BILINGUAL PUBLISHING GROUP

Journal of Environmental & Earth Sciences

https://journals.bilpubgroup.com/index.php/jees

REVIEW

Materials for a Regenerative Built Environment: A Review of Novel Green Construction Technologies

Yayuqiong Zeng [1], Qi Huang [2], Liuchun Zhang [3], Zhiwei Lin [4]*

[1] *Jiangxi Environmental Engineering College, Ganzhou 341000, China*

[2] *Ganzhou Architectural Design Institute Co., Ltd., Ganzhou 341000, China*

[3] *China Construction First Group Fifth Construction Co., Ltd., Beijing 100024, China*

[4] *Guangzhou Rong Baosheng Architectural Engineering Design Consulting Co., Ltd., Ganzhou 341000, China*

ABSTRACT

The built environment is a significant contributor to global resource use, Greenhouse Gases (GHGs) and construction and demolition waste, and the current approach of sustainable construction needs to evolve from a linear supply and use model, towards a more regenerative material system. The review article discusses new green construction technologies that can contribute to a regenerative built environment, which minimizes embodied carbon, carbon sequestration, circularity, and supports ecological functions and the health of the occupants. The article critically reviews the progress of the materials that are bio-derived and carbon-storing, such as engineered timber, bamboo, hempcrete, straw, cork, mycelium composites, algae-derived materials, cellulose and lignin-based materials. It also examines low-carbon or circular mineral-based alternatives like low-clinker cement, limestone calcined clay cement, geopolymers, alkali-activated binders, recycled aggregate concrete, carbon-cured concrete, re-used metals, re-used glass and earth-based materials. Furthermore, new technologies such as additive manufacturing, prefabrication and modular construction, smart materials, living systems, digital twin and material passports are assessed as means of system-level regeneration. The review emphasizes that regeneration can only be measured through whole life assessment and is not just a part of the material origin or embodied carbon but also through durability, circularity, toxicity, land use, scalability, ecological value and social acceptance. The

*CORRESPONDING AUTHOR:
Yayuqiong Zeng, Jiangxi Environmental Engineering College, Ganzhou 341000, China; Email: zyyq0929@163.com

ARTICLE INFO
Received: 27 May 2026 | Revised: 16 June 2026 | Accepted: 24 June 2026 | Published Online: 19 August 2026
DOI: https://doi.org/10.30564/jees.v8i8.13564

CITATION
Zeng, Y., Huang, Q., Zhang, L., et al., 2026. Materials for a Regenerative Built Environment: A Review of Novel Green Construction Technologies. Journal of Environmental & Earth Sciences. 8(8): 1011–1036. DOI: https://doi.org/10.30564/jees.v8i8.13564

results indicate that future buildings that are regens will rely on integrated material systems, not just material substitutions. The research priorities include standardized assessment frameworks, long-term field validation, circular design protocols, digital traceability and policy support for low-carbon and reusable construction materials.
Keywords: Regenerative Built Environment; Green Construction Materials; Bio-Based Materials; Low-Carbon Concrete; Circular Construction

1. Introduction

The built environment is at a turning point in its transformation. Buildings, infrastructure, and urban systems are no longer exclusively considered places that provide shelter and mobility, and create economic value; they are now also understood as systems that demand material resources and are experienced as a building that impacts climate stability, resource security, ecological health and well-being [1]. Traditional building methods rely on high-consumption materials like ordinary Portland cement, steel, aluminium, fired clay, synthetic insulation and petrochemical composites. These materials have facilitated faster urbanization and enhanced structural functionality, but come with high environmental costs of production, transportation, maintenance, and disposal, including high greenhouse gas emissions, resource consumption, construction and demolition waste and long-term ecological disruption. In the face of rising population and the need to renovate the existing building stock, the construction industry is challenged to satisfy the growing demand and drastically cut its environmental footprint [2,3].

In response, the idea of sustainable construction has changed considerably in the last few decades. Initial efforts concentrated on minimising the operational energy use of buildings by using passive building envelopes, efficient heating and cooling systems and renewable energy sources [4]. The focus has now turned to embodied carbon, material circularity, and whole-life environmental impacts more recently. The change has shown that materials used in building materials creation, refurbishment and maintenance are not background items but key factors in the performance of the built environment [5]. An efficient building can have a high carbon debt, if it uses materials with high carbon costs. Thus, material innovation is one of the most important routes to low-carbon, circular and climate-resilient construction.

The concept of a regenerative built environment is a new one, however, it goes further than 'doing less harm'. Green and sustainable construction may be focused on minimizing harm, but regenerative construction is about the design of built systems that actively rejuvenate, restore and improve ecological and social systems [6]. In this sense, the construction materials should not only be less harmful; they should be able to positively influence carbon sequestration, resource regeneration, biodiversity, indoor environmental quality, waste reduction and adaptability over the long term. The shift in this outlook necessitates a radical rethinking of the meaning, origin, functionality and re-entry of construction materials throughout their entire lifespan. This conceptual shift from conventional material selection toward regenerative material systems is illustrated in **Figure 1**.

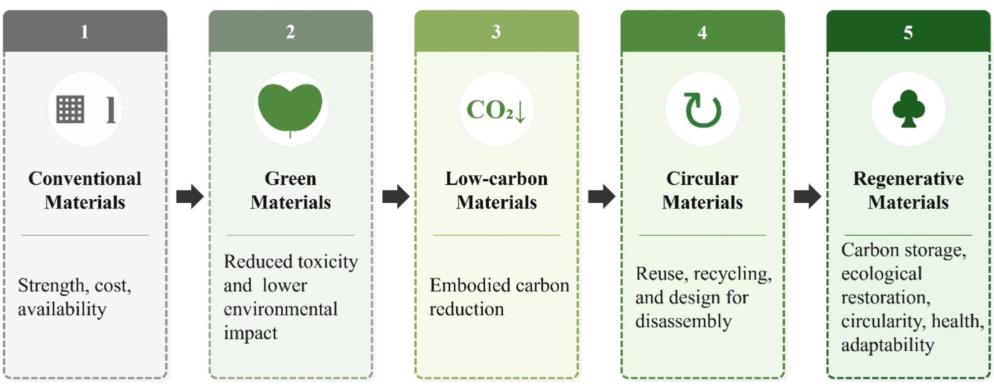

Figure 1. Evolution of construction material paradigms from conventional performance-based selection to regenerative material systems that integrate carbon storage, circularity, ecological restoration, human health, and long-term adaptability.

This transformation is linked to new green building technologies. Engineered timber, bamboo, hempcrete, straw bale, cork, mycelium composites, algae-based materials, and products made from agricultural-residue panels are all potential bio-based materials that could be used to store biogenic carbon, cut reliance on non-renewable raw materials, and enhance indoor environmental quality. The use of low-carbon mineral-based materials such as limestone calcined clay cement, alkali-activated binders, geopolymers, recycled aggregate concrete, carbon cured concrete and earth-based materials is available for applications that require high strength, durability and fire resistance. Recycled plastics, reclaimed metals, waste glass and construction demolition waste-derived products enable circular flows, and alleviate pressure on virgin materials. Simultaneously, cutting-edge technologies like additive manufacturing, prefabrication, modular construction, robotic fabrication, material passports, digital twins, and sensor-based performance monitoring are transforming material design, production, assembly, tracking, and reuse [7,8].

Although the field has made significant advances, at the same time it is still a fragmented field. In many studies, individual material classes are studied and not linked to the rest of the regenerative paradigm, for example, bio-based insulation, low-carbon concrete or recycled aggregates [9]. Other research focuses on carbon reduction and provides only brief consideration of biodiversity, toxicity, circularity, social value, and ecological restoration in the long-term. Moreover, since the emerging materials are evaluated with various boundaries for life-cycle assessment, the direct comparison is not easy. Some studies, for instance, measure cradle-to-gate while others measure cradle-to-grave or cradle-to-cradle impacts. Likewise, the potential for carbon negativity can be reliant on assumptions with regard to land use, biomass regrowth, service life, end-of-life treatment, and avoided emissions [10]. Such methodological differences render it difficult for the researcher, designer, policymaker and industry practitioner to identify the best technology for regenerative construction.

The third problem yet to be addressed is the connection between the novelty of material and its applicability. There are many green materials with potential environmental benefits at the laboratory or prototype level, however, they have challenges of structural reliability, fire resistance, moisture resistance, durability, standardization, cost, insurance, procurement, and building code acceptance [11]. Bio-based materials, for example, can have a low embodied energy and provide carbon storage but need to be protected from moisture, biological damage and fire risk [12]. Although the use of Portland cement can be cut down through the use of geopolymers and alkali-activated materials, the properties of various geopolymers and alkali-activated materials depend on the chemical characteristics of the precursors, the type of alkali-activator as well as on the curing conditions and the availability of local industrial by-products. Mycelium composites and living materials are innovations in the making and would need further validation to be used in structural or envelope applications. Thus, the environmental benefits alone are not enough to measure a material's regenerative properties; it must also satisfy technical, economic, regulatory, and social criteria throughout the building life cycle.

The novelty of this review is in the context of green construction materials, which are integrated and regenerative. This review advances beyond existing literature in three specific ways. First, whereas prior reviews typically examine bio-based materials, low-carbon cements, or circular technologies separately, we integrate all three pathways within a unified regenerative framework, explicitly mapping their complementarities and trade-offs (Sections 3–5). Second, while most studies focus predominantly on embodied carbon reduction, we propose and apply an eight-dimensional assessment criterion that includes circularity, toxicity, ecological impact, social value, and adaptability—preventing problem-shifting across environmental categories. Third, unlike descriptive reviews that catalogue green materials, we critically evaluate context-dependencies (e.g., biogenic carbon storage requires end-of-life verification; geopolymer benefits depend on activator chemistry) and link material innovation to system-level enablers (digital twins, material passports, modular construction).

This article aligns materials in a new, more comprehensive framework for the "regenerative built environment" rather than traditional categories of low-carbon materials, recycled materials, bio-based materials and energy-efficient materials. It explores the role of new construction technologies in reducing emissions and in storing carbon, achieving circularity, restoring ecology, improving occupant health, enabling adaptability, and building system-level resilience.

This review is therefore systemic in nature and brings the understanding of green materials beyond the product, connecting material origin and processing, material performance, assembly, maintenance, disassembly, re-use, and ecological reintegration [13].

Another contribution of this review is to organize a variety of material technologies in a single comparative framework with a common assessment logic. The research communities of the above-mentioned types of construction technologies are often considered distinct bodies of research. This review combines these fields to show the complementarities and trade-offs between the material pathways. For instance, bio-based materials can be very well suited for envelopes that need to store carbon, as well as lighter structures, while light-load and infrastructure, and foundation applications might still require cementitious systems with low carbon content [14,15]. Both types of materials can be improved by providing tracking, reusability and circular recovery through digital material passports and modular construction. This integrative approach is necessary since regenerative buildings will not be manufactured out of a single "ideal" material, but out of a well-designed mix of materials, technologies and life cycle strategies.

Multi-criteria evaluation is also highlighted for this review. Technical performance indicators such as strength, durability, thermal conductivity, acoustic performance, fire resistance and moisture performance are taken into account together with environmental indicators like embodied carbon, carbon sequestration, water footprint and waste reduction [16]. Other aspects examined are economic and social, such as cost, supply-chain maturity, local availability, labor requirements, occupant health and cultural acceptance [17]. The review will help to determine which materials are, in principle, promising and which are likely to be scalable, code-compliant and appropriate for actual regeneration construction.

Thus, the aims of this article are threefold. It begins with a description of the latest innovations in the field of green construction materials and technologies that can contribute to a regenerative built environment [18]. Second, it considers their environmental, technical, economic and circularity-related performance features, including opportunities and challenges [19]. Third, it outlines key areas of future research and development for material innovation, verification of performance, life cycle assessment, digital integration and policy development [20]. The review aims to offer a structured knowledge base for researchers, architects, engineers, material scientists, manufacturers, and policy makers, all of whom are striving for the next generation of regenerative construction systems.

