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EVALUATING THE ENGINEERING AND ESG PERFORMANCE OF SUSTAINABLE CONSTRUCTION MATERIALS: A SYSTEMATIC REVIEW

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ABSTRACT

The construction industry is a major consumer of natural resources and contributor to global carbon emissions. Sustainable Construction Materials (SCMs) offer promising alternatives to traditional building components by emphasizing environmental friendliness, economic viability, and social acceptability. This paper presents a systematic review of 15 mainstream SCMs, evaluating them across engineering performance and Environmental, Social, and Governance (ESG) indicators. Through an integrative methodology combining data from peer-reviewed literature and institutional guidelines, this study examines the technical, environmental, and economic attributes of materials such as bamboo, precast concrete, recycled plastics, and hempcrete. Findings suggest that while many SCMs exhibit commendable strength and energy efficiency, key challenges remain in economic analysis, lifecycle cost data, and social adaptability. The review also highlights critical research gaps, especially regarding human toxicity, housing affordability, and compliance with policy frameworks. This work provides guidance for researchers, engineers, and policymakers aiming to embed sustainability into construction practices.

Keywords: Sustainable construction materials, ESG performance, green building, engineering analysis, lifecycle cost, human toxicity, carbon footprint

1. INTRODUCTION

The construction industry is a critical sector that significantly impacts global environmental, social, and economic systems. Currently, buildings account for approximately 40% of global energy-related carbon dioxide (CO_2) emissions and are among the highest consumers of raw natural resources and energy. As the world confronts the challenges of climate change, urbanization, and resource scarcity, the role of the built environment in promoting sustainable development has never been more vital. This situation has led to an increased demand for alternative materials and construction strategies that reduce environmental harm while meeting functional, economic, and social performance criteria. In this context, Sustainable Construction Materials (SCMs) have emerged as a viable solution to enhance resource efficiency, reduce emissions, and support healthier and more resilient communities. SCMs broadly encompass a wide array of materials—ranging from rapidly renewable natural resources like bamboo and cork to industrial by-products such as recycled plastic, precast concrete, and ferrock. These materials are designed not only to lower environmental impact but also to offer potential improvements in thermal insulation, durability, indoor air quality, and even socioeconomic outcomes, such as job creation in local industries.

Despite their potential, many SCMs remain confined to experimental or pilot phases, lacking robust real-world performance data and comprehensive sustainability assessments. Existing studies often focus heavily on isolated technical or environmental properties, leaving economic and social implications underexplored. Moreover, inconsistencies in definitions, performance benchmarks, and regulatory acceptance contribute to a fragmented understanding of their applicability and scalability. To address this gap, this study presents a comprehensive review of 15 SCMs, categorized by their origin—natural, recycled, or hybrid. It evaluates each material through two critical lenses: (1) engineering performance and (2) sustainability, based on the ESG (Environmental, Social, and Governance) framework. This dual approach not only captures the functional performance of SCMs in real construction scenarios but also provides an in-depth look at their lifecycle impacts, cost implications, and societal benefits.

From an environmental perspective, this paper examines factors such as embodied carbon, energy usage, biodegradability, and pollution reduction. Materials that sequester carbon, minimize waste, and use less energy in production are highlighted as key contributors to achieving climate goals and reducing ecological footprints. From a social standpoint, the review focuses on attributes like housing affordability, thermal comfort, indoor air quality, and employment generation. SCMs that use local resources and labor, or those that contribute to better living standards through improved housing design, are considered socially beneficial.

In terms of governance, this paper explores how regulatory frameworks such as LEED (Leadership in Energy and Environmental Design), ACI (American Concrete Institute) standards, and national building codes influence the implementation and monitoring of SCMs. The governance dimension also assesses the transparency, scalability, and institutional support available for the adoption of SCMs at various scales. By synthesizing research across disciplines and geographies, this review provides a clear understanding of the current performance, research gaps, and future potential of SCMs. It also identifies materials that exhibit balanced performance across the ESG spectrum, as well as those requiring further exploration—particularly in areas like human toxicity, lifecycle economics, and community adaptability.

