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Review

Green Building Materials and Sustainable Practices: Environmental Impact and Shaping the Future of Civil Engineering

Osama Ahmed Ibrahim [1], Safinaz Khalifa[1], Mohamed G. Abdolwahab[1], Sherif Fakhry M. Abd-Elnaby[2]

[1] *Construction Engineering Department, Faculty of Engineering, Egyptian Russian University Badr City, Cairo 11829, Egypt.*
[2] *Construction Engineering Department, Faculty of Engineering, Egyptian Russian University / President of the Egyptian Russian University, Badr City, Cairo-Suez Road, 11829, Cairo, Egypt.*

*Corresponding author(s): Osama Ahmed, E-mail: osama-ahmed@eru.edu.eg,

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ABSTRACT

As sustainability increases in importance, civil engineering is forced to respond by integrating green building materials into the construction industry. This essay discusses new materials, including self-healing concrete and bio-cement, through several case studies, observing their potential for use in both structural and non-structural applications. Following Life Cycle Assessment (LCA) research, the article spreads the most important green advantages of the materials, i.e., lower carbon emissions, better disposal, and higher long-term sustainability. It additionally points out effective disposal methods by which these eco-friendly materials further reduce their environmental footprint beyond their primary use. In addition, the paper goes on to address future material innovation, the function of smart buildings in energy efficiency, and legislative incentives for green building. These are trends that are indicative of the increasing trend within the construction industry towards sustainability with the aim of achieving environmental targets and enhancing building quality, life, and service life. The trend is crucial in determining the future of sustainable construction.

Keywords: Green building materials, sustainable construction, Biocement, self-healing concrete, smart building systems.

1 .Introduction

The construction industry, as one of the basic growth drivers of economies, has long been associated with high resource consumption and environmental degradation [1]. With increasing global urbanization, the demand for new infrastructure increases, putting more pressure on natural resources and significantly contributing to environmental problems such as pollution, excessive energy use, and unsustainable waste production [2]. Traditional building materials, such as concrete, steel, and cement, have large environmental impacts, mainly stemming from high carbon emissions, energy-intensive production, and the minimal possibility of recycling [3]. The concept of "green building" has been one of the important strategies of sustainable development in response to these issues. Green building materials are integral to this change because they provide environmentally friendly alternatives that reduce the adverse impacts of construction on the environment [4]. These materials, over a building's lifecycle, are designed to reduce waste generation, reduce energy consumption, reduce greenhouse gas emissions, and increase the use of natural resources [5]. They also bring other benefits such as higher thermal insulation, better air quality, and increased health and well-being for building inhabitants [6]. Today, there are numerous types of green building materials available, which include recycled and renewable ones. Bamboo, recycled steel, fly ash-based concrete, Biocement and self-healing concrete are just a few examples [7]. These materials can be applied in structural roles, such as load-bearing elements, as well as non-structural functions like insulation, cladding, and flooring. Notably, advancements in material science are enabling the development of even more innovative materials that are not only environmentally sustainable but also provide superior performance characteristics. As previously discussed, self-healing concrete can autonomously repair cracks, thus extending the structure's life and reducing costs of maintenance, while bio cement significantly reduces carbon emission during production without compromising the strength and durability [8]. Then, there is the added dimension of the environmental impact due to the green building materials. Due to their energy efficiency, they consume fewer energy resources in their manufacturing and transportation compared to traditional materials. This significantly reduces the carbon footprint. Green building materials help reduce waste, using contents that are recycled, and where possible encourage the reuse of materials from demolition or renovation sites. They also play a role in mitigating climate change through the reduction in emissions of greenhouse gases [9]. The integration of green building materials into civil engineering projects requires an intimate knowledge of their applications and environmental impacts. Not only the direct benefits of using technology in terms of energy consumption and emissions but also the long-term environmental advantages of durability, resource efficiency, and recyclability at the end of life are all important aspects to take into consideration [10]. Since it provides a comprehensive evaluation of the environmental performance of any material, from extraction to disposal, LCA is one of the required tools for that purpose [11]. The aim of this essay is to give an in-depth analysis of the application of green building materials in civil engineering, examining both their structural and non-structural uses. It will also look at how they impact the environment in the long run as regards sustainability, waste management, and carbon footprint reduction. It will conclude by considering future developments surrounding green building in terms of integrated smart building systems, new advances in materials technology, and legislatively based incentives. Green building materials are in the forefront of this quest for a much greener future in the construction industry, and new developments in this regard represent the next frontier in sustainable construction.

Figure 1: Represent sustainable building construction scene.

2. Sustainability and Green Building materials

Sustainability is a wide term enveloping prudent management of environmental, social, and economic resources to secure the welfare of the present and future generations. It highlights the need for balancing the preservation and protection of natural systems against human demands [12]. On the other hand, green building materials are a particular use of sustainability. These materials are selected based on their green features, which include waste reduction in construction projects, energy efficiency, and reduced carbon emissions [13]. Although sustainability has a wide range of approaches, one of the most practical solutions is green building materials, which actively support the achievement of sustainable construction and development [14]. These three pillars are prerequisites if long-term stability and prosperity are to be nurtured [15]. Sustainability is underpinned by three interlinked pillars, as shown in Figure 1.

Environmental Sustainability targets ecosystem and natural resource conservation, pollution reduction, and promotion of renewable energy so that the environment can continue to perform its function of supporting life [16].

Economic Sustainability: Establishing financial mechanisms and economic development in a sustainable manner through time, ensuring resources are used effectively is yet another consideration of importance in green industries and technologies [17].

Social Sustainability pursues social equity, justice, and well-being; it assures access to basic needs and services for all people and creates resilient and strong communities [18].

These three pillars together form the basis of complete sustainability, in which protection of the environment, economic growth, and social equity are all sought after simultaneously. Green building materials contribute much to this holistic approach by aligning construction practices with sustainability goals.

Figure 2: The Three Pillars of Sustainability.

3. Application of Sustainable Materials in Civil Engineering.

Sustainable materials in civil engineering have been given high priority in the industry's move towards reducing its impact on the environment and promoting eco-friendly practices [19]. From large infrastructure projects down to residential buildings, sustainable materials are being used in most civil engineering projects. Their ability to reduce resource consumption, reduce carbon emissions, and improve the sustainability of structures makes them a very important component of modern constructions [20]. Green building materials can be used in both structural and non-structural elements of construction, providing various environmental benefits and performance. Structural applications usually involve load-supporting elements such as beams, columns, and foundations with high strength and durability requirements [21]. On the other hand, non-structural applications focus on elements such as insulation, cladding, and interior finishes, where sustainability is stressed through energy efficiency, recyclability, and low environmental impact [22]. More recently, new green materials were developed, which increased their potential applications and enabled engineers to meet environmental challenges without any compromise on performance.