In brief, a new material agenda is needed to shift towards sustainable and regenerative construction. This agenda should not only focus on less embodied carbon, but also on restoring material cycles, supporting ecological systems, fostering human health and allowing buildings to evolve [21]. Rigorous assessment, interdisciplinary integration and practical implementation strategies are necessary to enable the potential of novel green building technologies to materialize in making this transformation. The review aims to provide a comprehensive picture of recent developments and research on all of these material classes and to bring them together in one framework: the concept of materials for a regenerative built environment, which has been proposed as a key enabler of the transition from a built environment that is a driver of environmental problems to one that is a player in environmental solutions.

2. Regenerative Material Principles and Assessment Frameworks

2.1. From Sustainable Materials to Regenerative Material Systems

Regenerative building materials are more than just a sustainability goal of minimising environmental damage. The materials are usually considered in sustainable construction based on low embodied energy, greenhouse gas emissions, reclaimed materials, or reduced toxicity. These are all requirements, but they are not enough to achieve a regenerative built environment. Regenerative material systems are anticipated to have positive impacts on ecological, social and economic systems throughout their entire life cycle. This implies that a material should be efficient in a building, while also aiding carbon storage, circular use of resources, ecosystem restoration, local resilience, and human health [22].

The process of this change needs a paradigm change in the concept of construction materials. Typical materials selection approaches involve mechanical performance, cost, availability, durability and code compliance. These are not challenges that a regenerative approach necessarily dismisses, but rather are part of a larger framework of environmental accountability. A low-carbon concrete can also have less emissions than ordinary Portland cement concrete, but can still rely on limited industrial by-products or chemical activators that have unpredictable supply chains [23]. The same applies to bio-based materials, which can sequester carbon throughout their useful life but whose regenerative value depends on impacts to land usage, harvesting methods, distance travelled, treatment chemicals, durability and end-of-life [24]. So it is not possible to make judgements on regenerative performance based on any one indicator, like embodied carbon. It needs a multi-dimensional evaluation and takes into account immediate material impacts and long-term system consequences.

2.2. Core Principles of Regenerative Construction Materials

The following interrelated principles can be used to describe regenerative construction materials. The first is the carbon responsibility, which is made up of carbon reduction and carbon sequestration [25]. There are materials like engineered timber, hempcrete, bamboo, straw-based panels and some products derived from algae that can store biogenic carbon; mineral carbonation and carbon-cured cementitious materials can permanently bind CO_2 in chemical reactions. Note, however, that caution needs to be taken when considering carbon storage as it is dependent on service life, replacement cycles, biomass regrowth, and end-of-life processing. Carbon-storing material when landfilled, incinerated or replaced often, may not have the actual climate benefit it appears to have.

Second, circularity. The design of regenerative materials should aim at re-use, repair, remanufacture, recycling or biological reintegration [26]. This isn't just about the content but also the structure and arrangement of the content. A material that is bonded to another that cannot be separated without causing permanent damage to the item may not be recyclable. Thus, in this context, circularity is a design quality, rather than a material quality. The potential for future recovery is greatly enhanced by dry connections, modular components, standardized dimensions and material passports.

Ecological compatibility is the third principle. Regenerative materials should be free of toxic emissions, long-lived pollutants, and polluting extractive practices. The latter is especially significant for bio-based and recycled materials, where chemical additives such as preservatives, flame retardants, synthetic binders or waste streams that may be contaminated can have negative environmental impacts. Ecological compatibility also involves the possibility of contributing to the preservation of biodiversity, for example through bio-receptive façade materials, green roof substrates and through living material systems that create habitats or improve the urban microclimates [27].

Adaptability is the fourth principle. Buildings are systems with a long life, but the functions, users, climatic conditions and regulatory requirements are changing over time [28]. Flexible materials to use, repair, disassemble and replace can help prolong the life of the building and minimise future material demands. It is therefore not just about the material used, but also about the ability of the material to enable buildings to evolve without large-scale demolition, which is required for regeneration.

2.3. Life-Cycle Assessment and Whole-Life Carbon Evaluation

One of the most popular methods for assessing the environmental performance of construction materials is called Life-cycle assessment [29]. It offers a systematic framework to measure the impacts of raw material extraction, production, transport, construction, operation, maintenance, replacement and end-of-life processing. However, the practice of conventional LCA needs to be interpreted with care when applied to regenerative construction. Cradle-to-gate values are used to promote many emerging green materials, including the extraction and manufacturing, but not the transport, installation, maintenance, service life, or disposal. These boundaries can overestimate benefits in cases of high replacement rates, particular transportation needs or high chemical treatment needs.

A more comprehensive basis for comparison is the whole-life carbon assessment [30]. It encompasses embodied carbon as well as operational carbon, maintenance carbon and end-of-life scenarios. This is particularly relevant since the performance of low-carbon materials in actual buildings can vary. For example, a low embodied carbon natural insulation can help to lower operational energy if it has low thermal values, however if it has low moisture management, its life can be shortened which would lead to higher replacement emissions. On the other hand, a higher initial embodied carbon can lead to a longer useful life and reduced maintenance and service requirements, enhancing the performance of the product over its entire life.

One of the main problems in the evaluation of carbon is the accounting of biogenic carbon [31]. Assuming that the carbon stored in bio-based materials is temporary, one could ask whether such carbon should be counted as temporary storage in the atmosphere, depending on assumptions concerning sustainable harvesting, regrowth, forest or crop management, and the fate of the material after its use. It is misleading to consider all bio-based materials as carbon-negative. A more stringent method should consider temporary storage versus permanent sequestration and should account for sensitivity analysis of the various end-of-life paths.

2.4. Circularity Assessment and Material Flow Evaluation

Circularity assessment is a complementary method to LCA, which focuses on the use of materials in technical or biological cycles [32]. This presents a major difficulty in construction work as buildings are long-lasting, materials can be mixed (composite or bonded) or construction can involve demolition of materials with low value, creating a low-value waste stream. It is therefore important to consider future recoverability as well as recycled content within a regenerative framework. High recycled content materials can still be a source of linear waste if not separable or reusable at the end of life.

Flow analysis of materials can be used to determine the points of entry, storage and exit of resources in the built environment [33]. It is useful for the comprehension of urban buildings as material banks. Documented and recoverable steel beams, timber panels, façade elements, bricks, glass units and raised floor systems can often have value. Digital material passports can be used to achieve this by documenting material composition, origin, environmental information, maintenance history and reusability. For material passports to be effective in practice, however, there is a need for standardized data, long-term access to the information, owner models, and linkage with markets for demolition and reuse.

Circularity also needs to be differentiated between high-value and low-value recovery. Recycling concrete for road base is an example of downcycling concrete, but it still means that waste is not sent to landfill. The material value is preserved and further emissions are avoided if a structural component is used more than once in a similar use. Reduction, reuse, repair, remanufacture, high-quality recycling and finally energy recovery/disposal should therefore be prioritized based on value retention [19].

2.5. Technical Performance, Durability, and Risk Assessment

One of the drawbacks in some Green Materials discussions is the notion that if a material is environmentally friendly, it will be used in practice. In practice, building materials need to meet various technical criteria concerning structural strength, durability, fire resistance, water and moisture resistance, acoustical properties, thermal properties, health safety and maintainability [16]. Failure of materials that can be regenerated could result in further environmental impacts involving repair, replacement, and liability. Thus, sustainability is inseparable from durability—it is one of its basic prerequisites.

There are uncertainties associated with emerging materials because of limited standard testing methods and long-term field data. Materials such as mycelium composites, algae materials, biochar-enriched materials and new geopolymers may be promising in the laboratory, but need to be tested in different humidity conditions, under freeze-thaw, biological attack, UV degradation and construction tolerance [34]. Likewise, there may be variations in performance with recycled materials as the feedstock may vary. This is why quality control is crucial. Reliable classification, certification and prediction of performance are vital for market uptake otherwise.

Unintended effects should also be taken into account for risk assessment. To enhance the fire performance of bio-based materials, flame retardants can raise toxicity issues. There can be increases in embodied carbon when using chemical stabilizers on earth materials. The use of alkali activators in geopolymers can decrease the amount of cement needed, but create risks of handling and associated emissions in the supply chain. These examples demonstrate that single substitution logic in assessing materials in the context of regeneration is problematic. It isn't just about substituting one material for another, it's about optimizing the whole material system [35].

2.6. Health, Social Value, and Local Regeneration

Human health and social outcomes should be part of the assessment of regenerative material. Materials can affect the indoor air quality, management of humidity, thermal comfort, sound properties and the comfort of the building user [36]. Through their appropriate use, low-emission finishes, natural fibers, clay plasters, lime-based finishes and hygroscopic products based on bio-substances can positively contribute to the indoor environmental quality. But it's not enough just to be natural; it has to be safe, too. Careful consideration is needed for mold risk, allergens, VOC compounds in binders and chemical treatments.

Local sourcing is another key factor. Local manufacturing using regional biomass, agricultural residues, earth, recycled demolition waste or locally available industrial by-products can contribute to reducing transport emissions and boosting regional economies [37]. They can also help foster place-based architectural identity and community acceptance. However, it is important to remember that local sourcing is not a romantic concept. A locally sourced material that is not durable, is not well processed, or is not extracted correctly can have a poorer performance than an alternative, responsibly sourced material from a greater distance. Locality values are regenerated through ecological management, labor conditions, processing energy and performance over the long term.

Affordability and accessibility are also considered social values. Regenerative materials will continue to be high-cost specialty products unless prices are reduced [38]. There are several requirements for scalable solutions that must match housing needs, public procurement, the skills of the workforce and regulatory systems. This is particularly the case in areas experiencing rapid urbanization where material choices not only bring about carbon reductions but also contribute to housing equity and infrastructure resilience.

2.7. Toward an Integrated Assessment Framework

An integrated framework for regenerative construction materials should combine environmental, technical, circular, health, social, and economic criteria [39]. Such a framework must recognize trade-offs rather than seeking universal material rankings. No single material is regenerative in all contexts. Engineered timber may be highly suitable for mid-rise structures in regions with certified forests and mature timber industries, while earth-based materials may be more appropriate in climates and cultures with established earthen construction knowledge. Low-carbon concrete may remain necessary for foundations, infrastructure, and high-moisture environments, while bio-based insulation may offer greater benefits in envelopes and interior systems [40].

The most useful assessment method, therefore, is context- and system-specific. It should question the performance of a material in a specific building type, climate, supply chain, regulatory context and end-of-life situation. It should also take into account interactions between materials, assemblies and technologies. Many materials can be enhanced in their regenerative potential by modular design, reversible connections, digital tracking and maintenance planning [7]. On the other hand, insufficient detailing or incompatible assemblies can thwart the most eco-friendly products.

In general, a shift is needed from product assessment to life-cycle and systems thinking in assessing regenerative materials. The deeper question is whether a material is green, recycled, bio-based or low carbon, or whether it can help create a built environment that can lower emissions, conserve resources, restore functions, uphold human health, and be adaptive over time [41]. This overview serves as the basis to assess the material technologies to be discussed in the coming sections. In **Table 1**, the following are summarized: the key dimensions, indicators, regenerative relevance, and critical considerations of this assessment approach.

Table 1. Proposed assessment framework for regenerative construction materials, including carbon performance, circularity, technical reliability, health, ecological impact, economic feasibility, social value, and adaptability.

