

A Comprehensive Review on Challenges in the Adoption of Sustainable Materials in Construction

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Abstract

Construction is a key component of an economy's expansion and development, unfortunately, construction activities pose an environmental hazard through rising emissions, irresponsible use of natural resources and destruction of ecosystems and landforms. At present, the construction sector is responsible for an estimated 39 percent of all energy - related carbon dioxide emissions worldwide. Environmentalists claim that one of the leading remedies to these problems is the use of sustainable building materials. The purpose of the current review paper is a critical assessment of the sustainability - related barriers to the widespread use of sustainable building materials and the identification of the primary factors limiting adoption. Based on a thorough review of research published between 2022 and 2025, this paper includes scientific literature reviews, reports, journal papers, technical reports in the peer - reviewed journals, with results presented, collated, synthesized and analyzed.

Keywords: Green materials, Low carbon materials, Sustainable construction, Construction challenges, Lifecycle assessment, Circular economy, Embodied carbon, Artificial intelligence and Bio-based materials.

1. Introduction

Construction sector is among the major economic engines powering the world economy, but also creates significant externalities from an environmental perspective. Construction is a major source of green-house gases such as CO₂ emissions, uses about one-third of natural resources available on Earth, and generates large volumes of solid waste material that ends up at the landfills. The problem arises from the continued use of conventional building materials such as concrete and steel, which remain major sources of environmental pollution due to their energy-intensive manufacturing process and carbon-intensive footprint. It is therefore imperative to move away from the use of such conventional materials and consider alternatives. Sustainable building materials include recycled aggregates, bio-sourced materials, low-carbon binders, and innovative building materials like self-healing concretes and energy-efficient building materials. Even though these sustainable building materials could significantly reduce their environmental impact, improve efficiency, and preserve scarce resources, there are many barriers to their adoption.

In recent times, there have been many attempts in utilizing technological advances such as artificial intelligence (AI), building information modeling (BIM), and internet-of-things (IoT) towards sustainable construction. However, technological advances can be used to enhance the decision-making process and material selection process. On the other hand, the use of technological advances in sustainable material systems is still in its early stages. This review paper aims to critically examine possible barriers that may affect sustainable construction based on

current research between 2022 and 2025. The primary purpose of this paper is to identify significant barriers, uncover unexplored research gaps, and offer recommendations for further investigation. The structure of this review paper will be discussed in methodology, material classification, barriers encountered, comparative analysis, research gap, future opportunity, and conclusions.

2. Review Methodology

Structured literature review methodology was applied in order to ensure the systematic nature of the process of selection and analysis of the reviewed scientific literature. The literature review procedure entailed four steps, namely: identification of literature, screening of literature, evaluation of literature against specific criteria, and finally, selection of appropriate literature to be used.

2.1 Search Strategy

An efficient literature searching process was adopted involving the use of major academic database resources such as Scopus, Web of Science, ScienceDirect, and Google Scholar. Literature searching was performed through the use of keywords such as sustainability of construction materials, barriers of sustainable construction materials, reduction of embodied carbon in construction materials, sustainability issues of construction materials, bio-based construction material sustainability challenges, circular economy and construction materials, sustainability of construction material lifecycle assessment. Some of the Boolean operators used include AND and OR. Only English language literature was considered in this study including academic journals, conference papers, book chapters, and institutional reports published between January 2022 and March 2025.

3. Outcomes of Literature Review

Analysis of certain articles concerning systematic review demonstrates that there are a number of common trends which indicate the existing state of sustainable material usage. In particular, it is possible to speak about recyclable materials, bio-based materials, supplementary cementitious materials, and low-carbon composites, since they were demonstrated to reduce the negative impact of environmental, embodied carbon, and resource usage while ensuring the required structural performance levels [14], [15]. The use of modern technologies, including AI, machine learning, IoT, and BIM, helps to improve material selection and increase construction process efficiency, although they can be used more actively in terms of sustainability [1], [3]. The issue of cost, both initial and non-returnable, is regarded as the main challenge in using sustainable materials [9], [11]. In addition, lack of adequate knowledge and skills, insufficient number of qualified people, and poor technical knowledge form another challenge in practicing alternative methods. This is brought about by the unwillingness of the construction industry to adopt new things and change. Lack of proper regulation through poor policies, inconsistencies in standards, and lack of good assessment techniques forms another barrier to practice [8], [5]. Moreover, there is always a gap between theory and practice since most of the performance of sustainable materials in practice is done through lab experiments only [4], [13]. Lack of adequate research on how to transport and distribute these materials and poor performance of the material over time makes it a challenge when adopting these sustainable materials particularly, bio-based and geopolymers [10], [9]. This shows clearly that a holistic approach needs to be adopted in order to attain the set goals of implementation which includes policy making, innovation, cooperation, and standardization [6], [3]. It should be noted that developing countries experience more barriers due to lack of resources [9].

4. Classification of Sustainable Construction Materials

Materials for sustainable construction of buildings are classified on basis of source, production

process, impact on the environment, and their applications in the construction field. The current literature groups sustainable building materials into many different types that have various sustainability advantages but comes with different difficulties in their application [4], [10], [15].

4.1 Recycled and Reclaimed Materials

Recycled and reused construction materials come from both post-industrial and post-consumer wastes that are reused during construction to make them sustainable. The materials include recycled concrete aggregates resulting from demolished buildings, reused steel, crushed masonry, and recycled glass used as aggregates. They help reduce the need for natural raw materials, generate less amount of waste, and lower the energy consumption for construction activities. Construction and demolition wastes form a huge chunk of solid wastes around the world. Recycling and reusing the materials is therefore of vital importance [17], [18]. However, even with all these advantages, some challenges stand in the way of their usage. The recycled concrete aggregates have low compressive strength and high water absorption due to property differences resulting from the remaining mortar. Contamination and differences in sizes can also act as a challenge. Moreover, regulatory constraints prevent the use of these materials for making huge chunks of an overall structural material due to many regulations surrounding them.