Figure 3: Represent civil engineering construction site utilizing sustainable materials.

3.1. Structural Applications

Sustainable materials have been adapted for structural applications with the aim of preserving building and infrastructure integrity while meeting environmental standards. In recent years, there has been reengineering of traditional materials like concrete and steel to include sustainable options. One of the greatest advances in this respect regarding structural materials is the inclusion of recycled aggregates into concrete. It will cut down on exploitation of virgin materials and reduce landfill wastes using recycled concrete, fly ash, and other industrial by-products [23]. Recycled steel, in civil engineering, will become prominent very shortly since they are strong and can be used again without any compromise in quality; these are perfect materials to make components like beams and columns in buildings and bridges strong [24]. Furthermore, this situation can be improved with the high-strength, low-carbon concrete mixtures developed. Normally, there are very high percentages of supplementary cementitious materials like fly ash, silica fume, and slag in the binder, which again reduce the amount of clinker that is the major contributor of carbon emission in the cement [25]. In that respect, the discussed sustainable materials were found possessing some noticeable potential for large reductions of environmental impacts linked to building construction.

Moreover, advancements in composite steel-concrete beams have demonstrated improvements in structural performance, fatigue resistance, and long-term durability. Several studies have explored the effect of external post-tensioning, shear stud distribution, and partial shear connection on the behavior of these composite systems, providing sustainable alternatives for modern infrastructure projects [26–36]. By optimizing composite beam design, engineers can enhance structural efficiency while maintaining environmental sustainability.

3.2. Non-Structural Applications

The use of sustainable materials for non-structural purposes can make buildings and infrastructures more environmentally efficient. Most of the goals of these applications are centered on increasing a structure's energy efficiency, reducing operation expenses, and promoting the use of recyclable or renewable resources [37]. One of the most major non-structural uses of green materials is insulation. Some of the environmentally friendly insulation materials with good thermal quality include cellulose from recycled paper and natural fibers such as hemp and wool [38]. By maintaining the thermal efficiency of a building, such materials reduce the demand for mechanical heating and cooling, meaning less energy consumption and reduce greenhouse gas emissions. Cladding and roofing systems also make use of sustainable materials. For instance, the composites of recycled plastic and wood are used in exterior cladding that provide durability and require less maintenance and reduce dependence on virgin materials. Another exemplary case of how non-structural green materials could help to reduce energy consumption and the heat island effect in cities is the cool roofing materials which reflect more sunlight and absorb less heat [39]. Also, eco-friendly paints and finishes emitting low or zero volatile organic compounds (VOCs) are gaining in popularity. These materials not only contribute to improving indoor air quality and reducing health risks to occupants but also contribute to the overall sustainability of a building [40].

3.3. Innovative Materials

There have been new, innovative, green building materials that have emerged in the field of civil engineering over the past couple of years, which further the boundaries of sustainability and performance. These materials not only reduce environmental impact but also enhance functionality, therefore extending the service life of the structures and reducing long-term costs.

3.3.1. Self-Healing Concrete

Self-healing concrete is one of the major steps toward sustainable building material. This new type of concrete is engineered to autonomously and automatically heal the appearance of cracks without human intervention. Through the introduction of bacteria or other healing agents, this self-healing of the crack can be effectuated with exposure to either air or water [41]. This way, this ability of self-repair enhances the durability of the structure, reduces the number of repairs, and elongates the life of the concrete. As a result, there is less need for repairs and subsequently less use of new materials. The environmental benefits that self-healing concrete provides are quite large, especially in waste reduction and the use of resources. The production of concrete is a process that emits large amounts of carbon; therefore, by reducing the number of times concrete is replaced, there is a reduction in overall emissions related to maintenance and repairs [42]. In addition, self-healing concrete offers better resource management as less raw material is required in the life span of a building or infrastructure.

3.3.2. Biocement

Cement production contributes to about 8% of global CO_2 emissions and poses a huge environmental challenge. Biocement, therefore, offers an alternative to traditional Portland cement, providing sustainability. This new material reduces the amount of clinker—the largest source of emissions in the production of cement—through incorporating alternative binders like fly ash, slag, and limestone [43]. Biocement offers performance comparable to conventional cement but at a significantly lower environmental cost. Biocement reduces the clinker content and replaces it with industrial by-products, to cut carbon emissions by up to 30-50%, depending on the mix composition [44]. Its application in civil engineering projects is an important step toward minimizing the carbon footprint of the construction industry without giving up strength and durability requirements expected from large infrastructure. Apart from the reduction in emissions, Biocement contributes to resource efficiency by using waste materials from other industries, which have otherwise not been used, thus reducing the demand for virgin raw materials. This helps develop a circular economy and increases the overall sustainability of construction practices.

4. Environmental Impact Evaluation

The multi-dimensional environmental benefit of green building materials involves a reduction in energy use, carbon emissions, and construction waste; it assures long-term sustainability. Traditional construction practices cause a lion's share of the environmental challenges faced at the global level today, including high energy consumption, high emissions of greenhouse gases, and natural resource depletion [45]. These effects can be neutralized largely by using sustainable materials in civil engineering projects, hence preserving the environment. This section appraises the environmental impact of green materials in civil engineering with an emphasis on main areas that include carbon footprint reduction, waste management, and long-term environmental benefits.

Figure 4: Illustrating the environmental impact of green building materials in civil engineering.

4.1. Reduction in Carbon Footprint

The construction industry is one of the largest contributors to greenhouse gas emissions globally, with the major contributor being the manufacture and transportation of building materials [46]. In a critical response to this, the shift toward green building materials helps reduce the carbon footprint of construction significantly. This can be in several ways: energy efficiency in manufacture, use of renewable resources, and incorporation of waste into useful building materials.

