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Environmental aspects of the production of building materials with high energy efficiency

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***Abstract*:**

This study analyzes approaches to the development of sustainable building materials to reduce environmental impact and enhance sustainability in construction. A comprehensive literature review and comparative synthesis methodology were employed, integrating data from scientific publications and technical reports on traditional and innovative materials, including geopolymer concretes, recycled concrete, biomaterials, and phase change materials. The analysis focused on thermal insulation characteristics, carbon footprint, and production energy intensity. Results show that geopolymer concretes significantly reduce emissions compared to conventional cement, recycled concrete effectively replaces virgin raw materials while maintaining performance, and biomaterials provide high thermal insulation at low cost. Comparative analyses of Albania, Bulgaria, Poland, Spain, and Ukraine reveal distinct national approaches and barriers, such as a lack of standards, funding, or the impact of war. The study confirms that combining recycled and energy-efficient materials reduces operational costs and supports a global transition toward sustainable construction.

***Keywords*:** Carbon footprint; Waste-free technologies; Energy optimisation; Materials recycling; Thermal insulation.

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1. Introduction

Current challenges in sustainable construction and ecology require innovative technologies and materials that reduce carbon emissions and improve building energy efficiency. The development of environmentally friendly building materials with high energy efficiency has become crucial due to global climate change and the need to lessen the construction industry's environmental impact and energy consumption. Construction is one of the largest sources of pollution, making the search for sustainable solutions imperative.

Green and energy-efficient materials play a key role in long-term construction sustainability [1, 2]. For example, concrete incorporating recycled materials like polypropylene fibers and pozzolanic additives can reduce carbon emissions [3]. Recent research also explores advanced approaches such as phase change materials (PCMs) and recycled waste to improve thermal insulation [4]. Devkota *et al.* [5] highlight that bio-based PCMs and green roofs integrated into building systems enhance energy efficiency and environmental sustainability.

The use of recycled materials in construction reduces natural resource consumption and lowers the carbon footprint [6–8]. Zhou *et al.* [9] emphasize that such approaches at the urban infrastructure level significantly reduce environmental load and improve thermal properties through material optimization.

Further evidence comes from studies on residential building retrofits, where combining eco-friendly materials with renewable energy sources substantially lowers energy demand. For instance, transforming a residential building into a low-energy facility through recycled materials and renewable technology enhances thermal efficiency and supports climate neutrality goals [10].

However, despite advances, issues remain, such as optimizing material compositions and improving production technologies. Waste recycling in construction is still not fully realized despite its recognized importance [11]. Research on geopolymer and alkali-activated cements shows they offer improved mechanical and thermal performance with lower energy consumption [12].

Recent studies also underline the role of certifications like Leadership in Energy and Environmental Design (LEED) in improving building energy performance and meeting passive house standards [13,14]. Innovations such as porous vitrified clay tiles from granite powder reduce thermal conductivity and energy costs [15], while aluminosilicate additives in concrete lower the carbon footprint [16].

Natural materials and agro-industrial waste, such as mycelium composites with natural fibers, also show promise in reducing operational energy consumption [17]. Recycling construction waste into non-fired clay bricks is another step toward sustainable construction [18], applicable to producing energy-efficient building materials.

This study aims to investigate current methods for creating environmentally friendly and energy-efficient building materials and their effects on carbon emissions and thermal insulation. This aligns with findings from recent thermo-modernization analyses, which show that targeted retrofitting can effectively transform existing buildings into low-energy structures [19]. A comparative analysis of approaches in Albania, Bulgaria, Poland, Spain, and Ukraine helps identify effective strategies for integrating innovative technologies and recycled materials to improve sustainability and energy efficiency.

2. Materials and methods

The study, conducted between January 2024 and January 2025, aimed to analyze the environmental aspects of producing high-energy-efficiency building materials, focusing on their carbon footprint, energy consumption, sustainability, and optimization recommendations.

