

From bio-residues to construction applications: a comprehensive framework

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Abstract. Due to their ability to store carbon during growth, biomaterials are currently gaining attention in the construction sector to produce alternative building bio-components. Bio-residues in particular are quite promising, as applying them in construction might enhance strategies of circular bio-based economy. However, despite many studies and few products already on the market, a clear classification of bio-residues has not been available yet, and the experiences related to construction applications are scattered and fragmented. Hence, this paper offers a comprehensive framework by visualizing the production flows from bio-residues to building components. It operates a review of contemporary bio-manufacturing processes by classifying them based on their primary bio-sources, and it provides critical knowledge of their advancements, by displaying both established and emerging possibilities. By doing so, the study identifies lower energy-intensive applications, involving the direct transformation of fibrous agricultural materials into insulation building products, and more complex processes encompassing the extraction of intermediary bio-products, such as cellulose, and polymeric biocomposite. These last are starting points for promising technologies like electrospinning and additive manufacturing, with disruptive potential in manufacturing advancement. Indeed, the research highlights future research directions and initiates a potential tool to aid stakeholders in decision-making for a more sustainable built environment.

1 Introduction

The construction sector represents 36% of CO₂ emissions [1] and it undoubtedly stands as one of the major contributors to European (and global) energy consumption.

Buildings' impacts belong to two different and interrelated types of carbon emissions. Operational carbon, comprising impacts related to the correct operation of the building (lighting, heating, etc.); embodied carbon, resulting from the physical construction of buildings (including the processing of materials and material waste, their transport, assembly, and disassembly).

While over the last decades both research and politics have been particularly focused on optimizing Greenhouse Gas (GHG) emissions during building operations, through for instance the enacting of the EU Energy Performance of Buildings Directive [2], the embodied carbon related to materials used in buildings have gained attention just in recent times [3-4]. Indeed, studies have shown that the embodied impacts stemming from the production and installation of new materials can represent a significant contribution [5-7], ranging from 10% to as much as 80% (in more performative buildings) of the total emissions over a building's life cycle [4].

To mitigate them, recent studies have demonstrated the efficiency of substituting fossil-based materials with

bio-based ones, with particular emphasis on bio-residues.

Indeed, biomaterials contribute to carbon sequestration during plant growth [8], offering a significant potential in reducing the embodied carbon of buildings [9-10]. Moreover, they provide several additional benefits: they are renewable, frequently locally accessible and available in significant quantities. In this regard, the forecasted potential for fostering a possible added-value bioeconomy from lignocellulosic bio-residues in Europe indicates a range of 49-74 Mt for agro-industrial and 36-46 Mt for forestry residues by 2025 [11]. However, biomaterials and their residues do not only vary in their structural and thermal properties but most of all in manufacturing processing, sparking critical issues related to their actual environmental benefits for all building applications. Indeed, despite the literature that has already discussed methods to produce building bio-components made of bio-residues, experiences remain scattered and fragmented.

Given the above, this paper operates a review of contemporary bio-manufacturing processes, aiming to provide critical knowledge of their advancements. Technologies have been selected based on their direct contribution to biomaterials production for construction applications and their focus on utilizing agro-industrial residues.

It aims to offer a comprehensive framework by including both established and emerging technologies, thus providing insight into the production of building

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bio-components and their potential industrial scalability, in view of the future widespread utilization of bio-residues in the construction sector.

2 Production flows from agro-industrial residues to building products

The proposed framework summarizes into a visual map (Fig.1) those pathways from residues/bio-products to final building components, involving relevant manufacturing processes. It categorizes production flows based on their primary sources and highlights direct and indirect connections, encompassing the passage through different bio-products. Finally, it distinguishes between construction target applications,

according to buildings' layers as structure, insulation, space plane, and finishing.

According to the literature, there are many types of bio-residues, and they can be classified depending on their characteristics and production stage within the supply chain. Residues can be defined as primary (1st level), resulting from agriculture and forestry, or as secondary (2nd level), coming from industrial production processes [12].

Considering their physical composition and origin, it is possible to distinguish between lignocellulosic residues, which include both agro-industrial residues and forestry residues; farming residues, consisting of protein-based materials from animals such as wool and feathers; and marine residues, including seaweed, shellfish shells, fish bones, and algal blooms.