4.2 Bio-based Materials

Existing bio-based building materials currently used consist of bamboo, engineered wood, timber, hemp, straw, cork, mycelium composites, and flax. Benefits linked to the use of bio-based building materials are lower embodied energy, carbon capture, enhanced thermal insulation, and excellent sound insulation characteristics. In structural design and engineering, the application of engineered wood, for example, CLT and glulam, is common practice, whereby reinforced concrete and steel are frequently replaced with engineered wood for load-bearing elements [10, 25]. According to studies on life cycle assessments of reinforced concrete, steel, and mass timber structures from various geographic regions, mass timber structures have shown a reduction of around 33% to 36% in global warming potentials compared to reinforced concrete structures [25]. However, bio-based building materials suffer from numerous disadvantages such as moisture susceptibility, biodegradation, flammability, and inconsistent mechanical performance.

4.3 Low-Carbon and Supplementary Cementitious Materials (SCMs)

SCMs refer to waste products or natural materials used in partial replacement of Portland cement in concrete, reducing the embodied carbon in the material. Popular examples of SCMs include fly ash, ground granulated blast furnace slag, silica fume, rice husk ash, and calcined clays. In most cases, SCMs replace between 20 and 70 percent of the total amount of Portland cement used, lowering the embodied carbon by about 15 to 50 percent. Apart from SCMs, there are other alternatives for reducing carbon emissions, such as geopolymers concrete, in which the binders in concrete include alkali activated waste materials like fly ash and GGBS. Studies indicate that geopolymers concrete can be capable of attaining compressive strength of up to 70 MPa while also providing excellent resistance to corrosion.

Table 1 Compressive strength of sustainable and conventional building materials [Abera, 2024]

Sample no.	Sustainable building material	Compressive strength (MPa)
1	Recycled concrete	35.2
2	Bamboo composite	48.6
3	Hempcrete	22.8
4	Geopolymer	42.1
5	Fly ash-based concrete	39.4
6	Conventional concrete	42.9

When evaluating the compressive strength of various construction materials, one observes that certain eco-friendly materials exhibit comparable compressive strength with ordinary concrete. In this regard, bamboo composite emerges as the strongest material under study, potentially indicating its applicability in a load-bearing capacity. Moreover, geopolymer and fly ash concrete materials come close to the compressive strength of ordinary concrete. As such, these materials present themselves as efficient substitutes that have an added advantage of being environmentally friendly. Additionally, recycled concrete offers moderate compressive strength, which limits its use to secondary applications. Lastly, hempcrete possesses relatively low compressive strength and would work well in insulating or light construction applications.

Table 2 Tensile strength of sustainable and conventional building materials [Abera, 2024]

Sample ID	Material type	Tensile strength (MPa)
1	Recycled concrete	15.2
2	Bamboo	45.6
3	Hempcrete	8.9
4	Geopolymer	25.1
5	Conventional concrete	20.3
6	Steel	550.2

Tensile strength results varied widely across the materials tested, and the difference between conventional and sustainable options was one of the more telling aspects of the comparison. Steel was, by a large margin, the strongest material recorded. The gap between steel and everything else was not close, which is largely why it remains the default choice in structural work that demands high load capacity.

Among sustainable materials, bamboo came out on top. Its tensile strength was meaningfully higher than the other alternatives in this group, which gives it a credible place in construction scenarios where tension resistance is a real requirement. Geopolymer sat in the middle range, performing close to conventional concrete. That proximity in values makes it a reasonable

candidate for substitution where concrete would otherwise be used. Recycled concrete came in a bit lower, which narrows its role — better for secondary applications than anything demanding peak structural performance.

Hempcrete had the lowest tensile strength of the materials studied. This is not surprising given what it is generally used for. Load-bearing is simply not where hempcrete is applied, and the numbers reflect that. Its relevance is in insulation and non-structural elements, where its other properties carry more weight than tensile capacity.

Table 3 Flexural strength of sustainable building materials. [Abera, 2024]

Sample ID	Material	Flexural strength (MPa)
1	Bamboo	100–150
2	Engineered wood	40–100
3	Recycled concrete	3–10
4	Hempcrete	0.2–1.0
5	Straw bale	1–2
6	Rammed earth	0.1–0.5

Flexural strength results showed clear differences between the materials tested. Bamboo recorded the highest values, standing out from the rest by a fair margin. For a natural material, that level of bending resistance is hard to overlook, especially where structural demands are involved. Engineered wood also performed well, strong enough to be considered a practical alternative to conventional construction materials in many real applications. Recycled concrete sat in the middle. Decent performance, but not the kind of numbers that make it a first choice for anything under serious flexural load. Hempcrete, straw bale, and rammed earth all came in low. The drop from the top performers was significant. These materials have their place in construction, but that place is insulation, non-load-bearing walls, and low-stress elements — not structural members taking bending forces.

4.4 Insulation and Energy-Efficiency Materials

The products are mostly meant for building envelopes with an intention to increase their energy efficiency through reduced energy consumption. These include state-of-the-art thermal insulation materials such as aerogel blankets and granules with some of the best thermal conductivity rates of about 0.015 W/m·K, as well as VIPs and PCMs integrated in walls or concrete. The natural insulators are also included in this list, for example cellulose, sheep's wool, and hemp fiber batts, and reflective coating for cool roofs. The cool roof coatings deserve special mention for the reason that they utilize the principle of absorption and emission of latent heat from the PCM and serve the purpose of temperature moderation within the room. However, PCM application is associated with some shortcomings such as high price, leakage, unpredictability, and difficulties in application in already constructed buildings. The main reason for lack of popularity of aerogel among thermal insulators, despite being an excellent one, is its very high price owing to costly manufacture.