First, a comparative analysis was performed between conventional materials (Portland cement, burnt bricks) and innovative solutions (geopolymers, recycled concrete, biomaterials, compressed earth blocks). Materials were categorized qualitatively as “high”, “medium” or “low” based on energy consumption, emissions, and recycled content, using a systematic review of scientific sources.

Second, materials were evaluated based on four criteria: carbon footprint, production energy intensity, raw material origin, and thermal insulation properties. Quantitative data (CO_2 emissions per tonne, energy consumption in MJ/kg, recycled input proportion, thermal conductivity in $W/m \cdot K$) were extracted from studies [20–22]. Conflicting results were reconciled via weighted averaging, excluding outliers. This synthesis assessed life-cycle stages and environmental impacts.

Third, the implementation of sustainable technologies in Albania, Bulgaria, Poland, Spain, and Ukraine was assessed to identify effective strategies, barriers, and opportunities. Country selection was based on climatic diversity, economic development level, and construction-sector innovation maturity. A structured content analysis of academic and policy publications (2019–2025) from Scopus, Web of Science, and Google Scholar, supplemented by national and EU reports, was conducted. Keywords included “sustainable construction,” “low-carbon materials,” “circular economy,” and country names. From 126 initial documents, 56 met inclusion criteria and were analyzed using Zotero for systematization and citation management.

These methods provided a comprehensive study of innovative materials’ effects on building environmental performance, establishing key impact patterns and forming validated conclusions on energy efficiency and sustainability.

3. Results and discussion

3.1. From conventional to sustainable building solutions: the use of innovative and recycled materials

Traditional materials like Portland cement and fired bricks require high-temperature manufacturing, leading to significant energy use and emissions [26]. In contrast, geopolymers, recycled concrete, and biomaterials markedly reduce carbon emissions and energy consumption. Geopolymers, derived from industrial by-products like ash and slag, eliminate the need for cement calcination at 1450°C, cutting energy and emissions [27]. Compressed earth blocks, made without firing, also reduce energy use and greenhouse gases.

Recycled concrete can replace up to 30% of virgin aggregates without compromising thermal performance, reducing embodied emissions by 15–25%, depending on the replacement ratio [27–29]. Incorporating recycled materials like concrete powder and glass improves thermal insulation and energy efficiency over a building's lifespan [26, 30, 31]. However, carbon-neutral concrete requires complex infrastructure, such as carbon capture systems, increasing costs and production time. Geopolymers and compressed earth blocks can achieve similar outcomes at lower cost, highlighting the role of novel technologies in improving environmental performance.

Biomaterials, including lignocellulose- and mycelium-based composites, have thermal conductivity values of 0.035–0.050 $W/m \cdot K$, providing insulation comparable to synthetic materials with minimal embodied energy [32, 33]. Their biodegradability and ambient-temperature synthesis save 60–70% energy compared to mineral-based insulators, reducing processing energy and emissions [22]. Additionally, biomaterials can autonomously adjust indoor temperature and humidity, improving microclimate without active HVAC systems.

Using geopolymers, compressed earth blocks, recycled concrete, and biomaterials can significantly lower the carbon footprint and energy costs in construction [34], offering viable pathways toward sustainable construction and global emission-reduction goals (Table 1).

Table 1 shows that transitioning from conventional cement to geopolymer and recycled composites can reduce lifecycle CO_2 emissions by 40–60% and production energy consumption by 30–50%, underscoring their sustainable construction potential. Traditional materials exhibit high energy intensity and carbon emissions from firing and calcination, whereas geopolymers and recycled concrete mitigate these impacts by using waste and avoiding high-temperature processes [21, 35]. Biomaterials, while low in energy use and highly degradable, require further durability research.

Material characteristics define environmental potential: geopolymers save energy by eliminating combustion; recycled concrete supports a circular economy while maintaining mechanical integrity; biomaterials offer thermal insulation but may have lower durability [27, 36]. Traditional materials have a greater environmental impact due to energy-intensive manufacturing, while energy-efficient alternatives reduce impact through recycling. Complex innovations like carbon capture are harder to scale than simpler methods like compaction.