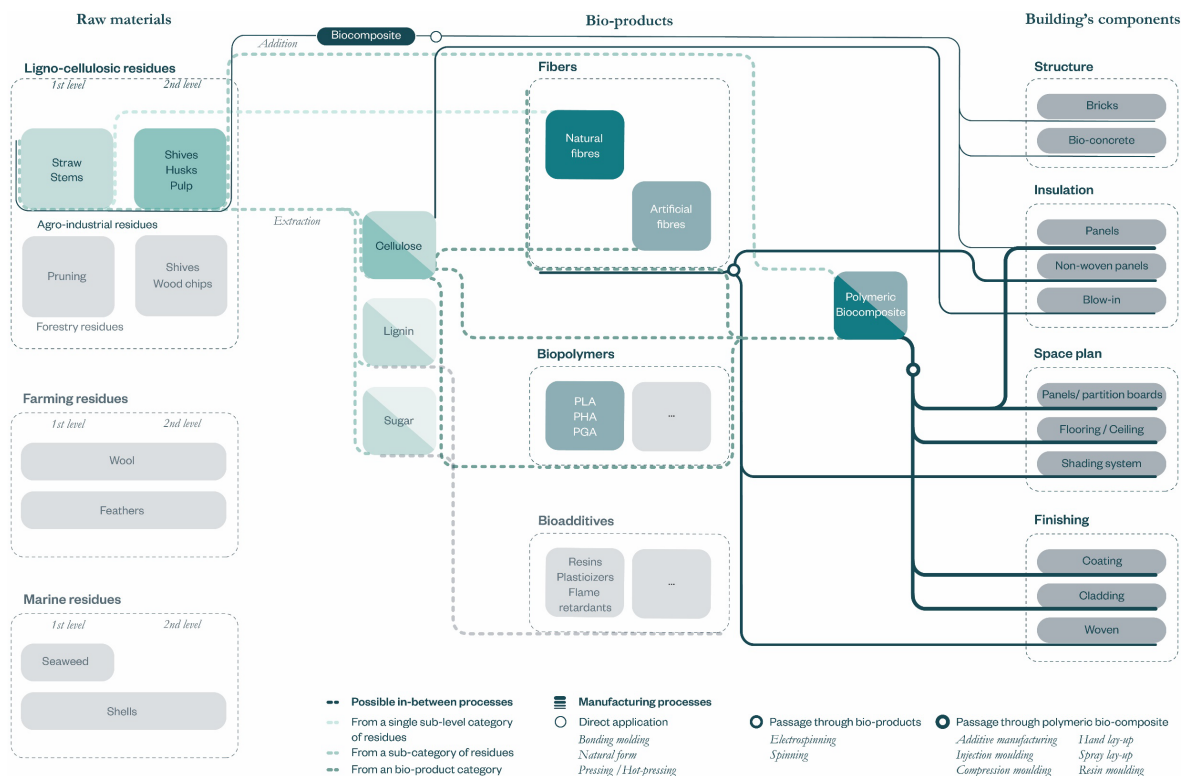


Fig. 1. Comprehensive framework to visualize processes for manufacturing bio-residues to construction products.

Among the others, lignocellulosic biomass stands out for its possible applications in the construction sector due to its abundance as a readily available resource worldwide, especially when sourced from local crops and, more in general, from the agro-industrial sector.

To obtain any building bio-component, lignocellulosic biomass can be differently manufactured. Indeed, bio-products are different depending on the amount and typology of manufacturing processes they need to go through, and their respective involved technologies, either established or experimental. In this regard, it is crucial to note that the final embodied carbon of any bio-component might depend on the number of passages the biomaterials they're made of need to come through to be finally incorporated into the building component. Conversely, bio-manufacturing

processes differ depending on the type of bio-source they start from.

The less energy-intensive manufacturing processes only consist of the direct transformation of agro-industrial residues into building products. Literature has already displayed a wide range of applications of many diverse agro-industrial residues, where typically a synthetic or natural binder is used [13]. These biocomposites are mainly suited for insulation [14-18] and potentially contribute to structural applications when combined with inorganic binders [19-20].