4.1.1. Energy Consumption

It reduces the environmental impact in many ways, most importantly by reducing energy use in production, transportation, and installation of green materials. Traditional materials like concrete and steel are very energy-intensive in their production since their manufacture depends on resource-intensive processes involving mining, refining, and smelting [47]. Most sustainable materials are designed to reduce energy use throughout their life cycle. For instance, the production of Biocement and recycled steel requires much less energy input than their conventional counterparts. The addition of industrial by-products, such as fly ash and slag, in the manufacturing of cement reduces the need to produce clinker, as it is this component in traditional cement that requires the most energy input [48]. In the same way, the recycling of steel dramatically reduces the energy demand in extracting and processing raw iron ore. On the aspect of transportation, locally sourced green materials or lightweight ones can further reduce energy consumption by minimizing fuel use in the supply chain [49]. In addition, sustainable insulation materials, such as wool, hemp, and cellulose, have low embodied energy and help to achieve a reduction in the operational energy consumption of buildings resulting from improved thermal efficiency [50]. These materials help in maintaining the indoor temperature stable and therefore reduce the need for heating and cooling systems and overall energy footprint of the building.

4.1.2. Greenhouse Gas Emissions

Another important facet of the environmental benefit of green building materials is the reduction in emissions of greenhouse gases. The production of conventional materials, such as cement, steel, and concrete, emits large amounts of CO_2, mainly because of the fossil fuels used in manufacturing processes. Cement alone accounts for about 8% of global CO_2 emissions and is, therefore, one of the most environmentally damaging construction materials [51]. Green materials, on the other hand, are often designed to reduce emissions at many levels of their life cycle. Low-carbon alternatives like Biocement and bio-based materials emit fewer GHGs in production. For example, Biocement replaces a portion of clinker, which is the main emitter of CO_2 in the production of cement, with industrial by-products, reducing its overall carbon footprint [52]. Moreover, materials like bamboo and timber are renewable, have low carbon emissions, and even act as carbon sinks, sequestering CO_2 while they grow [53]. Innovative technologies, such as self-healing concrete, can also cut down on emissions by extending the life span of structures and reducing the number of repairs and replacements that involve high-emission activities like demolition and reconstruction [54]. Moreover, the use of prefabricated and modular green building components can reduce emissions generated during the construction process by rationalizing material use and reducing on-site waste and energy use [55].

4.2. Waste Management

One of the major environmental impacts concerning the construction industry is that it is associated with waste management, because huge volumes of waste material normally arise during building, renovation, and demolition activities. Traditional construction practices contribute greatly to landfill waste, which further deplete natural resources [56]. Green building materials can help to overcome these problems by promoting reduction and recycling of materials, which leads to a more efficient use of resources and less environmental damage [57].

4.2.1. Reduction in Construction Waste

Green materials can substantially help to reduce the amount of waste generated from construction activities. One of the important strategies is the use of recycled materials in the production of new building components. Recycled aggregates can be used in concrete mixes to reduce the need for new materials and the generation of waste sent to landfills [58]. Similarly, reusing construction waste in new projects—like metals, plastics, and wood—will divert waste away from disposal sites, easing the pressure on natural resources [59]. Similarly, increased use of advanced modern modular construction techniques allows for more precise use of materials, reducing surplus waste generation onsite. Modular components are typically prefabricated in controlled factory environments where material use can be more efficient, and waste and offcuts are easier to recycle [60]. Compare that with traditional construction techniques, which can often generate a great deal of on-site waste stemming from imprecise measurement cutting and over-ordering.

4.2.2. Reuse and Recycling of Materials

Reuse and recycling materials are key in the circular economy; resources are continually reused to reduce waste and the environmental impact of human activity. Most sustainable materials in civil engineering are supposed to be recyclable at the end of their life cycle to be used in new works [61]. Certain materials, such as steel and aluminum, can be recycled repeatedly without any loss in their structural properties, a truly sustainable nature for construction projects. In addition, some building components, such as bricks and concrete blocks, can be retrieved and used in other construction, which will further reduce demand on raw materials and, therefore, the waste from the construction industry [62]. Equally important at the end-of-life disposal are the benefits of biodegradable materials, such as timber and bamboo; these break down naturally, releasing no harmful chemicals into the environment, hence they are more environmentally friendly compared to conventional materials, which often require energy-intensive recycling processes or find their way to landfills [63].

4.3. Long-term Environmental Benefits

The long-term environmental benefits of green building materials extend beyond the direct reductions in carbon emissions and waste. Sustainable materials contribute to the overall resilience and sustainability of structures and provide environmental advantages throughout their life cycle, from production to disposal [64]. Two of the important long-term environmental benefits include life cycle assessments and end-of-life considerations.

4.3.1. Life Cycle Assessment

Life Cycle Assessment (LCA) is a holistic approach to the assessment of the environmental impacts of materials throughout their entire life cycle, considering the energy and resources needed for extraction, processing, transportation, use, and disposal of materials [65]. In general, green building materials have more favorable LCA outcomes than conventional materials because they are designed to reduce resource depletion, energy use, and waste generation at every stage. For example, sustainable materials like Biocement and self-healing concrete have lower embodied carbon throughout their life cycle due to reduced energy inputs and longer service lives [66]. They reduce new construction and its environmental footprint by extending the life of a structure and reducing the need for repairs.

4.3.2. End-of-Life Disposal

End-of-life disposal is a factor that could determine the overall environmental impacts of building materials. Traditional materials normally end up in landfills at the end of their useful life, thus contributing to piles of waste and resulting in environmental degradation [67]. Green materials, on the other hand, are normally designed for recyclability or biodegradability to reduce their burden on the environment when a building is being decommissioned. For example, materials like timber and bamboo biodegrade without releasing any toxic by-products into the environment; others, like metals, are recyclable and can be used again in new works, thus closing the loop of resources [68]. The construction industry can considerably minimize its ecological footprint through planning for the end-of-life phase of materials, therefore contributing to more sustainable development practices.

5. Future Trends and Innovations

Construction is now being significantly transformed by emerging technologies and innovations that seek to address the environmental challenges posed by traditional building materials, while growing focus on sustainability, climate resilience, and energy efficiency drives development in advanced materials, design techniques, and policy frameworks that will define the future of civil engineering [69]. These innovations are not only designed to minimize the environmental footprint of construction but also to improve the performance, durability, and functionality of the structures [70]. In this section, we highlight some of the major trends and innovations that will probably shape the future of green building materials and sustainable construction practices.

Figure 5: Represent key trends and innovations in GBM and sustainable construction.