4.5 Innovative and Nanotechnology-Enhanced Materials

Construction materials that have been enhanced using nanoparticles include carbon nanotubes, nano-silica, nano-TiO₂, and graphene oxide. Of all these nanotechnology materials, self-healing concrete deserves attention due to its capability to heal itself by repairing cracks via processes such as bacterial, crystallization, and microencapsulation methods, hence increasing the durability of buildings while reducing maintenance cost. Despite the promising laboratory findings of nanotechnology materials, commercialization of products developed using them has not been achieved yet. There are numerous factors preventing their wide-scale adoption in commercial activities despite promising results, including high costs of nanomaterials production, health concerns related to nanoparticle exposure, inadequate occupational safety standards, lack of testing and quality control methods, and failure by regulatory agencies to incorporate guidelines on nanomaterials use.

4.6 3D-Printed and Digital Fabrication Materials

Construction 3D printing, or construction additive manufacturing, employs materials such as concrete, clay, soil, or recycled blends to print structural components in an efficient and sustainable way. By doing so, it can reduce material waste up to 60 percent more than conventional formworks, allowing for complex geometric forms and reducing manual labor. Concrete construction 3D printing has been employed for housing, bridge parts, and even wider infrastructural projects in countries like The Netherlands, China, and the United Arab Emirates. However, there are still several challenges in its adoption on a larger scale: dependency on printable mixes containing fast-hardening cements with possibly high amounts of embodied carbon, special and expensive equipment requirements, questions regarding reinforcement, and lack of standards for 3D-printed buildings. Nevertheless, scientists work on ways to implement recycled materials and lower-carbon binders in printable mixes.

4.7 Sustainable Pavement and Infrastructure Materials

Another example of sustainable building materials that plays an important role in sustainable construction is sustainable pavement materials. They are crucial due to the massive road network existing worldwide and their enormous material consumption. Such materials include reclaimed asphalt pavement (RAP), warm-mix asphalt (WMA), rubberized asphalt produced with reused tire rubber, alkali-activated materials made of slag and fly ash, and permeable pavements for effective management of stormwater [24]. According to current research, RAP allows reducing aggregate requirement up to 50% and decreasing the embodied carbon of pavement construction works by 20–30%. Nevertheless, the use of RAP is limited due to the poor quality of binders, scarcity of data on long-term rutting and fatigue resistance of the material, as well as conservative regulations of road administration bodies [24]. On the other hand, permeable pavements contribute to urban stormwater drainage in an eco-friendly manner; yet, they still face problems associated with clogging and decreased load-bearing capability, reduced durability under freeze-thaw conditions. In addition, the additive manufacturing approach applied in construction, that is, 3D-printing with the usage of concrete, clay, earth, or recycled mixes, demonstrates the potential for reducing material waste up to 60% compared to conventional approaches along with the ability to design complicated forms and labor reduction [23]. It was used extensively in the Netherlands, China, and the United Arab Emirates. Still, there are several limitations of 3D-printed construction related to the dependence on early strength cementitious mixes, which can be associated with increased embodied carbon, the high costs of equipment for 3D-printing of buildings, difficulty of applying reinforcement, and absence of standards for constructing 3D-printed buildings..

Table 4 Comparison of sustainable pavement materials by cost, emissions reduction, energy use, durability and scalability [Springer Discover Concrete, 2025]

Material/Technology	Cost (USD/ton)	CO ₂ Reduction (%)	Energy Savings (%)	Durability (lifespan in years)	Scalability
Recycled asphalt pavement (RAP)	25–45	30–40	20–25	15–20	High
Recycled concrete aggregate (RCA)	20–35	15–25	10–20	10–15	High
Rubberized asphalt	60–90	15–20	10–15	18–25	Moderate
Warm mix asphalt (WMA)	70–90	20–30	20–40	20–25	High
Fly ash	20–30	30–50	30–50	40–50	High
GGBFS (Slag)	25–35	40–60	25–40	40–50	Moderate
Bio-asphalt	90–130	35–45	15–25	15–20	Low
Recycled plastic pavement	60–100	20–30	10–20	20–25	Moderate
Pervious/porous pavement	60–85	Indirect (~10–15)	10–15	10–15	Moderate
Geosynthetics (e.g., Geogrids)	1.5–2.5/m ²	10–20	5–15	Enhances base lifespan by 30%	High

An analysis of sustainable construction materials and pavements reveals that there is a possibility for these materials to be efficient and practical while maintaining their sustainability qualities. Materials such as fly ash and GGBFS reduce carbon dioxide production and energy consumption while providing adequate durability, allowing for them to be effective replacements for conventional materials. Materials such as recycled asphalt pavement and recycled concrete aggregates provide cost-effective options with medium-level environmental benefits and high scalability, contributing to their adoption. More innovative options include the use of warm mix asphalt and geosynthetics, which improve performance by increasing durability and reducing energy consumption. Bio-asphalt and recycled plastic pavements present environmental advantages, although they face challenges in scalability and high costs. In terms of mechanical properties, bamboo and engineered woods provide exceptional flexural strength, allowing them to function well in carrying loads, while hempcrete, straw bale, and rammed earth lack strength and are appropriate for non-load-bearing purposes.

5. Challenges of Sustainable Materials in Construction

The move to adopt sustainable building materials faces a complicated array of challenges interrelated with each other and affecting their selection, implementation, and durability. Based on an analysis of many scientific works related to this topic, the following ten groups of barriers can be identified and discussed in greater detail further. The significance of these groups of barriers is determined based on their frequency of mention in various publications.

