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Circular Bio-Based Solution for Future Construction

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Abstract. To achieve the goal of fully circular buildings, the use of bio-based solutions is growing, with some buildings using natural waste or bio-based components. This study aims to explore the potential for integrating circularity principles into the use of bio-based components. The findings highlight six key factors that must be considered to ensure the success of circular bio-based components: environmental impacts, cost, locality, knowledge (cultural and technical), future use/reuse, and policies. The study also emphasises that locality plays a crucial role when selecting bio-based products and applying circularity principles. However, barriers such as policy limitations, cost concerns, and gaps in technical and cultural knowledge exist in certain regions. Therefore, it is essential to evaluate the availability of local materials and assess the potential for scaling up their use within specific regions. This approach ensures that bio-based solutions are effectively implemented, taking into account regional constraints and opportunities for growth.

Keywords: Bio-based materials · circular construction · waste materials · Sustainable construction

1 Introduction

Significant efforts are being made to achieve the 2050 goals of fully circular and zero-energy emission buildings. The question of how to create zero-energy and fully circular buildings is being explored by many scholars, addressing not just technical aspects, but also behavioural and organisational factors. The integration of technologies with socio-economic aspects is key to developing a successful approach toward fully circular buildings. In traditional construction, the emphasis was on using local materials, local labour, and climate-adaptive techniques to minimise costs and reduce environmental impact. There are examples of buildings, constructed years ago, that achieved energy efficiency while reflecting society's economy, and culture [1–3]. These vernacular buildings not only function as energy-efficient structures on their own, but when connected to neighbouring properties, they contribute to a sustainable neighbourhood that addresses local environmental, social, and economic demands. This concept can be expanded to a larger urban scale, leading to more sustainable cities with reduced negative impacts.

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However, as technology has developed and populations have increased, these aspects of construction have gradually been overlooked, resulting in polluted cities with high emissions and rising construction costs, and importation of materials from outside, while local materials are shipped to regions with different climatic conditions. Consequently, leads to an abundance of concrete, glass, and steel with high environmental impacts, rather than using bio-based and local materials. Furthermore, new materials, such as metal-intensive products, demand less maintenance over time and lead to overlooking the regular maintenance of our buildings compared and being more dependent on using critical material. Hence, integrating local solutions with modern construction methods can lead to minimising our environmental impact, achieving a circular economy, and positively influencing our society.

Significant efforts have been made to highlight how we use, reuse, and dispose of materials, as well as how we can minimise waste. This shift aims to transform the linear economy into a circular economy, where materials are not discarded after use but instead re-enter the cycle through reuse, recycling, or other strategies. The Waste Hierarchy, European Union [4] is one of the efforts which prioritises prevention above preparing for re-use; recycling; recovery; and disposal. Moreover, the R-Ladder is an expanded framework for transitioning to a circular economy, taking into account 10 factors instead of the more common 3 Rs (Reduce, Reuse, Recycle) [5]. These 10 Rs aim to minimise waste by extending the lifecycle of products. The idea is to consider these Rs from the start of the design and production process.

Additionally, another study [6] emphasises the importance of preservation, reclamation, and the reuse rate in construction work. Some examples in their study demonstrate how materials are reused in both renovation and new construction projects [7], with reuse being prioritised over recycling. Furthermore, Nina Martiz [8] provides practical examples of reuse, and use of bio-based materials, waste materials, second-hand elements, and recycled materials as local and reused strategies in various projects. This approach has proven effective, especially in regions facing economic challenges and extreme climate conditions.

This paper aims to integrate the circularity principles into bio-based buildings' components. It reviews studies on how bio-based solutions can contribute to the circular economy, emphasising not just the use of these materials, but also how to ensure they are returned to the life cycle after their end of use. Hence, based on the Brand's shearing layers [9], the types of bio-based materials studied so far, are explored as well as the challenges, barriers, and drivers to scaling up their use. Additionally, how to design these products circularly to minimise environmental impacts, energy consumption, and costs is studied. The research question of this study is "Which factors need to be considered for making circular bio-based buildings' components?

2 Circular Principles for Bio-Based Solutions

Bio-based materials and products are typically designed to enhance functionality, advance product development, reduce environmental impacts, and reuse agricultural waste. While they align with circularity principles in terms of material selection, more research is needed on the reuse and recycling of these products at the end of their lifecycle. Specifically, how these products can be designed for easy assembly, disassembly,

repair, maintenance, replacement, reuse, and recycling needs further exploration. Additionally, it's important to assess their environmental impacts, CO_2 emissions, energy use and costs through a life cycle assessment.

2.1 Consideration of Rs Principles

As mentioned above about Rs Principles that how contribute to a circular economy; some studies focus on the 3 Rs, while others expand the framework to include the 5 Rs (Repair, Reuse, Recycle, Refurbish, Remanufacture) [10]. Additionally, some researchers have further developed this concept to 10 Rs (Refuse, Rethink, Reduce, Re-use, Repair, Refurbish, Remanufacture, Re-purpose, Recycle, Recover) [5]. Applying these principles to the use of circular bio-based solutions during new construction, renovation, maintenance and demolishing of a building, can be illustrated in Table 1.

