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REVIEW ARTICLE

Biomaterials technology and policies in the building sector: a review

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Abstract
Traditional building materials have some drawbacks in the construction industry, particularly in terms of greenhouse gas emissions and energy consumption. Biomaterials derived from renewable sources are a promising alternative, significantly reducing the greenhouse effect and enhancing energy efficiency. However, traditional materials still dominate the construction sector, and there is a lack of understanding among some policymakers and developers regarding biomaterials. Here, we review building biomaterials and their policies and life cycle assessment through case studies. Bio-based materials have the potential to reduce over 320,000 tons of carbon dioxide emissions by 2050. They also exhibit advantages like decreasing water absorption by 40%, reducing energy consumption by 8.7%, enhancing acoustic absorption by 6.7%, and improving mechanical properties. We summarize recent advancements in mycelial materials, bioconcrete, natural fibers, and fiber-reinforced composites. We also explore the contributions of nanotechnology and microalgae technology in enhancing biomaterials' thermal insulation and eco-friendliness.

Keywords Climate change · Green building materials · Recycling biomaterials · Renewable building materials · Life cycle assessment · Energy-efficient construction

Introduction

The construction industry is essential in shaping the world's urban landscapes, providing shelter, infrastructure, and spaces where people live, work, and interact (Chen et al. 2022, 2023b; Yang et al. 2022). However, traditional construction practices heavily rely on resource-intensive and environmentally harmful materials, contributing significantly to greenhouse gas emissions, energy consumption, and depletion of non-renewable resources, and resulting in a significant ecological footprint (Chang et al. 2018; Farghali et al. 2023; Osman et al. 2022; Yang et al. 2023). Additionally, their production processes generate copious amounts of waste, exacerbating the environmental impact of the construction industry (Fořt and Černý 2020; Lima et al. 2021). As global awareness of environmental challenges rises, architects, engineers, policymakers, and stakeholders increasingly focus on sustainable and environmentally friendly building practices (Sarfraz et al. 2023). Biomaterials, derived from renewable resources, have emerged as a promising solution to revolutionize the construction sector, reducing its impact on the environment while providing innovative and cost-effective alternatives to conventional

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materials (Rusu et al. 2023). Therefore, improving energy efficiency, promoting the utilization of renewable building materials, and conservation of resources are essential for achieving carbon neutrality in the construction industry. The shift away from traditional building materials like cement, steel, and bricks toward sustainable and eco-friendly biomaterials will benefit ecological preservation.

As an innovative approach, biomaterials offer a new perspective on construction materials, harnessing the potential of organic substances, agricultural by-products, and waste materials (Freitas et al. 2021). The diverse range of biomaterials encompasses bioplastics (Oberti and Paciello 2022), biocomposites (Li et al. 2022), biocement (Yu et al. 2022), mycelium-based materials (Bitting et al. 2022), and more. Bioplastics provide eco-friendly alternatives for interior finishes, promoting healthier indoor environments (Hwang et al. 2020). Meanwhile, biocomposites offer lightweight yet durable structural components, enhancing energy efficiency (Beims et al. 2023). Biocement and geopolymers present greener options for concrete, reducing carbon emissions (Gebru et al. 2021). Mycelium-based materials contribute to a circular economy by offering biodegradable insulation and packaging solutions (Elsacker et al. 2020), while cellulose-based materials improve energy efficiency in cladding and acoustic panels (Darwish and Eldeeb 2023). Biodegradable formwork streamlines construction processes, while green roofing solutions enhance insulation. Sustainable insulation materials ensure thermal comfort with minimal environmental impact. Lastly, biomaterials in three dimensional (3D) printing revolutionize customization while minimizing material wastage (Chen et al. 2023a; de León et al. 2023). In light of these advancements, the potential of biomaterials lies in their renewability, capacity to sequester carbon, and ability to enhance indoor air quality, all contributing to the creation of healthier and more sustainable built environments.

This comprehensive review investigates biomaterial production's current state and potential within the construction sector, as shown in Fig. 1. Through an in-depth analysis of the available biomaterial types, their advantages, challenges, and successful implementation case studies, this study aims to illuminate the transformative impact of biomaterials on the construction field. Furthermore, the review delves into the regulatory and policy landscape surrounding biomaterials, assessing how regulations influence their adoption and drawing insights from exemplary practices. Technological advancements in biomaterial's production are scrutinized for their potential to drive broader adoption, while a comprehensive analysis of the benefits and risks associated with biomaterials use encompasses health, safety, and environmental sustainability considerations. The review concludes by presenting a forward-looking perspective, emphasizing opportunities and obstacles for increased adoption, and providing recommendations for future research and action. Overall, this review aspires to offer valuable insights into the pivotal role of biomaterials in shaping a more sustainable and resilient future for the construction industry.

Biomaterials production in the building sector

Biomaterials have emerged as a transformative and sustainable solution in the construction industry, offering a promising alternative to conventional materials (Liu et al. 2022c). Derived from renewable resources, biomaterials leverage the inherent properties of nature to create innovative and eco-conscious building materials (Alemu et al. 2022). They encompass a diverse range of materials, such as bioplastics, biocomposites, biocement, mycelium-based materials, and cellulose-based materials, each with unique benefits like reduced carbon footprint, improved indoor air quality, and resource conservation (Chen et al. 2023c; Pesode and Barve 2022). However, commercial viability challenges, industry standards, and regulatory compliance must be addressed to promote widespread adoption (Niculescu and Grumezescu 2022).

Table 1 demonstrates the five types of biomaterials commonly used in construction and summarizes their benefits and the associated challenges. It covers bioplastics, biocomposites, biocement, geopolymers, mycelium-based materials, and cellulose-based materials. These biomaterials offer notable benefits, such as sustainability, reduced carbon footprint, and improved indoor air quality. However, addressing production costs, meeting industry standards, and ensuring regulatory compliance remain critical challenges. The adoption of these biomaterials can facilitate resource conservation, contribute to a circular economy, and promote a sustainable paradigm within construction practices. Embracing biomaterials in construction paves the way for a greener and more sustainable future in the built environment.

While Table 1 highlights the promising potential of utilizing biomaterials in the construction industry to address environmental concerns and advance sustainable development, it is essential to acknowledge that various challenges impede their widespread adoption in the market. A significant hurdle lies in the commercial viability of biomaterials, as some presently entail higher production costs than traditional materials, posing a challenge in terms of market competitiveness (Badawy et al. 2021; Reshmy et al. 2021). To overcome this, efforts are needed to optimize production processes and reduce costs while maintaining biomaterials' environmental benefits and performance. Another critical challenge is ensuring that biomaterials meet performance standards and industry requirements (Harrington et al. 2020). Consistent performance, durability,

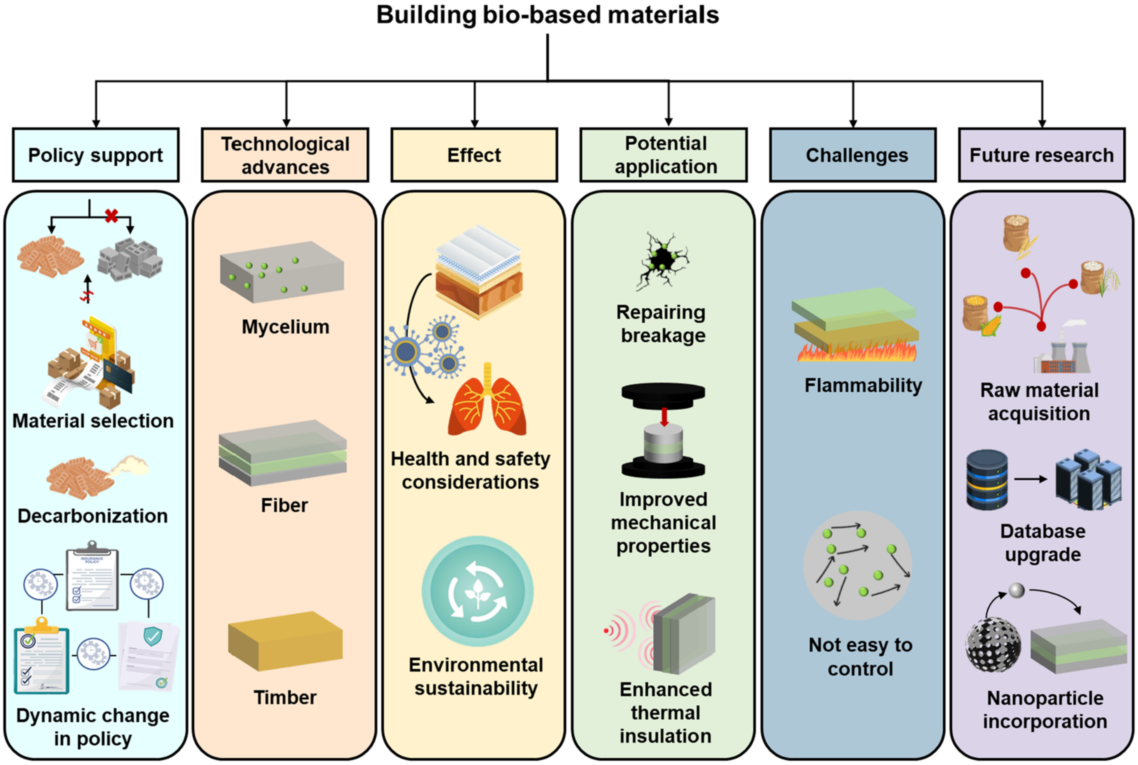

Fig. 1 Overview of biomaterial products' status and potential in construction sector. This figure presents a comprehensive overview of various aspects concerning bio-based building materials, encompassing policy support, technological advancements, impacts, potential applications, challenges, and future research directions. It underscores the significant policy support these materials have garnered due to their ability to contribute to decarbonization. The figure also details the typical composition of bio-based building materials, including mycelium, fibers, and wood. Furthermore, it highlights the health benefits and enhanced environmental sustainability these materials offer. The figure also illustrates the remarkable capabilities of biomaterials, such as their inherent self-healing properties, improved mechanical strength, and significant enhancement in thermal insulation. However, it confronts the challenges these materials face, addressing issues such as flammability and the complexities involved in mycelium growth management. Looking forward, the figure stresses the vital need to ensure a steady supply of raw materials and points to the urgent necessity of expanding databases and incorporating nanotechnology advancements in this sector

and safety are essential for gaining trust and confidence among construction professionals and building developers. Standardized testing protocols and material certifications are pivotal in achieving wider acceptance of biomaterials and encouraging their seamless integration into construction projects.

Additionally, navigating the complex regulatory landscape is another obstacle. Biomaterials are required to comply with various environmental and safety regulations, which can be challenging for manufacturers and industry stakeholders (Giubilato et al. 2020). Understanding and meeting regulatory requirements are crucial to avoid delays and ensure the sustainable use of biomaterials. Moreover, limited awareness and understanding of biomaterials among construction industry professionals and consumers also pose a challenge (Liu et al. 2022b; Osman et al. 2022). Building consumer awareness and educating stakeholders about biomaterials' environmental benefits and performance capabilities are essential to foster market penetration and broader use in construction projects. Finally, scaling up production is vital to meet the increasing demand for biomaterials (Orejuela-Escobar et al. 2021). This requires substantial investments in research and development, production facilities, and infrastructure. Futhermore, scaling up production is also crucial to ensure a consistent and reliable supply of biomaterials, making them more accessible and cost-effective for the construction industry.

Therefore, addressing these challenges necessitates collaborative efforts from researchers, manufacturers, policymakers, industry stakeholders, and consumers. By collectively overcoming these obstacles, biomaterials can become a central pillar in creating a more sustainable and resilient construction industry, contributing to a greener and healthier built environment for future generations. With a focus on optimizing production, meeting performance standards, navigating regulations, raising awareness, and scaling up production, biomaterials can pave the way for a more sustainable and eco-conscious future in construction.

Table 1 Benefits and challenges of various biomaterials in the building sector

Types of biomaterials	Benefits	Challenges	Key findings	Reference
Bioplastics	Sustainability, reduced carbon footprint, contributed circular economy	Higher production costs	Derived from renewable resources such as corn, sugarcane, and algae, bioplastics offer a sustainable alternative to petroleum-based plastics. Their biodegradability not only reduces plastic waste but also minimizes their environmental footprint	Oberti and Paciello (2022)
Biocomposites	Sustainability, reduced carbon footprint	Meeting industry performance standards, commercial viability	By blending natural fibers such as hemp, bamboo, flax, or kenaf with biopolymers, biocomposites form lightweight yet robust materials well-suited for structural elements and interior finishes. They play a pivotal role in conserving resources and diminishing the reliance on conventional materials	Ahmad et al. (2021)
Biocement and geopolymers	Sustainability, reduced carbon footprint	Complex regulatory compliance, ensuring consistent performance	Biocement incorporates biological additives or microorganisms to enhance cement properties, reducing carbon emissions during production. Geopolymers use industrial by-products or waste materials as binders, offering lower carbon emissions and environmental impact than ordinary Portland cement	Gebru et al. (2021)
Mycelium-based materials	Sustainability, reduced carbon footprint, contributed circular economy	Scaling up production, limited awareness and understanding	Utilizing the root-like structure of fungi, mycelium-based materials are grown within molds to form biodegradable and lightweight structures. They are used for insulation panels, packaging, and even furniture, contributing to circular economy principles	Alemu et al. (2022)
Cellulose-based materials	Sustainability, reduced carbon footprint, improved indoor air quality, improved energy efficiency	Commercial viability, meeting industry standards, regulatory compliance	Derived from plant cell walls, cellulose-based materials are used for insulation, cladding, and acoustic panels. They improve energy efficiency and indoor air quality while reducing environmental impact	Kausar et al. (2023)

This table presents six types of biomaterials utilized in construction: bioplastics, biocomposites, biocement, geopolymers, mycelium-based materials, and cellulose-based materials. These biomaterials confer distinct advantages, including enhanced sustainability, a diminished carbon footprint, and superior indoor air quality. Nonetheless, there are hurdles to their widespread adoption, encompassing elevated production costs, adherence to industry norms, and rigorous regulatory compliance. By integrating these biomaterials into construction, there is potential for substantial resource conservation, facilitating a circular economy, and fostering more ecologically sustainable building practices

In summary, this section shows that biomaterials offer a sustainable and transformative solution in construction, derived from renewable resources and showcasing nature's diverse potential. Despite their benefits, challenges include commercial viability, meeting performance standards, regulatory compliance, and limited awareness. Collaborative efforts are essential to overcome these hurdles and realize the full potential of biomaterials, fostering a greener and resilient construction industry for a sustainable future.