Alternatively, certain manufacturing processes necessitate additional extraction of intermediary bio-substances from raw biomaterials such as cellulose, lignin, and sugar. These substances play a crucial role in the production of various bio-products suitable for diverse and potentially more performative construction applications.

One of the significant categories of bio-products includes fibers, which can be either natural or artificially regenerated from cellulose. Additionally, bio-additives, as exemplified by the European REHAP project (2021), are increasingly widespread in the construction industry. Finally, polymeric biocomposite could serve as a more elaborated stage for utilizing both raw residues and bio-products, in combination with biopolymers. These last products are thus primarily used for building applications with shorter operational lifespans, suitable for space plan and finishing layers.

Indeed, Figure 1 focuses primarily on manufacturing technologies, listing and visually representing all encountered processes in the collection of experiences related to bio-manufacturing of bio-residues for construction applications. These technologies are a significant area for further research and action in the early-stage integration of construction production of building components. Consequently, the following paragraphs will specifically describe the highlighted bio-manufacturing processes based on their starting bio-source, emphasizing those showing promise in terms of innovation and potential industrial scalability.

3 Towards bio-manufacturing processes of agro-industrial residues

While the "fastest" applications involve the direct transformation of fibrous agricultural materials into building products (1), other manufacturing processes start from additional bio-products, like cellulose (2), and polymeric biocomposite (3) (Fig. 2).



Fig. 2. From left to right, fibrous agricultural materials, cellulose fibers, polymeric biocomposite.

3.1 Fibrous agricultural materials

Fibrous agricultural residues such as those derived from flax, hemp, cotton, cork, rice, etc. are commonly suitable for direct use in thermal and acoustical applications. This is due to their intrinsic characteristics, including high porosity and low thermal conductivity [21]. Indeed, the utilization of agricultural waste for building insulation products constitutes a significant scientific trend [22-23].

In this regard, [23] conducted a systematic review of thermal insulations made of biomasses, including agricultural residues, with specific attention to manufacturing methods. The prevalent methods outlined involve direct applications that integrate these residues while partially maintaining their morphological characteristics, thus preserving their favorable thermal and acoustical properties.

One of the most direct and cost-effective methods entails molding the biomass in its natural state, whether raw or packaged. This approach, commonly employed in rural construction, is well-suited for specific types of residues, like straw. However, it lacks durability, fireproofing, and mechanical strength.

Other types of agricultural residues may require additional processing, such as cutting, grinding, or mixing with other biomasses, to enhance their material properties, such as strength and fire resistance. Typically, if no binder is added, the material needs to be compressed under high pressure using manufacturing methods such as either "pressing molding" or "hot-pressing molding," which differ in terms of temperature used while processing. Conversely, if at least one binder, whether bio-based or artificial, is incorporated, the manufacturing technique is referred to as "bonding molding" [23].

Fibrous agricultural materials can also be combined with inorganic binders to produce biocomposite structural building products, such as bio-concrete, bio-bricks, or bio-aggregates.

Several start-ups and innovative enterprises, such as RiceHouse (<https://www.ricehouse.it/>), Ecological Building System (<https://www.ecologicalbuildingsystems.com/>), Strawcture (<https://strawcture.com/>), and ProSuber (<https://www.prosuber.com/>), have already implemented compression manufacturing techniques for producing both rigid and semi-rigid insulating panels. However, it is worth noting that the higher density and consequent lower porosity resulting from the compression may diminish the thermal insulation properties of the material. "Bonding molding" might then represent an alternative, but still, despite its potential to yield desirable mechanical and thermal properties [23], it requires longer production time, posing challenges for industrial-scale production.

3.2 Cellulose-based products

As above mentioned, cellulose is a primary intermediate that can be extracted from any lignocellulosic residue, each with different concentrations.

Methods of extraction are different: there are chemical, biological/enzymatic, and mechanical methods, such as steam explosion [24], that represent a less impactful process.

Thanks to its physical/chemical characteristics, cellulose is suitable for insulation purposes. In the construction sector, blow-in cellulose insulation technology is frequently employed to fill enclosed walls or attics. This method has been recognized to be both environmentally friendly and cost-effective, leading to widespread adoption within the industry (e.g. GreenFiber, Isocell, Applegate, Insulmax, etc.).