Assessment Dimension	Indicators	Relevance to Regenerative Construction	Critical Considerations
Carbon performance	Embodied carbon, carbon storage, carbon mineralization, whole-life carbon	Determines whether a material reduces or stores carbon across its life cycle	Carbon negativity must be verified through clear system boundaries and end-of-life assumptions

Table 1. *Cont.*

Assessment Dimension	Indicators	Relevance to Regenerative Construction	Critical Considerations
Circularity	Reusability, recyclability, repairability, design for disassembly, material passport compatibility	Supports closed-loop material flows and reduces virgin resource demand	Recycled content alone is insufficient if future recovery is not possible
Technical performance	Strength, durability, fire resistance, moisture behavior, acoustic and thermal properties	Ensures that green materials can meet real building requirements	Poor durability can offset environmental benefits through repair and replacement
Health and toxicity	VOC emissions, indoor air quality, mold risk, chemical additives, occupant comfort	Links material choice to human well-being and healthy indoor environments	Natural or recycled origin does not automatically mean non-toxic
Ecological impact	Land use, biodiversity, water demand, habitat support, pollution prevention	Evaluates whether materials contribute to ecological restoration or degradation	Bio-based materials require sustainable sourcing and ecosystem-sensitive production
Economic feasibility	Cost, availability, manufacturing maturity, maintenance demand, supply-chain stability	Determines whether regenerative materials can scale beyond niche applications	High initial cost may be justified only if whole-life benefits are demonstrated
Social value	Local sourcing, job creation, cultural acceptance, affordability, skills availability	Connects material innovation with community resilience and regional development	Local materials must still meet durability, safety, and environmental standards
Adaptability	Modularity, flexibility, replaceability, compatibility with future reuse	Extends building life and reduces future material demand	Irreversible assemblies can undermine otherwise regenerative materials

3. Bio-Based and Carbon-Storing Construction Materials

3.1. Engineered Timber and Mass Timber Systems

Engineered timber has emerged as one of the most visible embodied carbon material pathways for buildings, as well as for advancing the regenerative construction pathway. These products include cross-laminated timber, glue-laminated timber, laminated veneer lumber, and dowel-laminated timber, which make wood into a high-performance structural system for floors, walls, beams, columns and hybrid building assemblies. Engineered timber materials can reduce embodied emissions, lighten structure loads, increase prefabrication speed, and provide the ability to store biogenic carbon during the building's lifecycle compared to traditional reinforced concrete and steel structures [42].

However, the regenerative potential of mass timber relies heavily on forest management, harvesting, manufacturing energy, transport distance, design life and end-of-life scenarios. Sustainably managed forests can provide renewable material cycles, whilst forests with ecological degradation or monoculture forests can lead to biodiversity loss, soil degradation and carbon debt. So, the environmental worth of timber should not be taken for granted because of its biotic source. To make timber buildings part of the ecosystem regeneration process and not merely a transfer of stress from the construction site to a forest landscape, certification systems, regional forestry governance and transparency of supply chains are needed [43].

Technically, mass timber has many benefits in terms of prefabrication, accuracy and speed of construction. It offers a good strength-to-weight ratio for lighter foundation constructions, and may help to minimize transportation and crane requirements. It also offers aesthetic and biophilic attributes that can enhance the experience of the occupants. However, there are still issues with fire resistance, waterproofing, acoustics, connection design, and durability that must be addressed to allow for widespread adoption. There has been an increase in confidence in timber buildings, due to modern approaches to fire design such as charring calculations, encapsulation, sprinklers and hybrid structural systems, although there is some variation in acceptance from region to region. Moisture is of particular importance as it can affect the durability and the safety of the structure due to poor detailing during construction or operation. Therefore, it is important to recognize that mass timber is not a general solution for all concrete and steel structures, but rather a strong regeneration solution when used in the appropriate building system with careful design and responsible sourcing policies for the material [43].

3.2. Bamboo and Rapidly Renewable Structural Materials

Bamboo is now known as a rapidly renewable construction material with significant potential for low-carbon and regenerative building. Its high tensile strength, low density, high growth rate, ability to be harvested and re-grown, often in the same location, makes it very desirable for use in structural components, panels, flooring, temporary buildings and modular buildings, and façade applications. With widespread availability of bamboo in certain areas, local economies can benefit from bamboo; its use can cut down on the need to import materials, and it can reinforce local building traditions [44].

Engineered bamboo products try to address the dimensional irregularity and durability restrictions of raw bamboo by taking it apart and stringing it back together into a laminated board, scrimber, panel and composite structural product [45]. Such products can yield better mechanical consistency and better compatibility with today's building systems. But the regenerative value of bamboo is dependent on various factors like the intensity of processing, adhesives used, preservative treatments, logistics, etc. The bamboo products that are highly processed may need high-energy-use manufacturing and synthetic resins to enhance their bamboo benefits. Furthermore, chemicals to preserve the bamboo from insects, fungi and water can cause health and end-of-life issues.

The major challenge for bamboo construction is standardization. Bamboo is still not well harmonized with regard to its structural reliability, connection design, fire properties, and durability classification, as there are well-established grading systems, codes, and design practices for timber in many countries. This restricts its application in formal construction markets, in particular multi-story or public buildings. However, with local cultivation, low-toxicity treatment, modular design and community-based manufacturing, bamboo has great regeneration potential in suitable climates and regions. Its most significant value could be not only in the substitution of commonly used materials, but also in the development of sustainable building systems for a particular area that incorporate ecological regeneration and social and economic benefit [44].

3.3. Hempcrete, Straw Bale, Cork, Flax, and Agricultural-Residue Composites

Building envelopes play a significant role in building operation energy use, thermal comfort, moisture control and embodied carbon and thus, offer an important opportunity for bio-based envelope materials and insulation. Increasingly, a number of composites that utilize agricultural residues are being evaluated as alternatives to mineral wool, expanded polystyrene, polyurethane foam, and other traditional insulation materials, such as hempcrete, straw bale, cork, flax fiber, sheep wool, rice husk, bagasse, and others [46]. They have low embodied energy, are light in weight, renewable and can fix biogenic carbon during their useful life.

One of the most popular bio-based wall products is hempcrete. It is mainly manufactured using hemp shiv, lime-based binder and water to make a lightweight composite material, which has excellent heat insulation, vapor permeability, and moisture absorption properties. Typically, the use of hempcrete is not used as a main load-bearing material but can be combined with timber or steel. It is suitable for low-energy buildings due to its humidity and temperature control properties. But the low compressive strength, construction moisture sensitivity, curing time of hempcrete and the binder composition should be taken into account [47].

Straw bale building has the same regeneration potential as it is constructed from agricultural residue which could otherwise be wasted, burned or underutilized. Straw bales have a high insulation value and can be used as a load-bearing wall or an infill wall. If detailed properly with breathable plasters, moisture control, and proper roof protection, straw buildings can be durable and comfortable. However, public opinion, fire issues, pest resistance and code acceptance issues pose challenges. Other insulation, flooring, panels and composites are made of cork and flax. Cork is a renewable resource if not removed from the tree and flax fibers can be used to reinforce biocomposites and decrease the need for synthetic fibers [48].

Agricultural-residue composites play a crucial role in circular bioeconomy strategies. Consequently, rice husk, wheat straw, coconut fiber, sugarcane bagasse and other agricultural residues can result in value-added building materials, thus reducing waste. But the environmental effects of these materials depend on the binder used, the process temperature, durability, and competition with other applications including animal bedding, soil amendment or bioenergy. The key point to take from the critical insight is that residues are not impact-free just because they are wastes. Removing them from agricultural systems could have an impact on the carbon, nutrients cycles and local resource flow. Regenerative use, therefore, needs careful assessment on a regional level [46].

3.4. Mycelium-Based Composites

One of the most innovative classes of biofabricated construction materials is the mycelium-based composites [49]. They are made from the growth of fungal mycelium on sawdust, straw, hemp residues or other plant waste products. The mycelium grows through the substrate to form a light, porous composite material that can be dried or heated to prevent biological growth. This can be processed into insulation boards, acoustic panels, interior partitions, packaging and non-structural parts.

What makes mycelium materials so attractive is their low-temperature production, waste biomass, and biodegradability, as well as their possible biological cycle compatibility. Mycelium composites, in contrast to many traditional insulation and panel products, can be produced with a relatively low energy consumption and can be free of petroleum-based binding agents. They can have porous properties offering thermal and acoustic insulation and therefore they are potential candidates to be used for interior and envelope applications. They can also be used as molds, which helps to improve design flexibility and reduce waste during the manufacturing process [50].

These benefits notwithstanding, mycelium composites are still in the early phases of adoption in the construction industry. They typically have limited mechanical properties when compared to structural materials and are sometimes affected by the fungal species, the substrate, the density, the environment, and the post-treatment techniques. Moisture sensitivity is important because fungal-derived materials will break down if left in high humidity or will encourage biological activity. Additional improvements and verification of fire performance are also needed. Additives and coatings can improve resistance but they might decrease biodegradability, or add toxicity. So, the mycelium materials have demonstrated a good regeneration capability; however, at the time of this writing, they are not used in structural applications or on exterior surfaces due to a lack of durability, fire resistance, and standardization [50].

3.5. Algae-, Cellulose-, and Lignin-Derived Materials

Algae, cellulose, and lignin are all becoming a focus of interest as feedstocks for next-generation, regenerative materials. There are several ways in which algae-based systems can be applied to construction, such as bioreactive façades, bio-based binders, insulation materials, pigments, bio-plastics as well as carbonate formation processes [51]. Algae could subsequently be used in façade systems for carbon dioxide uptake, biomass production, shading and building energy systems. These applications point to a future where building skin is not just a passive surface but an active biological interface. But the algae-integrated systems are complex, and a lot of care needs to be taken with water, nutrients, light, maintenance, contamination and harvesting. They are very sensitive to the design of the system and not only the material.

Cellulose is one of the most abundant renewable polymers and is already being used in cellulose insulation, fiberboards, papers, coatings and composites [52]. Higher-level applications involve nanocellulose-reinforced materials, transparent wood, bio-based films, aerogels and high-performance fiber composites. Nanocellulose is especially interesting due to its high strength, low density and its capacity to enhance the mechanical and barrier properties of composites. But energy, water or chemical use can be very high in the production methods, so environmental performance must be measured using life-cycle assessment, not simply based on renewability.

Lignin, a major by-product of the pulp and paper industry, is also being studied as a binder, adhesive, carbon fiber precursor, resin modifier, and cementitious or polymer additive [53]. Its valorization may decrease the use of phenol and synthetic resins derived from fossil fuels. However, lignin's chemical complexity and variability make it difficult to use in industries. As with all "bio"-based feedstocks, the fundamental research question is not whether or not lignin can be used, but how it can be applied in a technically reliable, economically competitive, and environmentally benign way as compared to other available options.

Algae-, cellulose- and lignin-based materials signify a more comprehensive bio-based construction economy [14]. Their novelty is that they convert biological resources into functional elements of a building that store carbon, adapt to climate and/or can be circularly reintegrated. Many of these technologies, however, are still at an experimental or pilot scale rather than at the mainstream construction stage. Whether they will become a meaningful part of the future will hinge on scaling up production without producing too many chemicals, using too much land, or causing production to be unpredictable.

3.6. Critical Comparison of Bio-Based Materials

Bio-based, carbon-storing materials are among the most promising avenues towards a truly regenerative built environment, but they also illustrate the complexity of regeneration as a material concept [22]. The primary benefits of their use are that they can be sourced renewably, can potentially sequester carbon, have low embodied energy, enhance indoor environmental quality and can be integrated with circular or biodegradable pathways. They can substantially lower the need for mineral extraction and fossil-based products in appropriate applications, support local bioeconomies and improve the health of buildings.

The regenerative potential of bio-based materials, however, is very context-specific. Carbon storage is significant if biomass is produced sustainably and buildings have extended service lives, and there is no rapid carbon release at the end of their life [12]. Monoculture plantations, fertilizer application, irrigation needs, habitat alteration, and long-distance transportation can create environmental pressure through renewable feedstocks. In the service life, moisture, pests, and biological degradation may be a problem, while at the end of life, biodegradability can be a good thing. In the same way, health and circularity benefits can be lost because of changes in durability or fire resistance that result from chemical treatments.

It is important to note that another critical comparison is that the biomaterials are not simply a direct replacement for all of the conventional materials for construction [35]. While most bio-based products are suitable for insulation, panels, finishes, façades, and hybrid assemblies, mass timber and engineered bamboo can be used for structures. They are most likely to be used in combination with other low-carbon technologies. For instance, timber frames can be combined with hempcrete infills and clay plasters, cellulose insulating material, recycled metal connectors and demountable assemblies. These kinds of systems can offer more regeneration than individual materials.