5.1 Economic and Financial Barriers

High costs form the most prevalent barrier in the literature reviewed in relation to sustainable materials adoption. Sustainable materials cost more due to complex processes, special manufacture, and in some cases, importation. As such, sustainable materials cost roughly 10–40% more compared to conventional materials [9], [11]. The impact of increased costs can be felt especially in emerging markets where budget constraints influence project planning by developers with limited resources. Sustainable materials are said to provide economic value in the long term since they consume less energy, require fewer maintenance activities, and have better durability, but these advantages fail to be acknowledged since most building projects are assessed using a short-term approach, with horizons of 3-5 years for commercial buildings. In addition to that, the lack of financial instruments in the form of favorable funding, government incentives, and carbon pricing policy make sustainable materials less competitive. Finally, the low demand in the market constrains large-scale production that could drive down costs through economies of scale. Addressing this challenge will need collective effort in terms of creating market demand and scaling sustainable materials production through investments.

5.2 Regulatory, Policy, and Technical Performance Challenges

There are also performance and technical uncertainties associated with sustainable materials which act as barriers in their implementation in building constructions. Sustainable materials, especially biogenic and lower carbon emission type, are relatively novel compared to existing conventional materials such as ordinary Portland cement concrete and structural steel. Uncertainty exists with regard to the compression strength, fatigue, fire resistance, moisture sensitivity and creep among other mechanical attributes. In addition, since there is no standardized testing protocol for these materials, comparing the findings of different research studies becomes difficult [4], [15]. Moreover, sustainability of materials may present additional practical uncertainties such as compatibility with existing construction techniques, chemical reactions and thermal properties at interfaces. Regulatory and policy challenges play a vital role in restricting the utilization of sustainable materials. In general, regulatory regimes for sustainable buildings lack uniformity and enforcement mechanisms. Even though several environmental performance standards, including LEED, BREEAM and GRIHA have been established, consistent material level carbon assessment is not enforced through these standards [3],[8]. However, in many emerging nations, the absence of specific building codes endorsing sustainable construction materials, coupled with complex procedures for approving new materials, forces practitioners to opt for traditional materials. Even when there is a sophisticated regulatory framework, it is difficult to implement, as is evidenced by the difficulties associated with governance in projects such as the Dutch Building Agreement for Steel [7].

5.3 Environmental Assessment and Lifecycle Challenges

Lifecycle assessment (LCA) has been regarded as the key methodology in evaluating the sustainability of construction materials from an environmental perspective. However, it is impeded by methodological inconsistency in terms of variability in the definition of system boundaries, approaches to allocation, background databases such as Ecoinvent or GaBi, and choice of the functional unit. In addition, more than 300 scientific literature articles have revealed the lack of accounting for important sources of emissions, including transport emissions, on-site usage of machinery, and demolition during the end-of-life stage of buildings. In terms of barriers related to human and professional behavior, interpretive structural modeling demonstrates that one of the main limitations is the unwillingness of the design teams to take credit for reducing their embodied carbon footprint due to various cultural and professional constraints. Moreover, although initial decisions made in the design process can reduce carbon emissions by about 40–60%, this potential may not be actualized since there is a lack of readily available EPDs for projects.

5.4 Supply Chain and Market Structure Challenges

The immature supply chains in regard to sustainable materials constitute a true structural obstacle since they increase the cost factor and reduce the availability of such materials. The issues associated with insufficient capacity of local manufacturing, the inconsistency of material properties provided by new suppliers, increased lead times, as well as the geographically clustered production of specialized materials contribute to elevated risks and contractor uncertainty about green material choice [9], [10]. It affects particularly the use of bio-based materials in constructions because of their dependence on seasonal fluctuations in the availability of raw materials and the lack of processing facilities. Additionally, there is a deficiency of reverse logistics which hinders the implementation of the concepts related to the circular economy in practice. The literature review has established that it is impossible to fully capitalize on the reuse of building and demolition waste without having in place a system of recovery, sorting, recycling, and re-distribution [21]. Moreover, the existing market infrastructure incentivizes the selection of the cheapest options which undermines sustainability initiatives.

5.5 Awareness, Knowledge, and Skilled Labor Gaps

The findings of a qualitative study conducted in residential construction in Rwanda revealed that most of the architects and constructors do not have sufficient knowledge about the qualities of sustainable materials, methods of installation, and advantages in the long run. This phenomenon does not happen only in Rwanda, but rather across the world, especially in developing economies, due to insufficient training programs. Besides coordination issues between all parties involved in building processes, developers, designers, constructors, sub-contractors, and suppliers mentioned by Davies and Davies (2023) [6], there are very few specialists in sustainable materials' use, proper construction and installation methods, and quality control. Moreover, there are not many sustainable material aspects covered in undergraduate curriculums in architecture and engineering, thus making this phenomenon persist. Another obstacle to using sustainable materials is a shortage of skilled labor that is capable of installing, maintaining, and checking new sustainable products such as timber structures, hemp insulation, and geopolymers concrete.

5.6 Market Resistance and Industry Conservatism

The slow nature of the construction industry and its inclination towards conservatism is particularly prevalent in its willingness to adopt innovative solutions. Informed decision makers—be they contractors or developers—hesitate due to potential concerns related to warranties, insurance coverage, and legal liability in case something goes wrong with a product that they have not encountered before. As a result, the preference for the tried-and-true is reinforced by the reluctance to experiment and try something potentially risky. Furthermore, when clients are mostly interested in short-term savings—lower costs and faster construction—there is very little incentive

to consider alternatives. This tendency is compounded when there are no knowledgeable consumers who actively demand more sustainable solutions, such as institutions with ESG strategies. To make matters worse, many professional indemnity insurers will not cover innovative products that lack historical support.

