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BIO-RESIDUES FOR THE INSULATION OF BUILDING FAÇADES: A CLASSIFICATION OF EXPERIENCES

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ABSTRACT

Due to the significant contribution of the construction sector to the European (and global) energy consumption and to general population growth, studies are currently focusing on alternative ways to renovate our future cities and to build energy efficient buildings. As first mediator between outdoor and indoor environment, the element of façade becomes central, while bio-materials gain attention due to their ability to store carbon over their growth. Bio-residues, in particular, might prove the same environmental benefits given by bio-materials while avoiding additional land consumption for their production.

Even though many studies have been already carried out and a few products are already in the market, a clear classification of bio-residues is not available yet, and information come scattered and fragmented.

For this reason, this paper has the aim to provide clarity by operating an extensive work of literature review on the topic and, based on that, by defining macro-categories of bio-residues.

Finally, the paper illuminates current challenges, identifies trends, and assesses future opportunities for bio-residue applications in construction, while raising awareness about the intricacies of the topic, which relate to themes such as durability, land consumption, and circular construction.

Keywords: Bio-residues, Environment-conscious construction materials, Façade insulation.

INTRODUCTION

The construction sector is responsible for 36% of CO2 emissions [1] and stands as a significant contributor to European energy consumption. Over the last few decades, numerous European strategies and local regulations for climate mitigation (The Energy Performance of Buildings Directive of 2010, the Paris Agreement of 2015, and the European Green Deal of 2019) have been directed towards specific objectives, with buildings emerging as a central focus [2]

Undoubtedly, this subject is crucial. The European Commission has reported that 75% of the European building stock is energy-inefficient, despite 80–90% of it will still be in operation by 2050 [2], [3].

Hence, to align with the climate mitigation objectives set by the European Union for the year 2050, it becomes central that approximately 97% of the existing European building stock undergo retrofitting measures to enhance energy efficiency [5].

As primary subsystem through which prevailing external conditions can be influenced and regulated to meet the comfort requirements of the user inside the building [6], the element of building skin has a crucial role in enabling energy savings through the decrease of energy losses for heating-cooling purposes.

Indeed, its improvements are arguably one of the most effective interventions [7], contributing up to 50% of total building consumption [8], with a low pay-back time. [9]

Among the others, the use of high quantities of thermal insulation represents a common and efficient practice to meet high energy-efficiency standards [10], [11] and the practice is also underscored by the EU Directive 2018/844 and by many national building codes [12]

However, the production of insulation materials, reliant on fossil fuel-intensive processes [13], are frequently overlooked and questions regarding the risks of over-specifying the insulation levels have been emerging [14]

Recent studies highlight that while enhancing the thermal performance of buildings undoubtedly reduces operational energy, the embodied impacts stemming from the production and installation of new components can contribute significantly, ranging from 10% to as much as 80% of the total emissions over a building's lifecycle [15]. On the flip side, a judicious choice of building materials has the potential to decrease non-operational primary energy consumption by up to 40% [16].

Consequently, as buildings increasingly prioritize energy efficiency [17] attention has shifted from the operational life of buildings to the materials used, by addressing embodied carbon rather than solely concentrating on operational energy [13], [16]

This tendency is resulting in a growing interest in the use of low-carbon bio-based materials, as a possible key strategy for climate mitigation [19]-[20]

Bio-based materials offer various benefits: they are renewable, often locally available and during the plant's growth carbon is sequestered [21].

This means that when bio-based construction materials are used as buildings' components, their lifespan is usually defined by the building's service life and results in a temporary reduction of the CO2 concentration in the atmosphere. Moreover, it has been shown that the incorporation of a larger share of bio-materials can reduce the embodied energy in a building by about 20% [22].

Bio-based construction materials, however, do not only vary in their structural and thermal properties but also in processing and, more important, their availability of raw materials introduces questions regarding land use, sparking critical issues that demand attention [23].

Hence, relying on the intensified use of biomass for construction can only result in reduced Green House Gas emissions (GHG) if a sustainable forest management and sustainable agriculture are guaranteed [23].