The key takeaway is that it is not necessarily regenerative to build bio. It is regenerative when biological sourcing, material processing, building design, operational performance, maintenance and end-of-life recovery are aligned. Integrated design, reliable certification, long-term performance data and region-specific assessment are all essential prerequisites. Under these circumstances, bio-based and carbon-storing materials could play a role in moving from a linear extractive model of construction to a renewable, circular and environmentally regenerative material system [17]. The primary applications, regenerative potential, limitations and research needs of bio-based and carbon-storing materials have been summarized and compared in **Table 2**.

Table 2. Bio-based and carbon-storing construction materials: principal applications, regenerative potential, key limitations, and future research needs.

Material Category	Main Applications	Regenerative Potential	Limitations	Research Needs
Engineered timber and mass timber	Structural frames, floors, walls, hybrid systems	Stores biogenic carbon, reduces structural weight, and enables prefabrication	Fire design, moisture protection, forestry impacts, acoustic performance	Long-term durability data, sustainable forestry verification, and hybrid system optimization
Bamboo and engineered bamboo	Structural elements, panels, façades, flooring	Rapidly renewable, high strength-to-weight ratio, supports regional bioeconomies	Lack of standardized codes, treatment chemicals, and connection design	Structural grading systems, low-toxicity preservation, durability testing
Hempcrete	Wall infill, insulation, envelope systems	Carbon storage, vapor permeability, thermal and humidity regulation	Low structural capacity, curing time, and moisture sensitivity	Binder optimization, field performance, fire and moisture behavior
Straw bale systems	Wall systems, insulation, low-rise buildings	Uses agricultural residue, has a high insulation value, and low embodied energy	Public perception, pest risk, fire concerns, and code limitations	Standardized detailing, moisture monitoring, and long-term case studies

Table 2. *Cont.*

Material Category	Main Applications	Regenerative Potential	Limitations	Research Needs
Cork and flax composites	Insulation, flooring, panels, acoustic materials	Renewable, lightweight, low toxicity, good thermal performance	Cost, regional availability, binder dependence	Scalable processing, recyclable bio-binders, performance under humid conditions
Mycelium composites	Insulation, acoustic panels, interior partitions	Low-temperature biofabrication, waste biomass use, and biodegradability	Moisture sensitivity, low mechanical strength, and fire performance	Durability enhancement, non-toxic fire treatment, standard testing protocols
Algae-based materials	Bio-reactive façades, bioplastics, binders, and shading systems	Potential carbon capture, biomass production, and adaptive envelope function	Maintenance complexity, water and nutrient demand, system instability	Pilot-scale validation, life-cycle assessment, operational reliability
Cellulose and lignin-derived products	Insulation, panels, coatings, adhesives, composites	Renewable feedstock, waste valorization, potential fossil-resin replacement	Chemical processing impacts, feedstock variability, and moisture sensitivity	Low-impact processing, bio-based binders, end-of-life recovery pathways

4. Low-Carbon, Recycled, and Circular Mineral-Based Materials

4.1. Low-Carbon Cement and Concrete Technologies

Concrete is the most common material used in the construction sector globally. As cement becomes the focal point of the decarbonization challenge, it is imperative to consider the material's use within an integrated approach to a regenerative built environment. The high embodied carbon content of ordinary Portland cement stems from the energy required for clinker production at high temperatures and for limestone calcination. These have led to the development of a number of key strategies to minimize the environmental footprint of concrete, such as reducing clinker content, increasing the efficiency of the binder, and incorporating carbon capture and/or mineralization methods [54].

The use of supplementary cementitious materials such as fly ash, ground granulated blast-furnace slag (GGBS), silica fume, natural pozzolans, and calcined clays can partly replace Portland cement and enhance certain durability properties [55]. Of these, the most recent to receive attention is limestone calcined clay cement (LCC), which can significantly reduce the need for clinker and be produced using relatively abundant clay and limestone resources. Where appropriate kaolinitic clays are available, calcined clay would provide a more stable long-term supply than fly ash and slag, both of which are derived from power generation and steel production, which depend on coal. This is significant because some low-carbon binders are produced from industrial by-products of high-carbon industries, and their availability may decrease as the economy decarbonizes.

Other emerging approaches are carbon-cured concrete and CO_2 mineralization technologies. The processes introduce CO_2 during curing or aggregate production and allow it to react with calcium-bearing phases, forming stable carbonates. They have the potential for regeneration by combining emission reduction and partial carbon storage. This overall climate benefit will, however, vary according to the source of CO_2, energy demand, the extent of mineralization, transport logistics, and the impact on mechanical performance. It is thus important to consider carbon use as a whole-life carbon analysis, not as carbon negative [54].

There is a serious challenge with low-carbon concrete: the reliability of its performance. Concrete is used in high-rise buildings, bridges and tunnels, marine applications, safety-critical applications, and foundation applications. Any alternative binder should meet the requirements for strength development, workability, durability, reinforcement compatibility, shrinkage, creep, and resistance to aggressive environments. The problem isn't just about finding ways to cut down on cement; it's about doing so without causing premature failure or requiring a lot of maintenance. In the context of regeneration, the ideal concrete is not the one with the lowest carbon footprint, but the one required to perform the function with the fewest materials, a long service life, and a promising end-of-life [56].

4.2. Recycled Aggregate Concrete and Construction-Demolition Waste Valorization

One of the largest material flows in urban systems is construction and demolition waste (CDW). This waste can be recycled and used as aggregates, binders, blocks, panels, and other products, to help alleviate pressure on landfills and a reliance on the extraction of virgin stone, sand, and gravel. Hence, recycled aggregate concrete is an important circular solution, especially in urban areas where recycling and construction demand are occurring simultaneously [57].

This is achieved by crushing waste concrete and collecting the contaminants like steel, wood, gypsum, plastics, and soil before using them as recycled concrete aggregates [58]. The introduction of natural aggregates into new concrete can be reduced through their use, but they pose some technical challenges. Old mortar is frequently found in recycled aggregates, resulting in a higher porosity, water absorption and variation. If not managed properly, this can have a detrimental effect on the compressive strength, elastic modulus and durability. There may also be an interfacial transition zone between recycled aggregate and new cement paste that is weaker than that of conventional concrete. The limitations can be overcome by better crushing, pre-saturation, carbonation treatment, surface coating, mix design optimisation and partial replacement.

Moreover, the environmental benefits of RAC are related to the context. High-quality natural aggregates are locally available and recycling involves long-distance transportation or intensive processing, the carbon benefit might be low [59]. On the other hand, in built-up areas where landfill space is limited and there is a high demand for aggregates, recycled material can offer significant circularity benefits. But this is a familiar pattern in the field of assessing regenerative materials: recycled content is not always a good measure of sustainability. The benefit actually depends on the quality of recovery, avoided extraction, transport distance, processing energy and final application.

The valorization of CDW goes beyond concrete aggregates. Secondary materials generated from waste masonry, ceramics, glass, asphalt, gypsum and mixed mineral waste can be used to make road bases, cementitious binders, bricks, tiles, insulation and precast products. For high-value applications, however, sorting and contamination control are required. If the waste is not sorted correctly, it can contain chlorides, sulfates, organic residues or harmful substances that can negatively affect performance and safety. Thus, the use of circular mineral materials requires the involvement of materials science, as well as demolition practices, logistics, regulation, and market infrastructure [60].

4.3. Geopolymers and Alkali-Activated Materials

Some of the most advanced alternatives to Portland cement-based binders include geopolymers and alkali-activated materials [61]. They are made by reacting aluminosilicate-containing precursors like fly ash, slag, metakaolin, volcanic ash, mine tailings or calcined clays with alkaline solutions. These binder systems can be used in structural, repair and industrial applications and provide high mechanical strength, chemical resistance, and thermal stability.

The low-carbon potential is due primarily to the ability to reduce or eliminate Portland clinker. If industrial by-products or natural pozzolans are available, the use of alkali-activated materials can help to greatly reduce embodied emissions. They can also up-value waste streams that would be sent to landfill. Furthermore, certain formulations possess outstanding resistance to acid attack, sulfate attack, and high temperature, which may be beneficial for durability performance under specific conditions when compared with conventional cement systems [61].

Nonetheless, geopolymer should not be touted as an easy, one-size-fits-all solution to the cement problem. The environmental performance of their products is greatly influenced by the type of precursors, the composition of the activators, the curing temperature and transport distances [62]. Embodied energy and environmental impacts can be high for the two common activators, sodium silicate and sodium hydroxide. The advantage applies even less if heat curing is necessary. Additionally, variations in feedstock may influence setting times, strength development, shrinkage, and durability. The availability of fly ash-based systems, for instance, may be reduced as coal power is phased out, and the availability of slag depends on steel production methods.

Standardization is still a big challenge. Mature codes, testing protocols, supply chains, and contractor familiarity are all advantages of conventional cement and concrete. The standards for alkali-activated materials mix design, durability prediction, reinforcement corrosion, long-term creep and shrinkage, and quality control need to be clearer. They are most useful when local precursors are available and can be used safely and regularly, when there is minimal impact of activator and when the use of applications is based on proven efficacy, not on generic statements [61].

4.4. Recycled Metals, Glass, Plastics, and Composite Materials

Metals, glass, plastics, and composites are important in structural frames, façades, envelopes, services, interiors, and finishes, despite being less than a significant part of the mass in construction [63]. This is why their use in a circular manner is important in regenerative construction. Metals have special value because steel and aluminum can be recycled endlessly without changing their basic properties. Reuse also helps to save additional value, as it does not involve energy-intensive recycling and fabrication processes.

The most difficult aspect of metal reuse is not the technical but the system organization [26]. Structural members need to be documented, tested, and certified, deconstructed without damage, and matched to new design requirements. Digital inventory, standard member sizing, reversible connections, and re-use marketplaces can enhance this process. But liability, the absence of design codes for reused parts, uncertain availability, and extra inspection labor can restrain the implementation of reused parts. Any regenerative approach should first focus on direct reuse, then on high-quality recycling when that is not possible.

Another material with great circular potential but practical challenges is glass. Glass can be used in a variety of recycled glass products, including new glass products, concrete, tiles, insulation, foam glass, and decorative items [64]. But the quality of the recoveries is affected by contamination, color sorting, coating, laminates, and collection logistics. When used as an aggregate, waste glass can be incorporated into concrete, and when finely ground, it can serve as a supplementary cementitious material, provided it does not cause an alkali-silica reaction. Recycled glass can be used as foam glass insulation material with long-lasting, moisture-proof, and non-combustible characteristics, and this type of glass is suitable for use in certain envelope and foundation applications.

Recycled plastics and polymer composites are used to make lightweight building components, panels, pipes, decking, formwork, and insulation; and to divert plastics from landfill and the oceans [65]. However, their rejuvenative qualities are disputed. Plastics can also lower weight and moisture resistance, but in some cases, they are derived from fossil resources, can be a source of microplastics, and can be hard to recycle if additives, fillers, or fiber reinforcement are added. Recycled plastic products, thus, should be used in applications where there is a reasonable expectation of durability, safety, and recovery. Otherwise, they could be turning short-lived waste into long-lived but low-circularity building products.

4.5. Earth-Based and Locally Sourced Mineral Materials

Earth-based materials are among the oldest construction technologies. They are relevant again in the context of regenerative design, such as rammed earth, adobe, cob, compressed earth blocks, and clay plaster [66]. Their advantages are that they can be processed with low energy requirements, can be obtained locally, are recyclable, have thermal mass and vapor permeability, and can contribute to indoor relative humidity regulation. Many earth materials can be manufactured with relatively low heat input and reused in various ways with minimal processing, while fired brick or Portland cement products cannot.

When stabilized, compacted, and protected from excessive moisture, rammed earth and compressed earth blocks can be used to create sturdy wall systems. They also have a high thermal mass that can help reduce temperature fluctuations inside the building, particularly in areas with large diurnal temperature swings. Low-toxicity finishes and moisture-buffering capabilities can be enhanced in the interior with clay plasters. Earth materials are also attractive for low-carbon construction due to these qualities, as well as for their role in occupant comfort and their relation to local culture [40].