Case studies

Biomaterials hold the potential to revolutionize the construction industry, offering ecologically sustainable and efficacious substances (Yadav and Agarwal 2021). Several exemplary case studies underscore the feasibility of employing biomaterials for diverse structural elements. For instance, Choi et al. (2023) embarked on restoring a centennial edifice in South Korea, employing bio-based resources. They improved the structure's energy efficiency and acoustic ambiance by repurposing coffee waste sourced from local cafes. Outcomes revealed a remarkable 9% reduction in total heating energy consumption, plummeting from 18,221 to 16,634 kWh. This salutary environmental impact concurrently influences the economic outlay of building energy usage during operation. Additionally, computational simulations were executed to scrutinize the sound pressure levels inside the structure. In the realm of mid-frequency acoustics, the sound pressure levels diminished by as much as 7.39%, signifying a significant shift from 75.15 to 70.1 dB. Furthermore, the sound absorption coefficient of the coffee waste panels exceeded that of the ceiling by approximately 5 times to 9 times. Incorporating bio-based materials yielded conspicuous enhancements in this venerable architectural gem's energy efficiency and acoustic attributes.

In addition, in the research conducted by Niyasom and Tangboriboon (2021a), eggshells sourced from Thailand were introduced as an adjunct to conventional concrete. Following customary curing procedures, the findings revealed that the water absorption rate of concrete enriched with eggshell powder stood at a mere 1.62 ± 0.16%, marking a 40% reduction compared to its eggshell-free counterpart. This underscores powdered eggshell concrete's commendable durability, water resistance, and chemical resilience in juxtaposition with standard concrete. Experimental results elucidated that the mechanical attributes of the eggshell-infused concrete specimen and the control group were 55.68 ± 1.64 kN and 22.08 ± 0.66 MPa, respectively, as opposed to 49.35 ± 5.81 kN and 19.42 ± 2.25 MPa, consecutively. Whether evaluated in terms of maximum load or compressive strength, the eggshell-derived bio-based materials integrated into the composite concrete exhibited superior performance, fostering durability, environmental stewardship, long-term utility, and the promotion of sustainable concrete development. The outstanding physical and mechanical properties exhibited by eggshell concrete may serve as a pivotal factor in mitigating the maintenance costs associated with concrete structures.

Additionally, in their research endeavor, Ramírez et al. (2018) illuminated that polyurethane-coated hydrangea stems could function as a bio-based insulation material, thereby augmenting building energy efficiency. The findings indicate that commonly used polyurethanes and polystyrene endured low compressive stresses of only 0.3 and 0.1 MPa, respectively. In contrast, biomaterials exhibited significantly higher compressive stresses, reaching approximately 0.5 MPa. This represents a substantial improvement, approximately 1.7 times higher for the former and an impressive 5 times higher for the latter. Furthermore, the thermal conductivity of polyurethane-coated hydrangea stems surpassed that of polystyrene and uncoated polyurethane by 18.5 and 16.3%, respectively.

Moreover, on a global scale, nations invest significant resources in restoring fissures within existing concrete structures, making the application of fungi in concrete crack repair a topic of scholarly intrigue (Lee and Park 2018). Menon et al. (2019) elucidated that the emergence of cracks prompts water ingress into the concrete, stimulating the activation of dormant fungal spores residing on the concrete's surface. This activation, in turn, catalyzes the precipitation of calcium carbonate, thereby facilitating the remediation of these fissures. Employing fungi for concrete crack repair to curtail labor and time expenses associated with conventional repair methodologies has garnered empirical validation (Danish et al. 2020). Nevertheless, it is imperative to note that, presently, fungal interventions are limited to restoring small concrete cracks measuring less than 0.8 mm in width (Feng et al. 2021; Kurtis et al. 2017). Research efforts are ongoing to develop techniques suitable for addressing larger-scale fissures.

Overall, Table 2 presents four bio-based materials employed in engineering projects. Coffee waste composite boards manifest noise reduction and thermal insulation attributes among these. Concrete enhanced with eggshell powder demonstrates exemplary mechanical and physical prowess. The utilization of polyurethane-coated hydrangea stems as a bio-based material provides insulation capabilities. Additionally, integrating fungi into concrete yields bio-based materials with repair functions.

Table 2 Case studies of biomaterials used in building sector

Biomaterial	Country	Analytical approaches and tools	Production method	Mechanical properties	Physical properties	Environmental impact	Economic impact	Reference
Utilization of coffee waste composite boards in timber structures	South Korea	Design builder simulation and computer simulation analysis	Uniform mixing, heating (at 120 ℃), and pressurization (at 30 kPa)	Not applicable	The coffee waste composite board exhibited a significant decrease in sound pressure level up to 7.39% at medium frequency. Its latent heat capacity was measured at 842 J/g within the phase transition range	Buildings have reduced heating energy consumption by approximately 4% to 9%	Reducing the operational costs of commercial activities within the building	Choi et al. (2023)
Eggshell powder as an additive for concrete	Thailand	Scanning electron microscope and X-ray diffractometer	Grinding of eggshells for 90 min, mixing and stirring for 5–10 min, and waiting for curing	The eggshell concrete samples exhibited the highest maximum load and compressive strength, measuring 55.68 ± 1.64 kN and 22.08 ± 0.66 MPa, respectively	After 28 days of curing, the eggshell concrete samples had a water absorption rate of 1.62 ± 0.16%, which was 40% lower than the control group	Not applicable	Not applicable	Niyasom and Tangboriboon (2021a)
Hydrangea stem as an insulation material for buildings	Chile	Scanning electron microscope, fourier transform infrared spectroscopy and decagon devices	Spraying hydrangea stem with commercial polyurethane coating	The compressive stress of hydrangea stem coated with commercial polyurethane is 5 times that of expanded polystyrene and 1.5 times that of commercial polyurethane	Not applicable	Reducing the demand for polyurethane in buildings helps decrease its production, thereby avoiding the generation of exhaust gases and wastewater during manufacturing	Assisting buildings in reducing the cost of using commercial polyurethane blocks	Ramírez et al. (2018)

Table 2 (continued)

Biomaterial	Country	Analytical approaches and tools	Production method	Mechanical properties	Physical properties	Environmental impact	Economic impact	Reference
Utilizing fungi for concrete crack repair	United States of America	X-ray diffraction, scanning electron microscope, and transmission electron microscope	Injecting or spraying fungal spores and nutrient substrates into cracks	Not applicable	Fungi assist in the repair of concrete cracks by inducing the process of biologically and organically mediated mineralization, which leads to the precipitation of calcium carbonate	Not applicable	Lowering the labor-intensive and costly workforce required for the continuous inspection and maintenance of concrete infrastructure	Menon et al. (2019)

This table enumerates four bio-based materials used in engineering endeavors. Specifically, coffee waste composite boards exhibit both noise-reducing and thermally insulating properties. Concrete fortified with eggshell powder showcases superior mechanical and physical characteristics. The use of polyurethane-coated hydrangea stems offers notable insulation benefits. Furthermore, embedding fungi within concrete produces bio-based materials equipped with self-repairing capabilities

Despite the myriad advantages of using bio-based materials in construction, encompassing environmental sustainability, enhanced health outcomes, and economic benefits, their integration also present challenges. Chief among these concerns is the apprehension surrounding the durability and longevity of bio-based materials. Many of these substrates fail to attain the same levels of resilience and longevity as their conventional construction counterparts. They often exhibit susceptibility to factors such as biodegradation, insect infestation, and humidity, thereby engendering potential hazards to the structural robustness and longevity of edifices constructed from these materials (Rabbat et al. 2022). Moreover, Williams (2019) underscored that a substantial challenge in the current milieu of bio-based materials revolves around the vexing issue of standardization.

Presently, most nations or regions grapple with the absence of a cohesive and unequivocal framework of standards, thereby neglecting to delineate the corresponding performance requisites for bio-based materials within these frameworks (Chen et al. 2023b). This dearth of lucidity impedes the discernment and adoption of bio-based materials. Furthermore, extant building codes and regulations predominantly favor using conventional construction materials, posing a formidable impediment for architects, engineers, and contractors in their endeavors to confidently embrace bio-based materials. Additionally, the procurement of bio-based materials introduces another substantial challenge when employed in construction. The processing methodologies requisite for these materials necessitate specialized expertise and knowledge, consequently influencing construction expenditures and timelines. Moreover, the dearth of well-developed processing technologies continues to encumber the large-scale production and utilization of bio-based materials in the realm of construction (Lee et al. 2022).

This section discusses using bio-based materials in construction through various case studies, highlighting their potential to improve environmental sustainability and building performance. Examples include coffee waste composite boards for sound and energy benefits, eggshell powder-enhanced concrete with improved mechanical properties, hydrangea stem insulation material, and fungi-assisted concrete crack repair. Despite their advantages, challenges such as durability concerns, lack of standardization, regulatory barriers, and processing complexities hinder their widespread adoption in the construction industry.

Policy and regulatory framework

Policy and regulation of bio-based building materials

The construction industry is an essential sector for national economic growth, but it is also a consumer of natural resources and a producer of pollution emissions (Agboola et al. 2021). The greenhouse gas emissions generated by manufacturing building materials account for 5–12% of the global total greenhouse gas emissions (Masson-Delmotte et al. 2021). Fig. 2 shows the development trend of the global construction industry in 2021 compared to 2015. According to statistics, the amount of waste biomass generated by major crops has reached 3300 megatons. Effectively managing this surplus biomass presents a significant societal challenge (Wu et al. 2023). In the European context, it is evident that construction operations account for a substantial share of resource consumption, including approximately 37.5% of wood, 21% of steel, 65.5% of glass, and 75% of concrete (Geldermans et al. 2016).

Therefore, it is necessary to transform the traditional construction industry into a circular construction approach (Ghaffar et al. 2020). Utilizing biomaterials within the construction sector is a viable approach toward attaining a circular economy and fostering environmental sustainability. Various nations across the globe have devised numerous ways to resolve this predicament. The 2018 European Union Bio-economy Strategy emphasized the imperative of substituting fossil-derived resources within the building sector. It underscored the role of bio-based materials in facilitating the reduction of petrochemical usage within the industrial domain (European Commission 2018). The proposed revision of the European Union Building Product Regulation is an industry-specific measure and part of a series of sustainable product initiatives. The rule incorporates strategies grounded in circular economy principles, such as using recyclable resources and implementing recycling practices for generated products (Duque-Acevedo et al. 2022).

Figure 3 provides an overview of the proportion of buildings in the total final energy consumption for the year 2021, along with the construction industry's impact on global energy consumption and industrial emissions. Notably, in residential buildings across European Union member states, a prevalent issue is the suboptimal thermal efficiency of their building envelopes, adversely affecting the demand for space heating (Ahern and Norton 2020). It is worth noting that within the total building stock, measuring 25 billion m^2, approximately 75% is designated for residential use.