The broader objective of this study is not just to showcase the technical benefits of SCMs, but to advocate for their integration into mainstream construction through policy innovation, stakeholder collaboration, and multidisciplinary research. This holistic understanding is essential for aligning construction practices with the United Nations Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

In conclusion, SCMs have the potential to redefine how we design and build in a resource-constrained and climate-conscious world. However, realizing this potential demands a shift from siloed, laboratory-based studies to comprehensive, real-world evaluations that consider the engineering robustness, environmental impacts, economic feasibility, and social implications of sustainable materials. This paper aims to contribute to this transition by offering a structured, comparative analysis of 15 promising SCMs, thereby laying a foundation for future innovation and implementation in sustainable construction.

2. METHODOLOGY

This study employs a structured and systematic methodology to assess and synthesize current research on Sustainable Construction Materials (SCMs) with respect to their engineering, environmental, economic, and social dimensions. The aim is to present an integrated overview that can guide future academic inquiry, policymaking, and practical implementation in the construction industry. The research design combines a qualitative systematic literature review, comparative analysis, and integrated evaluation using ESG (Environmental, Social, and Governance) criteria. The methodology is structured into four stages: (i) literature identification and selection, (ii) data extraction and classification, (iii) performance evaluation of SCMs, and (iv) gap analysis and synthesis.

2.1 Literature Identification and Selection

The initial step involved a comprehensive literature search to identify relevant peer-reviewed publications, conference proceedings, and academic reports. Databases such as Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar were used. The keywords applied included combinations of: "Sustainable Construction Materials," "Green Building Materials," "Low-carbon materials," "Recycled Construction Materials," "Eco-friendly Building Materials," and "ESG in Construction."

The search was restricted to English-language articles published between 2010 and 2024 to ensure recency and relevance. Only studies that addressed at least one of the following dimensions were considered: (a) engineering performance, (b) environmental impact, (c) economic analysis, or (d) social sustainability. After removing duplicates and non-relevant records through title and abstract screening, a total of 176 papers were shortlisted. After full-text screening, 92 high-quality studies were selected for final review and analysis.

2.2 Data Extraction and Classification

For each of the selected studies, relevant data were extracted using a standardized form to ensure consistency. The information extracted included:

- Type and classification of SCM (natural or industrial/waste-based)
- Application in construction (e.g., structural, insulation, flooring)
- Engineering properties (e.g., compressive strength, durability, thermal resistance)
- Environmental indicators (carbon footprint, human toxicity, waste reduction)
- Economic indicators (initial cost, maintenance, lifecycle cost, ROI)
- Social aspects (job creation, adaptability, housing affordability)

The extracted materials were then classified into two broad categories: (1) Natural materials (e.g., bamboo, cork, straw bale, sheep's wool, rammed earth) (2) Industrial and waste-derived materials (e.g., recycled steel, precast concrete, hempcrete, ferrock, timber Crete, terrazzo)

Table 1 in the paper presents the classification of SCMs reviewed in this study.

2.3 Evaluation Criteria and Comparative Framework

To evaluate the sustainability performance of each SCM, this study adopted a multi-criteria assessment framework based on ESG principles. Each material was examined against three sets of criteria:

- Environmental indicators: Climate change mitigation (carbon footprint), human toxicity, and waste management.
- Economic indicators: Initial cost, maintenance cost, long-term savings, and cost-effectiveness.
- Social indicators: Thermal comfort, local resource availability, adaptability in diverse socio-economic settings, and contribution to housing affordability.

These criteria were selected based on their recurring use in high-impact studies and were cross-referenced with standards such as LEED, BREEAM, and UN SDGs.

Tables 2 to 5 summarize the engineering, environmental, economic, and ESG-based performance of the reviewed SCMs. Each indicator was scored qualitatively using a binary mark (✓ = present, × = absent) to map research density and data availability. This approach helped identify not just the strengths of each material but also the current research gaps.