Earth construction, however, is highly dependent on the type of soil, its quality, climate, design, and upkeep. Deterioration can result from water erosion, capillary rise, freeze-thaw cycles, and poor foundations and roof overhangs. The use of stabilizers (e.g., cement, lime, bitumen) can enhance strength and water resistance but can also increase embodied carbon and reduce recycling value. Therefore, the technical optimization of earth materials should take into account the durability and reversibility in the environment [66].

Yet another obstacle is regulatory acceptance. Even though earthen construction has a long history, it is still considered an unconventional building practice in many parts of the country. There is a lack of standardization in testing, a lack of expertise among contractors to use the product, and conservative permitting systems that limit use. From a regenerative point of view, earth materials are most interesting when they are locally available, are designed to be lightly stabilized, adaptable to climate conditions, and are incorporated into design elements to minimize their service-life requirements [67]. They are not just technologically remarkable, but also help to redefine the relationship between construction and regional geologies, skills, and low-impact material cycles.

4.6. Circular Design Integration

Low-carbon and recycled mineral materials can only reach their full regenerative potential when integrated with circular design strategies [19]. Material substitution alone is insufficient if buildings continue to be designed for demolition, mixed waste generation, and linear disposal.

The regenerative material life cycle shown in **Figure 2** highlights the need to prioritize reuse, repair, remanufacture, high-quality recycling, and biological reintegration over landfill, incineration, or downcycling. The first step of circular design is to minimize material demands by considering material usage through structural efficiency, adaptability, lightweight systems, and design optimization [68]. Sometimes it is better to avoid unnecessary material use than to use a lower-carbon material instead of a higher-carbon one.

Significantly, design for disassembly is important. If components of mineral materials can be separated and identified, then they can retain value, such as concrete, brick, stone, glass, and metals. Modular dimensions and layered construction assemblies with accessible fasteners and dry mechanical connections can facilitate future repair, replacement, and recovery [7]. Conversely, assemblies that use irreversible bonding can make it difficult to reuse the components, even if they're recyclable.

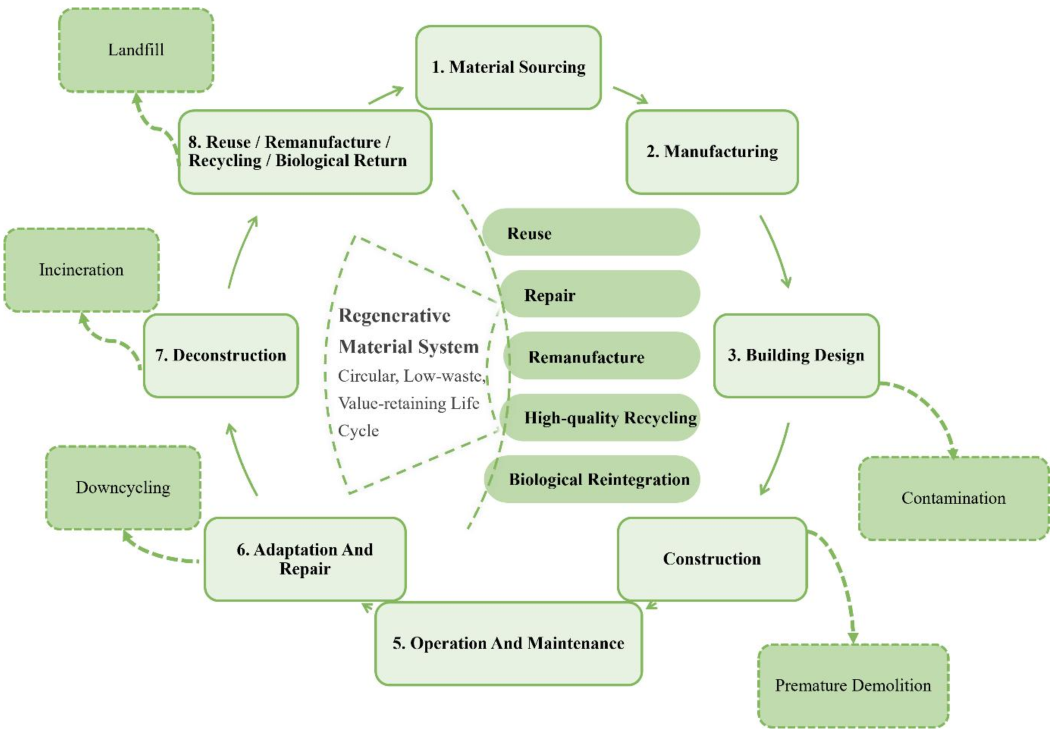

Figure 2. Regenerative material life-cycle model showing circular recovery pathways, including reuse, repair, remanufacture, high-quality recycling, and biological reintegration, while minimizing material leakage through landfill, incineration, and downcycling.

Digital technologies can enhance the circular integration. Material passports, building information modeling, digital twins, and sensor-based monitoring can track material composition, location, maintenance history, and re-use potential [8]. The tools treat buildings as material banks, thereby treating components as future resources rather than waste. But without real deconstruction skills, secondary markets, and legislation, a material passport can become a theoretical concept rather than a real game-changer.

One of the key lessons learned is that waste diversion is not the same as value retention, which is the ultimate goal of circularity [69]. Crushed concrete can be used in fill, which decreases landfill use, but at the same time, there is a loss of value of the original materials. More embodied energy and labor are saved when reusing precast elements, bricks, stone panels, or steel members. Likewise, creating concrete structures that will last for a long time and be adaptable may be more regenerative than making lower-carbon concrete for structures that will be torn down too early.

Finally, mineral-based materials will continue to play an important role in the built environment due to their intrinsic strength, durability, fire resistance, thermal mass, and their use in infrastructure applications [16]. Thus, the regeneration challenge is not the removal of mineral materials but rather a change in how they are produced, specified, consumed, preserved, and recovered. Low-carbon binders, recycled aggregates, geopolymers, re-used metals, circular glass, recycled plastics, taken with care, and earth-based materials are all significant avenues. They rely on context-specific evaluation, performance verification, circular design, and moving away from linear material use toward durable, recoverable, and resource-positive building systems. The primary low-carbon, recycled, and circular mineral-based material types covered in this section are compared here, highlighting their environmental benefits, practical challenges, and suitability for the application (**Table 3**).

Table 3. Low-carbon, recycled, and circular mineral-based materials, including their conventional material substitutes, environmental advantages, practical barriers, and best-fit applications.

Material or Technology	Conventional Material Replaced or Reduced	Main Environmental Advantage	Practical Barriers	Best-Fit Applications
Supplementary cementitious materials	Portland cement clinker	Reduces clinker demand and embodied CO_2	Limited or declining availability of fly ash and slag; variable quality	Ready-mix concrete, precast products, structural concrete
Limestone calcined clay cement	High-clinker cement	Uses relatively abundant clay and limestone while lowering cement carbon intensity	Need for suitable clay sources and production infrastructure	General concrete, masonry products, blended cements
Geopolymers and alkali-activated binders	Portland cement binders	Lower clinker dependence and potential use of industrial by-products	Activator impacts, feedstock variability, and limited codes	Precast elements, industrial floors, repair materials, and chemical-resistant applications
Carbon-cured concrete	Conventional curing and cement-intensive concrete	Stores CO_2 through mineralization and may improve early strength	CO_2 source, process energy, scalability, carbon accounting uncertainty	Precast blocks, pavers, panels, and selected structural elements
Recycled aggregate concrete	Natural aggregate concrete	Reduces virgin aggregate extraction and construction-demolition waste	Higher water absorption, strength variability, and contamination risks	Non-structural concrete, pavements, and selected structural concrete with quality control
Reused steel members	Newly manufactured structural steel	Preserves embodied energy and avoids remelting emissions	Certification, dimensional mismatch, reuse logistics, and liability	Structural frames, warehouses, and adaptive reuse projects
Recycled glass products	Virgin glass, aggregate, and insulation materials	Diverts glass waste and reduces raw material demand	Sorting, coating contamination, and alkali-silica reaction in concrete	Foam glass insulation, tiles, façade products, fine glass powder in binders
Recycled plastic products	Virgin plastic, timber, and some panel materials	Diverts plastic waste and creates durable, lightweight components	Microplastic risk, fire behavior, and limited recyclability after use	Decking, boards, panels, formwork, non-structural components
Earth-based materials	Fired bricks, concrete blocks, and synthetic finishes	Low processing energy, local sourcing, thermal mass, recyclability	Water sensitivity, code barriers, and labor skill requirements	Rammed earth walls, compressed earth blocks, clay plasters, and low-rise buildings

5. Emerging Green Construction Technologies and System Integration

5.1. Additive Manufacturing and 3D-Printed Construction

Additive manufacturing is seen as a transformative construction technology, as it not only changes the way buildings are put together but also how materials are designed and used [70]. In conventional construction, formwork, labor, and a conservative approach to detailing can restrict material use, leading to overuse, waste, and limited design flexibility. Three-dimensional printing allows for the layer-by-layer deposition of cementitious, earthen, geopolymer, recycled, or bio-based materials, and only deposits material where it is structurally and/or functionally needed. This capability can have a major impact on regenerative construction, as it can be used to reduce formwork waste, optimize geometry, minimize offcuts, and enable local production.

The green value of a 3D-printed building relies significantly on the building material. Despite the reduction in construction waste, the carbon gains from additive manufacturing may be compromised if it relies on high-cement mixtures, fast-setting admixtures, and high binder content. Hence, the most promising alternative is digital fabrication and formulation of low-carbon mixtures such as calcined clay binders, geopolymers, recycled aggregates, earth-based materials, and bio-derived additives. Earthen 3D printing is especially appealing due to the potential use of soils readily available in the area and the fact that it requires less energy for binder use; however, there are still challenges with durability, water resistance, and code compliance [71].

One significant technical challenge in 3D-printed construction is the need to incorporate reinforcement into the process. While concrete printing may generate complex wall geometries, there are still many structural applications that require tensile reinforcement, anchorage, ductility, and strong connections. Layer interfaces may also induce anisotropic performance (strength in different directions depending on print direction, bonding strength). Printability requirements, including pumpability, buildability, open time, and extrusion stability, can compete with long-term durability or low-carbon material requirements. The trade-offs highlight that additive manufacturing is not the same as a construction automation tool. It begins with digital design, material formulation, structural optimization, and life-cycle assessment working in synergy [70].

5.2. Prefabrication, Modular Construction, and Industrialized Building Systems

Prefabrication and modular construction contribute to regenerative building in several ways, including greater efficiency in materials use and construction quality, reduced waste, and enhanced future adaptability [71]. Factory-based production ensures better control of dimensions, moisture exposure, curing conditions, and assembly tolerances than site production. It can be of particular interest for bio-based materials, mass timber systems, lightweight panels, recycled steel modules, and high-performance envelope components. Industrialized construction can minimize on-site errors and material waste, thereby reducing embedded impacts and maintenance risks.

Modular construction also contributes to circularity, as its components can be designed for disassembly, transport, repair, and reuse [71]. A modular building can be retrofitted to become regenerative, but opportunities do exist for reversible assemblies and material traceability. If components such as volumetric modules, panelized façades, prefabricated timber elements, or service-integrated components are assembled using readily accessible mechanical systems rather than sealed or irreversible bonding, demolition waste can be minimized. The key benefit of a modular system is its regenerative value, particularly if the system is considered a long-term material bank and not a product with a short life.

But there are pitfalls in industrialized construction, too. While a degree of standardization may increase efficiency, excessive standardization could reduce adaptability to climatic and cultural conditions, materials, and architectural requirements. Modular units can also require additional transport, lifting, packing, and backup, which can offset the environmental benefits of long or under-optimized supply chains. Moreover, prefabricated systems are frequently based on central manufacturing sites, which can limit opportunities for local labor or create new industrial dependency [72]. So, besides speed and cost, the power of prefabrication to enable circular design, local value creation, low-carbon logistics, and long service life must also be considered.

