

A System Boundary Assessment of Emerging Materials: Manufacturing process of Microbial Bricks

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Abstract. The construction industry is under pressure to address climate change and resource scarcity, leading to a growing interest in emerging biobased materials. This research focuses on microbial bricks through a life cycle assessment (LCA) based on ISO 14042 standards and CML2001 impact categories, examining various environmental criteria across a defined system boundary: Manufacturing. The findings highlight the positive potential of biobased materials in contributing to a greener supply chain management for the construction industry, even more than clay that we know as an earth (green) material. The biggest differences lay in the use of fossil fuels, electricity, transportation, and the assembly process. By addressing challenges and leveraging opportunities, these materials can lead to a more resilient and ecologically conscious sector, in alignment with the sustainable development goals (SDGs) defined by the United Nations (UN). The aim of this study is to stimulate additional dialogue and cooperation among academic and industrial participants to promote sustainable advancements in construction materials and manufacturing methods, transcending mere superficial green initiatives.

1 Introduction

The urgency to address climate change and resource scarcity has driven the construction sector to explore innovative solutions. Biobased circular materials, including biomaterials such as timber, earth and clay [1,2,3], and biobased materials such as those derived from living organisms including bacterial cellulose, mycelium, and algae [4,5,6], present a promising avenue. However, there are various scalability challenges and opportunities embedded in the supply chain management (SCM), specific to each biobased material, imperative to be studied further for a healthier life cycle assessment (LCA).

While conventional construction materials such as concrete, timber or aluminium are already experiencing industrial momentum, the scalability and sourcing of biobased materials remain intricate [7]. On the other hand, logistics and transportation present another set of environmental challenges for the conventional materials [8], while living organisms and their products possess a do-it-yourself in-situ approach, ensuring a local supply, cut off in the

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transportation, and more responsible practices [9]. Another challenging aspect of biobased materials is the maintenance. The unique characteristics require specialised handling, and establishing efficient maintenance systems for these materials becomes imperative [10], while the conventional materials already have their own handling with established practices.

Green supply chain management (GSCM), a type of SCM, is an approach that integrates environmental sustainability into various aspects of the supply chain, aiming to minimise the overall environmental impact of the supply chain processes and products [11, 12]. GSCM recognizes the importance of environmental responsibility and seeks to balance economic objectives with ecological and social considerations. One of the most advantageous aspects of the integration of biobased materials into the GSCM is the use of renewable resources. Replacing conventional materials with the biobased alternatives holds promising advantages regarding achieving zero carbon practices. However, this replacement brings together the questions of how much the supply management of biobased materials is in line with these goals, and which life cycle stages of biobased materials have the most potential to achieve a greener SCM.

This study investigates the LCA of microbial bricks within a specific system boundary: Manufacturing, since it is one of the most critical stages of a material's life cycle, when the depletion of natural resources is concerned. The LCA is conducted in accordance with ISO 14042 standards and CML2001 impact categories. The results underscore the promise of biobased materials in fostering a greener SCM within the construction sector, especially for the manufacturing phase. By tackling obstacles and capitalising on potentials, the incorporation of these materials can foster a more robust and environmentally aware industry, aligning with the sustainable development objectives outlined by the United Nations.

2 Theoretical Framework

Climate change casts an undeniable shadow over our planet, and the construction sector is a major contributor. The International Energy Agency (IEA) reports that buildings are responsible for a staggering 36% of global energy-related CO₂ emissions, with nearly 40% of global energy demand stemming from their construction and operation [13]. A significant portion of this environmental burden lies in the manufacturing of building materials [14]. For millennia, clay bricks have been the cornerstone of construction, valued for their durability and fire resistance. However, their manufacturing process is far from environmentally friendly. The firing stage, a crucial step that involves heating the bricks to extremely high temperatures (often exceeding 900°C), relies heavily on fossil fuels such as coal or natural gas. This reliance translates to the release of significant quantities of CO₂ into the atmosphere. Considering the vast quantities of bricks used in construction projects globally, this translates to a substantial environmental impact [14].

