and hemp-based solutions vs. brick or concrete-based elements*	*External walls, internal walls, load-bearing and non-load-bearing, ground floors, internal floor, flat roofs, pitched roofs*	*60 years*	*Belgian building sector*	*Environmental GWP $kgCO_2eq/m^2$ BE (building element)*
Besana and Tirelli, (2022)	*Cradle to cradle comparative LCA: A1-C4*	*bio-based insulation materials (straw, cork, wood fiber, hemp, Mycelium 10cm) vs. mineral based materials (EPS, XPS)*	*Retrofit panels*	*Not specified*	*Milan, Italy*	*Environmental Embodied (kgCO2eq/m2) and stored (kgCO2)*
Cascione et al. (2022)	*cradle-to-cradle comparative LCA (A-D)*	*Mycelium, flax, timber*	*Circular bio-based wall panel, timber frame, steel frame*	*60 years,*	*Uk*	*Environmental GWP $kgCO_2e/m^2$*
Barrio et al., (2021)	*LC Sustainability Assessment (LCSA) = LCA, a Life Cycle Costing (LCC), and Social LCA (S-LCA) Modules A1-A5*	*Plywood board, BioPU adesive, BioPU foam*	*bio-based, multi-layer building wall panel*	*10 years*	*Europe*	*Environmental, economic and Social*
Sahmenko et al., (2021)	*Comparative, cradle to gate LCA: A1-A3*	*9 option: hemp composites and foam concrete*	*Wall solutions*	*Not specified*	*Latvia*	*Environmental GWP, $kgCO_2$-eq/m^2*
Zieger et al., (2020)	*Static LCA (sLCA) vs. dynamic LCA (dLCA)*	*Concrete, mineral wool vs. wood, straw*	*conventional wall vs. bio-based wall*	*50 years, 75 years, 100 years*	*France and Europe*	*Environmental, comprehensive*
Quintana - Gallardo et al., (2020)	*Comparative cradle to gate LCA: A1-A3*	*bio-epoxy resin composites vs. plasterboard*	*Drywall acoustic building partition*	*Not specified*	*Spain*	*Environmental, comprehensive*
Carcassi et al., (2020)	*Dynamic LCA: Levasseur model*	*Timber and insulation materials*	*Dry partition wall*	*200 years*	*Italy*	*Environmental GWP, $kgCO_2eq$*
Pittau et al., (2019)	*Dynamic LCA: A1-C4*	*Bio-composite with straw, hempcrete, timber and EPS*	*Retrofitting building facades*	*200 years*	*Europe*	*Environmental GWP_{dyn} ($MtCO_2eq$)*
Pittau et al., (2018)	*Dynamic LCA: A1-B1; B4; C1-C4.*	*Fast growing bio-based composites, timber, EPS*	*Thermal insulation panes*	*20 years, 100 years, 500 years*	*Europe*	*Environmental GWP_{dyn}*
Penalosa et al., (2016)	*Cradle to cradle dynamic LCA*	*CLT design, Increased bio-based, Traditional*	*structure*	*100 years (building service life 50-70 years)*	*Sweden*	*Environmental GWP100 $kgCO_2eq/m^2$ LA*
Pretot et al., (2014)	*Cradle to grave LCA*	*Hemp concrete*	*wall*	*100 years*	*Europe*	*Environmental GWP $kgCO_2eq/FU$*

A. *Type of LCA*

The examined literature reveals a focus on cradle-to-cradle or cradle-to-gate comparative assessments. A cluster of papers compares various materials, examining specific stages of the life cycle, particularly comparing different bio-based materials with traditional materials. Others concentrate solely on the production phase (A1-A3), while only two studies consider the entire life cycle (A1-C4). The results highlight that the production phase of bio-based materials plays a crucial role in determining their environmental performance.

Another group of papers explores a different approach by utilizing dynamic LCA, which incorporates time as a significant factor influencing the analysis and leading to varying outcomes. Dynamic LCA perspectives emphasize the importance of optimizing material consumption and maximizing the lifespan of bio-based materials. The results indicate that bio-based walls with shorter lifespans tend to have a greater positive impact on reducing greenhouse gas emissions than those with longer lifespans. Two studies conduct an LCA on a specific product from cradle to grave, primarily aiming to assess the environmental impact of the proposed solution without comparing it to other potential alternatives. In one case, the research focuses on comparing two LCA methodologies, particularly examining the differential results obtained from static and dynamic LCAs. This investigation demonstrates that the temporal aspect significantly influences the assessment of two materials used in a wall partition.

Lastly, one case proposes a research framework that combines the results of Life Cycle Costing (LCC) and a qualitative Social Life Cycle Assessment (S-LCA).