5.1. Advancements in Material Technology

The most relevant field of innovation in the construction industry has been the development of new materials with improved environmental and performance benefits, designed to reduce carbon emissions, improve energy efficiency, and increase the sustainability and durability of buildings [71]. Some of the key trends in material technology that are shaping the future of sustainable construction include:

5.1.1. Nanotechnology in Construction Materials

Nanotechnology has increasing applications in the development of advanced building materials featuring improved mechanical properties, sustainability, and energy efficiency, whereby nanomaterials such as Nano-silica, carbon nanotubes, and graphene are being used in the modification of concrete, coatings, and insulation materials to enhance their strength, thermal conductivity, resistance to corrosion, and wear [72]. For example, the use of Nano-silica in concrete improves its compressive strength and durability, while carbon nanotubes improve the tensile strength of construction materials [73], whereby these nanomaterials also help in lessening the environmental impact of buildings by extending their service life and thus decreasing the need for repairs and replacements. In a nutshell, the development of nanotechnology is going to play a very crucial role in the development of next-generation green building materials.

5.1.2. Bio-Based and Renewable Materials

The application of bio-based and renewable materials is an up-and-coming inroad as a sustainable alternative to traditional building materials. Mycelium, algae, and bioplastics, among other bio-based materials, are seen to have the potential to create biodegradable, low-carbon, and resource-efficient construction components [74]. Most can be produced from renewable resources and, in general, have lower environmental impacts compared to conventional materials like concrete and steel. For example, materials from mycelium, a root structure of fungi, are used for insulation, panels, or bricks. They have the advantage of being lightweight and biodegradable with excellent thermal and acoustic properties [75]. Another example is algae-based materials under development for use in bio-concrete and bio-cement applications; they sequester carbon dioxide during the growth phase and hence reduce the carbon footprint of buildings further [44].

5.1.3. 3D Printing and Prefabrication

The rise of 3D printing and prefabrication technologies is a revolution in the construction industry, allowing for customized, sustainable building components with little waste. Where 3D printing allows for precise material usage, it avoids the need for excessive raw materials; hence, it also decreases construction waste [76]. In addition, 3D printing technologies can also produce structures using various sustainable materials ranging from recycled plastics to biobased materials and even low-carbon concrete [77]. Another trend in reducing on-site waste and improving material efficiency is prefabrication, or off-site production of building components. Prefabricated materials can be produced in controlled environments to high standards of quality, optimizing the use of resources [78]. When used with sustainable materials, prefabrication techniques provide a fast, green form of construction that has less impact on the environment.

5.2. Integration with Smart Building Systems

With the increasing integration of smart technologies into the built environment, green building materials have very significant roles in enhancing energy efficiency and sustainability in smart buildings. Smart building systems are those that employ sensors, automation, and data analytics to optimize energy usage, monitoring of building performance, and enhanced occupant comfort [79]. Sustainable materials are fundamental in these systems since they are the means through which the efficient operation of a building is realized, hence saving energy [80].

5.2.1. Energy-Generating Materials

One of the most exciting innovations in sustainable construction has been the development of energy-generating materials capable of capturing and converting renewable energy from natural sources. Where Photovoltaic glass, for instance, integrated into building façades or windows, can generate electricity from sunlight and then contribute to the energy needs of the building, partially reducing reliance on external power sources [81]. Similarly, piezoelectric materials can produce electricity from mechanical stress or vibrations and therefore enable buildings to harvest energy from activities such as footfalls [82]. In that respect, energy-harvesting materials have become one of the fundamental steps toward the development of self-sustaining buildings able to produce their energy while minimizing their carbon footprint, thereby contributing to a greener energy ecosystem [83]. With the development in technologies of renewable energy, these materials will be widely applied and seen in smart building systems.

5.2.2. Smart Insulation and Adaptive Materials

Another emergent trend in construction includes smart insulation and adaptive materials; these are materials capable of dynamically responding to environmental conditions through a change in either their thermal or structural properties in a manner that optimizes building performances [84]. For instance, smart insulation materials are capable of automatically regulating heat transfer upon changes in temperature, thereby reducing the need for artificial heating and cooling systems and hence increasing energy efficiency [85,86]. Phase-change materials (PCMs), which absorb and release thermal energy during the change from solid to liquid and vice versa, are increasingly being used in building envelopes for passive thermal regulation [87]. The PCM can absorb excess heat during the day and release it at night for maintaining a comfortable indoor temperature and for the reduction of energy consumption [88]. The integration of adaptive materials in smart building systems gives further improvement in the sustainability and efficiency of energy in buildings.

5.3. Policy and Incentives for Green Building

Regulatory frameworks, policies, and incentives are as forcing the hand in this respect as they are promoting green building practices [89]. Many countries have realized the critical role that sustainable construction plays in combating climatic change and environmental degradation [90]. Besides, quite a good number of policies and incentives have been formulated to this end, for example, encouraging the use of green materials and technologies in construction.

5.3.1. Green Building Certifications

In Egypt, green building certification provides a critical driver for sustainable construction and a reduction in environmental impacts. A local certification, **Green Pyramid Rating System (GPRS),** has been developed, tailor-made for Egyptian local climatic and environmental challenges; it covers aspects such as energy and water efficiency, material use, and site sustainability [91]. International certifications such as **LEED, EDGE, and BREEAM** are also applied, mostly to high-profile or multinational projects [92]. Also, **TARSHEED** has been developed by HBRC and aims at improving energy efficiency in buildings in Egypt [93]. These are essential certifications that support sustainability and responsible use of resources within the Egyptian construction industry. Achieving green building certification not only improves the environmental performance of the buildings but also raises their market value and attracts more investors.

Figure 6: Represent green building certifications like GPRS, LEED, and BREEAM, reflecting sustainable construction practices.

5.3.2. Government Subsidies and Incentives

Many governments are now offering fiscal incentives, tax breaks, and subsidies to encourage the application of sustainable materials and construction practices. For example, some countries offer tax credits for buildings that meet certain energy efficiency or green certification standards [94]. Subsidies for renewable energy systems—like solar panels and wind turbines—help to lower upfront costs of building integrated sustainable energy solutions [95]. With the toughening of global climate commitments and environmental regulations, it is expected that policy-driven incentives will increasingly become one of the most important drivers for promoting green construction [96]. It will also quicken the pace of adoption of sustainable materials and drive innovation in the sector of construction.

5.4. Community and Stakeholder Engagement

Sustainable construction is not only about lessening the impact on the environment but also about creating structures that will enhance the well-being of communities and stakeholders. Involving local communities, industry stakeholders, and policymakers, the future of green building materials will increasingly be focused on guaranteeing that sustainability goals are reached in a socially responsible way [97].

