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REVIEW ARTICLE

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Towards net-zero with fast-growing biobased construction materials

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ABSTRACT
This review aims to bridge knowledge gaps in the use of biobased building materials in construction by critically analysing available scientific literature. We seek to inform stakeholders, promote sustainable practices, identify adoption barriers and highlight the opportunities provided by fast-growing biobased materials to achieve net-zero built environments. Through this review, we identify bamboo, hemp, straw, and mycelia as critical materials with substantial potential for carbon capture and storage. To achieve the net-zero built environment it will be necessary to create intersectoral synergies, specially between agricultural, forestry and construction. Our results indicate that the broad adoption of biobased materials is hindered by concerns related to durability, fire safety, cost, and standardized construction regulations. Nevertheless, these materials offer plenty of opportunities to valorize their local character and associated environmental services like their carbon storage potential. Thus, providing the foundation for the development of local regenerative intersectoral value chains.

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1. Introduction

Throughout history, humanity has faced environmental constraints at the local and regional levels (Diamond 2005), and it has had to adapt to new climate and resource scarcity conditions. True innovation arguably arises from adversity. *Homo sapiens* have adapted to the cold polar temperatures of the North Pole, to the tropical regions of Indonesia and to the high plateau of the Andes in less than 10,000 years, which is a considerably short period in terms of the geological timeline (Harari 2015). Some scholars, such as Condorcet, a French philosopher and mathematician, have advocated for radical democracy, relying on the genius of humankind to overcome catastrophes (Avery 2014). Some have argued that Condorcet was proven right with the arrival of the industrial revolution and the mechanization of agricultural practices. In the 1970s, Boserup, a Danish economist, conceptualized this notion by promoting the idea that humans need adversity to force them to make changes (Boserup 1981). It is nearly inconceivable to imagine a more significant challenge than that posed by climate change in these times. If we do not maintain the global increase in temperatures to a value below 1.5°C, the impacts of the climate crisis on human societies will likely be massive and last for centuries to come; these impacts may also disrupt, if not destroy, our social and economic models (Lenton et al. 2019).

The built environment is largely responsible for this situation, as it accounts for approximately 40% of the annual anthropogenic greenhouse gas (GHG) emissions (IPCC 2018). Half of these emissions are related to building operation, and the other half are related to building construction (Bajželj et al. 2013). Despite the many efforts that have been made, the emissions associated with construction activities have not fundamentally changed over the last ~50 years, although great progress has been made in reducing operational emissions (Röck et al. 2020). The construction industry is facing two pressures: rapid urbanization, with the

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equivalent of one New York City being developed every month (Swilling et al. 2018), and steep decarbonization of the materials used in this process. The Intergovernmental Panel for Climate Change (IPCC) recommends reducing GHG emissions by 50% in the next ten years and reaching carbon neutrality by 2040 (IPCC 2018). Therefore, it is imperative to start implementing effective solutions immediately. We must not delay and rely on the uncertain availability of technologies in coming decades, as it will be too late. Unfortunately, the existing solutions are not feasible because of they are not sufficiently scalable in the short term. For instance, implementing only carbon capture and storage, a primary solution promoted by the cement and steel industries, is not feasible because this technology cannot be applied at the necessary pace. Even the 2020 annual report from the Carbon Capture and Storage Institute shows that a 14,000% increase in storage capacity is necessary in the next 25 years, while in reality, an observed reduction of 30% has been observed in the past ten years (Page et al. 2020). It is widely acknowledged that it is more difficult for the building materials industry to decarbonize than the energy production or transportation industries (Davis et al. 2018). Thus, a pressing question arises: how can we renovate the existing building stock to reduce operational emissions, double the stock to accommodate continuous urbanization, and reach net-zero before 2050?

Natural building materials that can be derived from renewable biological sources, including plant and animal biomass and/or their byproducts, can serve as building materials, either in their original form or after reprocessing (Le et al. 2023). Moreover, these materials can be considered local solutions for temporarily storing carbon (Gauzin-Müller and Vissac 2021; Carcassi et al. 2022). These materials can drastically reduce emissions (Matthews et al. 2022) and shift them by ~60 years, thereby greatly contributing to the transition. To date, natural and biobased materials are not sufficiently used in the construction sector, mainly because they rely on expensive and time-consuming processing techniques. Moreover, it appears that we are shifting away from 'one size fits all' solutions, such as concrete, and moving towards singular material solutions, such as timber, that address multiple issues by contributing to afforestation, biodiversity protection, and construction. However, aiming to switch from concrete to timber can have major drawbacks (Pomponi et al. 2020), such as deforestation and land-use competition. The availability of biomass is not secured if we consider the growth rates of trees and urbanization demand for the next 20 years. However, fast-growing natural building materials, such as bamboo, hemp and straw, can meet this demand. While these materials are present in the building materials market in some regions (e.g. bamboo in parts of Asia and Latin America, hemp-based panels and insulation in Europe, and straw bale construction in North America), their market share remains very limited compared to conventional materials such as concrete, steel, and fired bricks. Barriers such as lack of standardized codes, industrial-scale processing infrastructure, and market acceptance have restricted their widespread adoption' (Göswein et al. 2022). Addressing the latent gaps in our understanding is crucial for fully harnessing the potential of biobased building materials (Göswein et al. 2021). There is a clear lack of comprehensive studies on long-term durability across diverse climate conditions. This research area could significantly inform the design and adoption of these materials. Furthermore, the aesthetic and cultural dimensions of biobased materials remain poorly quantified, limiting our understanding of consumer acceptance. Equally underexplored are the economics of large-scale production and distribution. There is a scant body of research on the feasibility of retrofitting existing infrastructure, which is an urgent need given the rapid pace of urbanization. Finally, while regulatory frameworks might act as powerful levers, specific insights into what forms of incentives or mandates can accelerate adoption are largely missing. Addressing these gaps is not only an academic exercise but also a critical step in making informed choices amid climate urgency, in navigating the challenges of urbanization, and in substantially influencing policy and commercial ventures. Filling these knowledge gaps is needed for multiple reasons. First, this research can provide actionable information for policy-makers and industry leaders to make informed decisions that align with sustainability and climate goals. Second, understanding these underexplored areas can allow for the scaling up of the adoption of biobased materials, making them a viable option for mass construction and renovation projects. This research is vital for meeting the stringent carbon budgets set for the building sector. In terms of global efforts, meeting these requirements is essential for mitigating climate change and adapting to its already manifested consequences.

The aim of this paper was to bridge existing knowledge gaps surrounding the use of biobased building materials in construction by synthesizing the available literature. The purposes of this research were to inform stakeholders, promote effective and sustainable practices, underscore the potential applications and inherent benefits of employing fast-growing biobased materials, and identify the key barriers that must be overcome regarding the uptake of these building materials. Thus, we employed a rigorous search strategy, and databases such as PubMed, Google Scholar, and Scopus were queried using a predetermined set of keywords and Boolean operators. The data extracted from these papers were subjected to quality assessment, followed by thematic categorization. In our paper, we elucidated the pivotal contributions of biobased building materials to climate change mitigation through their inherent ability to capture and store carbon. We highlighted their viability for creating durable, long-lasting structures while enhancing cultural connections to local environments. However, we recognized several obstacles to their broad implementation, such as economic limitations, regulatory challenges, and a significant gap in specialized training across the construction industry. We discovered the need for a collaborative approach involving updates to regulatory frameworks, the introduction of economic incentives, and broad educational efforts to fully leverage the benefits. We argued that we are at a crucial turning point, and we emphasized the need for unified action to utilize biobased materials as the key components of carbon-neutral buildings.

2. A diverse range of biobased building solutions

2.1. Selecting the right materials according to the bioclimate and bioavailability

To select natural building materials, one should consider the properties of their various constituents to finely tune them according to the local climate and availability of resources. Comfort, labour practices, and social impacts are critical to scale-up implementation. In addition, these measures help to ensure that the development of these materials is self-sufficient, supports local craftsmanship, and promotes fair labour conditions. Sonebi et al. (2022) observed that the adoption of local and sustainable building materials is crucial for the ecological and economic sustainability of construction projects in the Middle East and North Africa (MENA) region, highlighting a shift towards materials that align with the local climate and environmental conditions (Sonebi et al. 2022).