5.7 Data Limitations and Technology Integration Gaps

The application of AI and ML in improving sustainable material selection and predicting performance over time is currently limited due to poor quality data that is dispersed and unstandardized. Literature on ML and DL in sustainable concrete construction reveals that lack of standardization in datasets and poor data quality affect the validity and practical applicability of predictive models. Despite the potential benefits of advanced digital technologies such as digital twins and BIM lifecycle management that can potentially monitor material performance, optimize maintenance strategies, and inform material reuse at the end of life, their integration with sustainability information systems, including EPD, carbon accounting tools, and circular economy material databases, is still relatively nascent. Furthermore, analysis indicates that poor material specifications and inadequate digital decision-making aids are significant challenges for stakeholders, limiting the adoption of technological innovations toward sustainable construction practices.

5.8 Skilled Labor Shortage

Effective utilization of sustainable construction materials requires special skill sets that go beyond what would be needed to construct a regular building. The processes such as installing timber-based building structures, design of bio-based insulating materials, monitoring of quality in producing geopolymers concrete, as well as integration of building energy systems require specialized training that is not yet part of general training or educational curriculums [12], [6]. This is exacerbated by the worldwide shortage of skilled labor within the construction industry, whose number is likely to decline due to increasing demands in infrastructure and aging of the current workforce. This makes the number of laborers capable of handling these materials even more restrictive. As such, even in cases where there is a requirement for use of sustainable construction material, installation errors due to lack of specialized skill sets can lead to ineffective use of these materials.

5.9 Implementation and Scalability Issues

There is a large discrepancy between the behavior of sustainable construction materials under laboratory conditions and in real-life building sites. The vast majority of the results are obtained from experiments carried out in highly controlled environments, involving small samples and optimal curing processes, which do not reflect the realities of actual construction works [5], [13]. The difficulties increase when the materials are manufactured for actual implementation since issues such as quality control in production, variations in the characteristics of the raw materials, logistics problems, and obtaining adequate workability at the building site become relevant. For instance, laboratory-based geopolymers concrete may show a high sensitivity to the specific composition of the input materials such as fly ash and GGBS, whose chemical composition varies greatly from supplier to supplier, making its real-life performance unreliable [4].

Table 5 Consolidated Summary of Challenges in Sustainable Material Adoption

Parameter	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]	[21]	[23]	[24]	[25]	[26]
Waste Management	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	15%	-	-	27%	-	-	-	-
Resource Consumption	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	22%	-	-	-	-
Urbanization	-	-	-	-	-	12%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	16%	-	-	-	-
Circular Practices	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	9%	-	-	16%	-	-	-	-
Policy	18%	17%	-	13%	-	21%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12%	-	-	-	12%
Technology	-	-	-	-	-	9%	-	-	-	-	-	-	-	-	-	-	23%	-	-	-	13%	17%	-	14%	-
Others	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6%	-	-	-	8%
Regulations	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	28%	7%	-	-	-	-	-	-	-
Financial Constraints	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5%	-	-	-	-	-	-	-
Awareness	18%	-	-	11%	16%	-	-	-	-	-	24%	-	-	-	-	-	-	2%	-	-	-	-	14%	13%	-
Stakeholder Perception	-	-	-	-	33%	-	-	-	-	-	-	-	-	-	-	-	9%	3%	-	-	-	-	-	-	-
Specifications	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Policy Support	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Contracts	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Legal Framework	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	16%	-
Finance	-	18%	-	-	-	22%	-	-	-	-	16%	-	-	-	-	-	-	-	-	-	-	-	-	14%	-
Knowledge	-	22%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	13%	-
Infrastructure	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11%	-
Collaboration	13%	-	19%	-	-	-	-	-	14%	-	-	-	14%	-	-	-	-	8%	-	-	-	-	-	8%	-
Standardization	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12%	-
Material Type	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	18%	-	-	-	38%	-	21%	-	-	-
Embodied Carbon	-	-	-	-	-	-	-	-	-	-	-	-	-	33%	-	-	-	-	-	26%	-	-	-	-	-
Lifecycle	-	-	-	-	-	-	13%	-	23%	-	-	-	-	22%	-	-	-	-	-	23%	-	-	-	-	-
Building Configuration	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	8%	-	-	-	-	-
Biogenic Carbon	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	8%	-	-	-	-	-
CO2 Reduction	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	21%	-	-	-	-	-	-	-	-	-
Energy Savings	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	16%	-	-	-	-	-	-	-	-	-
Durability	-	-	-	-	-	-	-	17%	-	-	-	13%	-	-	-	14%	-	-	18%	-	-	-	-	-	-
Scalability	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11%	-	-	-	-	-	7%	-	-	-
LCA	-	12%	-	-	-	-	-	-	-	-	-	-	-	-	-	11%	-	-	13%	-	-	-	-	-	-
Operational Energy	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	26%
Material Production	-	-	24%	-	-	-	-	-	-	-	-	-	24%	-	-	-	-	-	-	-	-	-	-	-	18%
Construction Process	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	16%
Transport	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11%
Demolition	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12%
Environmental Impact	-	-	-	-	-	-	-	-	-	-	-	-	-	-	23%	-	-	-	18%	-	-	22%	-	-	-
Performance	-	-	-	-	-	-	-	-	-	-	-	-	-	-	21%	-	-	-	-	-	-	-	-	-	-
Economic	-	-	-	-	-	-	-	-	-	-	-	-	-	-	17%	-	-	-	-	-	-	-	-	-	-