5.4.1. Collaborative Design and Development

Sustainable construction projects have now adopted collaborative design processes that include participatory planning and stakeholder engagement [98]. Involving the local communities in the design and development stages ensures that the buildings will not only be environmentally friendly but will also fit the needs and tastes of the end-users [99]. Developments become inclusive, equitable, and socially sustainable; thus, they ensure that they enhance the quality of life of the entire community.

5.4.2. Education and Awareness

A major factor in the transition to industrial-wide transformation is the necessity of increasing optimal awareness of the benefits of sustainable materials and green building practices [100]. Additionally, educational programs, workshops, and industry events on sustainability will increase knowledge among architects, engineers, builders, and policymakers to ensure more wide-scale adoption of green building technologies [101]. Some of the community-based initiatives for awareness may also inspire homeowners and developers to move towards sustainable materials and practices in design [102].

6. Conclusion

The application of green building materials in civil engineering appears to be one step toward sustainable development based on the goal of reducing the environmental impact that construction holds while ensuring that the built environment is maintained with integrity and durability. Such materials, which are under development and include self-healing concrete and Biocement, have several benefits in terms of carbon emissions reduction and improvement in resource efficiency. Future material technology and construction practice advancements will, therefore, require strong policy frameworks and proactive stakeholder engagement in place if the wide adoption of these environmentally friendly solutions is to be assured as the industry goes forward. Green building materials, apart from tackling some of the most compelling environmental challenges, set a resilient and sustainable construction industry in motion—driving positive change toward a greener future.

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Conflict of Interest

The authors declare that there are no conflicts of interest regarding this research paper.

7. References

[1] Torres-Quezada JE, Sánchez-Quezada T, Vélez-Romero G. Construction Development, Economic Evolution, and Environmental Impact in Ecuador. InEnergetic Characterization of Building Evolution: A Multi-perspective Evaluation in the Andean Region of Ecuador 2023 Feb 2 (pp. 79-100). Cham: Springer International Publishing.

[2] Almulhim AI, Cobbinah PB. Urbanization provocateur: Reaching urban planning-led development in Saudi Arabia. Land Use Policy. 2024 Dec 1;147:107365.

[3] Althoey F, Ansari WS, Sufian M, Deifalla AF. Advancements in low-carbon concrete as a construction material for the sustainable built environment. Developments in the Built Environment. 2023 Nov 30:100284.

[4] Sangmesh B, Patil N, Jaiswal KK, Gowrishankar TP, Selvakumar KK, Jyothi MS, Jyothilakshmi R, Kumar S. Development of sustainable alternative materials for the construction of green buildings using agricultural residues: A review. Construction and Building Materials. 2023 Mar 3;368:130457.

[5] Sbahieh S, Serdar MZ, Al-Ghamdi SG. Decarbonization strategies of building materials used in the construction industry. Materials Today: Proceedings. 2023 Sep 1.

[6] Niza IL, de Souza MP, da Luz IM, Broday EE. Sick building syndrome and its impacts on health, well-being and productivity: A systematic literature review. Indoor and Built Environment. 2024 Feb;33(2):218-36.

[7] Nguyen MT, Fernandez CA, Haider MM, Chu KH, Jian G, Nassiri S, Zhang D, Rousseau R, Glezakou VA. Toward self-healing concrete infrastructure: review of experiments and simulations across scales. Chemical Reviews. 2023 Jun 7;123(18):10838-76.

[8] Lahmann D, Edvardsen C, Kessler S. Autogenous self-healing of concrete: Experimental design and test methods: A review. Engineering Reports. 2023 Jan;5(1):e12565.

[9] Nwokediegwu ZQ, Ilojianya VI, Ibekwe KI, Adefemi A, Etukudoh EA, Umoh AA. Advanced materials for sustainable construction: A review of innovations and environmental benefits. Engineering Science & Technology Journal. 2024 Jan 24;5(1):201-18.

[10] Kandpal V, Jaswal A, Santibanez Gonzalez ED, Agarwal N. Circular economy principles: shifting towards sustainable prosperity. InSustainable Energy Transition: Circular Economy and Sustainable Financing for Environmental, Social and Governance (ESG) Practices 2024 Feb 8 (pp. 125-165). Cham: Springer Nature Switzerland.

[11] Barbhuiya S, Das BB. Life Cycle Assessment of construction materials: Methodologies, applications and future directions for sustainable decision-making. Case Studies in Construction Materials. 2023 Jul 23:e02326.

[12] Kjell ON. Sustainable well-being: A potential synergy between sustainability and well-being research. Review of General Psychology. 2011 Sep;15(3):255-66.

[13] Goubran S, Walker T, Cucuzzella C, Schwartz T. Green building standards and the united nations' sustainable development goals. Journal of Environmental Management. 2023 Jan 15;326:116552.

[14] Omopariola ED, Olanrewaju OI, Albert I, Oke AE, Ibiyemi SB. Sustainable construction in the Nigerian construction industry: unsustainable practices, barriers and strategies. Journal of Engineering, Design and Technology. 2024 Jun 14;22(4):1158-84.

[15] Ghimire BJ. Three Pillars of Sustainable Development: Challenges versus Achievements. Journey for Sustainable Development and Peace Journal. 2023 Aug 30;1(02):132-46.

[16] Ismail A, Pardi F, Radzun KA, Hatta SK, Suratman MN, Ikhsan NA, Buyong F. Sustainable management of natural resources for environmental sustainability. Ecorestoration for Sustainability. 2023 Aug 7:417-38.

[17] Singh AK, Raza SA, Nakonieczny J, Shahzad U. Role of financial inclusion, green innovation, and energy efficiency for environmental performance? Evidence from developed and emerging economies in the lens of sustainable development. Structural Change and Economic Dynamics. 2023 Mar 1;64:213-24.

[18] Ly AM, Cope MR. New conceptual model of social sustainability: review from past concepts and ideas. International Journal of Environmental Research and Public Health. 2023 Mar 31;20(7):5350.

[19] Khan M, McNally C. A holistic review on the contribution of civil engineers for driving sustainable concrete construction in the built environment. Developments in the Built Environment. 2023 Nov 15:100273.

[20] Ma Z, Awan MB, Lu M, Li S, Aziz MS, Zhou X, Du H, Sha X, Li Y. An Overview of Emerging and Sustainable Technologies for Increased Energy Efficiency and Carbon Emission Mitigation in Buildings. Buildings. 2023 Oct 22;13(10):2658.