Materials originated from secondary bio-sources or biowaste streams enter thus the discussion, as possible solutions avoiding land consumption and as a method to recover large quantities of secondary materials flows and to produce different composites while generating circular processes [24].

Within the construction industry, circular bio-based building materials can be referred to as materials wholly or partly derived from renewable biological origins, or by-products and biowaste of plant and/or animal biomass that can be used as raw building materials and decorating items in construction, in their original forms or after being reprocessed [25].

Despite circular bio-based building materials have been already discussed in the literature [25], a clear work of systemization and categorization is still lacking, making it challenging to obtain a comprehensive understanding of the sector's state-of-the-art.

Therefore this paper has the objective to provide a comprehensive work of systemization and classification of experiences otherwise fragmented and scattered by means of a comprehensive literature review about bio-residues applications as insulating materials on building envelopes in the European landscape.

By doing so, it highlights the pros and cons of circular bio-based building materials and illuminates current challenges and trends within the sector.

Moreover, this paper raises awareness over the concept of circular bio-based economy [26], as complementary combination of two different construction approaches, bio-economy and circular economy, that together might produce a beneficial effect for both the building and the environment.

MATERIAL AND METHODOLOGY

Between January and February 2024, the author conducted a bibliographic search to identify applications of bio-residues on the building envelope to reduce its energy consumption.

The review considered publications in peer-reviewed literature and was complemented with a review of grey literature, comprising data collection and practice review.

The literature review combined first a four-step standard literature review methodology, as proposed by [27], and a second step of snowballing [28], [29], with the aim to identify missed articles the author was aware of.

Data were collected from Scopus with the aim to detect thermal insulating materials and composites realized using respectively totally or partially recycled materials whose development is only at an early stage or whose sales are still limited. To this purpose, the author used a search string that consisted of two main elements, including for each variants of commonly used terms:

1) Biomaterial

2) Façade

The research was secondly limited to the Engineering sector and to those papers reporting applications of bio-residues as specifically insulating components for the building envelope.

Further screening was thus operated by replying to the research question:

Which bio-residues have been already applied on the building envelope as insulating materials to reduce the energy consumption of buildings?

Is there any detectable trend among bio-residues applications as insulating materials in construction?

Which are the most promising materials and related strategies among the ones selected?

By doing so, the author identified an initial list of 409 papers. After checking the articles' titles, abstracts and conclusions for relevance, 40 papers remained treating specifically bio-residues applications as insulating materials, on top of which the author added 8 papers by means of a process of snowballing.

Parallel to the literature review, it was conducted practice research to get an understanding of the European market trends and to define the current marketability of bio-residues, defining triggers and obstacles of their commercialization.

RESULTS

The interest over bio-materials application in construction in view of climate mitigation of the construction sector grew exponentially over last decade, probably triggered by many national and international norms pushing towards the definition of more sustainable construction sector.

Indeed, the number of papers on this topic has experienced a significant increase, as the count rose from just 31 publications in 2019 to 107 in 2023. By February 2024, there are already 25 publications on record.

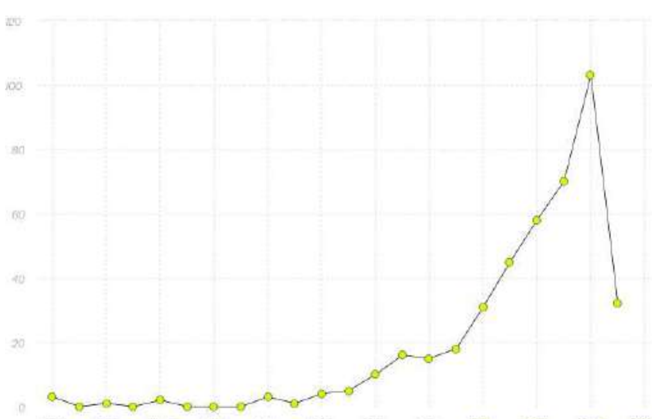

Fig. 01: Quantity of papers found on the topic during the last 20 years.