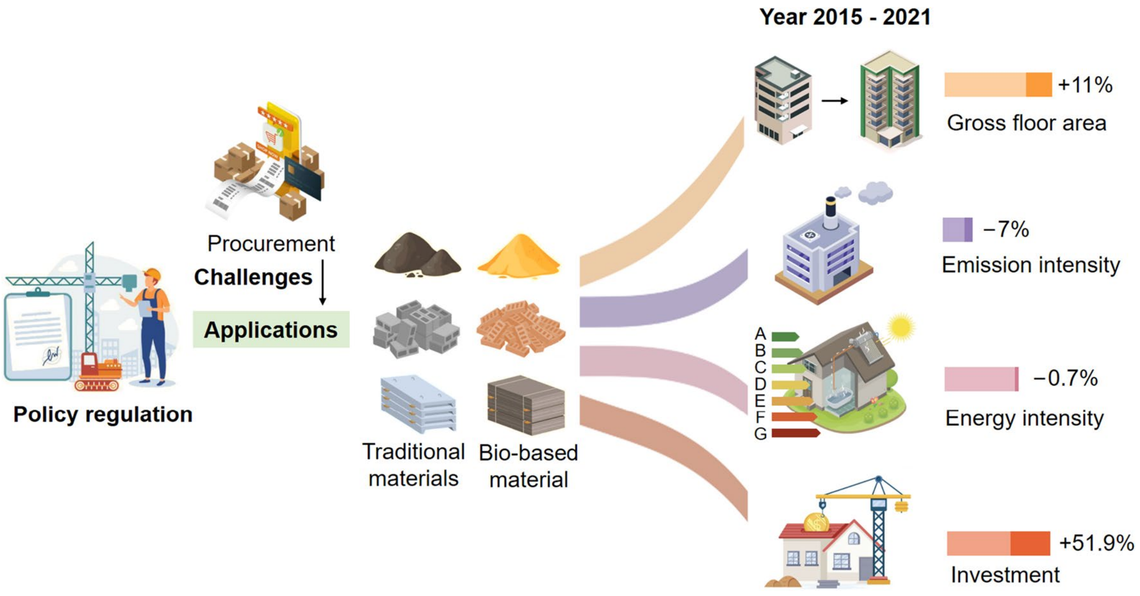

Fig. 2 Impact of policies and trends on bio-based building materials. This figure illustrates that the integration of bio-based building materials necessitates a comprehensive framework of policies and regulations for effective implementation. Presently, procuring these materials on a grand scale presents a significant hurdle when juxtaposed with conventional building materials within the construction sector. The enactment of such policies and regulations exerts a profound influence on the construction landscape. A comparative analysis of the industry's evolution between 2015 and 2021 reveals a notable 7% reduction in emissions attributable to construction activities, alongside a marginal decrease of 0.07% in energy intensity. Concurrently, the overall constructed area has witnessed an 11% augmentation, and there has been a substantial 51.9% surge in the total financial investment in the construction domain

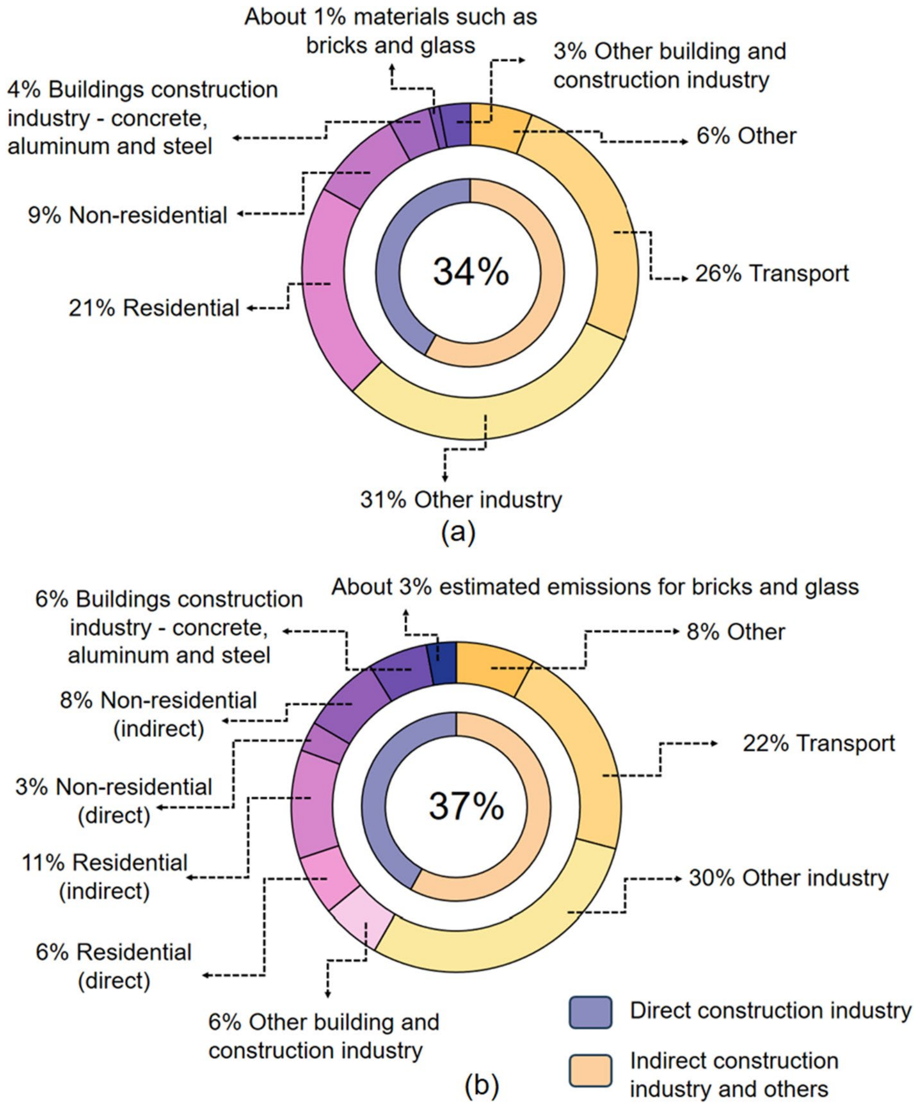

Fig. 3 Energy consumption and emission contributions in the building construction industry. **a** The share of buildings in the total final energy consumption in 2021; **b** the share of the construction industry in global energy and industrial emissions in 2021. The figure presents a pie chart differentiating between direct and indirect construction. In this context, "direct construction" refers to the immediate discharge directly employed in construction processes. On the other hand, "indirect construction" encompasses the comprehensive process of infrastructure development and the creation of building materials, spanning from raw material acquisition through to manufacturing, all rooted in foundational building principles. It is important to note that the numerical values depicted in the chart have been rounded for clarity; hence, they should not be summed to derive a total value

This residential sector accounts for about 22% of energy consumption (Loga et al. 2016). In the European context, heating is the primary energy-consuming activity, making up a substantial 71% of the total energy consumption in households. Implementing residential renovation projects to reduce primary energy consumption is a critical strategy in the European Union's endeavors to combat carbon emissions (Passer et al. 2016).

In the coming decades, most residential buildings in the European Union's 28 countries are expected to undergo renovations. To achieve the goal of controlling the increase in global temperature to less than 2 °C by 2050 and to endeavor to limit it to 1.5 °C compared with the pre-Industrial revolution level, as the Paris Agreement requires. The study by Pauliuk et al. (2013), to some extent, suggests that even the most optimistic scenario for building energy efficiency is difficult to achieve the goals of the Paris Agreement. Therefore, carbon capture and storage technology is critical (Rockström et al. 2017). Using timber construction and biologically derived materials presents a viable approach for enhancing the energy efficiency of buildings, enhancing the visual appeal of outside walls, and particularly for sequestering substantial quantities of carbon (Gustavsson et al. 2017).

In the construction industry, the production and use of biomaterials are influenced by policies and regulatory frameworks. In this context, Economidou et al. (2020) reviewed the European Union's policies on building energy efficiency over the past 50 years. The concept of the bioeconomy underscores the importance of sustainability and circularity in the use of biomaterials within the construction industry (Wydra 2019). Regulations directly associated with biomaterials pertain to biomass waste management, mainly stemming from agriculture, forestry, and household organic sources. To some extent, these waste regulations have implications for the policy landscape surrounding biomaterials. Within the European Union, a regulatory framework addressing waste and by-products has been established through the Waste Framework Directive (Philp 2018).

This classification imposes administrative and financial burdens on government structures to a certain extent and hinders investment in hostile existing business practices (Fava et al. 2015). In order to ensure the application rights of biotechnology, more efforts are needed to promote and strengthen cooperation and partnerships between technology providers, the private sector, and policy makers (Lokko et al. 2018). For policymakers, policies in regional development, national research and development, and global sustainability require sufficient flexibility and consistency across borders to prevent bottlenecks and barriers (Philp 2018). Biotechnology innovation reduces dependence on oil and fossil fuels, positively impacting the environment. The integration of certain biotechnological practices has become commonplace in industrialized nations. However, in numerous developing countries, the uptake of modern biotechnology as a means to foster consistent industrial development lags significantly behind (Lokko et al. 2018).

In summary, the impact of policies and regulations on adopting biomaterials is significant. The policy and regulatory framework aims to ensure that the production and use of biomaterials meet standards, reduce environmental and human health risks, and promote a more sustainable transformation of the construction industry. Firstly, policies incentivize the construction industry to seek more environmentally friendly and sustainable biomaterials, promoting material innovation and technological development. However, policies may also limit traditional building materials, and the construction industry may face procurement and application challenges. Therefore, when formulating policies, the government should balance all parties' interests and ensure the policies' rationality and enforceability.

Impact of policy and regulations on the adoption of biomaterials

The circular economy is a novel concept based on sustainable principles for resource optimization and recycling (Geissdoerfer et al. 2017). Embracing a circular economy approach within building biomaterials can be vital in averting irreversible damage. Utilizing bio-based materials and tailoring products to meet user requirements has demonstrated its effectiveness as a strategy for waste reduction and diminishing ecological footprints (Willskytt and Tillman 2019). Construction and real estate may be the most resource-intensive industries, consuming many materials and energy throughout their entire life cycle. Establishing an elastic and efficient circular supply chain is crucial for achieving a circular economy in the construction industry (Nasir et al. 2017). As one of the most influential industries in the world, decarbonization in the construction industry requires a significant paradigm shift from a linear economy to a circular economy and a sustainable economy oriented toward the future (Passoni et al. 2022). The application of biomaterials in the process of circular economy may help the construction industry achieve its sustainability and decarbonization goals from a life cycle thinking perspective (Dewagoda et al. 2022). More natural fiber-reinforced polymer materials have been developed in the past two decades for sustainability considerations. The natural fiber-reinforced composite material market is expected to reach over 3730 tons by the end of this year, and the composite annual growth rate is expected to exceed 9% during the forecast period (Intelligence 2023).

As shown in Fig. 4, providing accurate information to stakeholders is essential in achieving the application of biological building materials and decarbonization of the building materials industry. The government's policies encourage the construction industry to seek more environmentally friendly and sustainable building materials. To facilitate the effective implementation of a circular economy within the construction industry, it is imperative to incorporate social and economic considerations into the research framework. Furthermore, developing circular value chains through stakeholder collaborative efforts is crucial (Hossain et al. 2020). Formulating policies and regulations can be a robust driver for increasing market demand for biomaterials, ultimately contributing to sustainable bio-economy development (Aguilar et al. 2019).

Additionally, certain policies may restrict the utilization of traditional building materials, particularly those with high carbon emissions (Yang et al. 2023). These constraints compel construction companies to transition toward more environmentally friendly biomaterials to comply with policy requirements. Biomaterials, sourced from renewable resources, exhibit reduced carbon emissions in both their production and utilization, effectively reducing the construction industry's carbon footprint (Biswal et al. 2020). Not only do these materials contribute to lower carbon emissions, but they also offer a promising avenue for reducing overall waste in the construction process. As construction companies increasingly recognize the economic and environmental advantages of biomaterials, a gradual paradigm shift is underway, reshaping industry standards and paving the way for a more sustainable and ecologically conscious construction landscape.

In summary, policies and regulations profoundly impact the adoption of biomaterials in the construction industry. The support of policies and regulations has stimulated the development of the biomaterials industry and driven the expansion of related industrial chains. The industrial links

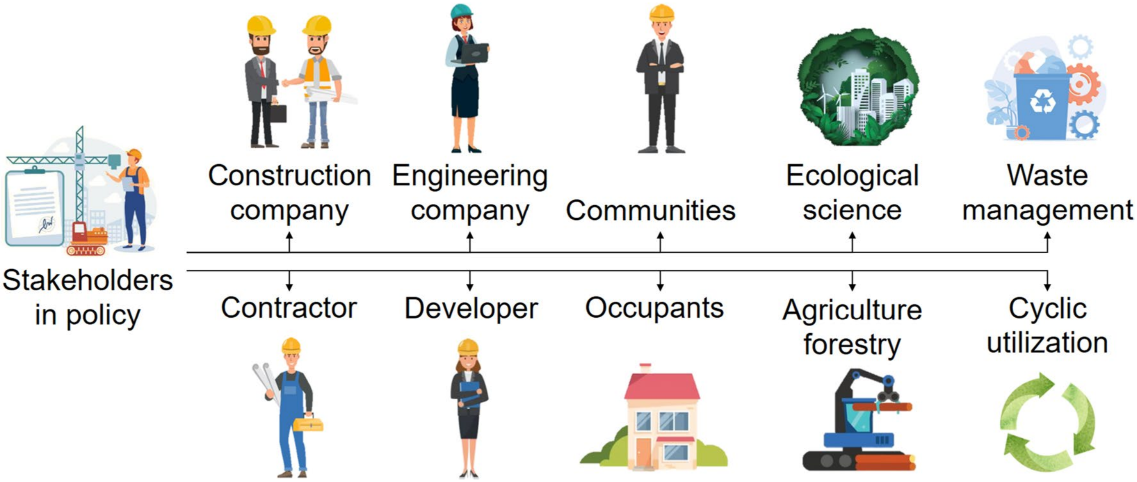

Fig. 4 Strategies for biomaterial integration and life cycle considerations in the low-carbon buildings. This figure shows the multifaceted strategies essential for transitioning to a low-carbon building milieu through biomaterial usage. It underscores the importance of strategies being deeply embedded in life cycle considerations and systematic thinking from an owner's perspective. The emphasis is the necessity for both financial and legislative stimuli to extend the lifespan of structures, thereby fostering the adoption of biomaterials in low-carbon renovations and refurbishments. The diagram also stresses the need for all stakeholders in the building materials sector to fully comprehend the environmental impact of their material choices across the building's life cycle. To ensure this comprehensive understanding, the figure illustrates the importance of providing stakeholders with accurate, timely data at critical decision points

in biomaterials' cultivation, extraction, processing, and final construction application have been promoted and developed. Through policy guidance and incentives, biomaterials have been widely applied, promoting innovation and development of biomaterial technology. This policy support has helped drive the construction industry toward a more environmentally friendly and sustainable direction, positively contributing to a more sustainable future.