5.3. Smart, Adaptive, and Multifunctional Materials

Smart and multifunctional materials transform construction materials from passive to active, helping improve building performance[7]. Examples of materials that can control energy, repair damage, reduce air pollution, or generate energy include: phase-change materials, self-healing concrete, photocatalytic coatings, building-integrated PV systems, thermochromic surfaces, and humidity-buffering materials. These technologies align with the aims of regenerative design, as they help lower operational energy demand, increase service life, and enhance indoor environmental quality.

Phase change materials (PCMs) can absorb and release heat as they melt and solidify, helping regulate building temperatures and minimize heating or cooling demands[73]. Their benefits are highest when the phase-change temperature is similar to the temperatures when a building is used and to the local climate. The environmental value, however, would rely on their encapsulation materials, long-term cycling stability, fire safety, leakage prevention, and end-of-life recovery. Likewise, the performance of an electrochromic glazing in mitigating the solar heat gain and glare needs to be considered, as do the embodied impacts, electronic control systems, cost, and replacement requirements.

Another promising technology is self-healing concrete, particularly for infrastructure and moist environments[74]. Healing mechanisms can be mineral admixtures, microcapsules, crystallization additives, or bacterial-induced calcium carbonate precipitation. Self-healing systems can enhance durability and minimize maintenance by sealing cracks and limiting water ingress. However, the regenerative value will depend on whether measurable life-extension benefits warrant the added materials, complexity, and costs.

Under proper light conditions, photocatalytic materials can break down some air pollutants and keep surfaces cleaner[75]. In the real world, however, they prove to be more or less effective depending on pollutant levels, surface exposure, weathering, and maintenance. A critical perspective is required, as multifunctionality can sometimes be exaggerated at the product level and may not be realized at the building or urban level. Smart materials should therefore be evaluated by means of established field performance data, not just lab-based indicators.

5.4. Nature-Based and Living Material Systems

Nature-based and living material systems are a more extreme form of regenerative building, aiming to integrate buildings with biological systems[12]. These ecosystem services include stormwater retention, urban cooling, support for biodiversity, improved air quality, acoustic buffering, and psychological benefits. These systems can participate in ecological cycles, unlike traditional green materials, during the building's operation.

Vertical greening and green roofs are some of the most advanced NbS technologies[76]. They can be used to help alleviate urban heat-island effects, delay stormwater runoff, enhance roof membrane durability, and create habitat for insects and birds. However, they depend on plant selection, substrate depth, irrigation, maintenance, structural capacity, and local climate. Unconstructed green systems can use up too much water, may not withstand drought, and can be difficult to maintain. So, their contribution to regeneration should be assessed based on their ecological functions, resilience, and resource requirements, not just their greenness.

Bio-receptive materials are intended to facilitate controlled colonization by mosses, lichens, algae, or other organisms[27]. These materials can create façades and city surfaces that serve as interfaces supporting habitat. They are questioning the traditional construction thinking that biological growth is always a problem. However, it is important to make an accurate distinction between beneficial colonization and harmful biodeterioration. Biological activity must be used to strengthen, not weaken, surface porosity, pH, moisture-holding capacity, structural protection, and maintenance strategies.

Also under consideration are microbial-induced calcium carbonate precipitation and biocementation[77]. Mineral precipitation, particle binding, crack sealing, and soil stabilization are some actions these processes perform, using microorganisms or enzymes. They can provide potential low-energy options for repair, ground improvement, and material formation. Yet there are issues concerning scalability, nutrient supply, process control, ecological safety, and durability that remain to be resolved. Living materials are therefore promising but require strict distinctions between biological performance and building safety and durability.

5.5. Digital Technologies Supporting Regenerative Materials

To create connections between material innovation and system-level regeneration, digital technologies are vital. All of these tools—building information modeling (BIM), digital twins, artificial intelligence, robotic fabrication, material passports, sensor networks, and blockchain documentation—can enhance the selection, tracking, assembly, monitoring, and recovery of materials [8]. They are important because they make material flows visible. Many circular strategies are hard to implement without a good understanding of composition, location, condition, and ownership.

By integrating material quantities with embodied-carbon databases and LCA tools, BIM can be helpful for low-carbon design. This will enable designers to make comparisons of the various materials in the early design stages, while there is the greatest opportunity to minimize impacts. Digital twins further break this down by connecting physical buildings to real-time performance data and facilitating predictive maintenance, adaptive operation, and better end-of-life planning. This is significant in regenerative construction because the material's value is tied to its performance and maintenance over time, as well as to its specifications at the initial construction [13].

Another important role of material passports is to record the value of materials [78]. They illustrate the product's composition, environmental information, how to take it apart, what can be done with it after use, and certifications. Passports can be used in conjunction with modular construction and reversible connections to make buildings potential material banks. But documentation using digital means alone does not ensure circularity. Data and information should be available for decades, not lost due to changes in ownership, and should link to real markets for reused materials. Moreover, information systems should not be overly complex to prevent them from being used by smaller companies or local construction companies.

AI and computational design can optimize designs, minimize material use, and explore design options with minimal impact. Robotic fabrication can enhance precision and create customized components with reduced waste. However, there are environmental costs associated with digital technologies, such as energy consumption, hardware needs, data storage, and e-waste. The regeneration value must, therefore, be assessed based on measurable reductions in material demand, emissions, waste, and maintenance rather than on the basis of the technology's sophistication alone [8].

5.6. Barriers to Implementation

There are technical, economic, regulatory, and cultural barriers to the implementation of emerging green construction technologies [79]. Technical challenges include limited long-term durability data, the absence of standard testing, uncertainty in fire and moisture performance, variable feedstock quality, and limited knowledge of the behavior of novel materials in real building assemblies. At the same time, a successful laboratory test may not necessarily result in reliability in the field, especially when the materials are subject to varying conditions of temperature, humidity, biological activity, construction tolerances, and maintenance practices.

Financial constraints are also very important. Several regenerative technologies have higher initial investment, lack supply chain uniformity, involve small-scale manufacturing, and have vagueness around insurance and warranties. Even if there is the ability to save on the same product over its life, the lowest up-front cost is often considered more important than long-term performance. This results in a disadvantage to materials with lower maintenance, operation energy, and/or end-of-life waste but higher initial investment [79].

Regulatory systems are also late to the game. Codes are intended for safety and reliability, but can impose limitations on the use of new materials when performance paths aren't clear. It can be costly to certify, test, and approve, particularly for smaller manufacturers creating bio-based or recycled products. Also, conservative industry culture slows down adoption. When responsibility for failure is in dispute, architects, engineers, contractors, insurers, and clients may shy away from using novel materials [11].

The second is the lack of an integrated assessment. Technologies are frequently sold on their own, and systems are required to regenerate. A smart material will require less energy in operation, but will be more difficult to recycle. Recycled composite can reduce waste, but may introduce toxicity or pose subsequent disposal issues. A bio-based panel may be able to store carbon yet fail in a wet environment. These compromises involve a multidisciplinary decision-making process in which materials science, architecture, engineering, ecology, economics, and policy must be considered [20].

5.7. Future Research Directions

Future work should include the transition from isolated innovation to proven renewable systems. Long-term field tests are urgently needed to evaluate durability, maintenance, fire responses, moisture, structural reliability, and interior health effects under real climatic and occupancy conditions [9]. In particular, this type of evidence is crucial for mycelium composites, bio-receptive materials, living systems, recycled composites, earth-based printed structures, and novel binders.

There's also a need for more consistency and transparency in life-cycle assessment methods [29]. Comparative studies must be clearly defined in terms of system boundaries, the service life duration, assumptions regarding biogenic carbon accounting, replacement cycles, transport distances, and end-of-life scenarios. Circularity, toxicity, biodiversity, water use, resilience, and social value are metrics that should be used alongside carbon metrics to evaluate regenerative materials. We need a more comprehensive evaluation to prevent the "passing the buck" effect between environmental categories.

Additionally, research into hybrid systems rather than single-material systems is needed. The emerging regenerative building will most probably use mass timber, low-carbon concrete, bio-insulation, recycled metals, digital passports, modular assemblies, smart envelopes, and nature-based systems. It is more important to understand the interactions among these components than to optimize each material individually. In the case of timber structures, for instance, digital monitoring could be used to alert to moisture-related risks, and, with modular design, low-carbon concrete or steel components could be reused [42].

Policy and market research are also needed. Acceleration of adoption can be achieved through public procurement, carbon disclosure, re-use standards, insurance mechanisms, and performance-based codes [5]. Lessons learned from demonstration projects should be transferable between building types and climates through post-occupancy evaluation and open data. The regenerative contributions, compatible materials, limitations, and future development needs of the major emerging green construction technologies are summarized in **Table 4**.

Table 4. Emerging green construction technologies and their roles in regenerative system integration, including additive manufacturing, prefabrication, modular construction, smart materials, living systems, digital twins, material passports, and computational design.

Technology	Regenerative Contribution	Material Compatibility	Main Limitations	Future Direction
Additive manufacturing/3D printing	Reduces formwork waste, enables optimized geometry, and supports localized production	Low-carbon concrete, geopolymers, earth materials, recycled mixtures, bio-based binders	Reinforcement integration, high binder content, anisotropic strength, and code uncertainty	Develop printable low-carbon mixtures and verified structural design methods.
Prefabrication	Improves quality control, reduces site waste, and shortens construction time	Mass timber, modular steel, bio-based panels, precast low-carbon concrete	Transport impacts, design rigidity, and centralized production	Combine prefabrication with local materials and design for disassembly
Modular construction	Enables reuse, relocation, repair, and adaptable building layouts	Timber modules, steel frames, hybrid assemblies, service-integrated panels	Upfront coordination, transport constraints, and dimensional standardization	Develop reusable, modular systems with material passports
Smart materials	Improve energy performance, durability, and adaptive comfort	Phase-change materials, electrochromic glazing, self-healing concrete, photocatalytic coatings	Cost, maintenance, uncertain field performance, and recycling complexity	Validate long-term whole-life benefits through monitored buildings
Living and bio-receptive systems	Support biodiversity, urban cooling, stormwater control, and ecological interaction.	Green roofs, living walls, bio-receptive concrete, microbial materials	Maintenance, water demand, biological control, and durability risks	Design climate-specific living envelopes with measurable ecosystem services
Digital twins	Support performance monitoring, predictive maintenance, and life-cycle optimization	All major material systems	Data management, cost, interoperability, and long-term accessibility	Link real-time building data with material condition and carbon performance

Table 4. *Cont.*

Technology	Regenerative Contribution	Material Compatibility	Main Limitations	Future Direction
Material passports	Enable reuse, traceability, circular procurement, and material banking	Reusable steel, timber, façade systems, modular components, recycled products	Data standardization, ownership, and market integration	Establish interoperable databases and legal frameworks for reuse
AI and computational design	Optimizes material use, structural form, and low-carbon design alternatives	Structural systems, façades, printed components, hybrid assemblies	Data quality, transparency, over-optimization, and digital energy use	Integrate AI with LCA, circularity metrics, and constructability constraints

Overall, emerging green construction technologies offer powerful tools for regenerative transformation, but their value depends on integration. Additive manufacturing, modular construction, smart materials, living systems, and digital platforms are not inherently regenerative. They become regenerative when they reduce material demand, extend service life, enable circularity, improve ecological function, support human well-being, and operate within transparent whole-life assessment frameworks [30]. The key challenge for the next phase of research and practice is to connect technological innovation with ecological intelligence, regulatory trust, and scalable construction systems.

6. Conclusion

A shift towards a regenerative built environment means a complete rethinking of construction materials as mere building inputs, and a reconsideration of them as active contributors to environmental restoration, circular resource use, and long-term social value. This review has highlighted that this transition can be realized in several ways through novel green construction technologies: carbon storage, reduction of embodied carbon, waste valorization, material circularity, indoor environmental quality, and integration with living ecological systems. But none of the materials or technologies can regenerate on their own. Careful coordination of material sourcing, processing, performance, assembly, maintenance, adaptability, and end-of-life recovery is a key part of regenerative construction.