2.1 Biobased materials

In the face of these environmental concerns, researchers are actively exploring the potential of emerging biobased materials. These materials are derived from renewable biological resources such as plants, bacteria, or fungi, offering a potentially more sustainable alternative to conventional construction materials [15].

Biobased materials often boast a lower embodied energy, meaning they require significantly less energy to produce compared to traditional materials, which translates to a direct reduction in CO₂ emissions associated with the production process [16,17]. Additionally, some biobased materials can even act as carbon sinks, actively sequestering atmospheric CO₂ during their growth cycle, further contributing to a positive environmental impact [18]. For instance, bioMason has devised a technique for cultivating materials using

microorganisms, in a way that bacteria, along with specific nutrients like nitrogen and calcium, create an optimal setting for natural cement formation at room temperature, yielding precast material in under five days [16]. Another example of practical use of biobased materials is that a team from the University of Colorado, Boulder [17], employed photosynthetic bacteria capable of absorbing carbon dioxide, sunlight, and nutrients to create calcium carbonate—a sturdy compound present in rocks, pearls, and seashells. Cultivated in a warm saline solution with additional nutrients, the bacteria were mixed with sand and gelatin. This mixture was then poured into a mould, where the gelatin solidified, providing a framework for bacterial proliferation. Over approximately a day, the bacteria deposited calcium carbonate throughout the scaffold, transforming the initially soft sludge into a more solid substance. Initially green in appearance, the colour fades as the material dries.

As seen from the examples above, the whole life cycle differs from the conventional construction materials. These materials are grown, instead of assembled in a way that the emergence of these materials is considered to be a paradigm shift for the architectural practice [18]. These projects, both small and large in scale, serve as tangible showcases of how advancements in biology can play a role in the development of sustainable built environments. As a result, conventional LCA methods and tools can fall short in evaluating the process thoroughly, additional calculations should be implemented.

2.2 Life cycle assessment (LCA)

Life cycle assessment (LCA) emerges as a crucial tool for objectively evaluating the environmental impact of these novel biobased materials. This standardised methodology assesses the environmental footprint of a product or service throughout its entire lifespan, encompassing all stages, from the raw material extraction, manufacturing to use, maintenance and ultimately disposal or recycling of the final product [16]. However, since the manufacturing process quite differs from the conventional processes due to the nature of biobased materials, LCA methods and tools should also be revised.

2.3 Microbial Bricks derived from bacterial cellulose (BC)

Bacterial cellulose (BC) is a particularly exciting biobased material with significant potential applications in the construction industry. Produced by certain species of bacteria, this cellulose exhibits superior strength, elasticity, and biodegradability compared to its plant-derived counterpart [19]. The manufacturing process of BC can be significantly less energy-intensive compared to conventional brick firing, with the potential for drastically reduced CO₂ emissions with minimal energy input, making it a potentially game-changing alternative for construction materials [6].

Through a LCA, the environmental impact of microbial brick production can be compared across all stages of their life cycles. While the manufacturing process itself might be less energy-intensive, factors such as transportation distances for raw materials or the end-of-life disposal of the biobased material could influence the overall environmental impact [17], however, these materials can be manufactured on-site as do-it-yourself (DIY) approach [7] so that these trade-offs can easily be mitigated by on-site growth facilities. By understanding these trade-offs and possible mitigation strategies, researchers and industry professionals can work towards optimising the entire life cycle of biobased materials to maximise their environmental benefits. Ultimately, a future where biobased materials become the norm in construction holds immense promise for reducing the industry's environmental impact and fostering a more sustainable built environment for generations to come. This transition towards biobased materials requires a multi-pronged approach.

3 Methodology

The methodology involves a LCA which is proposed to focus on the GSCM, to bridge the gap between industry and the developing biobased material industry. The LCA employed in this study is based on ISO 14042 standards (Standard No. 38498) cross-referenced with the CML2001 impact categories [20], involving the following criteria: Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Human Toxicity Potential (HTP), Freshwater Aquatic Ecotoxicity (FAETP), Terrestrial Ecotoxicity (TETP), Photochemical Oxidant Formation Potential (POFP), Acidification Potential (AP), Eutrophication Potential (EP), Abiotic Depletion Potential (ADP), and Resource Depletion Potential (RDP). The material is investigated through a specific system boundary: Manufacturing (see Fig. 1). In this scenario, while the conventional clay brick production process requires factories with machinery fueled by fossil fuels, production of microbial brick takes place as an on-site activity based on a customised material recipe as a DIY approach.