To sufficiently understand their potential application and synergy, we propose the following categorization of bio-based building materials and systems: plant-based materials such as algae and lignocellulosic fibres, animal-derived products like wool, fungal-based materials such as mycelium, and living microorganisms capable of biomineralization, including *Sporosarcina pasteurii* and *Bacillus subtilis*. These materials can be combined in different ways to create construction products that serve as aggregates, binders, reinforcements, or additives.

Table 1 provides a structured overview of natural building materials, categorizing them according to their origin and functional role within construction applications. The table highlights the diversity of compositions and processing methods used to achieve mechanical strength, durability, thermal insulation, and environmental resilience. Some materials, such as rammed earth and cob, rely on the natural composition of soil, where clay acts as an inherent binder, whereas others, such as hempcrete, can incorporate traditional natural binders to enhance insulation and workability. The use of additives such as volcanic ash in Roman concrete or calcium lactate in bacterial concrete showcases the long-standing practice of optimizing material durability through natural or engineered means. Similarly, mycelium-based composites leverage biological growth to form lightweight, self-binding materials, while innovations in green concrete explore alternative cement formulations to reduce carbon emissions.

In the context of natural building materials, it is imperative to consider the properties of their individual components, as these determine the material's suitability for specific environmental conditions and construction needs. Beyond technical considerations, the social and economic dimensions of these materials must also be acknowledged, with their successful implementation depending on labour practices, scalability, and the promotion of craftsmanship. This ensures that bio-based construction remains self-sufficient, supports local economies, and fosters fair labour conditions.

The classification presented in Table 1 underscores the adaptability of natural building materials, offering construction solutions that balance structural performance with environmental and social sustainability. This adaptability is not limited to bio-based resources; mineral binders such as gypsum and air lime have historically been used to enhance earthen techniques like rammed earth, which in many cases performed successfully for millennia without binder addition. Likewise, other earthen techniques, including cob and light clay,

Table 1. Natural building materials' categorization according to product origin and role in the final product/ performance characteristics.

Name		Aggregate	Binder	Other Additives
Roman Concrete		Crushed pottery and soil		Volcanic ash from Pozzuoli
Hempcrete		Hemp shives/ hurds	Lime	
Rammed Earth		Any crushed stone, sand and non-clay particles inherent in subsoil		Can be stabilized with natural binders or cement
Cob		Sand and non-clay particles inherent in subsoil	Clay inherent in subsoil	Vegetable fibre reinforcement
Light Clay		Sand and straw		
Bacterial Concrete		Sand	Limestone-producing bacteria	Calcium lactate
Mycelium Concrete		Agricultural waste	Mycelium tissue	
(Green) Concrete		Limestone aggregate and quartz sand	Magnesium oxychloride cement Alkali-activated cement calcium sulfoaluminate cement, etc.	

can be produced without binders, but they may also incorporate natural binders when required to improve durability, cohesion, or workability. The capacity to tailor both bio-based and mineral material compositions to specific climatic conditions, resource availability, and functional requirements enhances their feasibility for widespread implementation. Additionally, the integration of natural fibres in varying quantities enables greater material flexibility and improved insulation properties, as seen in initiatives developing formaldehyde-free binders for particle boards. Together, these approaches demonstrate a growing shift toward advanced, environmentally friendly, and health-conscious construction solutions. Through an informed selection of natural binders and fibres, designers and builders can contribute to circular economy principles, support local craftsmanship, and promote sustainable and regenerative construction practices.

2.2. Load-bearing construction systems

Depending on whether the final material bears load, a structural frame might be needed, potentially from a biobased source, such as timber or bamboo. Bamboo is an alternative nature-based structural material with great potential in the Global South (Zea Escamilla et al. 2019). After treatment, bamboo can be used in its raw cylindrical shape (bamboo poles) or in its engineered form (Zea Escamilla et al. 2018) (panels, columns and beams) (Sharma et al. 2014). Engineered bamboo has mechanical properties similar to those of cross laminated timber (Sharma et al. 2015; Li et al. 2018; Yang et al. 2020) and, it has been used in several demonstration projects worldwide (Taylor 2016), notably in Colombia (Takeuchi 2012; Luna and Takeuchi 2014). To date, a lack of standards for engineered bamboo has been the major barrier to its development. Nevertheless, a new International Organization for Standardization (ISO) standard for structural design with engineered bamboo is being developed by the Construction Task Force of the International Organization for Bamboo and Rattan (INBAR) (Liu et al. 2019). Furthermore, bamboo poles can be used in two types of construction systems: spatial trusses (Correal et al. ; Hong et al. 2020) and composite shear walls (Salzer et al. 2016; Zea Escamilla et al. 2018). Both systems use similar types of connections, the most common being the use of steel bolts and mortar grout to infill the first internodes of the connecting poles (Hong et al. 2019; Simi et al. 2022). This approach has been extensively tested and used in buildings (Zea Escamilla et al. 2019). The systems show remarkable performance when exposed to extreme lateral loads from winds and earthquakes (Salzer et al. 2017, 2018; Trujillo and Lopez 2020). The composite shear wall system is based on vernacular construction systems from Latin America. This system is the most researched and standardized, since at least six countries include bamboo shear wall systems in their building codes (Gatoo et al. 2014). Recently, a series of ISO standards dedicated to the grading (ISO 2018), testing (ISO 2019) and structural design of bamboo-based composite shear walls (ISO 2021) has been developed. 'Complementing these standardization efforts, the RILEM Technical Committee 322-MCB on *Mechanical Characterisation of Bamboo* has been established to advance international knowledge exchange and develop harmonized testing methodologies, thereby supporting the reliable adoption of bamboo as a mainstream structural material'.

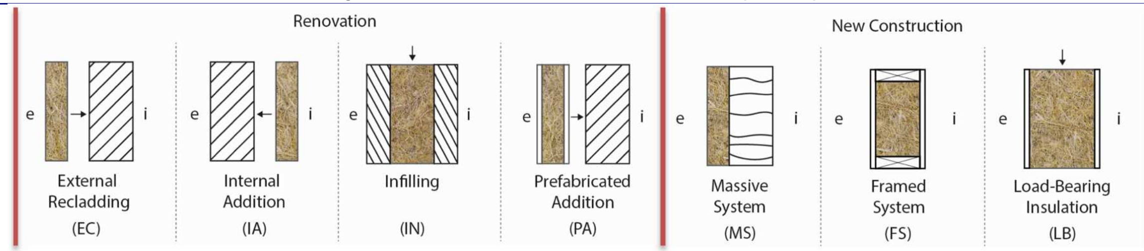
2.3. External thermal insulation and retrofit solutions

The three most common construction systems for external thermal insulation and retrofitting of walls are as follows: (1) an external thermal insulation composite system (ETICS), (2) a ventilated rainscreen façade (VRF), and (3) an additional face masonry layer (FML) wall with insulation used in retrofitting. A detailed description of these systems is presented in Table 2. An ETICS consists of insulation boards that are glued and attached via a dowel to the external wall and are coated with reinforced plaster (Churchill et al. 2021; Göswein et al. 2021). A ventilated façade has a continuous gap between the insulating layer and the cladding, which is open at both the bottom and the top (Carratt et al. 2020). The circulating air removes moisture by the stack effect. Options (1) and (2) are plastered façades. Adding a face masonry layer (option 3) allows for the creation of a brickwork façade. The additional layer creates a cavity in front of the original external wall, which can be filled with insulation material. All three systems contribute to the adaptation and mitigation of climate change effects and are compatible with biobased insulation materials. However, ETICS requires self-supporting boards, while the gaps or cavities in the other two systems can be filled with loose insulation material, such as straw. Notably, pressing the fibres increases their fire resistance (Blondin et al. 2020). Self-supporting boards can be made from plants, such as cork or oak bark (Cardoso et al. 2017; Zuluaga et al. 2022). These boards usually require a resin to harden the material and provide stiffness, which can be of natural or synthetic origin (Crosky et al. 2014). To produce insulating cork boards, cork granules can be compressed in a mould and subsequently expanded using steam, which causes the naturally occurring resin in the cork granules to reach the surface, thereby binding the granules (Gil 2009; Silvestre et al. 2016). In contrast, using synthetic resin, such as epoxy, or mineral binders, such as cement, increases the environmental footprint of the insulation material and prevents recycling of the material at the end of life (Densley Tingley et al. 2015). The loose material to be used in the box can be sourced from a wide range of biosources (Asdrubali et al. 2015), including plants and plant-like protists, such as hemp shives (Amziane et al. 2017) and wheat straw, or animal products, such as wool (Schiavoni et al. 2016).