Parameter	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]	[21]	[23]	[24]	[25]	[26]	
Efficiency																										
Recyclability	-	-	-	-	-	-	-	-	-	-	-	-	-	-	18%	-	-	-	13%	-	-	-	-	-	-	-
Innovation	-	-	-	-	-	-	-	13%	-	-	-	-	-	-	8%	-	-	-	-	-	-	-	-	-	-	-
Health	-	-	-	-	-	-	-	-	-	-	-	-	-	-	13%	-	-	-	-	-	-	-	-	-	-	-
Social	-	-	-	11%	-	-	-	-	-	-	8%	-	-	-	12%	-	-	-	-	-	-	-	-	-	-	-
Mechanical Performance	-	-	-	-	-	-	-	-	-	-	-	22%	-	-	-	-	-	-	-	-	-	18%	-	-	-	
Regulation	-	-	-	-	-	-	-	-	-	23%	19%	-	-	-	-	-	-	-	-	-	-	12%	-	-	-	
Material Substitution	-	-	-	-	-	-	-	-	-	-	-	-	-	21%	-	-	-	-	-	-	-	-	-	-	-	
Recycling	-	-	-	-	-	-	-	-	-	-	-	16%	-	14%	-	-	-	-	-	-	-	-	-	-	-	
Specification	-	-	-	-	-	-	-	-	-	-	-	-	-	16%	-	-	-	-	-	-	-	-	-	-	-	
Economic	18%	-	-	13%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Technical	16%	-	-	12%	-	-	-	-	-	-	16%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Management	22%	-	-	8%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Environmental	-	-	14%	9%	-	-	-	27%	-	-	-	-	22%	-	-	-	-	-	-	-	-	-	-	-	-	
Materials	-	-	-	12%	-	12%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Stakeholder Reluctance	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	31%	-	-	-	
Responsibility	-	-	-	-	23%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	21%	-	-	
Decision Hierarchy	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	16%	-	-	-	
Resistance	-	11%	-	-	22%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	22%	-	-	-	
Governance	-	-	18%	-	-	-	-	-	-	-	-	-	23%	-	-	-	-	-	-	-	-	-	-	-	-	
Supply Chain	-	-	18%	-	-	-	-	11%	-	11%	-	-	21%	-	-	-	-	-	-	-	-	-	-	-	-	
Mechanical Properties	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	23%	-	-	-	-	-	-	
Energy Efficiency	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	13%	-	-	-	-	-	-	
AI Optimization	-	-	-	-	-	-	24%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Material Properties	-	-	-	-	-	-	19%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Monitoring	-	-	-	-	-	-	12%	-	16%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Data Issues	-	-	-	-	-	-	8%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Interpretability	-	-	-	-	-	-	9%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Implementation Gap	-	-	-	-	-	-	13%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Carbon Reduction	-	-	-	-	-	24%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Institutional Capacity	-	-	-	-	-	7%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Digital Technology	-	-	-	-	-	-	-	-	27%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Optimization	-	-	-	-	-	-	-	-	13%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Training	-	-	-	-	-	-	-	-	8%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Material Innovation	-	-	-	-	-	-	-	-	-	-	-	27%	-	-	-	-	-	-	-	-	-	-	-	-	-	
Sustainability	-	-	-	-	-	-	-	-	-	-	-	18%	-	-	-	-	-	-	-	-	-	-	-	-	-	
Research Gaps	-	-	-	-	-	-	-	-	-	-	-	12%	-	-	-	-	-	-	-	-	-	-	-	-	-	
Operational Issues	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	18%	-	-	-	-	-	-	-	-	
Certification	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11%	-	-	-	-	-	-	-	-	

Parameter	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]	[21]	[23]	[24]	[25]	[26]
Information Barriers	-	-	-	-	-	-	-	-	-	24%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Cost	-	-	-	-	-	-	-	13%	-	17%	-	-	-	-	-	13%	-	-	-	-	-	8%	-	-	-
Incentives	-	-	-	-	-	-	-	-	-	14%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Labour	-	-	-	-	-	-	-	-	-	18%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Availability	-	16%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Market	-	12%	-	-	-	-	-	-	-	-	13%	-	-	-	-	-	21%	-	-	-	-	-	-	-	-
Energy	-	-	-	-	-	-	-	23%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Decision	-	-	-	-	16%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
MCDM decision	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11%	-	-	-	-	-	-	-