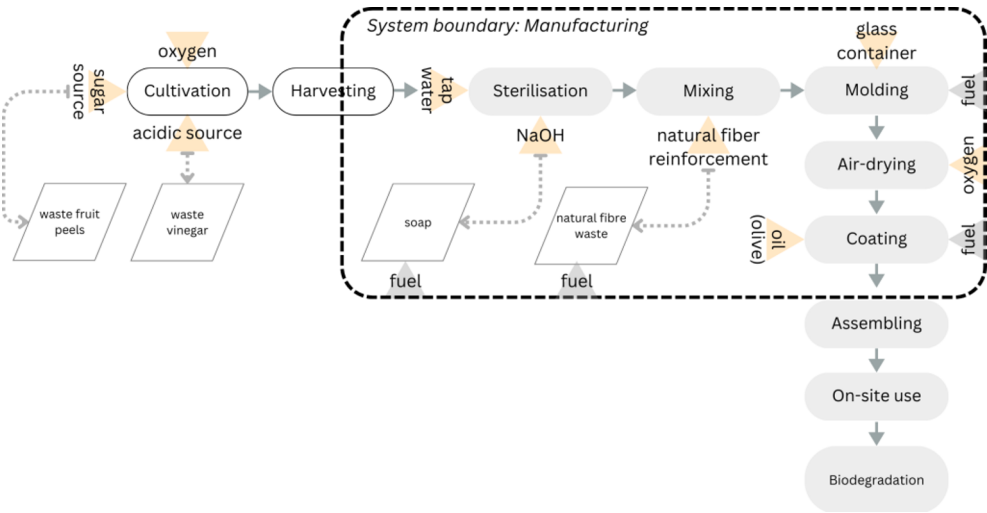


Fig. 1. Life cycle system boundary for microbial brick production: Sterilisation, mixing, moulding, air-drying, and coating

Since there is no commonly agreed dataset regarding the environmental impact of microbial brick manufacturing, several measurements are conducted (see Table 1). It is crucial to acknowledge that there are several additives (mostly organic) used in the process such as for reinforcement facilitated by jute fibres, NaOH sterilisation or oil coating, therefore the results still cannot achieve zero carbon yet, although there is a drastic change compared to the conventional materials.

Table 1. Environmental impact measurements for microbial brick manufacturing

Environmental Parameter	Measurement Method	Equipment/Instrument	Conditions/Considerations
Energy Consumption	Energy usage	Fluke Energy Meters, Power Monitors	Record energy consumption
Emissions	Greenhouse gases and air pollutants	Teledyne API Gas Analyzers, Emission Monitoring Systems	Analyze emitted gases
Water Usage	Water consumption and impact	Siemens Flow Meters, Water Quality Sensors	Monitor water usage
Waste Generation	Solid and liquid waste production	Mettler Toledo Scales, Waste Characterization Equipment	Quantify waste streams
Chemical Analysis	Analysis of chemical constituents	Agilent Spectrophotometers, Shimadzu Chromatographs, Titration Kits	Analyze material composition
Environmental Monitoring	Monitoring environmental parameters	Bosch Environmental Sensors, Onset HOBO Data Loggers	Monitor environmental conditions

4 Results

As revealed by the data on a per-kilogram basis, the results clearly highlight the significant environmental advantages of microbial brick manufacturing with very low values (Table 2).