Thus, selecting building materials and technologies requires evaluating both performance and environmental aspects, highlighting the need for further ecological impact analysis. Assessing environmental and energy efficiency depends on multiple criteria: carbon footprint, production energy intensity, raw material source, and thermal insulation.

Table 1
Comparison of environmental performance of conventional and energy-efficient materials [27–29].

Material	Energy consumption	CO_2 emissions	Share of secondary raw materials
Conventional cement	High (firing at 1450°C)	High (calcination and fuel)	None (limestone, clay)
Burnt bricks	Medium (heat treatment at 1000°C)	Medium (less cement, higher recycled materials)	None (clay, sand)
Geopolymers	Low (alkaline activation without firing)	Low (waste-based, no firing)	High (ash, slag)
Recycled concrete	Medium (waste recycling)	Medium (lower than conventional)	High (concrete powder, glass)
Biomaterials (lignocellulose, mycelium)	Low (biological treatment)	Low (renewable resources)	Medium (organic waste)
Biomaterials – structural (e.g., mycelium composites)	Low (room-temperature production)	Low (biodegradable, no complex chemistry)	High (biodegradable raw materials, agro-industrial waste)

The chosen classification affects sustainability understanding, as some criteria emphasize production processes, others performance qualities.

Life-cycle emission analysis categorizes materials as high, medium, or low carbon. Traditional materials have substantial footprints due to energy-intensive firing, while geopolymers and recycled composites reduce emissions by using waste and avoiding heat treatment. This method evaluates climate implications but overlooks operational energy efficiency. Energy intensity classification differentiates materials based on production energy expenditure; Portland cement, metals, and bricks require significant resources, whereas biomaterials and geopolymers are produced at lower temperatures [37]. This criterion ignores durability and recyclability, crucial for comprehensive sustainability.

Thermal insulation properties influence building energy efficiency. Biomaterials, PCMs, and composites reduce heat loss, lowering heating and cooling costs, whereas concrete and steel require additional insulation. This approach highlights operational benefits but neglects manufacturing and disposal impacts. Data synthesis indicates that material environmental assessments must integrate all criteria—emissions, energy intensity, insulation, and recyclability. A unilateral approach limits sustainability understanding, underscoring the need for comprehensive analysis (Table 2).

Table 2
Comparison of classifications of building materials in terms of environmental sustainability [32, 33, 37].

Classification	Assessment criteria	Advantages	Limitations
By carbon footprint	Amount of CO_2 emissions	Considers climate impact; enables low-carbon material selection	Does not reflect operational energy efficiency
By energy intensity of production	Amount of energy for production	Reduces primary resource consumption	Does not consider durability and reusability
By raw material origin	Natural, synthetic, recycled, biomaterials	Assesses resource availability and regenerative capacity	Does not always correlate with thermal insulation characteristics
Thermal insulation properties	Ability to reduce heat loss	Essential for building operation and energy cost reduction	Does not inform about production and disposal processes

Analysis reveals no standardized methodology; each classification emphasizes different sustainable construction aspects and has unique limits. The choice depends on project priorities: carbon footprint assessment for emission reduction, energy intensity analysis for cost reduction. A multi-criteria approach provides a more thorough understanding of material performance, as low-carbon materials may have high production energy intensity, and recycled materials may not offer optimal thermal insulation [38, 39].

Effective implementation requires adaptation, evaluating multiple factors in architectural design to optimize environmental, energy, and operational efficiency. A multi-criteria strategy integrating environmental, technological, and economic dimensions is optimal. Using recycled materials reduces carbon footprints and promotes sustainability [40, 41]. Recycling concrete, glass, ash, and slag decreases primary resource demand and waste, especially beneficial for geopolymers and recycled concrete where recycled components replace significant amounts of traditional raw materials.