Optimal approaches and insight learned from policy implementation

In pursuing sustainable development, various institutions, including the United Nations Environment Programme, the World Bank, and the European Commission, have put forth the concept of green economy and green growth to sustain economic activities. The objective is to enhance human well-being and social equity by maximizing resource efficiency and minimizing resource consumption. The biotechnology policy was initiated by the European Union in 2002, followed by the formulation of the world's first bio-economy strategy and action plan by the European Commission in 2012 (Ramcilovic-Suominen and Pülzl 2018). The new strategy posits that the bio-economy will facilitate the enhancement and fortification of the industrial framework of the European Union by establishing novel value chains and implementing environmentally sustainable and economically efficient industrial procedures. The global demand for bio-based products is growing, and it is expected that by 2030, the European Union's demand will increase to a market value of €50 billion (Bell et al. 2018). Building environmental objectives are continuously established to mitigate the construction sector's environmental impact. One method of defining such goals is to allocate global environmental or policy goals from top to bottom. Examples of assigned and specific goals include Earth's environmental carrying capacity (Brejnrod et al. 2017). However, with the development of these goals and comparison with the impact of existing buildings, current construction practices seem unable to achieve these goals (Mouton et al. 2023).

At present, the focus of people's attention on the circular economy in the construction industry is to reduce energy consumption during the use stage and choose building materials and tools that are less harmful to the environment. Building materials require global warming potential assessment; static life cycle assessment is the most commonly used method. However, a static life cycle is not the ideal evaluation method. One of the most critical issues in quantifying the carbon footprint of products in the static life cycle is the disregard for time scales. For example, Røyne et al. (2016) analyzed the life cycle of 101 forestry products and found that 87% of studies believe that biochar is neutral, meaning there is a balance between carbon sequestration. However, such a conclusion can lead to deviations in the actual value of the static life cycle. Another method is dynamic life cycle assessment, which considers the time taken for carbon absorption of greenhouse gas emissions. Many researchers use this dynamic life cycle assessment method for building materials (Liu et al. 2019). In this context, Pittau et al. (2018) studied the effect of carbon storage in biomaterials and lime-based materials using dynamic life cycles. Zieger et al. (2020) also showed that dynamic life cycles provide a more realistic and reliable structure, as all greenhouse gas emissions and absorption take into account their temporal arrangements. Global warming potential indicators can be expressed as absolute indicators within any time range.

The typical timeframe in static life cycle assessment often spans 100 years (Lueddeckens et al. 2020). However, it is increasingly evident that considering a longer time horizon beyond 100 years is necessary. When evaluating biomaterials, relying solely on static life cycle assessments may not be sufficiently objective, as this method does not account for temporary carbon storage. In contrast, dynamic life cycle assessments offer a more equitable approach for comprehensively assessing the actual impacts of all materials, whether they are biomaterials or not. Livne et al. (2022) analyzed the prevailing cross-sectoral land use conditions in Europe to evaluate biomass availability for supply purposes. The findings suggest that the existing forests and wheat plantings can adequately provide the necessary building materials. When considering resource availability and carbon storage potential, straw emerges as a material with superior characteristics compared to wood. On the other hand, cork exhibits moderate popularity, primarily in arid regions of southern countries. Furthermore, it is worth noting that timber cultivation is also land-intensive, and without sustainable forest resource management, carbon efficiently migrates from forests to urban areas (Pomponi et al. 2020).

In summary, extracting best practices and lessons learned from policy implementation is crucial for promoting and applying biomaterials in the construction industry. Through reasonable policy guidance, active cooperation and communication, and continuous improvement, biomaterials will play a more significant role in the construction industry, promoting its development in a more sustainable and environmentally friendly direction. Knowledge sharing and exchange should be encouraged in policy implementation to promote international experience sharing. Drawing on successful cases and lessons learned from other countries and regions can help optimize domestic biomaterial policies and practices. Policy implementation is a dynamic process that requires continuous improvement and optimization. The government should continuously learn and reflect, adjust policies and measures promptly based on actual results, and ensure that policies align with industry needs.

Technological advancements

Recent advancements in biomaterials production in buildings

In recent years, the construction industry's growing global focus on energy efficiency has drawn considerable interest, primarily from using bio-based materials. Bio-based construction materials are known for their enhanced insulation capabilities, impressive mechanical characteristics, lightweight nature, and eco-friendliness (Jędrzejczak et al. 2021). The incorporation of biomaterials into architectural practices is not a recent phenomenon. However, innovative biomaterials have entered the market with the increasing understanding of microbiology and advancements in synthetic biology technology. Notable examples include self-healing concrete (Speck and Speck 2019) and mycelium insulation materials (Zhang et al. 2022). What sets these new-generation biomaterials apart is their adjustability and ability to tailor unique material properties at the molecular level. For instance, Zhang et al. (2021) designed and prepared a novel core-shell carrier to extend the survival time of microorganisms in concrete. The advancement of this technique is anticipated to facilitate the utilization of microbial self-repairing concrete within the engineering field. Meanwhile, Schritt et al. (2021) successfully developed a sustainable, low thermal conductivity mycelium insulation material using beech sawdust and waste mushroom matrices, showcasing mycelium's promising research prospects in the insulation materials realm.

The widespread use of various bio-based materials in the construction sector is extensively documented, as highlighted in Table 3. These materials typically have low environmental impact, renewability, and ecological friendliness. Different biomaterials exhibit different performances in architecture. Wheat straw, mycelium, and others have performed excellently in heat and sound insulation fields. The use of bio-based building materials can help reduce dependence on traditional non-renewable materials, reduce the environmental impact of buildings, and promote the development of sustainable buildings.

The field of fungal architecture and design is currently rapidly developing. Mycelial materials can become a part of harmful carbon-building solutions. Efforts, including biological coatings, have addressed these waterproofing and durability issues (Almpani-Lekka et al. 2021). Utilizing mycelial composite materials cultivated on straw and hemp fibers demonstrates their inherent capacity to function as organic insulators, mainly attributable to their diminished density and reduced heat conductivity (Collet and Pretot 2014). Materials with lesser density contain a

Table 3 Characteristics and performance of bio-based building materials in sustainable construction

Biomaterial	Source	Product	Process	Conclusion	Reference
Humus	Byproducts in the conversion process of polysaccharides	Polyfuryl alcohol/humic thermosetting resin	The resin was composed of furfuryl alcohol, humin, and maleic anhydride in a 40:55:5 ratios. To start, furoic acid and humus were combined, and the mixture was vigorously stirred for 20 min at 105 ℃ until it formed a consistently thick black liquid. Subsequently, 2.5% w/w maleic anhydride was introduced in two separate additions. Once the temperature had cooled to 80 ℃, a 2.5% w/w initiator was added, and the blend was stirred for 5 min	Capable of producing thermosetting materials suitable for building products	Mija et al. (2017)
Mussel shell	Mussel	Concrete aggregate	The mussel shell was treated at 132 ℃ for 32 min, and coarse and fine sand was obtained through crushing and screening	The flaky shape enhances consistency and slurry aggregate adhesion, as well as improves water permeability. The organic content will reduce the bonding between the slurry and aggregate and increase porosity, affecting hydration	Martínez-García et al. (2017)
Curauá, jute, sisal fibers	*Agave sisalana*, *Ananasectifolius*, *Corchorus capsularis*	Fiber cement-based composite materials	The ratio of adhesive to sand to water/adhesive was 1:0.5:0.4. All the dry components were homogenized in a 5 L container at a temperature of 21 ± 1 ℃. Water and a high-efficiency water reducer were added and mixed at a speed of 125 rpm for 2 min. Any remaining materials in the mixer were removed, and the mixture was further blended at 220 rpm for 2 min, followed by a final mixing stage at 450 rpm for 5 min. Subsequently, the matrix was poured into the mold	Affect keratinization on the structural attributes, tensile properties, and the adhesion between fibers and the matrix in cementitious composites incorporating sisal, jute, and hemp fibers	Ferreira et al. (2017)

Table 3 (continued)

Biomaterial	Source	Product	Process	Conclusion	Reference
Wool, hemp fibers	Sheep, hemp	Wool and hemp fiber reinforced cementitious mortar	Added wool, plasma-treated wool, hemp, and plasma-treated hemp to the mortar separately	Adding wool to cement mortar increases bending strength and ductility, while wool enhances the fracture toughness of the mortar	Fantilli et al. (2017)
Ganoderma lucidum, bamboo fiber	Fungi, bamboo slices	Composite material paste	Bamboo fiber rich in mycelium was torn from the sealed bag into smaller pieces. Chitosan solution in weight ratios of 50, 60, and 70% was added to the enriched fibers and grind with a pestle and mortar until no more visible clumps were visible, forming a uniform mixture. A serum syringe with a tip diameter of 6 mm was used to manually extrude into a 5 cm-long pillar. Then, let the mycelium grow on the extruded pillar in the air at 23 ± 0.5 ℃ and 65–70% humidity for 20 days	Using extrudable compositions to construct composite materials that combine mycelium can achieve complex molding and design. The developed composition is expected to further explore the use of mycelium-binding materials in the structural application of agricultural waste	Soh et al. (2020)
Pleurotus ostreatus	*Pleurotus ostreatus*	Mycelial composite insulation brick	Filter patch bag containing 454 g of rye berries was sterilized at 121 ℃ for 2.5 h. After 7 days, the mixture of fungal strains and raw materials was removed from the bag and manually ground and homogenized. Then, 40, 42, and 45 g of mycelial raw materials were transferred to sterilized silica gel grinding tools for a 4-day growth period. Finally, the bricks were placed in an oven at 65 ℃ for 24 h to eliminate any living microorganisms in the mycelial composite material	The use of mycelium composite materials for building insulation reduces indoor temperature fluctuations. The natural growth of mycelium composite materials is expected to provide sustainable building insulation materials	Zhang et al. (2022)

Table 3 (continued)

Biomaterial	Source	Product	Process	Conclusion	Reference
Algae oil	*Schizochytrium sp.*	Biocarbamate-modified isocyanurate foam	They stirred the epoxy resin and/or polyols together for 10 s. Then, the water foaming agent, surfactant, catalyst, and physical foaming agent were added sequentially, stirring for 10 s to homogenize the mixture. Afterward, pre-weighed isocyanates were quickly added to the mixture, and the reaction mixture was stirred for 10 s. The foam was allowed to rise freely and left overnight at room temperature for curing before demolding	All elaborate foams are close to carbamate-modified isocyanurate foam in terms of kinetics and morphology	Arbenz et al. (2018)

This table categorizes various bio-based building materials, highlighting their low environmental impact, renewability, and eco-friendliness. It delineates the unique architectural performances of different biomaterials. For example, the table shows how wheat straw and mycelium excel in heat and sound insulation. By featuring these materials, the table underscores the dual benefits of reducing dependence on traditional non-renewable materials and lessening the environmental footprint of structures, thereby contributing to the development of sustainable building practices

significant quantity of dry air within the free air space, reducing heat conductivity. The attribute mentioned above renders materials possessing reduced density highly effective as insulators.

Utilizing mycelium-based biological foam exhibits significant promise for serving as an alternative insulation material in construction and infrastructure development (Yang et al. 2017). Furthermore, mycelium materials offer thermal and acoustic insulation properties, along with robustness and excellent fire resistance, rendering them a viable substitute for conventional building materials (Bitting et al. 2022; Manan et al. 2021). Polyurethane foam has been empirically demonstrated to possess commendable reliability and efficiency as a thermal insulation substance, rendering it suitable for producing insulation panels for floors, walls, and roofs. Andersons et al. (2020) developed a rigid high-density polyurethane foam containing bio-based polyols prepared from tall oil fatty acids.

Concrete is usually reasonably durable, but over time, it can crack, especially under humid conditions, which can corrode embedded steel bars, especially in water-based structures. It is also susceptible to damage from extreme temperatures, chemicals, and weather erosion. Barbieri et al. (2020) designed insulating lime concrete using raw wheat husks and compared it with hemp fiber concrete prepared using the same process. They found that raw wheat husks have great potential in applying bio-based materials. Using natural fibers, especially water hyacinth and bananas, as reinforcement materials in the construction industry have always been a hot research topic (Salas-Ruiz et al. 2019). Water hyacinth fiber and banana fiber both consist of cellulose fibers that are hollow and held together by lignin, cellulose, and hemicellulose matrix (Gowthaman et al. 2018). Cellulose and hemicellulose could confer tensile strength and moisture absorption properties to materials, whereas lignin imparts resistance against biodegradation (Bordoloi et al. 2018; Gowthaman et al. 2018). Okwadha and Makomele (2018) and Ramesh et al. (2017) found that water hyacinth extract can be used as a high-efficiency water-reducing agent to produce self-compacting concrete. Niyasom and Tangboriboon (2021b) confirmed this viewpoint by adding water hyacinth fiber, banana fiber, and eggshell powder to study the optimal formula for a concrete composition.