Table 1. Adapted 10R principles for bio-based solutions

Strategy	R principle		Phase
Prevention	Refuse	of using new/raw materials/non-waste products	Material selection phase
	Rethink		
	Reduce		
Preparing for reuse	Re-use	of bio-based components/waste products	(Re)Use phase
	Repair		
	Refurbish		
	Remanufacture		
	Re-purpose		
Recycling	Recycle processing of bio-based materials		End-of-life phase: Use waste as a source
Recovering	Recovering energy		

2.2 Design for Disassembly (DfD)

Regarding circularity, considerations of expansion, adaptability, disassembly, reassembly, and life cycle assessment are crucial when thinking about upscaling bio-based products [11]. Design for Disassembly (DfD) strategies promote the recovery and reuse of materials at the end of their lifecycle, enabling second-life applications and reducing overall life cycle impacts [12]. Several indicators of detachability have been identified [13], including the type of connections, accessibility of connections, intersections, and edge inclusion. Modular systems can significantly contribute to this objective. Additionally, establishing a circular supply chain that integrates agriculture with processing, manufacturing, construction, storage, and transportation [14], while also involving clients or project owners, engineers, installers, and maintenance people and considering product-service systems [15–17], is essential.

2.3 Life Cycle of Buildings' Components

The most significant stages in the life cycle are material production, maintenance, and replacement, particularly concerning finishes [18]. Considering the Brand's shearing layer and the lifespan of each layer [9] along with the expanded layer from another European study [19], it is evident that although the lifespan of the service layer is shorter than that of other layers (excluding the stuff layer), there is less emphasis on the circularity of building installations (mechanical, electrical, and sanitary services) (Fig. 1). However, a few studies [10] have explored using bio-based solutions for mechanical installations such as air ducts. Additionally, the primary energy demand and CO_2 emissions for various construction materials indicate that steel, cement, and ceramics [20] are the leading contributors to carbon emissions and primary energy use. These materials are primarily found within the Structure and Service layers. In the following section, the existing bio-based components are explored to determine which layer contains the most bio-based components and whether this aligns with the critical layers (Structure and Service layers).

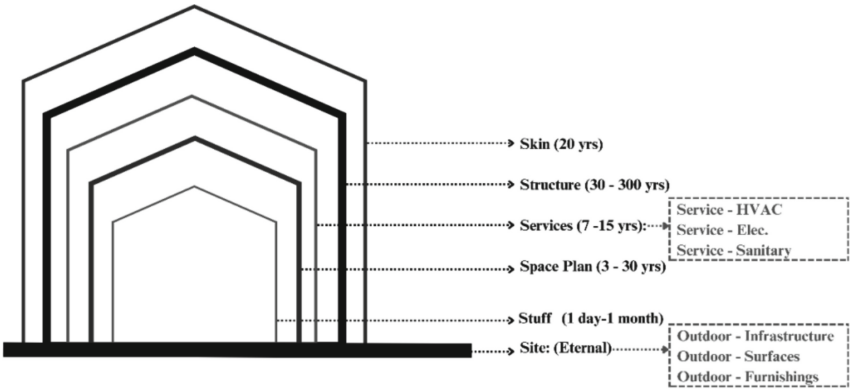

Fig. 1. A figure caption Fig. 2. The life span of each shearing layer, Adopted from the Brand's shearing layers and developed layers by Célia Chaussebel, et al., 2023

3 Existing Bio-Based Buildings' Components

There is no doubt that using bio-based materials is a promising strategy for reducing negative environmental impacts [12, 18, 21–26] and contributing to a circular economy [11, 14]. The key environmental impacts that bio-based solutions can contribute include global warming potential, particulate matter, and land use [18]. While bio-based materials can lower the climate impact of construction, assuming they are entirely climate-neutral is overly simplistic. Their environmental impact varies based on factors such as forest system modelling and LCA parameters [27]. In light of the 2050 goals and the Critical Raw Materials (CRM) Act [28], it is essential to be more selective when choosing materials for building components. There have been studies and efforts aimed at

Table 2. Different types of biobased materials and the assigned layer

Assigned Layer	Bio-based materials
Structure	Timber
	Mussel shell
Space plan	Mycelium bricks/insulation
	Flax boards
	Straw
	Reed
	Mussel shell
	Cork
	Jute
	miscanthus
	Sheep's Wool
	Cellulose Insulation
	Engineered/recycled Wood,
	Timber
	Bamboo Grass Flooring
	Cotton Fiberboard/insulation
	Recycled cotton/Paper Insulation
	Sunflower Husk boards/insulation
	Miscanthus Panels
	Coconut Fiberboard/wood/insulation
	Cornstarch-based Panels/insulation
	Flax Fiberboard
	Linoleum Flooring
	Walnut Shell Panels
	Cashew Nutshell-based Resins
Skin	Mycelium
	Hempcrete
	Mussel shell
	Coconut Shell Concrete
Outdoor space	Grasscrete

promoting bio-based components and addressing the barriers and challenges to scaling up these products, including policy, economic, and knowledge-related factors [11, 24]. Another study investigates land availability for the transition to bio-based construction,

raising important questions about the feasibility of upscaling bio-based components. The study found that existing forests and wheat plantations can sufficiently supply construction materials, with straw emerging as a more favourable option than timber [18, 22, 29].