2.4. Internal retrofit of historical buildings: thermal plaster

Historical buildings represent the image and history of a city during different periods. The European building stock consists of an estimated 160 million buildings, of which 14.3% are historic buildings that were built before 1919 and are under heritage protection (Popescu et al. 2012; Ascione et al. 2017). Currently, in south-western Europe, the high vacancy rate of city centres, due to the deterioration and lack of energy efficiency measures, reveals the urgent need for energy retrofitting (Claude et al. 2017). The hygrothermal refurbishment of old building envelopes is a challenge due to the specific behaviours of such systems. Conventional techniques for energy improvement consist of sealing the building envelope, which reduces air transfer and thus improves energy performance. This reduction in indoor air renewal impacts the internal humidity level in winter. This impact can lead to hygrothermal discomfort for occupants and the development of moulds that can degrade the building and affect the health of its inhabitants. Moreover, these solutions do not meet all the requirements, as they might affect the durability of the historical materials. Biobased solutions appear to be efficient, affordable, durable and healthy insulators for historical buildings (Claude et al. 2017b). Furthermore, to preserve the architectural value of the façade, internal insulation is often the preferred solution for this type of building (Corrêa et al. 2020). Furthermore, façades with interior insulation are relatively cold

Table 2. Performance and technical construction details considering various renovation and construction options per m^2.



Application	Description	Functions		Type of biomass	System thickness	Total weight	Biomass by weight	U value	GWP_{fossil}	Biogenic carbon	Reference
		Insulation	Structure		m	kg	%	W/(m²K)	kg CO_2 eq.	kg CO_2 eq.	
IA IN PA FS	Plant fibres	x		Diverse	0.19–0.22	10–16	85–100	0.24–1.00	3–14	(-31)–(-60)	(Ardente et al. 2008; Almeida et al. 2015; Schulte et al. 2021)
EC IA IN PA MS FS	Wood fibres	x		Wood	0.15–0.20	11–13	80–100	0.20–0.24	2–3	(-32)–(-59)	(Schulte et al. 2021)
EC PA MS	ETICS with insulating cork board	x		Cork	0.15–0.25	20–30	55–65	0.15–0.25	50–65	(-65)–(-75)	(Göswein et al. 2021; Zuluaga et al. 2022)
PA FS	Bamboo frame		x	Bamboo	0.12–0.30	35–43	5–20	0.10–0.20	27–53	(-6)–(-32)	(Zea Escamilla et al. 2018)
EC IA MS	Concrete-like blocks with fibres		x	Wood or plant fibres	0.20–0.60	202–285	10–23	0.125–0.20	3–116	(-76)–(-480)	(Pittau et al. 2018; Caldas et al. 2021)
PA FS	Timber frame with fossil-fuel derived insulation	x	x	Wood	0.30–0.39	45–76	21–45	0.125–0.20	57–420	(-61)–(-265)	(Spitz et al. 2012; Fouquet et al. 2015; Pittau et al. 2018; Cascione et al. 2022)
PA FS	Timber frame with straw	x	x	Wood, straw	0.36–0.50	82–196	32–100	0.15–0.26	16–183	(-82)–(-115)	(Pittau et al. 2018; Ben-Alon et al. 2021; Göswein et al. 2021; Cascione et al. 2022; Zuluaga et al. 2022)
LB	Loadbearing system with straw (bale or cob)	x	x	Straw	0.46–0.51	60–692	2–86	0.078–0.50	12–184	(-51)–(-76)	(D'Alessandro et al. 2017; Ben-Alon et al. 2021)
EC IA PA MS	MycoBamboo	x	x	Bamboo	0.35	274	8	0.56	84	(-37)	(Carcassi et al. 2022)

during winter, and the drying potential of the wall is reduced, which can lead to water condensation and degradation between the interior insulation and the wall (Straube and Schumacher 2007). Biobased insulation materials exhibit strong hygroscopic performance, thus regulating fluctuations in the indoor relative humidity due to the relatively high water vapour permeability (Ben-Alon and Rempel 2023). Experimental investigations in twin rooms with different wall and ceiling finishing materials have demonstrated that biobased or earth-based panels can reduce relative peaks in indoor humidity resulting from moisture production cycles by approximately 80% compared to the humidity in a plastered reference room (Mazelli et al. 2023). In Sweden, the indoor application of a hemp–lime composite has proven to be effective. This material uses local traditional materials and building methods, and the resulting product exhibits no difference in appearance from traditional lime renders. This similarity allows for the preservation of heritage while letting the building comply with modern standards of thermal comfort and energy efficiency (Strandberg-de Bruijn et al. 2019). In Portugal, similar results have been reported, indicating that the ability of biobased insulation material to absorb humidity is advantageous because it prevents water from migrating directly to cold surfaces (Silvestre et al. 2020). The main advantage of using biobased insulation in thermal plaster is not the low embodied GHG emissions, as plaster has a very minor contribution to the embodied impact of the building (Lawrence et al. 2014), nor is it the potential for carbon storage in the façade due to the small amount of material implemented; instead, the improvement in indoor comfort without the need for mechanical ventilation is the primary advantage (Jerman et al. 2019), as mechanical ventilation can be costly to implement in historic buildings, and it provides a significant embodied impact and nonnegligible operation costs for inhabitants.

2.5. Seismic performance

In general, the seismic performance of biobased materials depends strongly on the nature and mechanical properties of each material, as well as on the seismic mass, attributed to the weight of each material.

The use of timber (Frangi 2017) or bamboo-based (Laurence et al. 2017) structural elements (walls or frames) for seismic design or seismic retrofitting of buildings has emerged as an attractive design solution that leads to attractive seismic behaviour in these structures: Timber or bamboo structural elements are of low weight, thus leading to the development of low seismic forces in the structure.

However, specific attention should be given to the low lateral stiffness and high flexibility characteristics of these structural elements, which may lead to high seismic displacement demand, especially for high-rise buildings. The lateral strength and stiffness of timber frames depend significantly on the rigidity of the joints. In ancient Chinese timber buildings, the beams and columns were connected by tenon joints (plug-slot type connection), with the tenon as one component and mortise as another (Fang et al. 2001). In modern timber design, the beams and columns of earthquake-resistant timber buildings are connected using nails, dowels, glued-in rods or drilled-in screws (Frangi 2017). Within this frame, the lateral strength and stiffness of timber structures depend substantially on the stiffness of the aforementioned connections, which can be modelled using axial or rotational springs (Schilling et al. 2022). The determination of the seismic displacement and flexibility of timber structures is essential for the assessment of their seismic performance. Moreover, the use of walls, infilled frame-wall systems, braces, stiffeners or composite wall configurations can be applied to reduce the deformability of timber structures.

In many cases, the design seismic intensity acting on the timber structures can be exceeded by above-design seismic events. Therefore, the timber structures should manifest the ability to dissipate the seismic energy using ductile connections (Jorissen and Fragiacomo 2011; Ottenhaus et al. 2018). Large displacements and high ductility develop in connections with slender dowel type fasteners providing the joint is accurately designed to prevent brittle failure modes such as splitting (Jorissen and Fragiacomo 2011). Along these lines, the main limitations in the design of earthquake resistant-timber structures emerge from the ability of the design to limit the flexibility of the structures and to prevent brittle failure modes through the design of ductile connections. The seismic design of these structural elements should be aimed at high ductility capacity, which must exceed the corresponding seismic demand.

In many cases, the timber structures can be designed to fulfil multiple performance objectives simultaneously. Biobased infill panels can be attached to new or existing timber frame structures: The role of these infill panels is twofold, they can increase the stiffness of wall frames to improve their seismic performance characteristics, while improving the energy performance of the building when applied at its vertical envelope due to their low thermal conductivity. Tsiavos et al. showed in their 2022 work that the attachment of timber frames with biobased infill panels to the façades of existing masonry buildings can lead to significant synergy between the improvements in seismic behaviour and in the energy performance characteristics of existing buildings while minimizing the environmental impact of retrofitting (Zuluaga et al. 2022).