2.4 Gap Analysis and Validation

The final step was a gap analysis to identify under-researched areas within the scope of SCMs. This involved a cross-tabulation of the selected materials against the four dimensions—engineering, environmental, economic, and social—to reveal which materials were fully studied and which were not. For instance, it was observed that while materials like bamboo and hempcrete were well-documented in terms of engineering and environmental benefits, their economic and social analyses were limited.

A percentage breakdown was also conducted to show the relative strength of research focus across the 15 key SCMs. Only 5 out of 15 materials had comprehensive studies covering all dimensions. This highlighted the urgent need for holistic, multidisciplinary investigations in future SCM studies.

The data collection, classification, and evaluation processes were independently verified by two researchers to minimize bias and ensure methodological reliability. Discrepancies were resolved through consensus and expert consultation.

3. CLASSIFICATIONS OF SUSTAINABLE CONSTRUCTION MATERIALS

SCMs can be broadly classified into:

- Natural materials: bamboo, straw bales, rammed earth
- Recycled materials: recycled plastic, wood, steel
- Bio-based composites: mycelium, sheep's wool, plant-based polyurethane foam
- Innovative engineered products: precast concrete, ferrock, terrazzo

Table No:1

Types of SCMs Categorized by Origin and Application

S.No.	Material	Origin	Primary Application in Construction
1	Bamboo	Natural	Structural elements, flooring, wall panels
2	Cork	Natural	Insulation, flooring, acoustic panels
3	Straw Bales	Natural	Wall insulation, building envelopes
4	Sheep’s Wool	Natural	Thermal and acoustic insulation

5	Rammed Earth	Natural	Walls, foundations, load-bearing structures
6	Mycelium	Natural	Insulation panels, lightweight partitioning
7	Precast Concrete	Industrial	Load-bearing structural components, wall panels
8	Recycled Plastic	Industrial/Waste-based	Composite panels, pavers, insulation boards
9	Recycled Steel	Industrial/Waste-based	Structural framework, reinforcements
10	Recycled Wood	Industrial/Waste-based	Flooring, cladding, furniture
11	Plant-Based Rigid Polyurethane Foam	Industrial/Natural Hybrid	Thermal insulation, lightweight construction
12	Hempcrete	Industrial/Natural Hybrid	Wall infill, insulation, non-load-bearing walls
13	Ferrock	Industrial/Waste-based	Concrete alternative for pavements, masonry units
14	Timbercrete	Industrial/Waste-based	Blocks, bricks, wall systems
15	Terrazzo	Industrial/Waste-based	Flooring, decorative finishes

4. CHARACTERISTICS OF SUSTAINABLE CONSTRUCTION MATERIALS (SCMS)

Sustainable construction materials (SCMs) are gaining prominence in the built environment due to their distinctive characteristics that align with environmental, economic, and social sustainability goals. These materials are specifically selected or engineered to reduce negative environmental impacts throughout their lifecycle—from extraction and production to use and eventual disposal. One of the key attributes of SCMs is low embodied carbon. This means that the energy consumed and emissions generated during the production of these materials are significantly lower than those of conventional materials. For example, materials like bamboo or rammed earth require less energy to process and contribute less to greenhouse gas emissions.

Another important characteristic is high recyclability and renewability. Many SCMs originate from rapidly renewable resources, such as straw, cork, or mycelium, or are derived from industrial by-products like fly ash or recycled plastics. Their ability to be reused or reprocessed at the end of their useful life helps in creating a circular economy in construction.

Biodegradability further enhances their appeal, particularly for natural materials. This property ensures that the material can break down naturally without releasing toxins into the environment, thus reducing long-term waste and pollution.

SCMs like hempcrete and bamboo also offer carbon sequestration potential, actively absorbing and storing carbon dioxide during their growth or service life, contributing positively to climate mitigation.

Lastly, minimal environmental toxicity is critical. Many sustainable materials are free from volatile organic compounds (VOCs) and other harmful chemicals, leading to healthier indoor environments and improving occupant well-being.