B. *Type of materials and products*

All the literature examined in this analysis centers around the assessment of bio-based materials. In two cases, the exclusive material under assessment is hemp concrete. Here, the use of bio-based alternatives, such as Lime-MOC hemp composite precast panels and traditional hemp concrete wall wood frames, exhibits negative carbon dioxide balances, indicating their potential for carbon sequestration. Generally, the studies compare a range of materials such as straw, hemp, mycelium, and wood with more conventional and/or plastic based materials, showing how bio-based materials offer significant potential for reducing the carbon footprint of buildings, especially in exterior wall insulation applications. The assessments consider these materials in the context of specific final products. The majority of cases focus on wall partitions, encompassing both external and internal partitions, and occasionally addressing specific functionalities such as retrofitting existing buildings or thermal and acoustic properties. The remaining two cases concentrate on structural elements and encompass an entire multi-story building. Generally, the substitution of conventional materials with bio-based alternatives, including hybrid solutions, emerges as an effective strategy for reducing the environmental impact of building elements.

C. *Measured impact*

All the studies focus on the environmental impact as the main driver of the research. The overarching aim is to assess greenhouse gas (GHG) emissions and calculate the global warming potential (GWP) within the climate change impact category. Some studies extend their LCAs to encompass multiple impact categories, including ozone depletion, eutrophication, acidification, human toxicity (cancer and non-cancer-related), respiratory inorganics, ionizing radiation, ecotoxicity, photochemical ozone formation, land use, and resource depletion. Studies that employ dynamic LCAs introduce the element of time as a critical factor in the assessment. In general, the findings reveal that the capacity of bio-based materials to trap CO2 significantly influences their sustainability and environmental impression. Factors like inefficient construction methods and long transport distances can be compensated by the CO2 sequestration potential of bio-based materials. Only one study accounts for social and economic impacts as part of a comprehensive LCA calculation. This evaluation of bio-based materials provides insights into their economic and social dimensions. The research highlights that companies involved in bio-based material production should improve explicit communication of their social commitments and adhere to social responsibility principles.

V. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

The reviewed literature shows that, despite the different methods utilized to conduct LCAs analysis, bio-based materials result to be the most suitable option in the majority of the cases.

Predominantly, the majority of the studies focus on cradle-to-cradle or cradle-to-gate comparative assessments. These approaches compare different materials and examine specific stages of the life cycle, with particular emphasis on the production phase (A1-A3). Only a few studies consider the entire life cycle (A1-C4), which includes additional stages such as use, maintenance, and end-of-life. The results consistently highlight the significance of the production phase in determining the environmental performance of bio-based materials. This finding underscores the importance of optimizing manufacturing processes and sourcing sustainable raw materials for bio-based products. By improving the production phase, it is possible to enhance the overall environmental sustainability of bio-based materials.

Additionally, it is fundamental to underline that, although cradle-to-gate LCAs give important results, the dynamic LCAs conducted show a significant difference in terms of evaluation, due to the inclusion of the time in the analysis. In fact, even though the results remain promising, the time evaluations return meaningful outcomes, which underline the need to consider the usage and function criteria to use bio-materials in a correct way, to actually reduce the environmental impact of the building.

Nevertheless, although LCAs analysis generally highlight the potentials of bio-based materials in terms of environmental impacts when compared to more traditional materials in construction, it is necessary to underline that their usage in the sector is still limited because of several factors. Among these, it is important to specify that a more widespread use of these materials would imply a specific consideration on the consumption and regeneration of natural resources. For instance, an increased use of timber for the buildings, carries questions regarding forests management and wood availability. Pittau et al., (2018) focus on the assessment of fast growing bio-based materials, which could represent an answer to this problem, but the limits of these materials in terms of lifespan, structural performances and resistance to atmospheric agents suggest that future research and developments are still required.

Furthermore, despite the number of studies analysed, only one paper focuses on the social impact of such applications, which does not seem enough to conduct any evaluation on the matter. Nevertheless, this study highlights the importance of considering the economic and social dimensions of bio-based materials, urging companies to communicate their social commitments and adhere to social responsibility principles. For these reasons, future research should investigate more carefully comprehensive LCAs as, especially in terms of social impacts, engaging local communities and promoting social responsibility along the supply chain can enhance stakeholder benefits and foster the widespread adoption of bio-based value chains in Europe.

Moreover, since one of the most important aspects of bio-based materials is the opportunity to recycle or reuse them in several sectors, end of life scenarios should be included and investigated in future studies to encourage the importance of a widespread use of these materials and implement the knowledge on their potential in the sector. Lastly, further studies are needed to enlarge the scope of the research to other database and other areas than Europe, to collect a more comprehensive set of data which consider a wider cluster of materials and different environments.

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