However, the use of these biobased infill panels for the simultaneous increase of the seismic and the energy behaviour of the building requires selection of biobased materials that manifest high thermal insulation properties, while providing high lateral stiffness that reduces the deformability of the timber frame structure.

In contrast to timber-based materials, earthen materials, such as rammed earth or hempcrete, are of substantially higher seismic weight, which leads to the development of high seismic forces in the superstructure. These materials, when they are unreinforced, are characterized by low tension and compression strength and high susceptibility to cracking, when subjected to seismic loading. Moreover, the seismic displacement capacity of the materials is limited, thus leading to brittle types of seismic damage and failure that are not desired, according to the modern seismic design code provisions. Therefore, these materials require reinforcement and seismic protection mechanisms in case they are used in areas of moderate or high seismicity to prevent them from seismic damage.

The determination of methodologies that facilitate the optimal use of biobased materials for the design and renovation of buildings is of utmost importance for extending the application of these materials to a wide range of buildings worldwide. Along these lines, Tsiavos et al. used multi-criteria optimization algorithms that can lead to the selection of an optimal synergetic retrofitting system for buildings that facilitates simultaneous seismic rehabilitation, energy improvement and embodied carbon footprint minimization (Zuluaga et al. 2022). The determination of methodologies that facilitate the optimal use of biobased materials for the design and renovation of buildings is of utmost importance for extending the application of these materials to a wide range of buildings worldwide.

3. Consequences for the built environment

Considering the extreme variety of biobased materials and their versatility for use as internal partition walls, load-bearing materials and insulation materials, it is possible to construct buildings almost entirely from nature-based materials (Carcassi et al. 2022). These buildings have very low embodied carbon, as shown in the work of Andrea Bocco and his team researching Vegetarian Architecture (Bocco Guarneri 2020; Mazelli et al. 2023), which showed the impact of a load bearing strawbale house ranges between +20 kg CO_2/m^2 and -1,000 kg CO_2/m^{287}. These values are compared with those from current conventional construction (approximately +600 kg CO_2/m^2) or with the very ambitious sustainable standards (aimed at 350 kg CO_2/m^2) (Hollberg et al. 2019; Habert et al. 2020). Due to this difference and the remaining carbon budget, we must transform our built environment to create a fair post-carbon future; there is an urgent need to implement fast growing biobased materials for renovation and new construction worldwide (Habert 2019). The construction of future infrastructure can be considered a common need that will require massive amounts of concrete and steel, which are materials that are difficult to substitute (Hollberg et al. 2019). Therefore, we should consider the priority allocation of 350 Gt carbon from the total remaining budget to infrastructure (Rao et al. 2019). The maximum total remaining budget is 650 Gt until 2050 to keep the global temperature increase below 1.5°C (Gignac and Matthews 2015). This value indicates that Western Europe has a budget approximately −100 kg CO_2/m^2, while nations with low historical emissions and large expected future growths have budgets of approximately +200 kg CO_2/m^2. Importantly, both target values are unreachable with conventional construction systems. In contrast, buildings with fast-growing biobased materials may allow buildings to be produced in line with these climate targets (Bocco Guarneri 2014; Zea Escamilla et al. 2016).

The most critical aspect in the Global North is the renovation of existing buildings for reducing operational emissions (Göswein et al. 2022). The key concern in the Global South is to provide resilient housing solutions in a booming urbanization context without increasing GHG emissions. Regional studies have modelled the changes in building stocks in different scenarios. For instance, in Europe, emissions can be stabilized from Portugal to Norway. In Portugal, straw-based insulation is implemented, and the renovation rate is increased until full renovation is achieved in 2050 (not 30% with the current renovation rate); these practices allow for the stabilization of emissions to keep the global temperature increase below 2°C (Göswein et al. 2021). In Norway, timber construction is adequately implemented (Maniak-Huesser et al. 2021). However, zero-emission buildings can only be within reach when considering emissions that were avoided from the added photovoltaic (PV) capacity (Lausselet et al. 2021). In Europe, estimations show that by using straw as insulation material to renovate all existing facades, up to 3% of the total GHGs that were annually emitted by all sectors in 2015 can be removed by 2050 (Pittau et al. 2019). Other global studies have shown that this elimination value ranges between 0.6 and 6% of annual emissions (Arehart et al. 2021). This benefit from carbon removal must be considered in the carbon mitigation measures that can improve the energy efficiencies of buildings by adding insulation; this measure can reduce carbon emissions resulting from the use of energy-intensive insulation materials (e.g. rock wool, expanded polystyrene (EPS)) (Silvestre et al. 2020). Building operation represents 30% of European Union (EU) emissions and approximately 10% of global emissions. The production of building materials comprises approximately 10% of EU carbon emissions and 20% of global emissions. This result shows that only an approach that combines carbon removal and carbon mitigation measures can result in net-zero emissions in the built environment (Heeren and Hellweg 2019). For instance, a study from South Africa showed that it is possible to simultaneously stabilize emissions, provide affordable housing for all individuals, and accommodate the urbanization boom; however, these goals can only be achieved if the housing building materials are changed from fired brick blocks to unfired earth blocks (Göswein et al. 2017). In another study, the potential of the incorporation of bioaggregates (Amziane and Sonebi 2016) from plants into concrete is analysed, and this process can allow a net-zero emission building stock to be obtained (Göswein et al. 2021). In Table 2, we present an analytical comparison of diverse biobased building materials, categorizing them based on multiple factors. It is important to note the differences in the functions of these materials; some materials, such as plant fibres (RPFs) and wood fibres (RWFs), are primarily used for insulation, while others, such as bamboo frames (NBAs), serve structural purposes. Importantly, the data presented in Table 2 have diverse sources and preparation methods. Thus, its main purpose is to illustrate the different characteristics of biobased materials without performing a comparative study. Likewise, the construction systems illustrated in Table 2 (e.g. external recladding, internal addition, infilling, prefabricated addition, massive systems, framed systems, and load-bearing insulation) should be understood as generic schematic examples of how insulation materials may be positioned within a building envelope. These diagrams are not meant to prescribe construction details or technical solutions. We recognize that in practice, each option requires careful design to ensure adequate moisture protection, structural integrity.

Insulating materials, such as RPF and RWF, are similar in terms of their high biomass contents (85–100% and 80–100%, respectively), and they have comparably low U values, indicating their excellent thermal insulation capabilities. These materials exhibit negative biogenic carbon values, indicating carbon sequestration. In contrast, ETICSs with insulating cork boards (RCKs) have moderate biomass percentages (55–65%); however, their biogenic carbon values are very negative, indicating the strengths of the carbon sequestration capabilities. Among the different structural materials, NBAs have low biomass contents (5–20%) and low U values, making them thermally efficient. These materials have many different environmental impacts, ranging from increases in the fossil global warming potential (GWP) values in the NTF to negative biogenic carbon in the NTS. While there are overarching similarities in categories such as insulation and structure, each material presents a unique set of properties that may make it suitable for specific applications in sustainable buildings.

Moreover, in the case of renovation strategies, certain materials, such as RPFs and RWFs, are suitable for external cladding (EC) and internal addition (IA) due to their low U values and high biomasses (wt.%). Conversely, options such as ETICS with RCK are effective solutions for infilling (IN), given their moderate U values and low biomasses (wt.%). For new construction projects, timber frames with straw (NTS) and load-bearing systems with straw (NST) are suitable for massive systems (MSs) and load-bearing insulation (LB), providing a balance between structural stability and thermal insulation. For framed systems (FSs), materials such as NBAs and concrete-like blocks with fibres (NBLs) offer various degrees of biomass in terms of weight and U values, making them viable choices for projects that require the properties of strength and insulation. By implementing these materials in their most effective applications, the data in the table can guide decision-makers in selecting biobased materials tailored for specific construction and renovation projects. Moreover,