Fiber-reinforced polymer composites are known as biocomposites, which can be obtained from biomass or microorganisms, as well as synthesized from petroleum-based chemicals or bio-derived monomers (Gurunathan et al. 2015). Structural and engineering applications have utilized natural fiber composite materials to construct load-bearing structures, including beams, roofs, multipurpose panels, water tanks, and pedestrian bridges (Al-Azad et al. 2021). Nwankwo et al. (2023) showed that flax and jute are the most commonly used natural fibers, and epoxy resin is the most commonly used matrix in bio-based fiberglass composites. The durability of bio-based composite materials for structural applications needs further evaluation. Limaiem et al. (2019) found that fiber-reinforced polymer composites could increase the strength of damaged concrete by 150% and provide confined concrete samples with excellent ductility.

Compared with traditional building materials, bio-based materials developed using hemp stems, flax stems, and other materials are widely used in the research of thermal insulation building materials due to their hygrothermal properties. The chemical composition of bio-based materials is also believed to have a certain inhibitory effect on mold growth (Viel et al. 2019). Humus is derived via the process of acid treatment of polysaccharides and demonstrates intriguing prospects as a reactive, semi-ductile thermosetting matrix that is infused with cellulose fibers. Furthermore, incorporating humus has been found to enhance both the modulus and tensile strength of pure polyfurfuryl alcohol resin (Mija et al. 2017).

Pittau et al. (2018) showed that storing carbon in rapidly growing biomaterials is more effective than storing carbon in wood elements. Pittau et al. (2019) studied the carbon storage effect of bio-based building products when renovating existing facades. They found that rapidly growing bio-based materials have higher carbon sequestration potential than wood. In recent years, there has been a growing utilization of bioresins derived from polyfurfuryl alcohol, obtained from agricultural waste, in developing composite materials for civil engineering purposes. Carbon fiber-reinforced polymers have also emerged as a popular choice for structural reinforcement in various civil engineering applications, offering a diverse array of technical solutions.

Nevertheless, it is essential to note that bio-based epoxy resins have emerged as a potential alternative to address the issues of cost and environmental impact associated with conventional epoxy resins (Viretto and Galy 2018). Polyurethane, an essential polymer extensively employed in the construction sector, finds versatile applications in insulation, sealants, adhesives, concrete joints, and protective coatings (Somarathna et al. 2018). However, this polymer is obtained from isocyanates, and several researchers are working on developing bio-based polyurethane. Prociak et al. (2017) synthesized porous polyurethane composites using two rapeseed oil-based biopolyols. Kurańska et al. (2020) compared polyurethane synthesized from two different materials, lignin and rapeseed.

In summary, as the demand for sustainable building practices rises, ongoing research in biomaterial technology is anticipated to unlock even more environmentally conscious solutions, fostering a dynamic landscape where construction not only meets modern standards but actively contributes to mitigating environmental impact. The most recent advancements in manufacturing biomaterials in construction include mycelium materials, bioconcrete, natural fibers, and fiber-reinforced composite materials. These innovative biomaterials provide more ecologically friendly and sustainable options to the building sector and provide architects and designers with greater creative room. The construction industry is expected to bring more innovation, support the further integration of sustainable building concepts into practice, and create a better living environment for humanity in the future with the continuing evolution and use of biomaterial technology.

Potential impact of technological advancements on the biomaterials

The surge in demand for bio-based composite materials, particularly in response to the rising need for environmentally friendly options in the electronics industry, is fueling the growth of the natural fiber-reinforced composite material market (Mohanty et al. 2018). However, challenges like hygroscopicity, restricted processing temperatures, compatibility issues with most polymer matrices, and lower impact resistance compared to glass fiber-reinforced composites may impede the market's progress (Balla et al. 2019). Technological progress can improve biomaterials' production methods and processing techniques, thereby enhancing their performance and durability. This advancement may involve augmenting biomaterials' strength, stability, and thermal insulation capabilities, rendering them more suitable for various construction applications (Chen et al. 2020a). Some emerging biomaterials possess self-repairing or adaptive properties, a current research focus. Empowering biomaterials with the capacity to self-repair and adapt extends the lifespan of construction materials and reduces maintenance costs (Kumar et al. 2023).

Table 4 underscores the pivotal role of technological advancements in reshaping the utilization of biomaterials within the construction sector. These advancements have fostered refinements and enhanced efficiency in producing and processing biomaterials. Moreover, they have been instrumental in elevating the performance characteristics of biomaterials. Furthermore, these technological strides have been crucial in bolstering the sustainability of biomaterials. Collectively, technological progress has ushered in a promising era for biomaterial adoption in the construction industry, amplifying the integration of innovation, sustainability, and environmental considerations in building design and construction practices.

In the past decade, nanotechnology advancements have set the stage for significant progress in novel and enhanced biopolymer materials Mishra et al. (2018). A focal point of

Table 4 Evolution and impact of technological advancements in biomaterials for construction

Biomass	Product	Conclusion	Potential impact	Reference
Waste edible oil residue	Bioasphalt	Bio-oil has good potential as a bio asphalt binder	Material performance improvement	Sun et al. (2017)
Natural fiber	Natural fiber-reinforced polymer composites	Structural optimization of plant natural fiber reinforced polymer composites is expected to achieve sustainable lightweight buildings	Innovative structural design	Sippach et al. (2020)
Lignocellulose	Light wood foam	Lignin has the potential to enhance the structural integrity of foam, resulting in equivalent thermal insulation capabilities between wet and dry lignocellulose foam and dry polystyrene foam	Energy saving	Lohtander et al. (2022)
Bacillus pseudomycoides strain	Bacterial concrete	Use *Bacillus pseudomycoides* to repair concrete cracks; cracks heal after 68 days, but the healing rate is limited in deeper parts	Self-repair and adaptability	Algaifi et al. (2021)
Mycelium	Mycelial composite material	We have developed a multifunctional mycelium composite material for robotic abrasive wire cutting in biological and digital manufacturing pipelines	Digital construction and prefabrication	Elsacker et al. (2021)
Bio-based polyethylenes, thermomechanical pulp	Biocomposite materials	Thermomechanical pulp fibers can promote 3D compliance and improve the mechanical properties of biological composite materials	Customizable and personalized	Tarrés et al. (2018)

This table encapsulates the significant strides in technology that have augmented the production, processing, and overall efficacy of biomaterials. It illustrates the evolution of these materials into more refined and efficient forms, emphasizing their enhanced sustainability. The table portrays the consequent rise in potential for biomaterial adoption within the construction industry. It highlights how this integration spurs innovation, bolsters sustainability, and intensifies the focus on environmental aspects in both the design and execution of building projects contemporary nanotechnology research involves the exploration of cellulose constituents at the one-dimensional scale, ranging from 1 to 100 nm, with the potential to revolutionize the development of eco-friendly, high-performance materials (Xu et al. 2021). Cellulose, the most prevalent organic polymer on Earth, is capable of cost-effective industrial-scale processing, making it a promising candidate for green biotechnology applications in future building materials (Shogren et al. 2019). With its substantial market potential, surpassing 4 million tons, the cement industry stands as a lucrative avenue for integrating nano cellulose. Furthermore, cellulose aerogel is promising for advancing high-performance thermal insulation materials within the construction sector (Dufresne 2019).

Technological progress can improve the insulation performance and energy efficiency of biomaterials, helping to reduce building energy consumption. The renewable and eco-friendly properties of biomaterials can also reduce the impact of buildings on the environment, in line with the principles of sustainable architecture. One notable aspect of biotechnology in energy-efficient settings is the generation of bioenergy using integrated microalgae photobioreactors installed on external walls or rooftops (Talaei et al. 2020). The utilization of microalgae for biofuel production can be dated back to the 1980s and has garnered growing interest in response to the escalating need for sustainable energy sources (Abbasi et al. 2021). In contrast to other biofuel sources, microalgae stand out due to their high oil content and remarkable growth rate, capable of doubling their biomass in just 24 h. While runway ponds have lower construction and operational costs than photobioreactors, they are less productive (Xu et al. 2019). The building microalgae photobioreactor closely resembles its industrial counterpart and serves the purpose of microalgae cultivation (Elrayies 2018). The novelty of this technology resides in its seamless incorporation within the field of architecture. Photobioreactors designed for buildings can harness a range of microalgae species and pigmentation, enabling dynamic shading effects by manipulating algal concentrations or water levels.

In summary, technological advancements have potential positive impacts on adopting biomaterials in the construction industry, including innovative design capabilities, increased strength and stability, enhanced environmental friendliness, improved degradability and recycling, increased functionality, and data-driven innovation. However, while realizing these potential impacts, addressing the relevant technical, economic, and regulatory challenges is also necessary. New green synthesis methods and production technologies can reduce the environmental impact during the manufacturing process of biomaterials. Technological progress has improved the degradability of biomaterials, which helps reduce the burden on the environment. Some biomaterials can be recycled after their lifespan, promoting the development of the circular economy.

Emerging technology

Utilizing the biosynthetic ability of microorganisms to produce biomaterials is an emerging trend. However, producing mycelium materials from biological sources often entails complex and challenging extraction processes (Bitting et al. 2022). While mycelium offers potential solutions to various environmental issues, regulating product quality and reducing production costs remain significant challenges in its development (Haneef et al. 2017). The progressive expansion of the fungal mycelium facilitated the integration of the matrix particles, forming a cohesive composite material. Concurrently, the mycelium occupied the void spaces, effectively filling them. Subsequently, this composite material was shaped using a mold and subsequently subjected to a drying procedure, which arrested the organism's growth by inducing dehydration (Elsacker et al. 2020).

Recent advancements in fermentation technology have opened up promising possibilities for practical applications. However, further refinements are necessary to transform it into versatile materials like plastics. Despite the numerous advantages in terms of mechanical properties, lightweight nature, and ecological benefits associated with mycelium composite materials, their widespread adoption faces several constraints and challenges. The optimal design of substrate types for specific fungal species to enhance mycelium production and improve composite mechanics remains an unresolved issue (Verma et al. 2023). Table 5 highlights how biomaterial technology catalyzes diversity and sustainability within the building materials domain. The table underscores that the fusion of biomaterial technology with 3D printing enables precise structural design and construction throughout the building process. Moreover, biosensing technology emerges as a key research focus, offering the potential to create self-healing building materials and structures that adapt autonomously to environmental changes. Biomaterial technology is guiding the construction industry toward a future characterized by sustainability, environmental friendliness, and innovation.

Composite materials emerged in the mid-twentieth century and have become one of the hot topics in modern technology research (Rajak et al. 2019). Biomaterial composite technology combines different types of biomaterials with other materials to form composite materials with more comprehensive performance. By utilizing biomaterial composite technology, the limitations of a single biomaterial can be remedied, and its mechanical properties and functional characteristics can be improved. Green composite materials made from natural fibers and biopolymers have excellent

Table 5 The role of biomaterial technology in diversifying and sustaining building materials

Biomass	Method	Research objective	Reference
Fomitella fraxinea, *Ganoderma lucidum, Elfvingia applanata, Bjerkandera adusta, Microporus affinis, Trametes versicolor, Fomitopsis pinicola, Wolfiporia extensa, Postia balsamea, Ganoderma applanatum, Formitopsis pinicola, Fissurella Rosea*, *Trametes suaveolens*, *Trametes hirsuta*	Solid-state fermentation	Fungal mycelium leather	Raman et al. (2022)
Bio-based acrylate monomer	3D printing	Bio-based acrylic photopolymer resin	Voet et al. (2018)
Bio-based polyethylene, thermomechanical pulp	3D printing	Biological composite filament	Filgueira et al. (2018)
Thermomechanical pulp, polylactic acid	3D printing	3D printing wire	Zarna et al. (2022)
Microalgae	Biosensing technology	Microalgae photobioreactor used as an adaptive sunshade	Umdu et al. (2018)
Microalgae	Biosensing technology	The application of microalgae photobioreactors in energy and lighting	Talaei et al. (2021)
Microalgae	Biosensing technology	Algae windows potentially reduce building energy consumption	Negev et al. (2019)
Diatom powder, polymer fiber	Bionics	Large cement components and structures inspired by pearl texture	Soltan and Li (2018)

This table delineates how biomaterial technology is revolutionizing the construction industry by enhancing the diversity and sustainability of building materials. It details the integration of biomaterial technology with 3D printing, highlighting its role in improving the precision of structural design and execution. The table also explores the emerging domain of biosensing technology, illustrating its potential in developing building materials with self-healing properties and structures capable of autonomously adapting to environmental changes. Overall, the table presents biomaterial technology as a key driver leading the construction sector toward a future characterized by increased sustainability, environmental awareness, and innovative breakthroughs

mechanical properties and good biodegradability, which makes them good application prospects in industrial manufacturing (Abdur Rahman et al. 2023). Alsubari et al. (2021) delved into the potential application of natural fiber composites in sandwich structures. This indicates that combining biological fibers with polymer materials can enhance the strength and stability of the material. In addition, sensitivity to heat and flame damage is one of the main problems in the practical application of natural fiber-reinforced polymer composites, and the preparation of composite materials with natural fibers and polymers can effectively solve this problem (Kim et al. 2018).

Biosensing materials are a type of biomaterial that can respond to external environments. Some biomaterials can be used as adaptive components in buildings based on temperature, humidity, or lighting conditions. Talaei et al. (2022) reported a method of using microalgae bioreactors for building bio-adaptive sunshades. This indicates that the bioactive facade of microalgae can adaptively respond to environmental conditions and provide adaptive shading through changes in algal culture density (Tabadkani et al. 2020). The 3D printing technology has become a hot topic in biomaterial research and manufacturing. Through 3D printing, biological materials' shape, structure, and organization can be precisely controlled, achieving personalized and customized design. This provides new possibilities for fields such as tissue engineering, regenerative medicine, and biomimetic organs in the biomedical field. However, the lack of printable polymer varieties with advanced material properties has become a major bottleneck for the further development of this technology (Jiang et al. 2020). In additive manufacturing, 4D printing and 4D bioprinting are developing strongly, as they can provide intelligent materials for autonomous robot/actuator operation (Miao et al. 2018).