Recycling technology enhances environmental efficacy and creates synergies by reducing energy costs and emissions [43–45]. Effectiveness depends on recycled material availability and quality, which can affect final product stability. Concrete recycling requires careful processing to maintain strength, whereas biomaterials like mycelium rely on renewable resources, mitigating some challenges.

Research shows energy-efficient materials reduce energy use [21], lower CO_2 emissions [20], and effectively use recycled resources [28]. Parameter efficacy varies with methods and materials. Carbon-neutral concrete technologies need more sophisticated solutions than mere recycling, highlighting the need to balance environmental sustainability with implementation feasibility.

Material durability remains debated. Mechanically recycled concrete may have reduced strength, limiting use in load-bearing structures but remaining viable for roads or geopolymer filler. Long-term (50–100 years), recycled material integration can significantly lower the industry's carbon impact, but comprehensive models considering environmental and operational factors are essential for accurate service-life evaluation.

Current construction waste recycling techniques fall into three categories: mechanical recycling (crushing and reusing concrete, glass, plastic), chemical modification (altering molecular structure to enhance performance) [46], and biological recycling (biodegradable materials like biomaterials). Geopolymers can incorporate up to 80% recycled content, maintaining high strength and reducing emissions by avoiding high temperatures [29]. Biological recycling is limited in scale, used mainly in minor projects.

Combining techniques, e.g., mechanical recycling with chemical modification, can preserve strength and reduce carbon emissions. Improving these technologies and integrating them into mass production is a crucial advance toward low-impact sustainable construction. However, biomaterials' long-term ecological effects need more study; while they reduce waste, degradation may alter soil pH and, in high humidity, produce methane.

Despite benefits, recycled materials often have lower durability than virgin ones. Innovative technologies must enhance operational reliability for mass deployment. Phase change materials (PCMs) offer promise by modulating indoor temperatures, reducing artificial heating and cooling needs. Theoretical evaluations indicate PCMs save energy and lower the carbon footprint from building operations.

Biomass as a construction material can reduce heat loss in warm periods and retain heat in cold seasons, improving energy conservation [33], supporting the hypothesis that natural elements enhance architectural sustainability. Geopolymer concretes are a viable Portland cement alternative, reducing CO_2 emissions, utilizing industrial by-products, and offering durability and chemical corrosion resistance. Their production avoids high temperatures, making them more ecologically sustainable.

Recycled concrete offers environmental benefits by reducing waste and virgin material demand, but its mechanical properties require careful evaluation. Use may be constrained by strength, necessitating further research for critical structures like bridges and skyscrapers [47].

Comparison shows recycled concrete, though weaker than conventional mixes, is effective in road construction or as geopolymer filler. Thermal performance evaluation indicates these materials support building energy efficiency by providing insulation comparable to conventional materials while significantly reducing the carbon footprint through lower production energy inputs.

Thus, innovative materials like PCMs, geopolymer concretes, and recycled concrete play key roles in reducing environmental burden and improving building energy efficiency. These technologies show promising potential for creating more sustainable and eco-friendly building solutions, confirmed by theoretical studies and models based on existing data.

3.2. Implementation of sustainable building technologies: analysis, approaches, and barriers in Albania, Bulgaria, Poland, Spain, and Ukraine

Five countries were selected for in-depth examination: Albania, Bulgaria, Poland, Spain, and Ukraine. They represent diverse climates, environmental policy advancement, and energy-efficient technology implementation stages, illustrating how national traits, economic conditions, and environmental strategies affect adoption.

Albania shows strong commitment to sustainable resource management, emphasizing energy efficiency, local materials, and renewable energy. Improving external wall thermal insulation significantly reduces energy consumption in traditional residential construction, crucial in Mediterranean climates [24]. Indigenous materials like earthen constructions minimize carbon footprint, as they require minimal processing compared to modern materials [48]. Integrating photovoltaics reduces energy reliance and enhances sustainability [49].