The reported papers identify bio-materials applications by means of either extensive review [9][30][24], [25], [31]–[34], or of thermal characterization of specific materials, or by widening the topic by looking at the ability of bio-materials to reduce GHG emissions compared to traditional solutions [15], [16], [35]–[39].

Among biomaterials, bio-residues raise specific attention, as opportunities to introduce re-use and recycling practices in the construction sector, while operating on the embodied carbon and on the energy consumption of the building.

According to the conducted literature review, bio-residues applied in construction as thermal insulation can be categorized based on their origin, determining the following categories:

1) Agriculture bio-residues

2) Forestry bio-residues

3) Farming bio-residues

To these initial four categories, the author decided to add two additional categories based on the typology and relevance of the research findings.

4) Post-production/post-consumer residues indirectly coming from forestry and agriculture, such as newspapers/cardboards [40] and textile wastes [41], [42], [43].

5) Combination of different residues, collecting just a few experiences integrating bio-residues to other types of waste to obtain a circular insulating panel to reduce buildings' energy consumption.

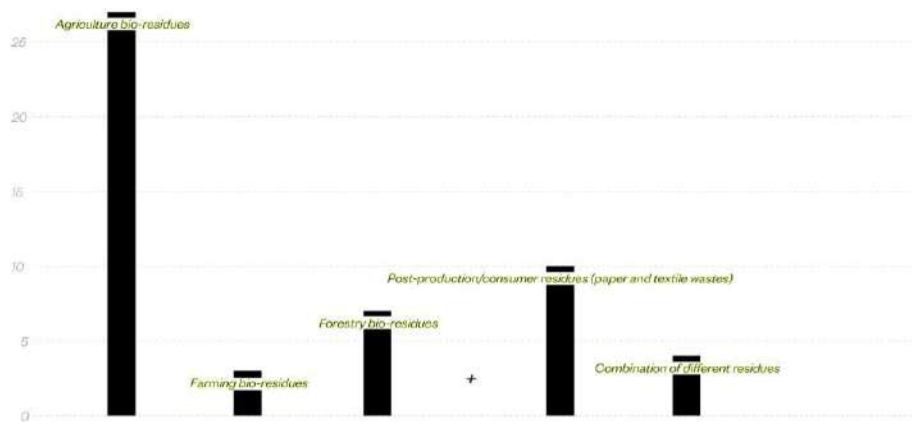

Fig. 02: Number of papers per category

A. Agriculture bio-Residues

Agricultural wastes are a readily available residue coming from local crops and they represent an infinite resource all around the world.

Re-using or recycling agro-industrial residues might be a winning strategy both to generate economic value through the development of innovative practices and products and to reduce possible environmental hazards and economic challenges related to its disposal into landfills, causing pollution of the air and water [46].

Materials like wheat straw, wheat stalks [47], [48], [49],[50] hemp stalks [51], rice straw [52], [53], [54], rice husks [55], corn cob [56], bagasse [57], sunflower stalks [58], olive-trees pruning [59], flax shives [60], cotton fibers and stalks [43], oil palm fibers [33], date palm fibers [61],[62],[63] tomato stems [64], pineapple leaves [9], banana peels [65], coconut husks [66], pomegranate peel [67] might enhance circular processes, while potentially reducing impacts due to transportation, as they'd be recycled in the proximities of the production area.

Among the others, wheat straw and hemp have been largely investigated since around a decade by now [68], [69],[70] due to their materials properties and to their availability all around Europe. While most of the read papers report the application of wheat straw as main ingredient of several bio-composite insulation panels or filling [23], [68], hemp shives emerge for the production of hempcrete for buildings' thermal insulation [71], [55], [72]–[75], or for the production of hemp wool.

Both plants have been identified to have great potential in view of large-scale construction and renovation due to their high-storage potential as fast-growing materials.

However, while using wheat straw for construction should not change the amount of land used or the intensity of crop production, hemp might not be sufficiently available across the world [76].