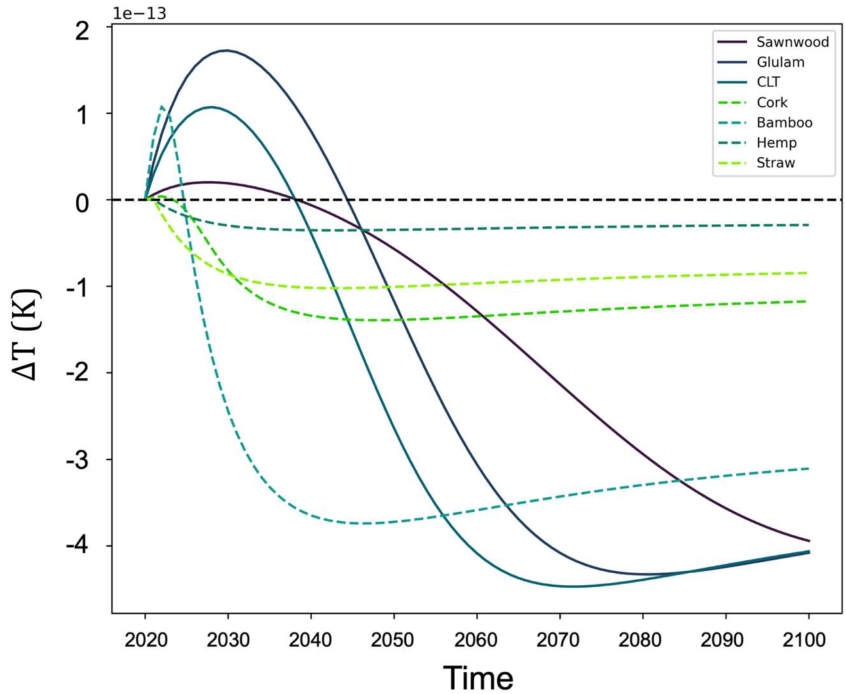


Figure 1. Global temperature change for 1 m3 of biobased materials considering emissions from extraction and manufacturing. Data sources and methodology from Göswein et al. (2022).

the CO_2 capture characteristics of fast-growing plants and wood are significantly different, as illustrated in Figure 1, which shows the global temperature change (GTP) measured according to the method described by Cooper et al.(2020). See the Supplement for further analysis details. Figure 1 shows that fast-growing materials can lead to net reductions in atmospheric CO_2 over the first few years due to their short rotation periods. In contrast, materials with long rotation periods contribute to short-term net warming, achieving neutrality only decades after implementation in a building. Consequently, biobased construction can reduce greenhouse gas emissions resulting from human activities by substituting carbon-intensive materials, such as concrete structures and polystyrene insulation. In addition, biobased construction removes CO_2 from the atmosphere. These materials can be used directly as insulation materials, such as strawbales or hempcretes (Amziane and Collet 2017), transformed into biochar, included in new building materials, such as hempcretes, and used to directly replace classic concrete (this process has recently been completed by the Swiss company LogBau AG in the form of KLARK – Climate Concrete[LO). However, to show this potential, new calculation life cycle impact assessment methods must be implemented that consider the difference between the natural rotation period in the biosphere and the storage period in the Technosphere (Pittau et al. 2018; Hoxha et al. 2020; Arehart et al. 2021). If the biomass storage period is longer than its rotation period, the effect on climate change is beneficial, while in the opposite case, the effect on climate change is detrimental (Cherubini et al. 2013; Guest et al. 2013).

4. A transformation beyond the building stock

Transforming the global building stock into a carbon sink by using biobased materials requires sufficient resources to be available. Moreover, for the intensive use of biomass, the land must be transformed in a manner that is compatible with such practices. A widely promoted solution for addressing the embodied emissions of buildings that is supported by researchers and policy-makers is to replace concrete and steel with timber (Churkina et al. 2020). However, supply and demand studies have shown that extensive timber resources are not available in the regions where the most construction activities will occur in the coming decades (Pomponi et al. 2020). Furthermore, increasing the harvesting rates of forests raises other concerns related to biodiversity and ecosystem services. Figure 2 shows the global demand and supply of fast-growing biobased materials. Scenario analyses of the large-scale use of bamboo being used as a

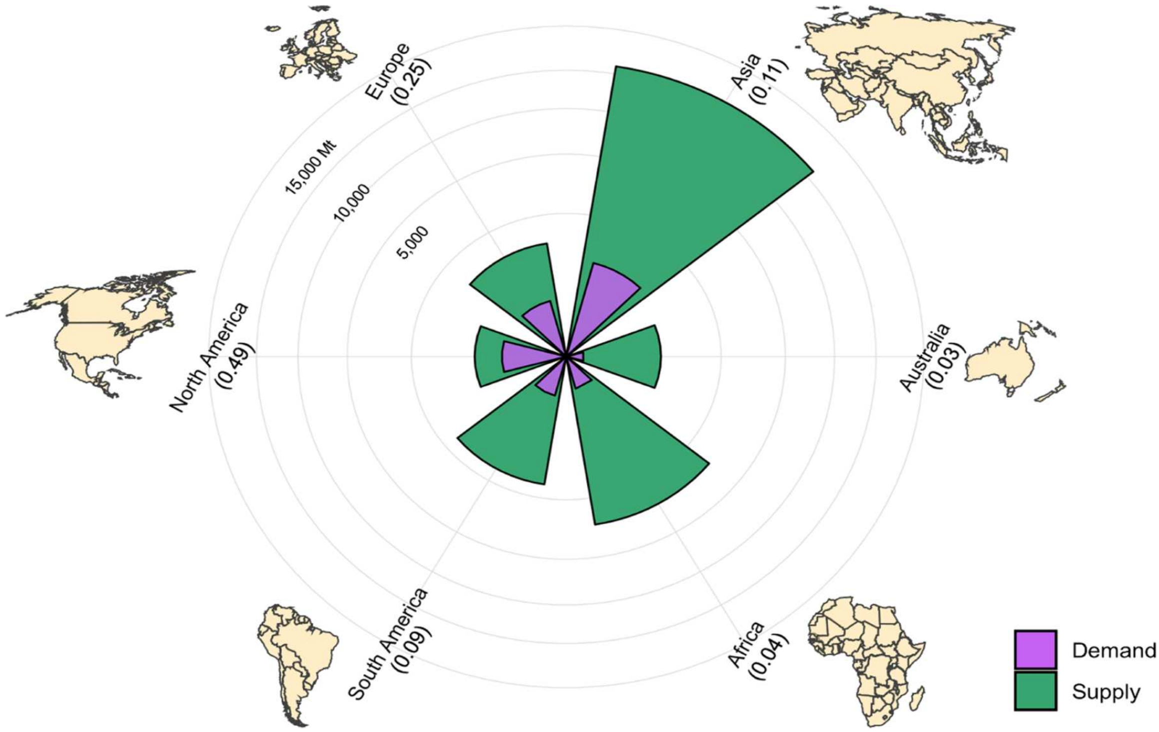


Figure 2. Balance of the supply and demand of fast-growing biomass in each continent from 2021 to 2050.

structural material in the Global South and of straw being used as an insulation material in the Global North have shown the potential for the supply to exceed the demand in buildings (Figure 2). In terms of demand, floor space estimates are derived from Güneralp and coauthors112, and a 3% retrofit rate is assumed in the Global North. In terms of the supply, straw availability is based on FAO113 data for all countries with a wheat-to-straw ratio of 6.5 tons/ha114 and 32% sustainable solid recovery115. The bamboo supply is calculated from FAO116 data, and the average ton per hectare is taken from the Chinese National Forestry and Grassland Administration117. Figure 2, shows that more than enough of these materials to address future demands. This simplified model, as detailed further in the Supplement, shows a global supply that is one order of magnitude greater than the global demand for both straw and bamboo. This extensive supply indicates sustainable management practices. This result is very different from that for timber (Pomponi et al. 2020), and the variety of fast-growing biobased sources that can potentially be used is not considered.

Even with the presence of sufficient raw material to sustain this transition, the implementation of these new practices will require the involvement of stakeholders throughout the value chain and after the construction process in both the agriculture and forestry sectors. Construction practitioners are notoriously reluctant to change because of the long durations of construction projects, the high costs and the fact that different stakeholders usually act in isolation. However, according to a recent analysis (UNEP 2021), key decisions about the type and volume of construction are made by governments, international organizations, financial institutions and major market players during the financing stages. Therefore, these decision makers can transform the building stock by integrating sustainability metrics, such as the inclusion of embodied carbon in building standards and certifications; the regulation of material procurement to prioritize sustainable materials; and a focus on the regenerative aspect of a circular economy. All these approaches can benefit biobased material and their value chains. The same analysis reveals that the key stages for resource use in terms of type and volume are the material sourcing/production, building construction, and building renovation stages (UNEP 2021). Therefore, the decision-making process is driven by economic factors. However, material prices depend on many factors: short-term vs. long-term considerations, such as purchase price vs. potential to reduce operational costs, logistics and transportation, local labour costs and the (non)-existence of the material producing industry (Marzouk and Amin 2013; Musarat et al. 2020). Moreover, the market price is decisive, while the costs of negative consequences on the natural environment and human health are excluded.