Different types of bio-based materials and their applications are presented in Table 2 [14, 21, 22, 29–32]. The results indicate that most efforts are directed toward components related to the Space plan layer, while the most critical materials are utilised in the Structural and Service layers. Therefore, it is crucial to increase the development of bio-based solutions for other layers as well.

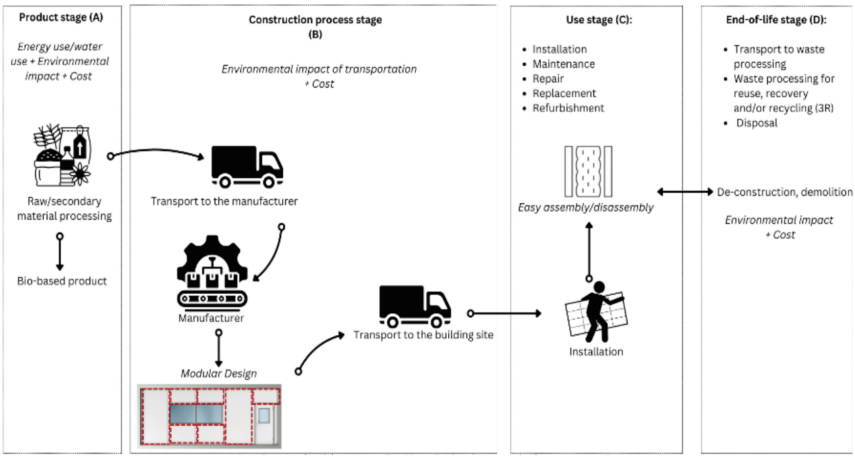

Fig. 2. Schematic stages of LCA for bio-based components developed by authors based on the study of Pargana, N., et al., (2014)

4 Discussion and Conclusion

The study explored the implementation of circularity principles when using bio-based buildings components. The findings show that it is important to consider the role of localisation in promoting the circular economy, since exporting materials to other regions may diminish its effectiveness by adding environmental and logistical costs. Using bio-based materials in construction enhances the use of local resources, supports the development of local value chains, and encourages responsible production practices, ultimately driving economic growth and improving well-being [25]. These efforts are key to achieving circularity goals. Some of the locality-focused considerations include: Sourcing local building materials (using resources available on-site, such as earthen building techniques); Bio-based construction; Incorporating salvaged and recycled materials; and Designing for disassembly while considering labour requirements. To achieve circular bio-based solutions in construction, several key factors must be addressed:

- Locality: Utilising local resources reduces transportation emissions and strengthens regional economies. Sourcing materials like locally grown agricultural products, or natural waste.
- Knowledge (labour resources and techniques): Using local labours and appropriate techniques are crucial for effectively developing circular bio-based components. This includes training workers in the use of bio-based materials, modular construction methods, and disassembly practices.
- Environmental impact: Bio-based materials typically have a lower environmental footprint compared to conventional materials like steel and cement, which are major contributors to CO_2 emissions. However, a thorough assessment of their environmental impacts, through LCA, is needed to evaluate their overall benefits.
- Local economy: Circular bio-based construction can stimulate local economies by creating demand for locally sourced materials. It can also reduce dependency on imported, and high-emission materials.
- Future use/reuse of components (easy assembly and disassembly): DfD ensures that materials can be easily reused or recycled at the end of a component's life. This approach prioritises modular design, making components easy to disassemble not only extends the life of materials but also decreases costs related to demolition and waste management.

Policy: The growth of circular bio-based solutions requires strong policy support to integrate all key factors (environmental impacts, cost, locality, knowledge, and future use/reuse) into a cohesive policy roadmap. Policies should provide clear guidelines and incentives that encourage the adoption of bio-based materials, promote circular practices, and address regional barriers.

Additionally, the life cycle [33] of bio-based components needs to be considered across four stages:

- Production: The production and processing of raw materials should use less energy, and water, have a less environmental impact and be cost-effective.
- Construction: During the building phase, techniques should focus on minimising transportation, and modular design, with a focus on less energy use, and less emissions.
- Use: Bio-based materials should be repairable and maintainable, and should be easily disassembled of components.
- End-of-life: When bio-based components reach the end of their lifecycle, they need to be reused, or recycled, ensuring minimal waste (Fig. 2).

In conclusion, while significant efforts have been made in developing components for the Space plan layer, which typically involves less critical material use, there has been less focus on the Structure and Service layers. These layers, which utilise more critical materials, have seen fewer initiatives for integrating circular bio-based alternatives, highlighting the need for increased attention and innovation in these areas. It's essential to think long-term and prioritise actions: first, prevention; second, reduction; and finally, production during material selection at each stage and for each layer. The study recommends further study on the life cycle of bio-based components to contribute significantly to a circular built environment.

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