Table 2. LCA for microbial brick production based on ISO 14042 standards, cross-referenced with the CML2001 impact categories

Life Cycle Stage	GWP (kg CO2 eq)	ODP (kg CFC -11 eq)	HTP (kg SO2 eq)	FAET P (kg PO4 eq)	TETP (MJ)	POFP (kg ethylene eq)	AP (kg SO2 eq)	EP (kg PO4 eq)	ADP (MJ)	RDP (MJ)
Sterilisation	0.012	0.005	0.008	0.007	0.013	0.009	0.010	0.006	0.014	0.012
Mixing	0.015	0.006	0.009	0.008	0.014	0.010	0.011	0.007	0.015	0.013
Moulding	0.018	0.008	0.011	0.010	0.016	0.012	0.013	0.009	0.017	0.015
Air-Drying	0.010	0.004	0.006	0.005	0.008	0.007	0.009	0.004	0.002	0.010
Coating	0.020	0.010	0.013	0.012	0.017	0.014	0.015	0.011	0.018	0.016

Sterilisation, which involves the elimination of microorganisms from the materials used in brick manufacturing, demonstrates minimal environmental impact across all assessed categories. The greenhouse gas emissions (GWP) associated with sterilisation are estimated to be 0.012 kg CO2 eq, indicating a very low contribution to climate change. Similarly, ozone depletion (ODP), acidification (HTP), eutrophication (FAETP), abiotic resource depletion

(TETP), and non-renewable energy consumption (RDP) during sterilisation are all below 0.014 units of their respective metrics, suggesting negligible environmental effects. Mixing, moulding, and coating stages show slightly higher environmental impacts compared to sterilisation, reflecting the energy-intensive nature of these processes. However, the values remain relatively low, with GWP, ODP, HTP, FAETP, TETP, and RDP respectively. Air-drying, which relies solely on natural processes involving air and oxygen to dry out the microbial brick in the mould, exhibits the lowest environmental impact among the assessed stages. With minimal energy consumption and no direct emissions associated with the process, air-drying contributes negligibly to greenhouse gas emissions, resource depletion, and other environmental metrics.

5 Conclusion

The data presented in this research support the potential of microbial bricks as a sustainable alternative in the construction industry, offering reduced environmental impact across a defined system boundary. However, biobased materials are a relatively new field, and ongoing research is necessary to improve their performance characteristics, such as durability and fire resistance, to meet the requirements of the construction industry. Despite these challenges, by fostering collaboration between researchers, industry professionals, and policymakers, the construction industry can pave the way for a more sustainable future.

References

1. M.Parlato, S.M. Porto, & G. Cascone, JAE, 52(2), 1154–1165 (2021)
2. H.B.Bostanci, & A.M. Tanyer, 7th IPCMC2022, LNCS, vol. 9999, pp. 42–57. Springer, (2022)
3. P.C. Mengue, M.Mbessa, R.C. Kaze, A. Adesina & C. Pettang, (2022)
A. Hoenerloh, D. Ozkan, & J. Scott. Biomimetics (Basel), 7(2): 55, (2022)
4. E. Elsacker et al., Fun.Bio.&Bio. 8, 18 (2021)
5. G.D. Turhan, G. Varinlioglu, M. Bengisu, Int.J.Arc.Com., 21(4), pp.781-794, (2023)
6. G.D. Turhan, eCAADe41, 2, 39-48, (2023)
7. J.Malinen, V. Nousiainen, K. Palojärvi & T. Palander. CJFE, 35, 91–100 (2014)
8. K. Kamiński et al., Cellulose, 27, 5353–5365 (2020)
9. H. Ahmad, Cellulose 28, 2715–2761 (2021)
10. R. Jaggernath & Z. Khan, 11(1), 37–47 (2015)
A. Noiki, E. Salawu, A. Afolalu, J. Kayode & L. Lawal. SEB-SDG, 1–10 (2023)
B. Jeske, Wo.Fi.Sci., 43(3), 208–222 (2011)
11. M.K. Dixit, M. Fernandez-Garcia, S. Lele & R. Khanna, En.&Build., 228, 110462 (2020)
12. F. Almomani, A. Abdelbar & S. Ghanimeh. Sustainability, 15(13), 10438, (2023)
13. bioMason, “Biocement”. <https://biomason.com/biocement> [Accessed 02.03.2024]
14. C.M.Heveran et al. Matter, 2(2), 481-494, (2020)
15. R.Morrow, B.Bridgens, L.Mackenzie, Birkhäuser, (2023)
16. Klemm, D., et al., Carbohydr.Polym. 254, 117313 (2021)
17. J.B.Guinée, (ed.), Centre for Environmental Science, Leiden University, (2001)