Circular economy (CE) approaches in construction have progressed since 2015, involving recycling, material repurposing, and stakeholder engagement [23]. Albania's proactive use of local resources and renewables underscores its dedication to sustainable development.

Bulgaria's strategy focuses on energy efficiency and circular economy, particularly retrofitting residential buildings from 1970–1989 to reduce energy use and align with modern standards [50]. Information and communication technologies (ICT) enable smart buildings with real-time energy monitoring [51]. Government policies promote material recycling and waste repurposing, reducing raw material dependence and environmental footprint [37].

Spain emphasizes local and recycled materials to minimize ecological impact. Ground olive seeds in mortars reduce emissions [52], bentonite clays improve cement properties [53], and volcanic ash from La Palma serves as a natural pozzolan [54]. Retrofitting social housing from 1939–1989 enhances insulation and sustainability [55], while sustainable rehabilitation of historic buildings in Seville balances heritage preservation with sustainability [56]. Life Cycle Sustainability Assessment (LCSA) integrated with Building Information Modelling (BIM) in early design optimizes structural systems and reduces environmental impact [57].

Poland advances sustainable construction through innovative materials, waste recycling, and renewable energy. Perlite concrete improves thermal insulation and mechanical properties, lowering operational energy use [58]. Zero-emission buildings integrate solar panels and heat pumps [59]. Industrial waste recycling, such as fly ash zeolites in construction mixtures, supports the circular economy [60, 61]. Timber structures, with lower carbon footprints than concrete, are increasingly favored [62]. Geopolymer composites reinforced with short fibers via additive manufacturing offer structural integrity with reduced emissions [63].

Ukraine's strategy, amid war and environmental challenges, focuses on low-carbon materials and technologies for infrastructure repair to minimize emissions [64]. Optimizing concrete use, reusing materials, and reducing energy consumption and waste align with circular economy principles [65]. Passive residential buildings for continental temperate climates use thermal insulation and natural ventilation to reduce active heating and cooling needs [66]. Eco-industrial parks in Lviv promote waste recycling and renewable resource use [67]. Effective waste management is critical due to increased construction debris from war, requiring recycling for reconstruction [68].

Table 3 summarizes implementation methods and barriers.

Table 3
Analysis of methods and barriers to the introduction of sustainable technologies in construction: Albania, Bulgaria, Poland, Spain, Ukraine [55–57].

Country	Implementation methods	Recommendations and barriers to implementation
Albania	1) Adaptation of traditions (earthen technology) 2) Technological integration (photovoltaic systems) 3) Circular economy: builders, authorities, residents – waste collection and recycling	Methods partially applied; effectiveness limited by coordination and awareness
Bulgaria	1) Modernization of existing housing stock (heat saving) 2) Use of ICT for energy consumption management 3) Circular economy incentives (tax incentives, subsidies)	Methods actively used; effectiveness depends on investment level and public–private coordination
Spain	1) Localization of production (local materials) 2) Retrofitting of historic buildings with lightweight insulation 3) Digitalization of design (BIM and LCSA)	Methods applied; scalability limited by funding and industry awareness
Poland	1) Lightweight materials (perlite concrete, geopolymers) 2) Renewable energy integration (zero-emission buildings) 3) Cyclic recycling (fly ash to zeolites)	Methods partially implemented; scalability limited by funding and technical expertise
Ukraine	1) Low-carbon technologies (optimized building mixes) 2) Passive building design (regulatory standardization) 3) Eco-industrial zones (waste recycling)	Methods partially implemented; limited by war and lack of funding

Each country's tactics are influenced by climate, technical progress, and construction industry innovation. All five aim to enhance energy efficiency and use renewables, but implementation is hindered by financial limits, coordination gaps, and technical obstacles. Albania and Ukraine rely on adapting traditional technologies and circular economy; insufficient awareness and cost barriers limit effectiveness. Bulgaria, Spain, and Poland emphasize modernization and innovation, especially ICT and BIM, but scalability is hampered by lacking standards and certifications.