Literature documents also a growing interest on rice residues.

Rice is the most productive crop in the world [77], [78] and its recovery might be crucial especially in developing countries like East and Southeast Asia, currently responsible for the 90% of global rice production, that are facing decades of exponential demographic and urban growth.

Studies have already shown its potential as building component for insulation in many ways [79], [54], [53] and differently from many other bio-residues applications in construction, bio-products coming from rice residues have been already commercialized. In Europe, the activity of *RiceHouse*, an Italian company developing new building materials, is quite relevant due to its ability to connect with the main rice producers of the country to recover wastes for further remanufacturing (*https://www.ricehouse.it/*) .

Finally, residues coming from crops such as sunflowers, rapeseed and oil palm are gaining attention in Europe, due to new policies for biomass production that are acting as a trigger for changing crops destinations, and that might potentially generate additional waste as leaves and fibers [9], [32].

B. Forestry Bio-Residues

The European wood processing industry currently generates more than 50 million m3 of wood wastes [80], [81] mainly in the form of wood chips and shavings [82].

Quantitative considerations over this type of bio-residues might suggest great potential for future applications in construction and many studies documented diverse types of bio-insulating composite panels adopting wood residues alone [83], [82] or in combination with other materials [84],[85].

Recently, cork has raised particular attention in the academic sector. Indeed, cork was discovered to be hydrophobic and to have a low Thermal Conductivity (0.046 W m−1 K−1) [32].

This material, with a global production of approximately 201,428 tons per year [31], is mostly used as main material of insulating bio-composites. Papers document its application with cement [86], with giant reed [87], with rice husk, as base of a bio-polymer [88], with gypsum [89], [90].

However, even though cork insulating panels are already available in the market, its production is low and confined to a few specific regions of the world and only 4% of it can be supplied for building insulation [30], which is not enough for future extensive applications in the building sector.

C. Farming Bio-Residues

Farming bio-residues derive from animals and when talking of bio-insulation they mainly comprise feather and sheep wool. The number of papers treating these materials is way less compared to the ones concerning agro-residues.

However, on the market sheep wool is already available in the form of 100% sheep wool soft mats, rigid or semi-rigid panels made of sheep wool and polyester fibers, and loose-fill fibers [32]. They're presence on the market is strictly connected to the local availability of raw material and thus on the local presence of sheep farming. The author found many industrial producers of wool insulation in Ireland and in the United Kingdom, (*SheepWool insulation*, (*https://www.sheepwoolinsulation.com/*; *Chimney Sheep, https://chimneysheep.co.uk; Thermafleece*, *https://thermafleece.com/*), but they're also a few scattedered experiences also in Austria, (*Lehner wool, https://www.isolena.com/de/*), in Slovenia, (*Soven*, *https://www.soven.si/*) and in Italy (*Pagano, https://www.paganocom.it*).

Lately the interest over feather construction applications has been growing due to the high global consumption of poultry [91] and to the consequent need to enhance feather reuse and recycling strategies, to finally avoid burial in landfills and incineration. Indeed, sustainable alternative applications of them could reduce environmental issues and open up new opportunities for the expanding farming industry [92].

However, these materials present many problems of durability and degradation, including ageing, weathering, mould and algae growth, decay, waterlogging, and insect infestation [93], that need to be addressed for further development.

D. Post-Production/Post-Consumer Bio-Residues

This category collects those bio-insulating panels integrating post-production/post-consumer wastes coming from the textile and paper industry. The topic is actually central, as the annual post-production waste generation is expected to increase by 70%, from 2.01 billion tons in 2016 to 2.2 billion tons and 3.40 billion tons in 2025 and 2050, respectively [94]–[96].

The Waste Framework Directive, which imposes the mandatory separate collection of textile waste in all Member States by 2025, preventing landfill (currently 57% of the total waste), incineration (25%), or export of textile wastes to non-European countries [97], intensifies the urgency of addressing the theme.