[21] ElSharkawy M, Mourad Y, Gomaa A, Salama M, Hassan M, Eid A, Seif A. Sustainable criteria Assessment for traditional and green building materials. InProceedings of the International Conference on Smart Cities 2023 (pp. 161-186).

[22] Balansa DN. Assessing passive refurbishment measures: energy efficiency, economic impact, and embodied energy in typology D-9, La Pau, Barcelona (Master's thesis, Universitat Politècnica de Catalunya).

[23] Shukla BK, Bharti G, Sharma PK, Sharma M, Rawat S, Maurya N, Srivastava R, Srivastav Y. Sustainable construction practices with recycled and waste materials for a circular economy. Asian Journal of Civil Engineering. 2024 Jul 6:1-22.

[24] Hao H, Bi K, Chen W, Pham TM, Li J. Towards next generation design of sustainable, durable, multi-hazard resistant, resilient, and smart civil engineering structures. Engineering Structures. 2023 Feb 15;277:115477.

[25] Terán-Cuadrado G, Tahir F, Nurdiawati A, Almarshoud MA, Al-Ghamdi SG. Current and Potential Materials for the Low-Carbon Cement Production: Life Cycle Assessment Perspective. Journal of Building Engineering. 2024 Aug 22:110528.

[26] A. El-Sisi, A. Hassanin, F. Alsharari, N. Galustanian, and H. Salim, "Failure Behavior of Composite Bolted Joints: Review," CivilEng, vol. 3, no. 4, 2022, doi: 10.3390/civileng3040060.

[27] A. El-Sisi, F. Alsharari, H. Salim, A. Elawadi, and A. Hassanin, "Efficient beam element model for analysis of composite beam with partial shear connectivity," Compos Struct, vol. 303, 2023, doi: 10.1016/j.compstruct.2022.116262.

[28] Ahmed Ibrahim Hassanin, and Hesham Fawzy Shabaan "Effects of Uniform Load on Externally Post-tensioning Composite Beams under Multiple Degrees of Shear Connection," IOP Conf. Series: Earth and Environmental Science, 1026, 2022, doi:10.1088/1755-1315/1026/1/012024.

[29] A. A. El-Sisi, A. I. Hassanin, H. F. Shabaan, and A. I. Elsheikh, "Effect of external post-tensioning on steel–concrete composite beams with partial connection," Eng Struct, vol. 247, p. 113130, Nov. 2021, doi: 10.1016/J.ENGSTRUCT.2021.113130.

[30] A. I. Hassanin, H. F. Shabaan, and A. I. Elsheikh, "Cyclic loading behavior on strengthened composite beams using external post-tensioning tendons (experimental study)," Structures, 2021, doi: 10.1016/j.istruc.2020.12.017.

[31] A. I. Hassanin, H. F. Shabaan, and A. I. Elsheikh, "Fatigue loading characteristic for the composite steel-concrete beams," Frattura ed Integrità Strutturale, vol. 15, no. 55, pp. 110–118, 2021, doi: 10.3221/IGF-ESIS.55.08.

[32] A. I. Hassanin, H. F. Shabaan, and A. I. Elsheikh, "The Effects of Shear Stud Distribution on the Fatigue Behavior of Steel – Concrete Composite Beams," Arab J Sci Eng, 2020, doi: 10.1007/s13369-020-04702-4.

[33] A. I. Hassanin and S. G. Abo Sabaa, "Biophilic Design (Criteria and Procedures) on the Existed Hospitals," Research & Development in Material Science, vol. 4, no. 3, p. 4, 2018, doi: 10.31031/rdms.2018.04.000589.

[34] A. I. Hassanin, "Overview on FRB Pre-Stressed Tendons and its Fatigue Behavior," Modern Concepts in Material Science, 2019, doi: 10.33552/mcms.2019.01.000510.

[35] A. M. EL Shihy, H. F. Shabaan, H. M. Al Kader, and Ahmed I.Hassanin, "Effect of Partial Shear Connection on Strengthened Composite Beams with Externally Post-Tension Tendons," Journal of Material Science & Engineering, vol. 06, no. 02, pp. 6–11, 2017, doi: 10.4172/2169-0022.1000318.

[36] A. EL-Shihy, H. Shabaan, H. Abd-Elkader, and A. Hassanin, "Effect of Using Partial Continuounity by External Post-Tension on The Simple Composite Beams as a Strengthening Technique," Egyptian Journal for Engineering Sciences and Technology, 2016, doi: 10.21608/eijest.2016.97133.

[37] Ahmad Z, Ahmed HA, Shahzada K, Li Y. Vulnerability of Non-Structural Elements (NSEs) in Buildings and Their Life Cycle Assessment: A Review. Buildings. 2024 Jan 10;14(1):170.

[38] Martínez B, Mendizabal V, Roncero MB, Bernat-Maso E, Gil L. Towards sustainable building solutions: Development of hemp shiv-based green insulation material. Construction and Building Materials. 2024 Feb 2;414:134987.

[39] Basyouni YA, Mahmoud H. Affordable green materials for developed cool roof applications: A review. Renewable and Sustainable Energy Reviews. 2024 Sep 1;202:114722.

[40] Mohamed EF, Awad G. Advanced Nano-biotechnology for Chlorinated Volatile Compound Pollutants Control. Environmental Management and Sustainable Development. 2023 May 1;12(1):34-66.

[41] Hassanin A, El-Nemr A, Shaaban HF, Saidani M, Shaaban IG. Coupling behavior of autogenous and autonomous self-healing techniques for durable concrete. International Journal of Civil Engineering. 2024 Feb 1:1-24.

[42] Helal Z, Salim H, Ahmad SS, Elemam H, Mohamed AI, Elmahdy MA. Sustainable bacteria-based self-healing steel fiber reinforced concrete. Case Studies in Construction Materials. 2024 Jul 1;20:e03389.

[43] Devgon I, Sachan RS, Kumar A, Kumar D, Sharma A, Karnwal A. Investigating the potential of delignified rice husk as a carbon-rich resource for extracting glucose and its utilization in biocement production through fungal isolates. Environmental Science and Pollution Research. 2024 Mar 18:1-4.

[44] Ibrahim, O., Abbas, A., Hassanin, A., Ibrahim, W., Abd-Elnaby, S. A Literature Review of Bio-cement: Microorganisms, Production, Properties, and Potential Applications.. *ERU Research Journal*, 2023; 2(4): 554-574. doi: 10.21608/erurj.2023.321807

[45] Chen L, Huang L, Hua J, Chen Z, Wei L, Osman AI, Fawzy S, Rooney DW, Dong L, Yap PS. Green construction for low-carbon cities: a review. Environmental chemistry letters. 2023 Jun;21(3):1627-57.