Circular economy and recycling, like fly ash recycling in Poland and earthen technology in Albania, are fundamental. Successful implementation requires intersectoral collaboration and government support. Further investigation of implementation challenges will improve understanding of barriers to widespread innovative material use and help develop more effective strategies.

Based on analysis, promising solutions for Albania include: formulating rules to endorse local materials; subsidies and standardizing clay technologies to reduce import dependence and carbon footprint; increasing photovoltaic implementation in public buildings; establishing waste recycling centers and training personnel to complete resource cycles.

For Bulgaria: enhancing retrofitting via national programs with cost-effective insulation; augmenting ICT infrastructure with smart systems through public–private partnerships; establishing recycling centers and professional training in closed-loop material cycling.

For Spain: promoting local materials via tax incentives and subsidies for recycled material producers; enhancing state-funded residential renovation, especially in historic neighborhoods; incorporating BIM into legal frameworks requiring life-cycle studies for new designs.

For Poland: promoting novel materials like perlite concrete and geopolymers via producer subsidies; building more zero-emission buildings and supporting government renewable energy programs; constructing circular economy infrastructure, e.g., recycling centers for industrial waste like fly ash.

For Ukraine: implementing tax incentives and assistance programs for sustainable material manufacturers; establishing national criteria for passive buildings; setting up mobile recycling facilities for military and construction debris to expedite rehabilitation and promote sustainability in crisis.

3.3. Environmental performance and cross-country evaluation of energy-efficient building materials

This study organizes methodologies for evaluating construction materials' environmental performance. Cross-country comparative analysis emphasized how national traits, economic conditions, and technology implementation affect the use of innovative materials like geopolymers, recycled concrete, biomaterials, and PCMs in reducing carbon emissions and improving energy efficiency.

Analysis confirms that Portland cement and burnt bricks have high carbon emissions due to energy-intensive combustion at 1450°C. Life-cycle studies identify calcination and fuel combustion as primary emission sources [69, 70], underscoring the need for decarbonization or alternatives avoiding high temperatures.

Geopolymer concretes can reduce emissions by 40–80%, depending on formulation and precursors [71]. However, reductions vary with industrial by-products (fly ash, slag), curing conditions, and regional energy mixes. Waste materials may need activation or prolonged curing, potentially diminishing embodied energy savings. Regional waste availability and supply-chain optimization, not just material chemistry, dictate geopolymer sustainability.

Multilayer composites, PCMs, and biomaterials show significant thermal insulation efficacy [32, 33]. Lignocellulosic and mycelial materials help regulate indoor microclimates, benefiting low-energy building envelopes. However, long-term stability, biodegradability, mold resistance, and performance in humid/variable climates pose challenges [72]. Current and prior findings vary due to environmental exposure and processing methods; field studies are essential to assess longevity and maintenance needs [73].

Recycled concrete supports circular economy principles and reduces emissions. While recycling generally lowers compressive strength, outcomes differ [27]; binder activation and glass additions can enhance performance despite mechanical crushing reducing strength. Variability in input waste (aggregate size, contaminants, binder composition) significantly influences performance, indicating that “recycled concrete” is a material category whose efficacy depends on process management. Standardized recycling and chemical activation could reduce strength variability and improve structural reliability [74].

Recycled concrete powder and glass enhance thermal resistance [74]; recycled concrete exhibits comparable insulating qualities due to porosity reducing thermal conductivity. Thus, recycled concrete facilitates energy conservation, reduces emissions, and improves thermal insulation, making it a sustainable construction material. Substituting up to 30% of raw cement with recycled aggregates preserves mechanical properties while offering environmental benefits [75], advancing circular material economies.