Bionics is a rapidly developing discipline in engineering and architectural design (Sommese et al. 2022). The scope of bionics ranges from architecture to materials science and chemistry, continuously providing new and innovative insights into engineering problems. Many types of intelligent and responsive building envelope structures have been developed through bionics, and designing building skins through bionics is one of the research hotspots in achieving sustainable building systems (Al-Obaidi et al. 2017). Biomimetic concrete composite and bacterial reinforcement materials are mainly used for structural purposes. Biomimetic building envelopes are used for building purposes and other physical functions, such as temperature, humidity, and light control. Manufacturing these biomimetic materials and structures is often challenging as their structures are typically non-monolithic structures with complex shapes. 3D printing technology has shown great application prospects in the research of biomimetic materials (Ahamed et al. 2022).

In summary, the technological advancements in the production of biomaterials in the construction industry provide new opportunities for promoting sustainable building and environmental design. With the continuous development of science and technology, we can foresee that the application of biomaterials in the construction field will become more extensive and diverse. At the same time, technological progress also helps to solve the challenges of some biomaterials in practical applications, promoting their broader application in the construction industry. The synergy between technological progress and biomaterial innovation not only enhances sustainability in construction but also fosters a more resilient and adaptive approach, ensuring the continued evolution of biomaterial applications in addressing the ever-changing demands of the construction industry and environmental considerations.

Health and safety considerations

Potential health issues of bio-based building materials

Indeed, the production and application of biomaterials in construction have delivered numerous benefits concerning environmental friendliness and sustainable development. However, Fig. 5 underscores that there are also potential health and safety concerns to consider alongside these advantages. Certain biomaterials can potentially contain allergens or components that can trigger allergic reactions. Notably, some natural fiber materials, including hemp and cotton, have been known to cause skin allergies in susceptible individuals (Elfaleh et al. 2023). Some volatile organic compounds may be released into the air during the production and use of biomaterials, leading to indoor air pollution. These volatile organic compounds may produce irritating odors and adversely affect the human respiratory tract and health (Adamová et al. 2020).

Although some of these mixtures are clearly defined, many have unclear characteristics or contain components with unknown or variable chemical properties and are classified as substances with unknown or variable components, complex reaction products, or biomaterials (Lai et al. 2022). Using biomaterials in buildings is likely to face the risk of long-term exposure to these unknown reaction products. Microbially induced calcite precision is a popular biological process in current construction biotechnology. However, a more accurate definition should be urease-dependent calculus carbonate crystallization and adhesion to a solid surface (Ivanov et al. 2019). Traditional microbially induced calcite precision may increase the risk of infection by urease-positive bacterial strains.

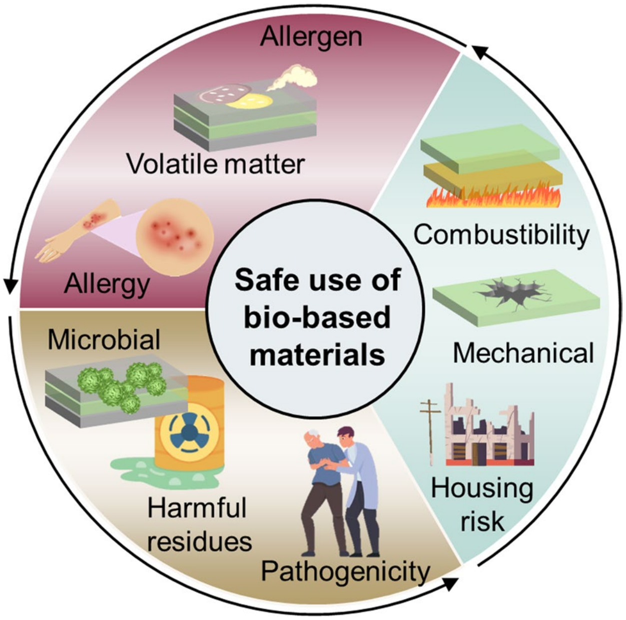

Fig. 5 Potential health and safety issues of biomaterials used in buildings. This figure illustrates the various health and safety concerns associated with the use of natural fibers like cotton and hemp, as well as certain biomaterials, in construction and other applications. It highlights the issue of volatile emissions during production and processing, which can adversely affect public health, particularly targeting the upper respiratory system. The diagram also points out the risk posed by natural fibers that are highly moisture-absorbent, which can become hotbeds for the growth of fungi and molds. Additionally, it sheds light on the potential dangers of residual pesticides and heavy metals in biomaterials, underlining their harmful effects on human health. Consequently, the figure emphasizes the necessity of thorough evaluation of these biomaterials' mechanical and combustion properties to ensure they meet safety standards in structural applications

In addition, some biomaterials, especially natural fiber materials, may have high water absorption and are prone to the growth of fungi and molds. The growth of these microorganisms may lead to the deterioration of the indoor environment and may cause health problems such as asthma and allergic rhinitis (Brambilla and Sangiorgio 2020). Proper material handling and maintenance are vital to preventing the growth of fungi and molds. Viel et al. (2019) developed a method to identify bio-based composites' anti-fungal development ability. Some biomaterials may contain harmful components, such as heavy metals, pesticide residues. These harmful ingredients may harm human health (Devi et al. 2022). During production and use, it is necessary to ensure the source and quality of materials to reduce the potential risk of harmful components. Some biomaterials have lower combustion performance and may accelerate the spread of fire in the event of a fire. Therefore, it is necessary to research the thermal insulation and fire resistance performance of biological building materials (Zhou et al. 2022). Some biological materials may not have the same mechanical properties as traditional building materials, especially in terms of load-bearing and structural performance. Therefore, when selecting and using biomaterials, it is necessary to fully evaluate and test their mechanical properties to ensure their safety performance in buildings.

In summary, although the production and use of biomaterials in construction have many advantages, paying attention to their potential health and safety issues is also necessary. Appropriate material selection, production process control, building design, and maintenance can minimize the risks of potential health and safety issues, ensuring the sustainable application of biomaterials in the construction field. Continuous monitoring throughout the entire life cycle of biomaterials is essential. Actively carrying out public awareness and educational activities can enhance the abilities of construction professionals and the public. By promoting an understanding of the benefits and potential risks associated with biomaterials, the industry can collectively contribute to safer practices, ensuring the responsible and sustainable integration of these innovative materials in construction projects.

Strategies for mitigating health and safety risks

Employing biomaterials within the construction industry while mitigating health and safety risks necessitates implementing comprehensive strategies and measures (Galanakis et al. 2022). Strict material selection and quality control are crucial before using biological materials. It is necessary to standardize and reasonably regulate the market regulation of the biomaterial industry (Friedrich 2019). Supply chain collaboration is crucial for small and medium-sized enterprises in the bio-based energy industry (Jernström et al. 2017). For the customer base, obtaining high-quality biomaterials from reliable suppliers and selecting biomaterials that comply with relevant standards and specifications can better ensure that their performance and safety meet the requirements.

When promoting the use of biomaterials, certification and evaluation should be based on scientific research and experimental data (Mouton et al. 2023). Evaluate the safety and performance of biomaterials through independent institutions, certify and standardize them, and ensure their compliance and safety in buildings. Providing relevant safety training for practitioners in construction projects that use biological materials is very important. The training content can include methods for the correct use and handling of biological materials and measures to address potential health and safety risks. At the same time, provide detailed usage guidance and operation manuals to help practitioners use biomaterials correctly.

Establish a monitoring and evaluation mechanism for using biomaterials and regularly track biomaterials' performance and safety status. Monitoring includes the physical properties, chemical composition, and volatile organic compound release of materials. The evaluation results will provide the scientific basis for policy formulation and improvement and help identify and address potential security issues on time (Mnasri et al. 2020). Maintaining reasonable indoor environmental control is critical to reducing health and safety risks in buildings using biomaterials. Proper ventilation and humidity control can help prevent the growth of fungi and molds in biological materials while reducing the accumulation of volatile organic compounds (González-Martín et al. 2021). Some biomaterials have specific flame-retardant properties (Liu et al. 2022a). However, they should not only rely on the properties of the biomaterials themselves but also develop corresponding fire-extinguishing and emergency plans. Ensure that the fire extinguishing equipment in the building is complete and provide corresponding fire safety training to practitioners. Effective risk management in the circular economy may be one of the effective means to reduce environmental and human health risks (Bodar et al. 2018).

In summary, using biomaterials in the construction industry to reduce health and safety risks is a continuous improvement process. Governments, industry groups, and companies should continuously monitor pertinent technologies and research advancements. This practice enables the prompt revision of pertinent norms and guidelines, enhancing biomaterials' safety and suitability. The implementation of various measures, such as the careful selection of biomaterials of superior quality, adherence to scientific certification standards, provision of safety training, regular monitoring and evaluation, implementation of environmental control measures, and establishment of fire emergency plans, can significantly mitigate the potential health and safety hazards associated with the utilization of biomaterials in the construction sector. Moreover, these strategies foster the sustainable utilization of biomaterials in construction practices.

Benefits and risks of using biomaterials in buildings

The growing concern over global warming has placed significant pressure on society in recent decades, with the construction industry substantially contributing to greenhouse gas emissions. Hence, the pursuit of mitigating the carbon footprint of the building sector through practical approaches has been a focal area of research for dedicated professionals in the field. The concept of sequestering carbon within permanent building structures is gaining recognition as a promising avenue for research. In the context of the biochar cycle, sourcing bio-based materials from sustainable forests is typically viewed as carbon–neutral (Liu et al. 2023b). This is because the harvested biomass is replaced by new tree growth, and the carbon dioxide absorbed during the growth period is roughly equivalent to the carbon dioxide released at the end of the biomass product's life cycle. Consequently, assuming time is not factored into the life cycle assessment, the carbon neutrality of bio-based products implies an eventual achievement of climate-carbon neutrality.

The harvested biomass is regenerated in new trees, and the amount of carbon dioxide absorbed during rotation is roughly the same as the amount of carbon dioxide released at the end of the life of the biomass product. Based on this assumption, if time is excluded from the life cycle assessment, the carbon neutrality of bio-based products will inevitably lead to climate-carbon neutrality. Following this theory, a dynamic life cycle assessment method was developed to account for the timing of carbon absorption and greenhouse gas emissions (Levasseur et al. 2012). Interestingly, a study examined the influence of augmenting the utilization of biomaterials in construction on the climate. The research revealed that buildings incorporating substantial amounts of bio-based materials exhibit a reduced impact on the overall life cycle climate (Peñaloza et al. 2016). However, the results may differ significantly, assuming that forest carbon sequestration occurs before or after material manufacturing. The service life of a building also affects the evaluation results.

Compared to traditional building systems, walls insulated with rapidly growing biomaterials exhibit net negative radiation forcing. However, wooden elements lead to an increase in the global worm impact of the building life cycle. Pittau et al. (2018) found that rapidly growing biomaterials have more significant potential as carbon sinks than wood. In particular, when straw is employed as an insulating material, its capacity to sequester atmospheric carbon is notably efficient within a short time frame. Moreover, Pittau et al. (2019) concluded that fast-growing bio-based materials have higher carbon sequestration potential than wood. Building materials made from artificial and chemical components pose challenges in terms of recyclability, human health, and their adverse environmental impact during disposal (Jin et al. 2017).

Take hemp, for instance; it can be cultivated in rotation to enhance soil quality. Moreover, hemp, being a natural material, boasts exceptional water absorption properties, promoting improved air exchange within buildings and preventing dampness. Bio-based building materials can also regulate indoor humidity levels and enhance indoor air quality and human comfort. However, more research is necessary to understand the dynamic effects of moisture hysteresis on bio-based building materials (Promis et al. 2018). Traditional synthetic polymers like carbon fiber and glass fiber are known for their lightweight properties and high strength. However, the production of synthetic fibers is associated with significant energy consumption, primarily reliant on fossil fuels, making it an energy-intensive industry (Sen and Jagannatha Reddy 2014). To put it into perspective, manufacturing one metric ton of carbon fiber demands an estimated energy input of approximately 300 GJ. In contrast, an equivalent quantity of natural hemp fiber can be produced with a significantly lower energy requirement, only 5 GJ. Energy consumption is directly linked to greenhouse gas emissions during fiber production. For instance, the production of carbon fiber produces approximately 29,500 kg of carbon dioxide per ton. Similarly, fiberglass production contributes to carbon dioxide emissions ranging from 1700 to 2500 kg per ton.

In contrast, natural fibers like hemp, flax, jute, and kenaf have considerably lower carbon dioxide emissions, with values of 410, 350, 550, and 420 kg per ton of fiber, respectively (Nwankwo et al. 2023). Moreover, the processing of synthetic fibers can have adverse environmental effects, as they generate toxic by-products during synthesis and are not recyclable, which conflicts with the goal of sustainable development. Natural fiber-reinforced polymers do not suffer from these issues. As a result, many researchers are focusing on developing bio-based composite materials due to their cost-effectiveness and environmental advantages.