There is potential in bio-based and carbon-storing materials, such as engineered timber, bamboo, hempcrete, straw, cork, mycelium composites, algae-derived, cellulose, and lignin-based materials, that can decrease reliance on fossil and mineral resources, and store biogenic carbon. Their value lies in the most effective use of sustainably managed feedstocks, locally appropriate, durable and recoverable via circular or biological pathways. However, they should be used with care and consideration of the effects on the land, fire resistance, moisture management, chemical treatment, durability, and scalability. A product with a bio origin is not automatically regenerative.

Low-carbon, recycled and circular mineral-based materials are still significant as concrete, metals, glass, earth and mineral composites will continue to be used in many structural and infrastructure applications. Low-clinker cements, limestone calcined clay cement, geopolymers, alkali-activated binders, carbon-cured concrete, recycled aggregates, reused steel, recycled glass and earth-based materials could help to mitigate the embodied impacts and promote the circular material flows. However, their effectiveness relies on the availability and accessibility of their region's feedstocks, quality control, performance verification, and whole-life carbon assessment. Recycled content and low-carbon claims need to be judged on durability, processing energy, transport energy, contamination risks, and future recoverability, in particular.

New construction technologies like additive manufacturing, prefabrication, modular construction, smart materials, living systems, digital twins, and material passports are the system-level elements required to realise the regenerative potential of green materials. These technologies can help minimize waste, facilitate easy disassembly, improve construction accuracy, streamline predictive maintenance, and preserve the value of materials throughout the building's lifecycle. But they are not regeneratively produced. They are benefits that are dependent on the measurable reduction of resource demand, the extension of service life, the improvement of ecological function and the support of the circular recovery.

One of the key findings in this review is the need to move beyond one-parameter evaluation when selecting materials for regeneration. Embodied carbon is necessary, yet it cannot be the only factor considered in designing durable, non-toxic, circular, environmentally friendly, resilient, affordable, locally capable, and healthy buildings and spaces. Future work needs to therefore focus on harmonised life-cycle assessment methodologies, long-term field performance data, fire and moisture testing, implementing digital material traceability, developing scalable biofabrication methods and establishing policy avenues to enable re-use and low-carbon procurement. Finally, regenerative construction will become an output of low-carbon, circular, adaptive, ecologically compatible and socially desirable material systems, not just isolated green products.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new data were created or generated in this study.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

References

[1] Wilbanks, T.J., Fernandez, S. (eds.), 2014. Climate Change and Infrastructure, Urban Systems, and Vulnerabilities: Technical Report for the US Department of Energy in Support of the National Climate Assessment. Island Press/Center for Resource Economics: Washington, DC, USA. DOI: https://doi.org/10.5822/978-1-61091-556-4

[2] Shukla, S.K., Kaul, S., 2024. Advanced Building Materials. In Thermal Evaluation of Indoor Climate and Energy Storage in Buildings. CRC Press: Boca Raton, FL, USA. pp. 1–36. DOI: https://doi.org/10.1201/9781003415695-1

[3] Bungau, C.C., Bungau, T., Prada, I.F., et al., 2022. Green Buildings as a Necessity for Sustainable Environment Development: Dilemmas and Challenges. Sustainability. 14(20), 13121. DOI: https://doi.org/10.3390/su142013121

[4] Kitsopoulou, A., Bellos, E., Tzivanidis, C., 2024. An Up-to-Date Review of Passive Building Envelope Technologies for Sustainable Design. Energies. 17(16), 4039. DOI: https://doi.org/10.3390/en17164039

[5] Temizel-Sekeryan, S., Rios, F.C., Geremicca, F., et al., 2023. Circular Design and Embodied Carbon in Living Buildings: The Missing Potential. Journal of Architectural Engineering. 29(3), 04023013. DOI: https://doi.org/10.1061/JAEIED.AEENG-1445

[6] El Kouche, J., 2024. Regenerative Construction: Overview and Key Insights [Master's Thesis]. Politecnico di Milano: Milan, Italy.

[7] Slamani, M., Louhichi, B., Amroune, S., et al., 2026. Next-Generation Composite Materials and Manufacturing: A Review of Smart, Sustainable, and Digital Advancements. Advanced Materials Technologies. 11(9), e01409. DOI: https://doi.org/10.1002/admt.202501409

[8] Sajadieh, S.M.M., Noh, S.D., 2025. A Review of Digital Twin Integration in Circular Manufacturing for Sustainable Industry Transition. Sustainability. 17(16), 7316. DOI: https://doi.org/10.3390/su17167316

[9] Habert, G., Göswein, V., 2026. Building to Heal: Regenerative Design and the Impact of Sustainable Construction Materials, 1st ed. Routledge: London, UK. DOI: https://doi.org/10.1201/9781003405672

[10] Housh Sadat, S.Z., Bararzadeh Ledari, M., Dehvari, H., et al., 2024. Aligning Net zero energy, carbon Neutrality, and regenerative concepts: An exemplary study of sustainable architectural practices. Journal of Building Engineering. 90, 109414. DOI: https://doi.org/10.1016/j.jobe.2024.109414

[11] Saini, H., Ledwani, L., 2024. A review on application of green materials in different construction systems, their processing, surface modification, testing and certification. MRS Energy & Sustainability. 11(2), 267–303. DOI: https://doi.org/10.1557/s43581-024-00088-0

[12] Raja, P., Murugan, V., Ravichandran, S., et al., 2023. A Review of Sustainable Bio-Based Insulation Materials for Energy-Efficient Buildings. Macromolecular Materials and Engineering. 308(10), 2300086. DOI: https://doi.org/10.1002/mame.202300086

[13] Lisco, M., 2025. Reuse Strategies in Building Design [PhD Thesis]. Lund University: Lund, Sweden.

[14] Pacheco-Torgal, F., 2025. An introductory overview of bio-based construction materials. In Advances in Bio-Based Materials for Construction and Energy Efficiency. Elsevier: Amsterdam, The Netherlands. pp. 1–14. DOI: https://doi.org/10.1016/B978-0-443-32800-8.00008-1

[15] Behera, D., Liu, K.-Y., Rachman, F., et al., 2025. Innovations and Applications in Lightweight Concrete: Review of Current Practices and Future Directions. Buildings. 15(12), 2113. DOI: https://doi.org/10.3390/buildings15122113

[16] Jain, A.K., 2023. Climate Resilient, Green and Low Carbon Built Environment, Green Energy and Technology. Springer Nature: Singapore. DOI: https://doi.org/10.1007/978-981-99-0216-3

[17] Oyefusi, O., 2025. From Green to Regenerative Supply Chain Management in Construction: Development of a Robust Integrated Decision-Making Approach to Facilitate the Paradigm Shift. Te Herenga Waka—Victoria University of Wellington: Wellington, New Zealand. DOI: https://doi.org/10.26686/wgtn.29319578

[18] Ahmadizadeh, M., Heidari, M., Thangavel, S., et al., 2024. Development of new materials for sustainable buildings. In Sustainable Technologies for Energy Efficient Buildings. CRC Press: Boca Raton, FL, USA. pp. 30–48. DOI: https://doi.org/10.1201/9781003496656-2

[19] Baniya, B., 2023. Circularity in Facility Management: Conceptualisation and Potential Areas for Circularity-Oriented Actions. Sustainability. 15(11), 8460. DOI: https://doi.org/10.3390/su15118460

[20] Kumar, D., Maurya, K.K., Mandal, S.K., et al., 2025. Life Cycle Assessment in the Early Design Phase of Buildings: Strategies, Tools, and Future Directions. Buildings. 15(10), 1612. DOI: https://doi.org/10.3390/buildings15101612

[21] Almusaed, A., Yitmen, I., Myhren, J.A., et al., 2024. Assessing the Impact of Recycled Building Materials on Environmental Sustainability and Energy Efficiency: A Comprehensive Framework for Reducing Greenhouse Gas Emissions. Buildings. 14(6), 1566. DOI: https://doi.org/10.3390/buildings14061566

[22] Bühler, M., Hollenbach, P., Köhler, L., et al., 2024. Unlocking resilience and sustainability with earth-based materials: a principled framework for urban transformation. Frontiers in Built Environment. 10, 1385116. DOI: https://doi.org/10.3389/fbuil.2024.1385116

[23] Barbhuiya, S., Das, B.B., Adak, D., et al., 2025. Low carbon concrete: advancements, challenges and future directions in sustainable construction. Discover Concrete and Cement. 1(1), 3. DOI: https://doi.org/10.1007/s44416-025-00002-y

[24] Mouton, L., Allacker, K., Röck, M., 2023. Bio-based building material solutions for environmental benefits over conventional construction products – Life cycle assessment of regenerative design strategies (1/2). Energy and Buildings. 282, 112767. DOI: https://doi.org/10.1016/j.enbuild.2022.112767

[25] Zakkour, P., Kuijper, M., Dixon, P., et al., 2024. Carbon storage units and carbon storage obligations: A review of policy approaches. International Journal of Greenhouse Gas Control. 133, 104087. DOI: https://doi.org/10.1016/j.ijggc.2024.104087

[26] Baiani, S., Altamura, P., 2022. Reusable Cities: A Circular Design Approach to Urban Regeneration through Materials Reuse. In: Battisti, A., Baiani, S. (eds.). Sustainable Development Dimensions and Urban Agglomeration. IntechOpen: London, UK. DOI: https://doi.org/10.5772/intechopen.105219

[27] Parveen, S., Tariq, M., 2023. Bioreceptive Building Materials for Urban Ecology. New Environmentally-Friendly Materials. 2(1), 41–55. DOI: https://doi.org/10.55121/nefm.v2i1.856

[28] Mlote, D.S., Budig, M., Cheah, L., 2024. Adaptability of buildings: a systematic review of current research. Frontiers in Built Environment. 10, 1376759. DOI: https://doi.org/10.3389/fbuil.2024.1376759

[29] Mattinzioli, T., Lo Presti, D., Jiménez Del Barco Carrión, A., 2022. A critical review of life cycle assessment benchmarking methodologies for construction materials. Sustainable Materials and Technologies. 33, e00496. DOI: https://doi.org/10.1016/j.susmat.2022.e00496

[30] Keyhani, M., Abbaspour, A., Bahadori-Jahromi, A., et al., 2023. Whole Life Carbon Assessment of a Typical UK Residential Building Using Different Embodied Carbon Data Sources. Sustainability. 15(6), 5115. DOI: https://doi.org/10.3390/su15065115

[31] Leinonen, I., 2022. A general framework for including biogenic carbon emissions and removals in the life cycle assessments for forestry products. The International Journal of Life Cycle Assessment. 27(8), 1038–1043. DOI: https://doi.org/10.1007/s11367-022-02086-1

[32] Samani, P., 2023. Synergies and gaps between circularity assessment and Life Cycle Assessment (LCA). Science of The Total Environment. 903, 166611. DOI: https://doi.org/10.1016/j.scitotenv.2023.166611

[33] Kolkwitz, M., Luotonen, E., Huuhka, S., 2023. How changes in urban morphology translate into urban metabolisms of building stocks: A framework for spatiotemporal material flow analysis and a case study. Environment and Planning B: Urban Analytics and City Science. 50(6), 1559–1576. DOI: https://doi.org/10.1177/23998083221140892

[34] Gunaware, P.D., 2025. Next-Generation Sustainable and Ultra-High-Performance Materials for Climate Resilient Structures. Open Access Journal of Multidisciplinary Research. 1(7), 17–28. DOI: https://doi.org/10.