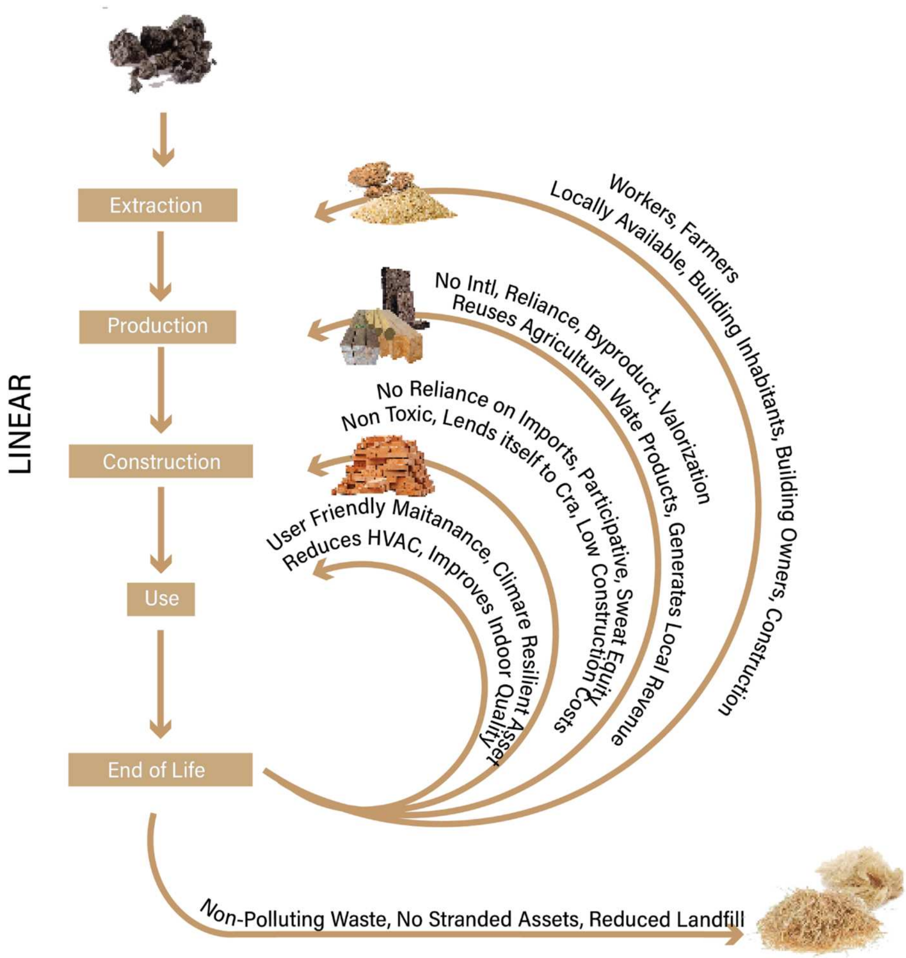


Figure 3. Conceptualization of the potential benefits of using biobased materials for valuable stakeholders across the construction chain.

We live in a time where the number of individuals benefiting from a globalized economy is decreasing. In addition, globalization backlash has led to nationalistic politics becoming of greater concern than economic politics. Therefore, the mechanisms by which we extract building materials, the locations where we source them, and the largest global share of material use seem increasingly important. The change should not be replacing the material used. Instead, a deep systematic change is needed that allows local communities to create value through nearby renewable material sourcing, production and use. Moreover, technical knowledge can be transferred between countries due to digitization and international connectedness. Biobased building materials can extend the value chain to many industries beyond the construction sector. In agriculture, many materials are considered waste or byproducts, but they could be used in construction. In the energy and waste management sectors, we must consider biowaste as a valuable source of energy to divert from fossil fuels. Therefore, biowaste in these sectors is a clear competitor and must be considered for the transformation of these resources into building materials. However, the added value for agriculture and local producers can be considerably increased if biowaste is upcycled into building materials rather than downcycled into biofuels. Promoting fast-growing biobased materials for construction can transform the value chain, valorize local actors and provide additional revenue to agriculturists. These sectors are transformed through the scaling up of bio-based material systems used in construction, thereby generating benefits for carbon emissions (Zea Escamilla et al. 2016) and increases in the resilience levels of these sectors. Finally, high-quality buildings can reduce human health issues and associated costs.

In Figure 3, we present a synthesis of the vast transformative potential of biobased building materials across the construction value chain. Rather than advocating for a substitution of conventional materials, we chart a comprehensive pathway for systemic change at each key stage: extraction, production, construction, use, and end-of-life. During the extraction phase, the agricultural sector can make significant gains. Materials traditionally viewed as agricultural waste can be sustainably harvested and converted into valuable resources, thereby increasing the economic viability and reducing the environmental footprint of the sector (Carcassi et al. 2022). In the production stage, the use of biobased materials promotes clean technologies and low-energy solutions (Sommese and Ausiello 2023). Local producers can benefit from the upscaling of these materials, particularly given that they possess greater value when upcycled into construction rather than downcycled into biofuels (Manrique 2021). The energy and waste management sectors, which are competing interests in biowaste utilization, must evolve to recognize these added values (Irwin Klausmeier 2023). In the construction phase, we strive to highlight the immediate reductions in carbon emissions and increases in the resilience of the sectors involved. The implementation of biobased materials can support the achievement of ambitious net-zero targets and contribute to local value chains, further strengthening local economies and systematically transforming them into truly circular economies. During the use phase, inhabitants of buildings constructed or renovated with biobased materials may experience health benefits due to improved indoor air quality and thermal comfort, which translates into long-term cost reductions in healthcare and energy (Newsham et al. 2013). At the end-of-life stage, these materials often have good recyclability or biodegradability characteristics, aligning with the principles of circular economy. Biodegradable products can be reintegrated into agricultural or natural systems, closing the loop and allowing local communities to benefit again. Furthermore, the role of digital connectivity is pivotal in sharing knowledge and best practices across regions, thus enhancing the widespread adoption and continuous improvement of biobased materials.

Moreover, the reliance on locally available materials and the integration of local labour, particularly through workers and farmers, will inevitably stimulate local economic growth. By sourcing materials locally, capital is directly infused into the local economy, thus supporting small-scale producers and minimizing capital flight to foreign entities. By reducing dependency on international imports, this model insulates local industries from volatile global market prices and exchanges rate fluctuations. This economic resilience translates to steady employment opportunities and potentially relatively stable regional economies. Furthermore, the use of biobased materials to process agricultural byproducts by steaming has established a secondary market for agricultural waste. These materials provide an additional revenue stream for farmers and mitigate waste disposal costs, thus making agriculture increasingly profitable and sustainable while providing regenerative materials for the construction sector.

Importantly, biobased materials inherently highlight community engagement, and they utilize local knowledge. This participatory approach ensures that the nuances of local systems, both ecological and cultural, are incorporated into the production process.

With their rich repository of knowledge, local communities can offer insights into sustainable farming practices, optimal harvest times, and crop selection to yield the best byproducts for construction. This knowledge, amassed over generations, is invaluable in fine-tuning the regenerative process for maximum effectiveness and sustainability. By weaving the threats of economic viability and local knowledge, biobased materials offer more than just a sustainable production model. This model has evolved into a holistic system that values local prosperity and expertise, setting a benchmark for the mechanisms by which industries can enter the fabric of local communities rather than just extracting value from them.