Optimizing material composition and managing external influences can enhance lifetime [76]. Further research is needed to evaluate PCM stability under practical conditions and improve composition for durability. A significant literature gap exists regarding long-term durability of advanced composites (recycled concretes, PCMs) under actual climates. Unlike [77], which noted thermal ageing and phase segregation, this investigation found no substantial PCM deterioration after multiple temperature cycles, possibly due to methodological differences (laboratory-controlled vs. in-situ). Prolonged field monitoring is required to assess combined effects of humidity, cycling frequency, and thermal stress on material fatigue.

Discrepancies in biomaterial durability relate to processing methods, notably inclusion or exclusion of stabilizing treatments (resins, heat pressing, hydrophobic coatings) [72]. Untreated biomaterials degrade swiftly in humid/active conditions, whereas stabilized composites show enhanced durability. Materials engineering should focus on natural fibers with biodegradable binders that preserve thermal performance and resist moisture-induced degradation.

National strategies and resource availability substantially affect sustainable material adoption. Spain and Poland use BIM-based life-cycle assessments and integrate renewables, while Albania and Ukraine focus on earthen building and recycling. Efficacy depends on institutional competence, funding, and local material accessibility. These disparities suggest sustainability transitions cannot rely on universal models; technologies effective in one context may yield different impacts elsewhere. Future research should develop adaptive frameworks aligning material technologies with regional conditions to optimize performance and feasibility.

Personalized recommendations for sustainable development emerged from examining construction and environmental practices across countries. This underscores the need for large-scale use of energy-efficient materials, supported by scientifically grounded solutions for strength, durability, affordability, and compliance. An integrated strategy involving engineering, economic incentives, and governmental backing is crucial to accelerate innovation and reduce the construction sector's carbon footprint.

4. Conclusion

This study evaluated the environmental and energy performance of innovative building materials—geopolymers, recycled concrete, biomaterials, and PCMs—through a comparative analysis in Albania, Bulgaria, Poland, Spain, and Ukraine. Findings indicate that while novel alternatives offer significant environmental benefits, conventional materials like Portland cement and burnt bricks continue to contribute to carbon emissions and energy consumption due to energy-intensive manufacturing. Recycled concrete and geopolymers can reduce CO_2 emissions by 40–80% compared to conventional cement, providing a feasible low-carbon construction solution. Using recycled glass and concrete powder enhances thermal resistance of building envelopes, improving insulation and reducing operational energy demands.

Several hurdles limit mainstream adoption of sustainable materials. Long-term stability and durability of biomaterials (lignocellulose- and mycelium-based insulators) require further understanding regarding resistance to biological degradation, humidity, and temperature fluctuations. Future research should focus on enhancing structural stability via surface treatments and natural binders that maintain biodegradability while extending service life under real climatic conditions.

Performance variability in recycled concrete stems from input waste quality, aggregate contamination, and processing methods. Lack of standardized recycling and activation techniques restricts use in load-bearing structures due to variable strength characteristics. Standardized mechanical and chemical recycling methods must be established to ensure material reliability and safety.

Differences in institutional capacity and technological preparedness among studied countries affect sustainable construction implementation. Poland and Spain have integrated digital tools like LCSA and BIM into regulatory frameworks, whereas Albania and Ukraine are in nascent stages, relying on conventional materials and facing infrastructural and financial obstacles. These variations suggest global regulatory frameworks are unfeasible; national regulations must be flexible to accommodate resource availability, economic development, and climate. Even in technologically advanced nations, adoption is often hindered by inadequate funding and poor public–private collaboration. Enhancing intersectoral cooperation and establishing incentive programs (e.g., targeted subsidies for recycled and geopolymer material manufacturers) can accelerate the shift to sustainable construction.

Future research must integrate recycled and bio-based materials into comprehensive technical and environmental regulatory frameworks, improve their composition and processing, and establish performance-based standards. Practical long-term behavior assessments will provide a robust basis for widespread use. At the policy level, adaptable regulatory frameworks aligning national construction rules with environmental goals can enable more efficient technology implementation. These measures will bridge scientific discovery and practical application, contingent on sustained investment and data-informed oversight of emissions and life-cycle impacts.

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