Contemporary architecture enjoys the versatility of biomaterials, offering a wide range of options. However, the utilization and progress of bio-based construction materials heavily rely on the availability and accessibility of raw resources. There is still a lack of empirical data in the engineering field to ascertain whether the mechanical properties of bio-based building materials are on par with traditional construction materials. Composite materials constructed from natural fiber-reinforced polymers exhibit static mechanical properties akin to those of traditional composite materials (Akhil et al. 2023; Ramaswamy et al. 2022). Nonetheless, recent studies have pointed out that plant fiber-reinforced polymer composites exhibit more noticeable creep characteristics than conventional composites reinforced with glass or carbon fibers.

As a result, this phenomenon has garnered significant attention within the field of structural design (Blok et al. 2019). Due to the relative lack of experience in engineering applications, the long-term performance of plant fiber-reinforced polymer composites remains an unresolved concern (Kossakowski and Wciślik 2022). The creep analysis of traditional fiber-reinforced polymer composites is usually completed by studying the viscoelastic behavior of fibers and matrix separately or only considering the viscoelastic behavior of the matrix. However, cellulose and pectin in plant fibers exhibit viscoelastic properties similar to polymers, which means that the time-dependent behavior of plant fiber-reinforced polymer composites is not only caused by polymers but also by plant fibers. The time-varying nature of natural plant fibers makes creep behavior an essential factor that needs to be studied before applying plant fiber-reinforced polymer composites (Xu et al. 2023).

In summary, using biomaterials in buildings has many advantages, including environmental protection and sustainability, low energy production, improving the indoor environment, biodiversity conservation, and promoting rural economy. However, paying attention to potential health and safety risks such as allergic reactions, fungal and fungal growth, insufficient mechanical properties, volatile organic compound release, and fire risks is also necessary. Through scientific and reasonable material selection, quality control, research certification, safety training, environmental control, and fire emergency plans, these potential risks can be effectively reduced to ensure the safe and sustainable application of biomaterials in buildings. Utilizing biomaterials has the potential to decrease the reliance of the construction sector on finite resources and foster its progression toward an ecologically conscious and sustainable trajectory. In the realm of architecture, the significance of materials lies in their capacity to serve as sustainable and renewable substitutes for conventional construction materials.

Environmental sustainability considerations

Environmental sustainability has gained recognition as a strategic approach aimed at curbing the over-exploitation of natural resources, reducing energy consumption, mitigating pollutant emissions, and minimizing waste generation (Arora 2018). According to the Energy Transition Act for Green Growth, greenhouse gas emissions are projected to decrease by 75% by 2050 compared to 1990 levels. Additionally, by 2025, recycling rates should reach 55%, non-recycled waste must be reduced by 50%, and thermochemical conversion should be promoted (Rabbat et al. 2022). Efforts to reduce energy consumption and carbon emissions have significantly shifted toward replacing traditional insulation materials with lower embodied energy alternatives (Marinela et al. 2015). The utilization of biomass resources for bioenergy applications, such as home heating, has been widely adopted globally (Vijay et al. 2022). Furthermore, for greenhouse gas mitigation, more environmentally friendly materials generated from woodland management, farming, and repurposing have been developed (Lieder and Rashid 2016). This section primarily focuses on the environmental sustainability of building biomaterials, addressing their environmental impact, strategies for minimizing this impact, and the advantages and challenges associated with using biomaterials for environmental sustainability.

Environmental impact of biomaterials production and use in buildings

The environmental impact of producing architectural biomaterials is complex and multi-faceted. Firstly, biomaterials often demand substantial water and land resources, potentially adversely affecting local environments and ecosystems. Utilizing water resources for the cultivation, growth, and processing of biomaterials can result in overexploitation of water sources and water body pollution. Similarly, the use of land resources may contribute to land degradation, biodiversity loss, and ecosystem disruption. Therefore, responsible resource management is crucial to mitigate these detrimental environmental consequences.

Secondly, while producing biomaterials is generally more environmentally friendly than traditional materials, it still requires a certain energy consumption level. The production processes for biomaterials, which include fermentation, extraction, and processing, require energy input (Mishra et al. 2023). Although the energy consumption of biomaterials is usually lower compared to the production process of traditional materials, there is still a particular energy consumption and possible carbon emissions. Therefore, to reduce the environmental impact of biomaterial production, more renewable and clean energy sources should be sought to meet production needs.

However, the production of biological materials can also enable the recycling of materials and positively contribute to the environment. For example, the production process of building materials based on hemp guarantees that 29% of the fibers and 14% of the shives are recycled (Dutreix et al. 2017). In addition, for wood-plastic composites, up to 30% of high-quality wood-plastic waste can be reintegrated into new biomaterial products. This practice contributes to the sustainability of biomaterial production (Liikanen et al. 2019; Petchwattana et al. 2012; Sommerhuber et al. 2017).

The utilization and recycling of bio-based materials positively influence the environment, although the environmental impact during their recycling phase cannot be overlooked. The first point is that certain biomaterials, such as cork, exhibit excellent adiabatic properties. As a widely used biomaterial, black cork particles undergo a sophisticated treatment process to enhance the energy efficiency of buildings, making them suitable for floor covering and insulation (Gupta and Maji 2020; La Rosa et al. 2014). Using cork and other bio-based materials as construction materials can facilitate energy conservation efforts and carbon emissions, thereby mitigating greenhouse gas emissions and combatting climate change (Le et al. 2023). Rabbat et al. (2022) also discovered that the expected energy recovery from bio-based insulation waste by 2050 offers significant environmental and economic benefits, and the practice of energy recovery from such waste could prevent the emission of approximately 312,771 tons of carbon dioxide equivalent. This substantial reduction in greenhouse gas emissions represents a significant step toward mitigating climate change impacts. Secondly, biomaterials have the potential to enhance indoor environmental quality under their natural composition, non-toxicity, and superior wet and thermal properties that enable effective regulation of temperature and humidity levels compared to certain conventional materials (Tran Le et al. 2010). For example, hemp and sheep wool absorb 10 and 30 times more water than typical insulations, respectively (Platt et al. 2023).

Additionally, biomaterials offer advantages in the treatment of construction waste. When a building reaches the end of its useful life or requires renovation, the disposal and management of biomaterials are often more environmentally sustainable and less burdensome than conventional materials. For instance, wood-based products can be crushed and recycled for animal bedding, composting, or particle board production (Azambuja et al. 2018), and sheep's wool and cork can be used in compost production (Casas-Ledón et al. 2020; Schiavoni et al. 2016), which helps reduce construction waste, relieve pressure on landfills, and promote sustainable resource use. However, the use of biological materials can also have a negative impact on the environment. European Commission (2011) stated that the landfilling of wood-based products takes up a large amount of land and space, and the release of methane and its leachate (additives, paints, varnishes, glues) can seep into soil and water and cause pollution.

However, Tang et al. (2022) found through research that recycling biological building materials can save land. This large space could be repurposed for other ecological or developmental uses, promoting efficient land use and management. In addition, gases with environmental impacts are emitted during the transport and transfer of biological materials, for example, filling cannabis-based panels releases 90% of carbon dioxide and 9% of methane during transport of about 30 km to a harmless storage facility (Schiavoni et al. 2016). The environmental impact of producing and using building biomaterials is a multifaceted issue. While there may be adverse effects during the production phase, including resource and energy consumption and pollutant emissions, using biomaterials can enhance building energy efficiency and improve indoor environmental quality. Additionally, they offer environmental benefits regarding waste disposal. To mitigate the environmental impact of biomaterials, it is essential to adopt sustainable production practices, efficiently manage resources, and incorporate environmental considerations throughout their use and handling.

Strategies for reducing the environmental impact of biomaterials production and use in buildings

Employing bio-based materials in construction presents numerous opportunities for environmental sustainability. However, to mitigate potential adverse impacts, it is essential to adhere to several pivotal strategies during the production and utilization of these materials. Sustainable procurement of bio-based materials is the first step, which should involve cultivation methods that maintain or enhance soil health, biodiversity, and other ecosystem services. Utilizing locally available bio-based materials can mitigate the environmental impacts associated with long-distance transportation. Secondly, optimizing the production process is crucial. Energy-efficient production technologies should be used, and renewable energy should power these processes wherever possible.

Furthermore, efforts should be made to minimize production waste, with any unavoidable waste repurposed or recycled. For instance, Schmidt et al. (2004) conducted life cycle assessments for flax wool and cellulose wadding. According to this study, the wastes were collected and sent to a recycling plant, which might be converted into low-grade items. Moreover, design strategies can also help extend the lifespan of materials. Bio-based materials should be used to enhance the durability and lifespan of the building, reducing the need for frequent replacements that can lead to additional resource consumption and waste production. Employing deconstructable designs that allow for easy disassembly of building components at the end of the building's lifespan can facilitate the recycling and reuse of bio-based materials or enable their safe biodegradation.

Finally, conducting a comprehensive life cycle assessment is imperative, as depicted in Fig. 6. Life cycle assessment is an exhaustive analysis method that accounts for the environmental repercussions of every phase of a product's life cycle. This involves the initial stage of raw material acquisition and the associated environmental costs, progressing to the processing and manufacturing stages, where these raw materials are transformed into useful products. The assessment continues during the product's active use, evaluating the environmental impacts throughout its functional life. Finally, considering the product's end-of-life, considering environmental implications linked with disposal, recycling, or reuse. The application of life cycle assessment is instrumental in identifying and working toward reducing potential environmental impacts inherent at each phase of the life cycle. The objective is to promote sustainable practices in all stages of product life, thereby contributing to a eco-friendlier and more sustainable world.

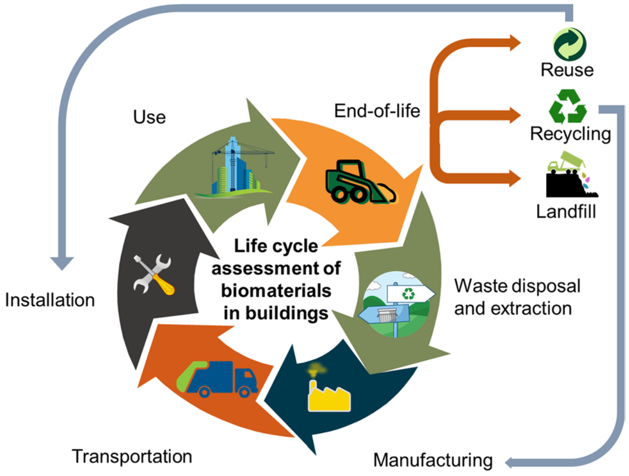

Fig. 6 Environmental sustainability of building biomaterials. The figure provides a holistic portrayal of the entire life cycle of biological building materials. This encompasses diverse stages: from raw material extraction, manufacturing, transportation, and installation to usage, end-of-life, and waste disposal. These stages chronicle the full spectrum, starting with raw material sourcing, advancing through processing and distribution, and culminating in practical application. A distinctive advantage of biological building materials emerges at the end-of-life phase: they can often be repurposed or recycled, showcasing a commitment to eco-friendly waste management practices. Nonetheless, it is worth noting that some waste derived from these materials still finds its way to landfills. This all-encompassing life cycle perspective both highlights the sustainable promise of biological building materials and underscores areas warranting enhancement

Benefits and challenges of using biomaterials for environmental sustainability

In the quest for environmental sustainability, the utilization of biomaterials emerges as a pivotal factor. These materials, sourced from natural and renewable origins, align closely with the principles of ecological balance, significantly promoting sustainable environmental development. Nevertheless, while biomaterials offer numerous advantages, including the reduction of greenhouse gas emissions and decreased reliance on fossil fuels, they also encounter various challenges in practical applications. These challenges encompass intricate supply chains and concerns related to water and soil pollution.

Benefits

The utilization of biomaterials provides a comprehensive array of advantages. These benefits are geared toward bolstering environmental sustainability. These benefits are wide-ranging and multifaceted, encompassing crucial domains such as the significant reduction of waste by minimizing the use of non-renewable resources. Additionally, they include effective carbon sequestration aiding in combating climate change, heightened energy efficiency contributing to a reduced carbon footprint, and efficient resource conservation promoting the sustainable use of our planet's resources.

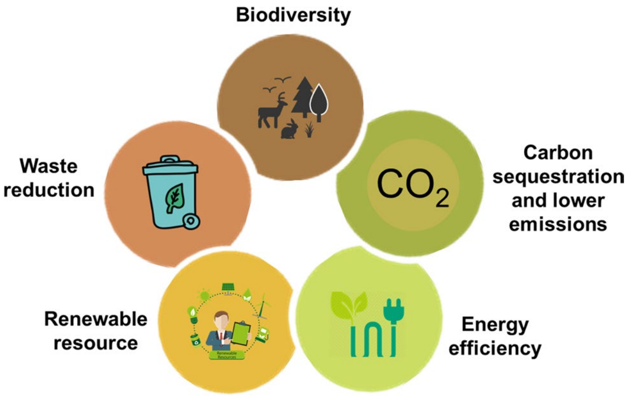

Fig. 7 Benefits of using biomaterials for environmental sustainability. The figure vividly outlines the manifold environmental sustainability advantages of utilizing biological materials. Foremost, these materials are pivotal in carbon sequestration; they actively absorb carbon dioxide, diminishing detrimental emissions and thus, playing an instrumental role in countering climate change. Serving as renewable resources, they present a sustainable alternative to nonrenewable counterparts, consistently renewing themselves over time. Furthermore, their propensity for biodegradability facilitates waste reduction, substantially curtailing environmental contamination. From an energy perspective, they outshine many traditional materials, often demanding less energy throughout processing and production phases. Moreover, the cultivation and deployment of these materials fortify biodiversity, endorsing a rich spectrum of life. This not only enriches the ecosystem but also buttresses its overall resilience and equilibrium

These key benefits, as illustrated in Fig. 7, underscore the inherent value of biomaterials in our quest for a sustainable future. Carbon sequestration and lower emissions: biomaterials, particularly those derived from plants, can help sequester atmospheric carbon dioxide during their growth phase. This can contribute to a reduction in the overall amount of greenhouse gases in the atmosphere and assist in ameliorating the effects of climate change. In addition, producing biomaterials typically results in lower carbon dioxide emissions than conventional materials. Liu et al. (2023a) claimed that bio-based building materials have excellent carbon sequestration capabilities. They also found that buildings constructed with glued laminated bamboo emitted approximately 70% of the carbon during the operation phase compared to timber buildings. Renewable resource unlike many conventional building materials, biomaterials are derived from renewable sources that can be replenished over time (Gregory et al. 2021). This ensures a continuous supply of materials without depleting non-renewable resources. Waste reduction: many biomaterials are biodegradable and can be composted at the end of their life cycle, such as wood-based products and cork, reducing the amount of waste that ends up in landfills (Casas-Ledón et al. 2020; Höglmeier et al. 2015; Rabbat et al. 2022; Schiavoni et al. 2016).