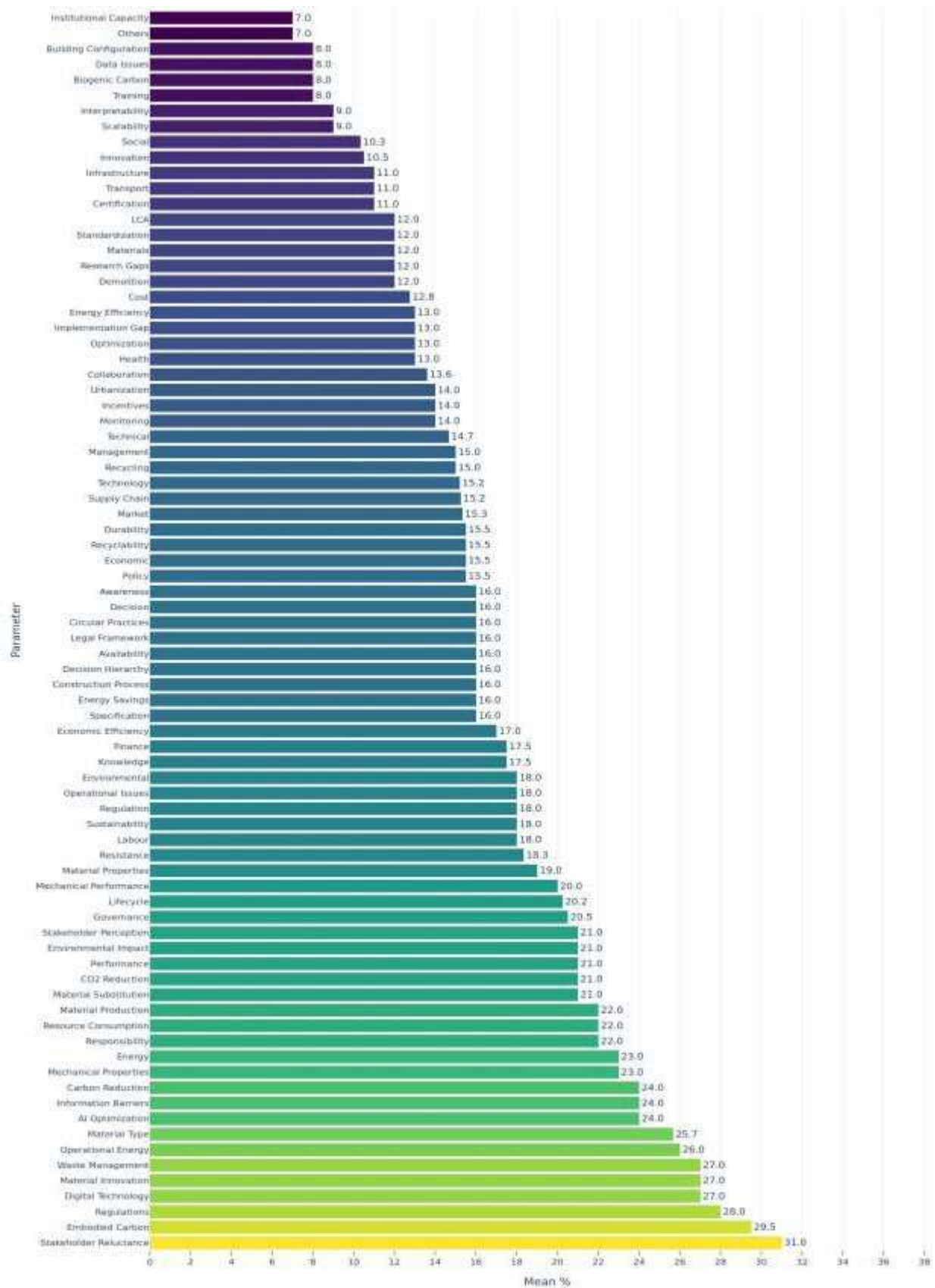


Figure 1 adoption barriers of sustainable materials

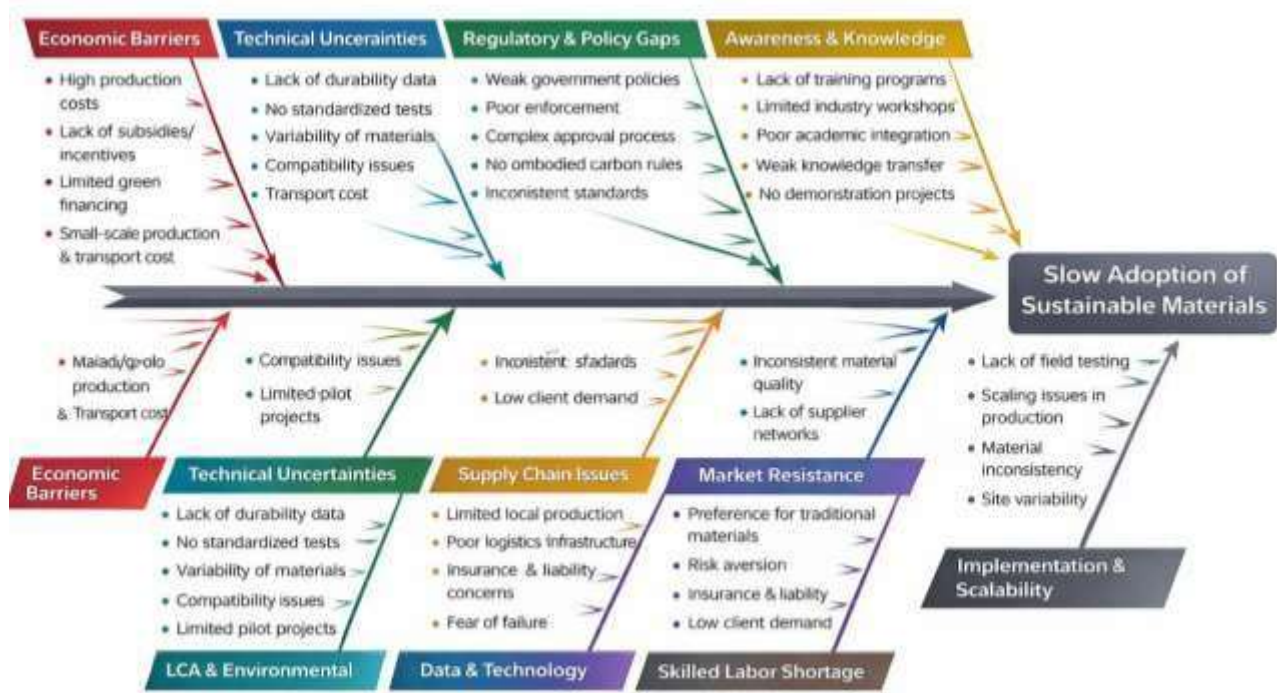


Figure 2 Factors influencing key barriers in sustainable material adoption

6. Research Gaps

Although there have been many advancements in sustainable building material development and research, a persistent gap between research and practice remains apparent throughout the literature. There are a number of critical gaps that impede the application of these materials in practice. The following sections present an in-depth analysis of some of the most critical gaps observed in the research literature.

6.1 Lack of Real-World Implementation Studies

There is another weakness in the existing literature, that is the excessive focus on laboratory results, instead of real-life applications. For example, much information about geopolymers concrete, hemp-lime structures, PCM panels, and self-healing concrete pertains to small-scale tests that do not accurately reflect conditions of real construction sites. The climate variability, environmental changes at the construction site, differences in the quality of work, and interaction with other structural components have been disregarded. Therefore, the effectiveness of applying laboratory findings in practice is unknown, and people doubt the feasibility of their implementation. A vicious cycle emerges: due to the lack of practical experience, usage rates remain low, while because of low application rates, there is still a lack of practical knowledge. To overcome this problem, more pilot projects should be launched in cooperation with stakeholders.