Nowadays, research is shifting to innovative methods to extract artificially regenerated nanofibers from cellulose. In this regard, electrospinning is raising attention, as it might enable the production of non-woven fabric [25]. Even though still largely

experimental, research is currently investing to possibly adopt this technology in the construction sector (e.g. ABC Department of Politecnico di Milano “GREENTEX” project: <https://tinyurl.com/GREENTEX>), demonstrating its foreseen potential for the production of non-woven fiber panels suitable for different buildings’ applications, such as acoustic insulating panels.

3.3 Polymeric biocomposite

The investigation into agricultural residues and fibers has been significantly driven by their potential as bio-reinforcements within advanced polymeric composite for various sectors, including construction.

A biocomposite material comprises a matrix material, which is either a bio-based or synthetic polymer [26], along with, as a reinforcement, natural fibers, extracted either from bast (flax, hemp, kenaf, nettle, etc.) from seed, (cotton, rice, etc.), or from leaf (banana, sisal, etc.).

In this context, one of the most promising and exceptional investigated biopolymers is PLA, as it can generate a fully bio-based biocomposite. Indeed, it is produced from the conversion of sugars derived from natural and renewable sources, which makes it biodegradable and fully sustainable.

Both literature [27-29], and the industry document many different processes for manufacturing polymeric biocomposite. Some of them, as outlined by [29], are widely diffused and potentially effective for industrial applications, including injection molding (e.g. Arburg), extrusion, and compression molding. Alternatively, methods like hand layup and spray layup are common but better suited for experimental scales. Meanwhile, technologies such as resin transfer molding and vacuum infusion are currently still time and cost-intensive.

Among the others, additive manufacturing, especially 3D printing technology, is progressively gaining attention for its potential in industrial scalability through digital fabrication. Additive manufacturing for construction purposes encompasses both experimental building applications, such as insulation and paneling, primarily at low Technology Readiness Levels (TRL) [30-31], to the utilization of 3D printer blends already existing in the market, compatible with large-scale 3D printing machines. However, currently, the most utilized bio-based blends for large-scale 3D printing in the construction sector are based on the utilization as a binder of inorganic materials, such as clay or earth.

Even though polymeric biocomposite materials display good mechanical properties, they still lack durability compared to more traditional solutions, and this limits their current application in construction to building systems with a short operational life, such as coating, finishing, paneling, etc.

Indeed, these materials are still in their infancy. Future developments and research though might improve biopolymers’ performances and durability, with the disruptive potential to transform conventional design and manufacturing methods [32].

4 Conclusions

This paper aimed to collect and systemize both experimental and established processes for manufacturing bio-based building components from bio-residues into a sole comprehensive visual overview. By doing so, it provides insights into the development and possible impact of each method, from established techniques like pressing molding to innovative processes such as electrospinning and additive manufacturing, offering promise for significant technological advancements in manufacturing.

However, the research is confined to categorizing and explaining single manufacturing processes based on their primary sources. This preliminary framework in the complex field of bio-manufacturing necessitates a further systematic analysis of case studies to develop an operative technological roadmap.

Despite this limitation, the outlined framework contributes to delineating future research directions.

A critical issue in bio-manufacturing is the industrial scalability of production. To evaluate the economic feasibility of using agro-industrial residues for building materials, further research must not only assess production technology scalability but also factors such as feedstock availability, impacted by cultivation seasonality and residue characteristics. Additionally, integrating supply chains poses challenges, such as the lack of crop and post-harvest management, mechanization chains, and territorial infrastructure. Even established bio-based building components, like hempcrete, face obstacles to wider market adoption in ensuring an adequate supply of industrial cultivation for construction demand.

The lack of economic investment at the supply chain level could stem from the experimental stage of using these materials in construction. In fact, another significant challenge is the technical feasibility and standardization of bio-products for building applications. Bio-products often necessitate additives or binders to meet required building standards, such as durability, fire resistance, or mechanical strength, that might hinder their potential secondary reuse.

In general, more complex processes and products’ composition might be able to provide building materials comparable to traditional ones, but often at the expense of significant energy consumption and limited materials reversibility and separability. In this regard, further research might focus on the energy assessment of specific building components, either made of bio-based materials, traditional materials, or recycled ones, utilizing Life Cycle Assessment analysis for comprehensive evaluation.

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