Furthermore, biomaterials can be derived from waste products, presenting an avenue for repurposing waste into valuable materials. For instance, cork waste can be transformed into novel insulation panels, concrete, and lightweight coatings (Abu-Jdayil et al. 2019; Schiavoni et al. 2016). Similarly, waste generated from hempcrete can undergo a crushing and screening process to extract coarse and fine aggregates, subsequently employed as fillers in asphalt mixtures and sustainable alternatives to sand in mortars (Ben Ghacham et al. 2017). Energy efficiency is another advantage of biomaterials production, often requiring less energy than conventional materials (Wu et al. 2022). Additionally, certain biomaterials, like cellulose wadding, can serve as effective thermal insulation, enhancing building energy efficiency and reducing heating and cooling energy consumption. Moreover, cultivating plants for biomaterials can positively impact biodiversity when managed sustainably. Crop rotation practices can enhance soil health and create habitats for diverse wildlife species.

Challenges

While biomaterials hold significant potential for achieving environmental sustainability, they pose specific challenges requiring resolution. One of the primary challenges relates to the substantial energy and water consumption involved in recycling bio-based materials. Notably, fiber cleaning and reprocessing processes impose considerable demands on resources. This heavy reliance on energy and water resources can exacerbate existing concerns related to energy scarcity and amplify water stress, particularly in regions prone to drought conditions. Consequently, it is crucial to carefully balance the environmental advantages of recycling against these resource requirements to ensure a genuinely sustainable approach.

Additionally, according to Colajannni et al. (2023), the production and recycling of biomaterials often involve complex supply chains and require extensive resources. Factors such as cultivation, harvesting, processing, and transportation present their own challenges. For instance, cultivation might demand significant land and water resources (Torres-Rivas et al. 2021), while transportation can contribute to greenhouse gas emissions. These complexities can complicate the large-scale production and use of biomaterials, potentially leading to higher costs and posing environmental and economic challenges.

Finally, although biological materials may have less impact on the environment in the later stages of use and waste treatment, they can also produce some pollution in the landfill process. European Commission (2011) stated that the landfilling of wood-based products would occupy a large amount of land and space, and the release of methane and its leachate (additives, coatings, varnishes, glues) can leach into soil and water and cause contamination (Tran Le et al. 2010). In addition, biomaterials may consume energy and produce a certain amount of environmental pollution during production. Therefore, a comprehensive life cycle assessment is essential to understand and minimize these potential impacts.

In summary, the environmental sustainability of bio-based materials in construction are discussed, including their impacts, strategies for reducing these impacts, and the benefits and challenges of sustainability. While bio-based materials are generally more environmentally friendly than conventional materials, their production still requires energy; thus, renewable and clean energy sources should be prioritized to minimize environmental impacts. Bio-based materials, such as construction materials based on hemp and wood-plastic composites, can promote recycling. Utilizing and recycling bio-based materials positively impacts the environment, significantly reducing energy consumption and carbon emissions and enhancing building energy efficiency. Due to their natural, non-toxic nature and excellent hygrothermal performance, they also enhance indoor environmental quality. However, one should also consider the emissions during the transportation of these materials and the potential pollution to soil and water sources from wood-based products' landfilling. Strategies to minimize the environmental effects of biomaterials include sustainable procurement, energy-efficient production, minimizing waste, prolonging material lifespan, and comprehensive life cycle assessment. Utilizing bio-based materials promotes environmental sustainability due to benefits in carbon sequestration, waste reduction, energy efficiency, and resource protection. However, challenges still exist, such as high energy and water consumption in recycling, complex supply chains, high resource demand, and potential pollution. Comprehensive life cycle assessment is critical to addressing these challenges.

This section explores the environmental sustainability of bio-based materials in construction, highlighting their positive impacts, strategies for reducing environmental effects, and the associated benefits and challenges. While bio-based materials offer environmental advantages over conventional ones, their production still requires energy, emphasizing the need for renewable energy sources. These materials can promote recycling, leading to reduced energy consumption, carbon emissions, and improved building energy efficiency. However, considerations must be given to transportation emissions, potential pollution from wood-based product disposal, and the need for strategies like sustainable procurement and comprehensive life cycle assessment to minimize environmental impacts and ensure sustainability.

Perspective

Engineering, architecture, computational design, and biodesign multidisciplinary research may produce fascinating work by designing and constructing utilizing mycelium-based composites. Mycelium-based biocomposites, which are energy-efficient and environmentally friendly, are a potentially sustainable lightweight alternative material (Gou et al. 2021). New technological, aesthetic, and sustainable solutions in architecture are conceivable using mycelium-based building materials. Leveraging physiological processes such as self-regulation, adaptability, autonomous growth, and self-healing, researchers can create novel paradigms that are less dependent on technological infrastructure compared to current "smart building" technologies (Almpani-Lekka et al. 2021).

The area of fungal architecture is progressing thanks to expanded digital design choices, which have fundamentally altered planning practices. Without the need for adhesives, mycelial networks can connect bricks and even yield new crops of mushrooms. As described by Adamatzky et al. (2019), living fungal mycelium enhanced with nanoparticles can be incorporated into structures that autonomously grow into precisely envisioned geometries. These structures exhibit attributes such as waste management and self-healing. Fungi have demonstrated their ability to respond to stimuli, contributing to the concept of "biological" smart buildings. Furthermore, Attias et al. (2020) have pioneered sustainable alternatives to synthetic foams by leveraging mycelium fiber networks. Ongoing research continuously explores mycelium's use to create cleaner buildings and design products with sustainable life cycles.

Plant fibers can potentially enhance polymer biocomposites' tensile strength, stiffness, and impact resistance. Natural fiber-reinforced polymers are renewable, cost-effective, and biodegradable and can improve the seismic resistance of concrete structures and increase the flexural strength of reinforced concrete beams (Wang et al. 2020). In the case of hybridized biocomposites based on agricultural wastes, raw rice husk materials were blended with polyvinyl alcohol in a cement matrix to obtain hybridized composites with improved mechanical properties at lower densities (Pakravan et al. 2018). In low-moisture situations requiring strong mechanical qualities, fiber polymer composites manufactured from agricultural waste can be employed. These manufactured biocomposites are compatible with biomass pellets, absorbing most of the stress on rural infrastructure (Mu et al. 2021).

Biocomposites can significantly reduce costs by their excellent dynamic mechanical properties to develop sustainable green buildings. In addition, high energy storage modulus and low damping coefficients can be applied to the connecting structures of buildings (Bahlouli et al. 2023). Building materials with integrated latent heat storage biocomposites contribute to the energy efficiency of buildings. In order to provide hygrothermal comfort in buildings, Ismail et al. (2022) created straw concrete composites with appealing thermal conductivity and acceptable mechanical strength for insulation of new structures and thermal rehabilitation of old buildings. Jeon et al. (2019) utilized porous and biological phase change materials to prepare latent heat storage biocomposites that are physically and chemically stable and inexpensive to help regulate the temperature of buildings.

New design, planning, and construction techniques that consider the material's characteristics throughout a building's life cycle, as well as the behavior of the fungal material with precisely controllable physical properties, dispersal characteristics, and fire resistance, are required in order to introduce fungi to the construction industry (Almpani-Lekka et al. 2021). Higher fiber content usually enhances strength but impairs ductility (Chen et al. 2020b). Biodegradation of plant fiber-reinforced composites can be challenging to control, and despite exhibiting good specific properties, there is a great deal of variability in their performance, for example, nonlinear mechanical behaviour, poor long-term performance, and low impact strength (Ramesh et al. 2017). Using plant fibers, wood, or wood-based composites as matrices for phase change materials in building applications poses significant challenges related to biodurability and fire resistance (Nazari et al. 2020). The flammability of plant-based materials has been identified as a limiting factor for their use in construction, contradicting many national building guidelines (Yadav and Agarwal 2021). For example, producing new wood biomaterials involves timber harvesting, which impacts soil and raises concerns about climate change mitigation (Beims et al. 2022). Effective policies and forest management practices are, therefore, crucial for the sustainable utilization of woody materials. Given that lignocelluloses materials are of biological origin, they are susceptible to degradation by various biological agents, including bacteria, fungi, and insects.

The precise composition of bio-based construction technologies dramatically influences the material required. Demand for raw materials based on the production of building materials can vary considerably depending on location and producer, and local availability, transportation distances and efficiency are important considerations for the effect of implied carbon emissions on bio-based materials (Göswein et al. 2018). Moreover, there is still a great deal of uncertainty in acquiring data in biologically based natural environmental systems, which is addressed through sensitivity analyses in future studies. Standardized benchmarks are needed to improve the applicability and use of bio-alternative materials in construction. There is still a significant gap in public demand and awareness of bio-based materials, and there is still no specific and complete policy system for governments to regulate them (Jones 2017).

Fungal building materials require attention to indicators that affect the survival of fungi in harsh environments, including temperature, composition of the growth medium, concentration of fungal spores, and concentration of chemical additives (Luo et al. 2018). Nanoparticles with vast surface areas, high particle number densities, and low percolation thresholds are employed in biocomposites to improve adhesion, moisture resistance, and structural qualities (Winandy and Morrell 2017). It has been demonstrated that nanoparticles may enhance barrier qualities, provide ultraviolet ray resistance without impairing transparency, serve as additives to manage release delivery systems, increase flame retardancy, and form foams with tiny cellular structures (Sabo et al. 2015). Advanced wood and bio-based composites may perform much better in established markets by using a range of nanoparticles, which can also speed up the creation of new composites and markets.

In order to have an impact on the building industry, materials must be modified to meet performance criteria or selected for less controlled applications that do not require high performance, and further research and development are needed to improve the performance of biocomposites. Databases containing data on the availability of agricultural residue production and information on the availability of raw materials could both be further explored, and the prediction of quantities and areas could ultimately help to develop materials that can be used effectively in buildings (Sangmesh et al. 2023). More researches are required to create building materials containing natural fibers and to investigate their structural and thermal behavior because exposure to corrosive environments impairs the structural performance of building composites. Related durability issues must also be addressed in the future (Luhar et al. 2020). Biocomposites must be carefully constructed for each application, taking into account the fiber composition, member configuration, and composite application direction (Corona et al. 2016). To effectively use the waste material and create lightweight composite structures for prospective applications, more studies are required to determine the ideal percentages of fiber loading and chemical treatment (Vinod et al. 2021).

In conclusion, bio-based building materials can be vigorously developed in the future as mycelial building materials, which have a self-healing effect on building structures. Fiber biocomposites have a great potential to enhance the strength of building structures and also offer great possibilities for the thermal storage of materials. However, the uncontrollable nature of mycelial materials and the combustibility of fiber biomaterials are drawbacks to their development. While providing legislation and public credibility, bio-based building technologies also require further optimization of material ratios and properties so that highly adaptable bio-based materials can be designed.

Conclusion

Bio-based materials offer a promising path toward carbon neutrality, contributing to mitigating global climate change and minimizing waste generation. The production of renewable biomaterials demands lower energy inputs, fostering enhanced energy efficiency. The diverse array of biomaterials further optimizes land utilization and management practices. Biomaterials enhance both the mechanical attributes and biodegradability of building components, opening opportunities for recycling. Nevertheless, it is crucial to consider the substantial energy and water consumption associated with the recycling of bio-based materials, as well as the potential environmental impacts during biomaterial production. Biomaterials also face challenges related to technological advancements, economic viability, market oversight, and awareness limitations. Commercial viability, compliance with performance standards, and regulatory adherence remain areas of concern. Additionally, there is a lack of harmonized normative standards for implementing bio-based materials in construction, posing durability challenges due to bioerosion. Supportive policies and regulatory frameworks have spurred innovation in biomaterial development for construction, albeit sometimes imposing procurement and utilization constraints. The dynamic adaptation of policies through mutual sharing and communication has accelerated the progress of biomaterials in the construction industry. Selecting materials carefully, implementing stringent production controls, and robust maintenance practices can reduce health and safety risks. Furthermore, developing relevant codes and guidelines contributes to mitigating safety risks associated with biomaterials. Mycelial building materials represent a promising advancement, reinforcing structural integrity, durability, and mechanical strength while addressing challenges related to fire resistance and control. To further enhance their stability, it is essential to ensure a stable supply of raw materials, expand data and information resources, and explore the integration of nanotechnology with bio-based materials.

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