5. Remaining challenges to be overcomed

5.1. Lack of building codes

On the regulatory side, more can be done to encourage the use of fast-growing biobased materials. One common complaint by construction stakeholders is the lack of building codes for the load-bearing capacity and fire safety characteristics of biobased materials. Even when these materials are environmentally certified, there is insufficient information about the mechanical behaviours of products (Dias et al. 2020). However, in the last 10 years, standards and tests have demonstrated the suitability and performance of these materials. For example, bamboo building codes already exist, and the International Organization for Standardization (ISO) Technical Committee 165 on Timber Structures recently issued three standards for testing methods and structural design: two on round bamboo(ISO 2019, 2021) and one on engineered bamboo (ISO 2022). Other examples include existing standards for compressed earth blocks, which have been used for a long time (Houben and Boubekeur 1998). Local adaptations of this standard can be found in New Zealand (NZS 1998), where standards for designing structures to withstand earthquakes have been thoroughly developed. Africa currently has a standard for compressed earth blocks (ARSO 2018). Vernacular construction techniques have started to be standardized, such as for adobe construction, where an international committee agreed to validate adobe production and construction processes (ABNT 2020). Considering all these examples, there is not a lack of standards but rather a lack of knowledge from individuals in the construction sector. From their perspective, biobased materials are advantageous for environmental sustainability only and are, therefore, are not worthy of additional investment. The implementation of high embodied emissions standards can change this attitude. We urgently need to train individuals on the multifunctional and regenerative potentials of these materials and urge policy-makers to define good metrics to change practices.

5.2. Training of construction actors

Even if a structured supply chain for fast-growing biobased materials already existed, it would still require the training of architects, engineers, and construction workers for implementing these materials. Without the involvement of intermediary individuals, the implementation of these materials will not be possible (Simpson et al. 2020). Training courses are in high demand in many places worldwide. However, these courses are usually bottom-up initiatives attracting already convinced individuals rather than the majority of professionals. To make this knowledge mainstream, premier construction associations need to be involved. These associations need to offer training activities, although they might not be funded by the usual sponsors of these associations. Their involvement can provide the required quality and credibility for using these materials. Similar approaches are needed at academic institutions. If top-ranked universities are not teaching engineers or architects with these materials, they will suffer from a lack of credibility. Moreover, choosing products and materials for construction should be based on their ability to meet specific performance requirements. However, in practice, the industry tends to favour conventional materials due to their familiarity, and often seen low cost. This creates a disincentive for adopting alternative, more sustainable materials that may not perform to the same high standards.

5.3. Harmonizing carbon accounting in life cycle assessment

With the increased constraints on the construction sector to create net-zero carbon buildings, the use of fast-growing biobased materials may benefit from accounting for the carbon storage delivered. Even if the storage is temporary, climate scientists understand that fast temporary storage systems can lead to carbon peaking before 2050 and, therefore, avoid crossing an irreversible tipping point; however, permanent and long-term storage systems will need to be considered by 2100 (Matthews et al. 2022). However, there is currently no agreement within the scientific community or standards on accounting for the potential benefits of temporary carbon storage in biobased materials (Tellnes et al. 2017; Hoxha et al. 2020). The classic LCA method only considers fossil fuel emissions that contribute to climate change, while recent methods include the contribution of biogenic emissions in a static or dynamic manner (Arehart et al. 2021). With dynamic LCA calculations, it is important to consider the time needed to regrow the plant, i.e. the rotation period. Harvesting a plant does not remove CO_2 from the atmosphere, as this process is only completed via the transfer of carbon from a forest or a field to a building. However, once a new plant is growing, thereby sequestering CO_2, and once an old plant is stored in a building, there is a reduction in carbon in the atmosphere. For example, the whole life cycle of wheat straw is as follows. In spring, the plant grows and captures CO_2 from the atmosphere. In July, the wheat is harvested, and its straw byproduct is first cut and then burned or composted, releasing CO_2 into the atmosphere. Therefore, the sum is null for the climate; it belongs to the biogenic carbon cycle and does not contribute to climate change. However, if our LCA model considers that straw is used as a building material instead of being released into the environment and that the next year, wheat is replanted and regrown, we determine a net removal of carbon from the atmosphere. The same occurs for a tree in a forest, except that the time of tree growth is relatively long and, therefore, the addition of carbon storage is relatively slow. Consequently, fast-growing biobased materials are the fastest and least expensive carbon capture systems for achieving negative carbon emissions in buildings.

5.4. Overcoming fears of a lack of durability and fire safety

Good design and craftsmanship can make any material durable. Conversely, poor maintenance decreases the service life of a building and increases its impacts, regardless of the material (Dias et al. 2022). The material needs to be durable in use, and it must add to the appreciation and care for the building, thereby enabling it to achieve permanence (Delgado et al. 2013). For instance, one can find houses made of straw bales that are approximately 100 years old in France or even made from hay in Nebraska. However, if this building is abandoned, biobased materials can reintegrate materials during their natural cycles. In the previous century, we assumed that one could build everlasting buildings. Concrete appears eternal, although real-world examples contradict this belief. In contrast, strawbales seem ephemeral, although with regular maintenance, they can span centuries. There is a clear need to study the durability of biobased materials and to perform standard tests to compare materials and products. However, there is a clear need to deconstruct our false notions about material durability. We must be willing to use the building and take advantage of the value we added to this building. In this manner, community-based maintenance strategies can be enhanced, and – context-specific material solutions can increase building resilience due to the availability of local craftsmanship. In addition to maintenance, a regular concern of building users and owners regarding timber and other biobased materials is their fire resistance (Toppinen et al. 2018). The strict fire safety regulations for timber buildings and the requirements of additional fire suppression systems are considered among the main barriers to their wide implementation (Maniak-Huesser et al. 2021). However, fire safety design is well regulated by standards in Europe (CEN 2002, 2004). In general, while timber and engineered wood/bamboo can be adopted in exposed structures by ensuring acceptable residual safety due to the slow progression of combustion during fire (Kippel et al. 2014), most biobased materials and, more generally, combustible products can be challenging when used for building insulation or external finishing. Recent fire tragedies in buildings across Europe have shown the risk of installing combustible materials along building façades, such as extruded polystyrene (XPS) and expanded polystyrene (EPS)(McKenna et al. 2019; Marriage 2022). To prevent severe fire damage, recent standards in many countries have limited the use of non-class A materials in external insulation or cladding, especially in VRFs where the stack effect contributes to the flames (Asimakopoulou et al. 2020). Even if material densification can reduce the combustion speed (e.g. through a compression process that reduces the interspace between fibres or particles), an A0 class, referring to non-combustible materials that do not contribute to fire spread, is generally required for installation in façades of multistorey buildings. Mineral binders, such as cement, lime, or even clay, that are often used in biobased components to bond or cover vegetal particles (e.g. hempcrete, wood-wool cement boards, bio-concrete, and clay mortar) provide surface protection to natural fibres, drastically slowing the flame activationtime (Belayachi et al. 2017; Zuo et al. 2018). Moreover, the risk of fire diffusion along the façade can be largely reduced through the design of fire barriers, which are normally short strips of mineral wool installed around windows or slab connections, that stop the combustion of the material (Čolić and Pečur 2020; Engel and Werther 2021).

5.5. Aesthetics of natural materials: cultural barriers to adoption

Contemporary architectural materials have been dominated by an aesthetic paradigm that favours standardization, a high degree of surface-level customization and a narrow set of material hygrothermal behaviours. Given that the design of biobased materials is initially controlled by dynamic parameters (i.e. temperature, light, humidity, and nutrient levels) in a natural environment, such materials embody localized aesthetics in relation to climate and ecology. For the same species of plant grown in two different regions, the aesthetic features of derived natural fibres, including colour, texture, fibre length and texture, may vary widely due to cultivar type, harvest age, and climatic and geological conditions. For earth-based materials, differences in colour and texture are determined by differences in organic matter, inorganic compound presence and historic geological formations. Therefore, a holistic approach that considers the physical and environmental benefits of such materials and the sociocultural context that influences their adoption across different regions is required (Amziane and Sonebi 2016). Physical properties of natural materials may have unique yet comparatively limited and non-standardized contributions to material aesthetics. Although such place-based material identities can be direct driver for adopting local materials, these can also serve a barrier for promoting the acceptance of natural materials (Joye 2011). In examining current practices of biophilic design, the acceptance and increased value of natural material aesthetics have gained traction across the building sector. Coined by the American ecologist E.O. Wilson, biophilic design expresses the mechanisms by which design can foster connection to nature-based systems, and it has been integrated into the core of green building certification programmes such as the 'Living Building Challenge' (International Living Future Institute 2019). Key drivers for the integration of these programmes into contemporary buildings are centred on associating natural materials in indoor applications with quantitative metrics of health, well-being, and productivity (Gillis and Gatersleben 2015). However, as biophilic-inspired interiors can mimic the conditions and positive effects of walking in a forest landscape, the integration of natural materials may introduce biotic elements (fungi and bacteria) and biotic behaviours (moisture retention and breathability) that result in indoor smells, changes in material visual appearance and reductions in the perceived indoor environmental comfort. The reintroduction of biotic elements and passive biobased material behaviours may reduce the direct control of thermal comfort as well as perceived safety in the built environment. Given such materials compete with 'progressive', high embodied carbon materials and participate in twentieth century mechanical conditioning systems, biobased materials require new, aspirational social and cultural identities to drive their adoption. Furthermore, given the largely 'antibiotic' culture in buildings stemming from the pervasive use of material coating practices and rigorous cleaning protocols as part of prevailing antibiotic indoor cultures, the development of new aesthetic identities and perceptions for natural building materials will require a transdisciplinary and culturally specific approach (Joye 2011).