[46] Bošković I, Radivojević A. Life cycle greenhouse gas emissions of hemp-lime concrete wall constructions in Serbia: The impact of carbon sequestration, transport, waste production and end of life biogenic carbon emission. Journal of Building Engineering. 2023 May 1;66:105908.

[47] Aydin M, Degirmenci T. The impact of clean energy consumption, green innovation, and technological diffusion on environmental sustainability: new evidence from load capacity curve hypothesis for 10 European Union countries. Sustainable Development. 2024 Jun;32(3):2358-70.

[48] Debnath A, Jeengar R, Maity D, Sen R. Bio-inspired synthesis of nanocrystalline calcite demonstrating significant improvement in mechanical properties of concrete: a construction-nanobiotechnology approach. Environmental Science and Pollution Research. 2024 Sep 17:1-9.

[49] Humbert MS, Brooks GA, Duffy AR, Hargrave C, Rhamdhani MA. Economics of Electrowinning Iron from Ore for Green Steel Production. Journal of Sustainable Metallurgy. 2024 Aug 5:1-23.

[50] Raza M, Farhan A, Abu-Jdayil B. Lignocellulose− Based Insulation Materials: A Review of Sustainable and Biodegradable Solutions for Energy Efficiency. International Journal of Thermofluids. 2024 Sep 1:100844.

[51] Terán-Cuadrado G, Tahir F, Nurdiawati A, Almarshoud MA, Al-Ghamdi SG. Current and potential materials for the low-carbon cement production: Life cycle assessment perspective. Journal of Building Engineering. 2024 Nov 1;96:110528.

[52] Cheng D, Reiner DM, Yang F, Cui C, Meng J, Shan Y, Liu Y, Tao S, Guan D. Projecting future carbon emissions from cement production in developing countries. Nature Communications. 2023 Dec 11;14(1):8213.

[53] Tripathi A, Yadav S, Nishtha, Nkengnamai M, Thakur A. Bamboo: A Fast-Growing Species to Mitigate Carbon Footprint. InForests and Climate Change: Biological Perspectives on Impact, Adaptation, and Mitigation Strategies 2024 Sep 19 (pp. 469-487). Singapore: Springer Nature Singapore.

[54] Zhang Y, Sattar S, Cook D, Johnson K, Fung J. Systematic Review of Embodied Carbon Assessment and Reduction in Building Life Cycles. NIST Special Publication. 2024 Sep 18.

[55] Ullah H, Zhang H, Huang B, Gong Y. BIM-Based Digital Construction Strategies to Evaluate Carbon Emissions in Green Prefabricated Buildings. Buildings. 2024;14(6):1689.

[56] Ismaeel WS, Kassim N. An environmental management plan for construction waste management. Ain Shams Engineering Journal. 2023 Dec 1;14(12):102244.

[57] Zeyad AM. Sustainable concrete Production: Incorporating recycled wastewater as a green building material. Construction and Building Materials. 2023 Dec 1;407:133522.

[58] Ma W, Hao JL, Zhang C, Di Sarno L, Mannis A. Evaluating carbon emissions of China's waste management strategies for building refurbishment projects: contributing to a circular economy. Environmental Science and Pollution Research. 2023 Jan;30(4):8657-71.

[59] Santos G, Esmizadeh E, Riahinezhad M. Recycling construction, renovation, and demolition plastic waste: review of the status quo, challenges and opportunities. Journal of Polymers and the Environment. 2024 Feb;32(2):479-509.

[60] Bello AO, Khan AA, Idris A, Awwal HM. Barriers to modular construction systems implementation in developing countries' architecture, engineering and construction industry. Engineering, Construction and Architectural Management. 2024 Jul 25;31(8):3148-64.

[61] Oyejobi DO, Firoozi AA, Fernandez DB, Avudaiappan S. Integrating Circular Economy Principles into Concrete Technology: Enhancing Sustainability Through Industrial Waste Utilization. Results in Engineering. 2024 Sep 5:102846.

[62] Jonnala SN, Gogoi D, Devi S, Kumar M, Kumar C. A comprehensive study of building materials and bricks for residential construction. Construction and Building Materials. 2024 Apr 26;425:135931.

[63] Hailemariam EK, Hailemariam LM, Amede EA, Nuramo DA. Identification of barriers, benefits and opportunities of using bamboo materials for structural purposes. Engineering, Construction and Architectural Management. 2023 Aug 15;30(7):2716-38.

[64] Dsilva J, Zarmukhambetova S, Locke J. Assessment of building materials in the construction sector: A case study using life cycle assessment approach to achieve the circular economy. Heliyon. 2023 Oct 1;9(10).

[65] Hasheminezhad A, King D, Ceylan H, Kim S. Comparative life cycle assessment of natural and recycled aggregate concrete: A review. Science of The Total Environment. 2024 Aug 8:175310.

[66] Mouton L, Allacker K, Röck M. Bio-based building material solutions for environmental benefits over conventional construction products–Life cycle assessment of regenerative design strategies (1/2). Energy and Buildings. 2023 Mar 1;282:112767.

[67] Saeed F, Mostafa K, Rausch C, Hegazy T. Environmental Impact and Cost Assessment for Reusing Waste during End-of-Life Activities on Building Projects. Journal of Construction Engineering and Management. 2023 Oct 1;149(10):04023099.

[68] Sadar JS, Bohnenberger-Fehr S, Chen C, Rusenova G. Unearthing sustainable material futures. InSustainability and Toxicity of Building Materials 2024 Jan 1 (pp. 517-544). Woodhead Publishing.

[69] Tiwari A. Advancement of materials to sustainable & green world. Advanced Materials Letters. 2023 Jul 1;14(3):2303-1724.

[70] Umoh AA, Adefemi A, Ibewe KI, Etukudoh EA, Ilojianya VI, Nwokediegwu ZQ. Green architecture and energy efficiency: a review of innovative design and construction techniques. Engineering Science & Technology Journal. 2024;5(1):185-200.

[71] Amran M, Murali G, Makul N, Tang WC, Alluqmani AE. Sustainable development of eco-friendly ultra-high performance concrete (UHPC): Cost, carbon emission, and structural ductility. Construction and Building Materials. 2023 Sep 22;398:132477.

[72] Malik S, Muhammad K, Waheed Y. Nanotechnology: A revolution in modern industry. Molecules. 2023 Jan 9;28(2):661.