Literature reports many experiences regarding the re-integration of textile flows as building insulating materials [38], [99]–[105] and a few products are already available on the market. *VRK isolatie*, for instance, is a Dutch Company that produces different types of insulating panels made of recycled textiles, such as denim jeans and sweaters (*https://materialdistrict.com/material/metisse-recycled-textile-insulation/*). Nevertheless, post-consumer waste comprises a mixture of natural/synthetic fibers that make materials' separation still challenging, hindering the extensive reuse of obsolete textile.

The only paper-based product officially registered as a building material is cellulose fiber insulation, known as one of the most sustainable insulative materials [106].

Experimental experiences though document the use of paper and cardboard as part of a composite [107], [108], [109], [110].

A promising path, still facing challenges again related to durability and resistance to moisture and bacteria.

E. Combination of Different Residues

Studies regarding the preparation of insulating panels by combining bio-residues and other types of wastes are also growing. Even if they represent a small percentage of papers, compared to those treating bio-residues alone or with other types of binder, the author decided to mention them, as it is believed they might be crucial to enhance circular construction strategies.

More specifically, ref. [61] proposes an experimental study on the manufacturing of composite panels based on date palm leaflets and expanded polystyrene wastes. Ref. [111] prepared building insulation foam materials by combining blast furnace slag and waste photovoltaic glass powder and rice husk ash wastes. Ref. [112] added glass fibers to the organic substrate of mycelium and agro-industrial residue to reduce flammability.

Currently, these types of applications are not commercially available, and their realization depends on various factors, including the availability of both bio-residues and additional wastes, which may vary in terms of material properties. Nevertheless, this construction method is innovative as it integrates bio-economy and circular economy in a comprehensive and cohesive manner.

DISCUSSION AND CONCLUSION

The paper in particular displayed a systemization of past contributions in the field of bio-residues applications as façade insulating materials and proposed their classification in view of the future development of bio-retrofitting strategies of the European building stock.

This research enters a period of progressive societal awareness over the theme of climate change and environmental impact and its topic is quite relevant.

Given the above, a few consideration can be finally draw. When thinking of a complete shift towards bio-materials application in construction, bio-residues represent the solution to avoid environmental impacts associated to land consumption and to changing crops cultivation, that still might affect biodiversity. They have been generally proved to have good thermal performances, (and this is crucial for energy façade retrofitting) and to guarantee better outcomes for the environment and human health in comparison to synthetic ones.

In this regard, circular economy enters the discussion and it leads to several different considerations.

At the scale of material, the re-integration of bio-residues of different types would close loops of chains of production currently linear. Moreover, by combining different typologies of residues it might be even possible to reduce the large amount of construction waste currently generated by the building sector, in view of future circular strategies of retrofitting. Among approaches to mitigate climate change and other the environmental impacts of the construction industry, transforming the built environment from a linear to a circular economy model is a determinant strategy, even more if combined to a bio-economy model. Hence, it's also crucial to grant durability and reuse of bio-components. This mindset might be even more relevant when thinking to third world countries, like China and India for instance, with their impressive dimensions and their growing demography.

When looking closer to bio-residues applications as façade insulating materials, literature reports the environmental relevance of both using fast-growing materials and of locally available materials.

Indeed, fast-growing materials, such as cereals, hemp or corn for instance, are able to recover the embodied carbon associated with their building application just in a few years.

Using locally available bio-residues instead might avoid energy wastes related to transport, while enhancing local economy.

However, when talking of façade applications, requirements like fire resistance, mechanical resistance and resistance to moisture and bacteria need to be addressed. Past studies report several examples of problems of using bio-wastes, mostly related to durability [113]–[118].

With the aforementioned information in mind, it is thus possible to conclude that, even though bio-residues offer great potential as bio-insulating materials components for facades, their full potential remains largely untapped and still an opportunity. Nevertheless, their diffusion may increase in the coming years due to recent European initiatives promoting their use [119] Green Deal 2019), to consequent public funding and raising interest of private companies. A great opportunity for further developments in view of a more sustainable built environment.

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