47760/OAJMR.2025.v01i07.002
[35] Mannucci, S., 2025. Beyond Sustainability: Paradigms for Complexity and Resilience in the Built Environment. Urban Science. 9(6), 212. DOI: https://doi.org/10.3390/urbansci9060212
[36] Kujundzic, K., Stamatovic Vuckovic, S., Radivojević, A., 2023. Toward Regenerative Sustainability: A Passive Design Comfort Assessment Method of Indoor Environment. Sustainability. 15(1), 840. DOI: https://doi.org/10.3390/su15010840
[37] Kazmi, R., Jain, D., 2025. Role of Construction Material Transport for Achieving a Circular Economy in the Construction Industry: a Systematic Literature Review. Circular Economy and Sustainability. 5(5), 3743–3761. DOI: https://doi.org/10.1007/s43615-025-00553-z
[38] Yahia, A.K.M., Rahman, M.M., Shahjalal, M., et al., 2024. Sustainable Materials Selection in Building Design and Construction. International Journal of Science and Engineering. 1(4), 106–119. DOI: https://doi.org/10.62304/ijse.v1i04.199
[39] Sala Benites, H., Osmond, P., Prasad, D., 2022. A Future-Proof Built Environment through Regenerative and Circular Lenses—Delphi Approach for Criteria Selection. Sustainability. 15(1), 616. DOI: https://doi.org/10.3390/su15010616
[40] Haque, M.M., Uddin, S.Z., 2024. A Review on Sustainable Building Materials and Their Role in Enhancing U.S. Green Infrastructure Goals. Journal of Sustainable Development and Policy. 3(4), 65–100. DOI: https://doi.org/10.63125/bfmmay79
[41] Khoshnava, S.M., Rostami, R., Mohamad Zin, R., et al., 2020. The Role of Green Building Materials in Reducing Environmental and Human Health Impacts. International Journal of Environmental Research and Public Health. 17(7), 2589. DOI: https://doi.org/10.3390/ijerph17072589
[42] Giacomello, E., Perrucci, G., Trabucco, D., 2024. Reducing the embodied carbon using bio-based building materials: the biogenic carbon content of timber. IOP Conference Series: Earth and Environmental Science. 1402(1), 012037. DOI: https://doi.org/10.1088/1755-1315/1402/1/012037
[43] Ijeoma, M.W., 2025. Advancing Life Cycle Assessment of Mass Timber: Environmental Performance, Circular Design and End-Of-Life Strategies [PhD Thesis]. Clemson University: Clemson, SC, USA.
[44] Bredenoord, J., 2024. Bamboo as a Sustainable Building Material for Innovative, Low-Cost Housing Construction. Sustainability. 16(6), 2347. DOI: https://doi.org/10.3390/su16062347
[45] Li, Y., 2023. Bamboo-Wood Structural Composite Lumber: Material Grading and Product Development [Master's Thesis]. University of British Columbia: Vancouver, BC, Canada.
[46] Kumar, V., Abubakar, A.S., Qureshi, T., et al., 2025. Sustainable Building Materials from Agricultural Wastes. In: Shaffie, E., Hassan, R., Arshad, A.K., et al. (eds.). Sustainable Green Infrastructure. Springer Nature: Singapore. pp. 97–119. DOI: https://doi.org/10.1007/978-981-96-1486-8_6
[47] Asghari, N., Memari, A.M., 2024. State of the Art Review of Attributes and Mechanical Properties of Hempcrete. Biomass. 4(1), 65–91. DOI: https://doi.org/10.3390/biomass4010004
[48] Antunes E Sousa, G.J., Silva, S.P., Fernandes, F.A.O., et al., 2026. Cork-Based Composite Materials for Multifunctional Engineering Applications: Processing, Performance and Research Challenges. Applied Composite Materials. 33(3), 86. DOI: https://doi.org/10.1007/s10443-026-10468-z
[49] Madusanka, C., Udayanga, D., Nilmini, R., et al., 2024. A review of recent advances in fungal mycelium based composites. Discover Materials. 4(1), 13. DOI: https://doi.org/10.1007/s43939-024-00084-8
[50] Liadi, M.A., Ayodele, T.O., Tijani, A., et al., 2026. From Biomass to Biofabrication: Advances in Substrate Treatment Technologies for Fungal Mycelium Composites. Clean Technologies. 8(2), 30. DOI: https://doi.org/10.3390/cleantechnol8020030
[51] Roudbari, M.S., 2025. Algae-based building materials: Applications, challenges, and prospects. In Proceedings of the 3rd International Conference on Recent Advances in Engineering, Innovation & Technology, Brussel, Belgium, 10 March 2025.
[52] Marinho, E., 2025. Cellulose: A comprehensive review of its properties and applications. Sustainable Chemistry for the Environment. 11, 100283. DOI: https://doi.org/10.1016/j.scenv.2025.100283
[53] Mili, M., Hashmi, S.A.R., Ather, M., et al., 2022. Novel lignin as Natural-Biodegradable binder for various sectors—A review. Journal of Applied Polymer Science. 139(15), 51951. DOI: https://doi.org/10.1002/app.51951
[54] Luhar, S., Ashour, A., Luhar, I., 2026. Decarbonising the Cement and Concrete Industry—A Step Forward to a Sustainable Future. Journal of Composites Science. 10(5), 226. DOI: https://doi.org/10.3390/jcs10050226
[55] Fode, T.A., Chande Jande, Y.A., Kivevele, T., 2023. Effects of different supplementary cementitious materials on durability and mechanical properties of cement composite – Comprehensive review. Heliyon. 9(7), e17924. DOI: https://doi.org/10.1016/j.heliyon.2023.e17924
[56] Backes, J.G., Del Rosario, P., Petrosa, D., et al., 2022. Building Sector Issues in about 100 Years: End-Of-Life Scenarios of Carbon-Reinforced Concrete Presented in the Context of a Life Cycle Assessment, Focusing the Carbon Footprint. Processes. 10(9), 1791. DOI: https://doi.org/10.3390/pr10091791
[57] Xiao, J., Yu, C., Wang, B., et al., 2026. Recycled ag-

gregate concrete design, application and challenges. Nature Reviews Clean Technology. 2(1), 67–83. DOI: https://doi.org/10.1038/s44359-025-00125-2

[58] Su, Y., Yao, Y., Wang, Y., et al., 2023. Modification of Recycled Concrete Aggregate and Its Use in Concrete: An Overview of Research Progress. Materials. 16(22), 7144. DOI: https://doi.org/10.3390/ma16227144

[59] Zhang, M., Liu, X., Kong, L., 2023. Evaluation of carbon and economic benefits of producing recycled aggregates from construction and demolition waste. Journal of Cleaner Production. 425, 138946. DOI: https://doi.org/10.1016/j.jclepro.2023.138946

[60] Sorout, J., Raj, S., Kaur, D.P., et al., 2023. Waste-Based Bricks: Evaluation of Strength Behaviour of Bricks Containing Different Waste Materials as an Additive. Water, Air, & Soil Pollution. 234(7), 424. DOI: https://doi.org/10.1007/s11270-023-06438-x

[61] Pacios, A., Tejado, E., Martín, A., et al., 2024. High-temperature performance of clay-enhanced alkali-activated binders: A sustainable alternative to Portland cement. Construction and Building Materials. 453, 138860. DOI: https://doi.org/10.1016/j.conbuildmat.2024.138860

[62] Sbahieh, S., McKay, G., Al-Ghamdi, S.G., 2023. Comprehensive Analysis of Geopolymer Materials: Properties, Environmental Impacts, and Applications. Materials. 16(23), 7363. DOI: https://doi.org/10.3390/ma16237363

[63] Reisch, D., Temme, K., 2025. Plastics in Architecture: Trends of a Building Material in Transition. In: Buettner, A., Weidner, E. (eds.). Springer Handbook of Circular Plastics Economy. Springer Nature: Cham, Switzerland. pp. 1073–1096. DOI: https://doi.org/10.1007/978-3-031-66209-6_56

[64] Bristogianni, T., Oikonomopoulou, F., 2023. Glass upcasting: a review on the current challenges in glass recycling and a novel approach for recycling "as-is" glass waste into volumetric glass components. Glass Structures & Engineering. 8(2), 255–302. DOI: https://doi.org/10.1007/s40940-022-00206-9

[65] Gupta, R.K., Agarwal, S., Mukhopadhyay, P., 2024. Plastics in Buildings and Construction. In Applied Plastics Engineering Handbook. Elsevier: Amsterdam, The Netherlands. pp. 683–703. DOI: https://doi.org/10.1016/B978-0-323-88667-3.00010-2

[66] Bailly, G.C., El Mendili, Y., Konin, A., et al., 2024. Advancing Earth-Based Construction: A Comprehensive Review of Stabilization and Reinforcement Techniques for Adobe and Compressed Earth Blocks. Eng. 5(2), 750–783. DOI: https://doi.org/10.3390/eng5020041

[67] Koda, E., Vaverková, M.D., Reddy, K.R., et al. (eds.), 2025. Emerging Trends in Sustainable Geotechnics: Keynote Volume of EGRWSE 2024. Springer Nature: Singapore. DOI: https://doi.org/10.1007/978-981-96-2714-1

[68] Dumée, L.F., 2022. Circular Materials and Circular Design—Review on Challenges Towards Sustainable Manufacturing and Recycling. Circular Economy and Sustainability. 2(1), 9–23. DOI: https://doi.org/10.1007/s43615-021-00085-2

[69] Cervantes Puma, G.C., Salles, A., Turk, J., et al., 2025. Circular Economy Best Practices in the Built Environment. In: Bragança, L., Griffiths, P., Askar, R., et al. (eds.). Circular Economy Design and Management in the Built Environment. Springer Nature: Cham, Switzerland. pp. 5–24. DOI: https://doi.org/10.1007/978-3-031-73490-8_1

[70] Pajonk, A., Prieto, A., Blum, U., et al., 2022. Multi-material additive manufacturing in architecture and construction: A review. Journal of Building Engineering. 45, 103603. DOI: https://doi.org/10.1016/j.jobe.2021.103603

[71] Faleschini, F., Trento, D., Masoomi, M., et al., 2023. Sustainable mixes for 3D printing of earth-based constructions. Construction and Building Materials. 398, 132496. DOI: https://doi.org/10.1016/j.conbuildmat.2023.132496

[72] Rocha, P.F., Ferreira, N.O., Pimenta, F., et al., 2022. Impacts of Prefabrication in the Building Construction Industry. Encyclopedia. 3(1), 28–45. DOI: https://doi.org/10.3390/encyclopedia3010003

[73] Rashid, F.L., Al-Obaidi, M.A., Dulaimi, A., et al., 2023. A Review of Recent Improvements, Developments, and Effects of Using Phase-Change Materials in Buildings to Store Thermal Energy. Designs. 7(4), 90. DOI: https://doi.org/10.3390/designs7040090

[74] Hossain, M.R., Sultana, R., Patwary, M.M., et al., 2022. Self-healing concrete for sustainable buildings. A review. Environmental Chemistry Letters. 20(2), 1265–1273. DOI: https://doi.org/10.1007/s10311-021-01375-9

[75] Pavel, M., Anastasescu, C., State, R.-N., et al., 2023. Photocatalytic Degradation of Organic and Inorganic Pollutants to Harmless End Products: Assessment of Practical Application Potential for Water and Air Cleaning. Catalysts. 13(2), 380. DOI: https://doi.org/10.3390/catal13020380

[76] Theodoridou, I., Vatitsi, K., Stefanidou, M., et al., 2025. Nature-Based Solutions for Urban Buildings—The Potential of Vertical Greenery: A Brief Review of Benefits and Challenges of Implementation. Urban Science. 9(10), 398. DOI: https://doi.org/10.3390/urbansci9100398

[77] Lungu, K., Shikabonga, J., Mulenga, M., et al., 2025. Microbial-Induced Calcium Carbonate Precipitation in Road and Building Construction: A Systematic Review of a Novel Approach to Aggregate Formation. International Journal for Multidisciplinary Research. 7(2), 42864. DOI: https://doi.org/10.36948/ijfmr.2025.v07i02.42864

[78] Senarathne, H.N.Y., Weerasinghe, N.P., Zhang, G., 2025. Developing a Standardized Materials Passport Framework to Unlock the Full Circular Potential in the Construction Industry. Sustainability. 17(14), 6337. DOI: https://doi.org/10.3390/su17146337

[79] Ahmed, A.M., Sayed, W., Asran, A., et al., 2023. Identifying barriers to the implementation and development of sustainable construction. International Journal of Construction Management. 23(8), 1277–1288. DOI: https://doi.org/10.1080/15623599.2021.1967577