6.2 Insufficient Long-Term Durability and Performance Data

Another important gap still pending is the lack of durability information on sustainable construction materials that should last at least 50-100 years. However, there is a huge number of sustainable building materials, such as bio-based insulating materials, geopolymers concrete, nanocomposite materials, and PCM materials that have not yet been tested for long periods of time, typically 1-5 years, under laboratory conditions or limited field tests. Many questions related to their behavior during long-term use are still open, like creep and shrinkage in geopolymers materials, resistance of timber and bamboo materials to environmental degradation, stability of PCMs to cyclic thermal degradation, nanoparticle leaching, and performance of recycled aggregate

concrete in aggressive conditions.

6.3 Absence of Standardised Frameworks and Evaluation Methods

One major limitation identified in the literature review is the lack of globally recognized standards for testing and evaluating sustainable construction materials. Without universally recognized standards for conducting tests, comparing results becomes difficult. It is therefore important that globally recognized standards be set up for all types of sustainable construction materials. For instance, the lifecycle analysis method is highly subjective due to differences in boundaries, databases, and calculations used to arrive at certain conclusions. As such, the lack of uniformity makes it difficult for stakeholders to gain confidence in the method and utilize it. It is therefore crucial that globally accepted standards for sustainable construction materials be established, including Environmental Product Declarations based on ISO 14040/14044 and EN 15804 standards and guidelines for evaluating fire, moisture, structural integrity, and quality characteristics of sustainable construction materials.

6.4 Limited Integration of AI, BIM, and Digital Technologies

Despite numerous technological breakthroughs like AI, BIM, and IoT being acknowledged as essential tools for achieving sustainability in construction, these innovations are not well-integrated within the material sustainability perspective. The literature lacks an analysis of integrating AI, BIM, and IoT into sustainable materials [3], [1]. Most publications analyze each tool on its own and not in relation to sustainable materials. Despite the immense capabilities AI holds in the optimization of material mixing, prediction of materials' future performance, and circularity through material tracking, AI implementation has some limitations that must be addressed. These include the lack of standardized and accessible material databases for feeding AI, lack of BIM libraries holding sustainability data, lack of IoT systems for continuous monitoring of the materials' performance, and the lack of comprehensive decision-making systems taking into account such factors as performance, costs, and carbon footprint of the materials among others.

6.5 Weak Policy Implementation and Governance Gaps

It is well known that sound policy-making is critical to ensuring sustainable construction; however, the existing gap between what the policy says and what is practiced remains an issue. It was found that complex certification procedures for green buildings may discourage all parties involved from being sustainable despite the availability of financial benefits. At present, there are many obstacles to achieving progress on a global level, including the absence of strong governmental support, a lack of incentives, and unclear regulatory framework. A significant governance issue is the gap between national ambitions in terms of sustainability, such as net-zero emissions targets, and the regulatory system overseeing construction. This problem often manifests itself in the absence of new legislation and regulations in such areas as building codes, procurement processes, and urban planning practices.

6.6 Gender, Social Equity, and Community Perspectives

A significant oversight in sustainable construction literature relates to the consideration of social equity and inclusivity when selecting and implementing the use of materials. There is seldom any research that analyzes the distribution of the socio-economic and environmental advantages of sustainable construction across various socio-economic classes, whether the sustainability criteria are biased towards more affluent consumers, and how cultural values and preferences influence material acceptance. Answering these queries is vital for a socially equitable and inclusive transition to sustainable construction. In future research, emphasis needs to be placed on assessing the affordability of sustainable housing for poor households, encouraging community engagement in material selection, particularly in informal and vernacular constructions, and integrating traditional and indigenous knowledge into sustainable material innovation.

7. Future Directions and conclusion

Based on the findings of the literature review and related gaps, the following strategic steps must be taken to increase the responsible adoption of sustainable construction materials. First, it is important to make sustainable materials competitive and economically viable through increased production efficiency and using local resources. As such, there should be further development and implementation of affordable geopolymer binders, strengthening the bio-based supply chain, and proving lifecycle cost effectiveness to promote sustainable construction materials [9], [24]. Another strategic step concerns the introduction of strong regulatory measures, such as mandatory carbon reporting, standardization of EPD, green procurement policies, and subsidies in the form of tax breaks and loans for supporting sustainable construction [8], [19]. International cooperation and targeted aid for developing countries in the areas of capacity building and climate finance should also be considered.

Further technological innovation based on artificial intelligence (AI), Building Information Modeling (BIM), IoT and digital twins, can provide significant opportunities for improving the process of selecting construction materials, monitoring their performance, and material life cycle management [1], [3]. Besides, implementing circular economy principles in terms of designing buildings for disassembly, reuse of existing materials, and recycling is an area of promising opportunities [17], [18]. Improvements in education and workforce training programs to equip construction specialists with necessary skills and competencies related to sustainable construction materials are another step that needs to be taken [12], [6]. In addition, establishing standardized LCA approaches and carbon accounting will increase transparency, facilitate more accurate comparisons, and promote better decisions regarding material choice [20], [15].

To summarize, the importance of sustainable construction materials cannot be overstated because they are vital for mitigating the negative environmental effects and meeting the global climate change goals. However, there are many obstacles that limit the adoption of sustainable construction materials in practice. Based on the findings of the literature review, economic, technical, regulatory, and social barriers to increasing sustainable materials usage must be addressed simultaneously. The main strategic steps in this case include promoting practical applications of research, enforcing the current regulatory framework, improving supply chains, increasing stakeholders' awareness, and bridging the regional gap.

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