[73] AlTawaiha H, Alhomaidat F, Eljufout T. A Review of the Effect of Nano-Silica on the Mechanical and Durability Properties of Cementitious Composites. Infrastructures. 2023 Sep 4;8(9):132.

[74] Ahmed Ibrahim Ali, O., Ibrahim Hassanin Mohamed, A., Ibrahim, W., Osama Abd-Al Ftah, R., R. hamed, S., Fakhry M. Abd-Elnaby, S. Enhancing Concrete Performance through Microbial Intervention: A Comprehensive Experimental Study. *Engineering Research Journal*, 2024; (): -. doi: 10.21608/erj.2024.311680.1087

[75] Ibrahim, O.A., Mohamed, A.I.H., Ibrahim, W. *et al.* The influence of adding *B. subtilis* bacteria on the mechanical and chemical properties of cement mortar. *Beni-Suef Univ J Basic Appl Sci* **14**, 3 (2025). https://doi.org/10.1186/s43088-024-00591-w

[76] Al-Qahtani S, Koç M, Isaifan RJ. Mycelium-based thermal insulation for domestic cooling footprint reduction: A review. Sustainability. 2023 Sep 3;15(17):13217.

[77] Khan M, McNally C. Recent developments on low carbon 3D printing concrete: Revolutionizing construction through innovative technology. Cleaner Materials. 2024 May 16:100251.

[78] Ahmed GH. A review of "3D concrete printing": Materials and process characterization, economic considerations and environmental sustainability. Journal of Building Engineering. 2023 May 1;66:105863.

[79] Jayawardana J, Kulatunga AK, Jayasinghe JA, Sandanayake M, Zhang G. Environmental sustainability of off-site construction in developed and developing regions: a systematic review. Journal of Architectural Engineering. 2023 Jun 1;29(2):04023008.
[80] Apanavičienė R, Shahrabani MM. Key factors affecting smart building integration into smart city: technological aspects. Smart Cities. 2023 Jul 31;6(4):1832-57.
[81] Abobakirov A. Energy Efficient Building Materials in the Design of Buildings and Structures. HOLDERS OF REASON. 2023 Dec 30;1(3):406-12.
[82] Marei YA, Emam M, Ahmed ME, Attia AA, Abdelrahman MA. Thermal and optical investigations of various transparent wall configurations and building integrated photovoltaic for energy savings in buildings. Energy Conversion and Management. 2024 Jan 1;299:117817.
[83] Raju SK, Kannan S. Enhanced building energy harvesting through integrated piezoelectric materials and smart road traffic routing. Letters in Spatial and Resource Sciences. 2024 Dec;17(1):25.
[84] Salama R, Al-Turjman F. Sustainable energy production in smart cities. Sustainability. 2023 Nov 17;15(22):16052.
[85] Junaid MF, ur Rehman Z, Ijaz N, Farooq R, Khalid U, Ijaz Z. Performance evaluation of cement-based composites containing phase change materials from energy management and construction standpoints. Construction and Building Materials. 2024 Feb 16;416:135108.
[86] Zhu L, Tian L, Jiang S, Han L, Liang Y, Li Q, Chen S. Advances in photothermal regulation strategies: from efficient solar heating to daytime passive cooling. Chemical Society Reviews. 2023.
[87] Tripathi BM, Shukla SK. A comprehensive review of the thermal performance in energy efficient building envelope incorporated with phase change materials. Journal of Energy Storage. 2024 Feb 15;79:110128.
[88] Tamer T, Dino IG, Baker DK, Akgül CM. Coupling PCM wallboard utilization with night Ventilation: Energy efficiency and overheating risk in office buildings under climate change impact. Energy and Buildings. 2023 Nov 1;298:113482.
[89] Chen L, Hu Y, Wang R, Li X, Chen Z, Hua J, Osman AI, Farghali M, Huang L, Li J, Dong L. Green building practices to integrate renewable energy in the construction sector: a review. Environmental Chemistry Letters. 2024 Apr;22(2):751-84.
[90] Soroos MS. Global institutions and the environment: an evolutionary perspective. The Global Environment. 2023 Apr 14:27-51.
[91] Arafat MY, Faggal AA, Khodeir L, Refaat T. Customizing the green pyramid rating system for assessing university buildings' sustainability: A stakeholder-involved weighting approach. Alexandria Engineering Journal. 2023 Nov 1;82:446-58.
[92] Darko A, Debrah C, Chan AP. Introduction to Green Construction Projects. In Developing a Body of Knowledge for Green Construction Project Management 2025 (pp. 77-105).
[93] Aly H. Improving the Energy Efficiency of Residential Buildings in Egypt through Whole Building Simulations.

[94] Yuan S, Li C, Wang M, Wu H, Chang L. A way toward green economic growth: Role of energy efficiency and fiscal incentive in China. Economic Analysis and Policy. 2023 Sep 1;79:599-609.
[95] Reddy VJ, Hariram NP, Ghazali MF, Kumarasamy S. Pathway to sustainability: An overview of renewable energy integration in building systems. Sustainability. 2024 Jan 11;16(2):638.
[96] Shao J, Huang P. The policy mix of green finance in China: an evolutionary and multilevel perspective. Climate Policy. 2023 Jul 3;23(6):689-703.
[97] Goh CS, Ting JN, Bajracharya A. Exploring social sustainability in the built environment. Advances in Environmental and Engineering Research. 2023 Jan 18;4(1):010.
[98] Adhi AB, Muslim F. Development of stakeholder engagement strategies to improve sustainable construction implementation based on lean construction principles in Indonesia. Sustainability. 2023 Mar 31;15(7):6053.
[99] Lucchi E. Regenerative design of archaeological sites: a pedagogical approach to boost environmental sustainability and social engagement. Sustainability. 2023 Feb 18;15(4):3783.
[100] Nguyen MV. Assessing the readiness for sustainable building material adoption: a study from construction organizations of different sizes. Engineering, Construction and Architectural Management. 2024 Aug 16.
[101] Poorisat T, Aigwi IE, Doan DT, GhaffarianHoseini A. Unlocking the potentials of sustainable building designs and practices: A Systematic Review. Building and Environment. 2024 Sep 16:112069.
[102] Simpeh EK, Adade NA, Pim-Wusu M, Mensah H, Asante-Antwi AS, Aazore FK. Assessing homeowners' awareness of green technologies in residential housing development: evidence from Ghana. Technological Sustainability. 2024 Jul 17.