5.6. Economic barriers to affordable scaling

The commercialization of natural building materials is viable (Amziane and Sonebi 2016), but it is largely led by start-up companies and a few medium-scale enterprises, who must bear the brunt of the higher costs associated with natural material collection, quality control and standardization compared to reconstituted wood, cement, plastic, metal, and fossil-fuel-based insulation materials. For example, natural fibres and bio-adhesives derived from agricultural waste are important and undercapitalized feedstocks for natural building materials; however, these raw materials can be highly distributed or erratic in availability, and they can be poor or non-standardized in quality (Dey et al. 2021). In practice, the supply of raw lignocellulosic materials for scaling up production to compete with fossil fuel-based material alternatives is limited unless the material is located close to large agricultural production contexts or the material has the flexibility to leverage a range of seasonal agricultural byproducts as feedstocks. Unless biomass sectors are incentivized to develop efficient collection and quality control systems for their waste, the production costs of natural building material enterprises will remain high. Furthermore, as the value of agricultural byproducts increases or as agricultural byproducts enter competition with other transformation pathways, the costs of 'free' or 'low-value' agricultural byproducts can increase (Pavlenko et al. 2016). In recent decades, due to declining expertise in working with natural materials, the green skilling of construction labour and the increased time spent by design and construction professionals to ensure the proper installation of these assemblies are translated into increased service costs. For relatively new materials and production processes, such as mycelium-based manufacturing, new skills and processes for factory environmental control can be translated into high operational costs. As a result, the business strategies of biobased start-up enterprises are to identify and develop high-value products, including custom acoustic panels, high-performance material assemblies, and furniture and luxury products, to address the additional costs associated with development (Yang and Ogunkah 2013; Elsacker et al. 2020; Kunz et al. 2020). These products are priced at a level that a large segment of consumers cannot afford, further increasing the barrier to large-scale adoption.

6. Conclusions and outlook

Our primary aim in this paper was to highlight the potential of using biobased building materials. Their intrinsic properties make them viable options for long-lasting construction and active contributors to climate change mitigation through carbon capture and storage. The location-based aesthetics of these materials can enhance the culture of the area by tying communities to their local environments. However, the journey towards mainstream adoption is limited by various challenges, including aesthetic preferences, economic obstacles, and specialized skill requirements. Based on our findings, we can be cautiously optimistic about the potential benefits of biobased materials. We see that this transition in the bult environment is a monumental task. Achieving this transition can require unprecedented levels of cooperation and innovation across disciplines, industries, and governments. To truly capitalize on the potential of biobased materials, a cultural shift is needed. We need to break away from the comfort zones of standardized solutions and venture into the unique characteristics that these materials offer. Simultaneously, economic barriers to entry must be reduced, potentially through subsidies or other financial incentives, to make these materials accessible and affordable. On the regulatory front, policies need to be updated to incorporate the benefits and specific requirements of biobased materials. This update includes incentivizing the agricultural sector to streamline the supply chain and training the labour force in the construction sector to effectively operate with these materials. Public procurement is seen as a force driving market demand. In terms of education, we need to equip architects, designers, and builders with the knowledge and tools they need to make informed choices about material selection, enabling them to fully appreciate the potential of biobased materials. We must educate developers and end-users to observe short-term costs and understand long-term benefits, both to themselves and the planet. In conclusion, the next 25 years offer a narrow yet viable window to make sweeping changes in how we think about and use building materials. If managed correctly, biobased materials might be the key to addressing climate and housing challenges. Therefore, to address the urgent questions of climate change, urbanization, and construction sustainability, a comprehensive, multipronged approach must be adopted without delay. We stand at a pivotal moment in history where our collective actions can set a transformative course for generations to come. With the advancement of technology, we must develop our ability to innovate solutions that are sustainable, culturally enriching and economically viable. Biobased materials offer a compelling case for how we can rebuild our world in harmony with nature rather than in opposition to it. The studies we have explored paint a picture of a future in which buildings are not merely shelters but also active contributors to ecological well-being and community resilience. This is a future where aesthetics concern both superficial appeal and are profoundly connected to the land and the local environment. This is a future in which economic viability aligns with ecological responsibility. Therefore, we can view the next 25 years not as a countdown to potential disasters but as a path for launching a sustainable, equitable, and regenerative built environment. The road may be long and fraught with challenges, but it is ripe with opportunity. Therefore, let us come together – researchers, policymakers, builders, and consumers alike – to seize these opportunities and build a future we all know is possible.

7. Supplement

In Figure 1, the GTP was calculated using the methodology described by Cooper et al. (2020) using a two-part temperature response model. The GTP associated with the cradle-to-gate GHG emissions (CO_2 and CH_4) of one kg of biobased material was calculated, considering forwards-looking regrowth of the material (Cooper et al. 2020). Cradle-to-gate emissions were assumed to be those emitted in 2020, and regrowth was assumed to begin in the same year by considering a normal regrowth curve.

Life cycle inventory data were sourced from the Ecoinvent database while assuming values for the rest of the world; data concerning glulam (Puettmann and Wilson 2005), bamboo (van der Lugt and Vogtländer 2015) and hemp (Zampori et al. 2013) were not unavailable in Ecoinvent. Only the greenhouse gases carbon dioxide and methane were considered, and other gases were assumed to be negligible. The biomass regrowth model considered a normal regrowth curve (Cherubini et al. 2011) with all carbon removed since the year of construction and the growth rate of the plant, which was ~90 years for sawn wood (Eriksson et al. 2007), ~40 years for glulam (Diaz et al. 2018), ~9 for cork (Knapic et al. 2016), ~5 years for bamboo (Zea Escamilla et al. 2016), and one year for straw and hemp.

To develop Figure 2, a demand and supply analysis was performed to assess the amount of fast-growing biomass in each continent between 2021 and 2050. To develop the demand, regional estimates of floor space growth were utilized by Güneralp et al. (2017) under the S50 scenario. The existing building stock and buildings constructed before 2020 on the continents of North America, Australia, and Europe were considered to undergo an annual retrofit rate of 3% (BPIE 2019). No retrofitting of the building stock was assumed for other continents. New construction considered additional floor space growth between 2020 and 2050 due to changes in population and gross domestic product. The existing retrofitted buildings and new construction projects were combined to determine the total amount of floor space that could use fast-growing biomass across the analysis period. For new construction projects in North America, Europe, and Australia, straw insulation was assumed, with an average biomass content of 14.57 kg/m^2 (Pittau et al. 2018). For new construction projects in South America, Africa, and Asia, bamboo pole and glue-laminated bamboo construction typologies were assumed, each with an average biomass content of 31.3 kg/m^2 (Zea Escamilla et al. 2018). The supply of straw was modelled using country-level data from the Food and Agriculture Organization (FAO) by Göswein et al. (2022). For North America, Europe, and Australia, the harvested wheat area was converted into straw considering a wheat-to-straw ratio of 6.5 tons/ha (Dai et al. 2016). Some of the resulting straw had to be left in the fields to conserve soil quality and for conventional competitive uses, such as feed bedding. Accordingly, 32% of the available supply was removed (Lesschen et al. 2013). The supply of bamboo in South America, Africa, and Asia was modelled using bamboo area data (Xu et al. 2019) for China. The ratio between supply and demand was calculated and presented below each continent label in parentheses. Values less than 1.0 indicated a sufficient supply on the continent, while values greater than 1.0 indicated an insufficient supply.

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