Together, these characteristics contribute not only to environmental protection but also to enhanced energy efficiency, reduced resource consumption, and improved building performance.

5. Engineering Performances of Sustainable Construction Materials

Engineering performance metrics are crucial for adoption in structural design. Key parameters include:

- Compressive and tensile strength
- Workability and setting time
- Thermal insulation
- Acoustic performance

Table No:2

Engineering performances of selected SCMs

Material	Compressive Strength	Tensile Strength	Thermal Insulation	Durability	Workability	Remarks
Bamboo	Moderate to High	**Excellent**	Moderate	High	Good	High tensile strength; suitable for structural framing and reinforcement.
Hempcrete	Low to Moderate	Low	**Excellent**	Moderate	Easy to work with	Superior insulation and breathability; not suitable for load-bearing.
Recycled Plastic	Moderate	Moderate	Good	High (Non-biodegradable)	Moldable, but varies by type	Limited structural use; best for non-load applications like panels or tiles.
Timbercrete	Moderate	Low to Moderate	Good	Moderate	Moderate	Lightweight and insulating; ideal for blocks and wall construction.
Rammed Earth	Moderate to High	Low	Moderate	High (with treatment)	Labor-intensive	Strong compression; low tension resistance; eco-

						friendly alternative.
Recycled Steel	Very High	High	Poor	**Excellent**	Fabrication required	Best for structural frameworks; energy-intensive production offset by reuse.

Results show that bamboo and hempcrete exhibit excellent tensile and insulation properties, respectively, while recycled plastic has limitations in structural load-bearing capacity.

6. SUSTAINABILITY PERFORMANCE OF SUSTAINABLE CONSTRUCTION MATERIALS

The sustainability of Sustainable Construction Materials (SCMs) can be effectively evaluated using the ESG (Environmental, Social, and Governance) framework. This holistic approach enables researchers and decision-makers to assess the multi-dimensional impacts of these materials in real-world construction. The evaluation consists of three key dimensions:

- **Environmental**: Focused on reducing carbon emissions, lowering energy consumption, and minimizing solid waste generation throughout the life cycle of materials.
- **Economic**: Concerned with affordability, including initial installation costs, long-term maintenance, and potential savings across the material's life cycle.
- **Social**: Assesses how materials improve human well-being, such as enhancing indoor air quality, thermal comfort, and contributing to affordable housing.

The following tables summarize the environmental and economic performances of selected SCMs based on current research trends.

Table No: 3

Environmental Performance of Selected SCMs

Material	CO_2 Emission Reduction	Energy Efficiency	Waste Minimization	Environmental Toxicity	Remarks
Bamboo	High	High	Moderate	Low	Carbon-sequestering and fast-growing; minimal environmental impact.
Hempcrete	High	Very High	High	Very Low	Excellent insulation; absorbs CO_2 during curing.
Recycled Plastic	Moderate	Moderate	High	Variable (depends on type)	Reduces landfill plastic; some

					forms may leach toxins.
Cork	High	High	High	Very Low	Renewable; supports carbon sequestration and low impact.
Recycled Steel	Very High	Low	Very High	Low	Energy-intensive to recycle, but prevents ore extraction.
Timbercrete	Moderate	High	High	Low	Combines waste with cement; better than traditional bricks.

Table No: 4
Economic Performance of Selected SCMs

Material	Initial Cost	Maintenance Cost	Lifecycle Savings	Affordability Index	Remarks
Bamboo	Low	Low	High	High	Cost-effective and locally available in many regions.
Hempcrete	Moderate	Low	High	Moderate	Higher upfront cost, but savings in insulation.
Recycled Plastic	Moderate	Low	Moderate	High	Affordable in mass production; some types costly to process.
Cork	High	Low	High	Low	Durable and low maintenance but expensive raw material.
Recycled Steel	High	Moderate	High	Moderate	High cost, but valuable in structural use and reuse potential.

Timbercrete	Moderate	Low	Moderate	Moderate	Good for affordable housing; lighter than concrete.

7. ENVIRONMENTAL, SOCIAL, AND GOVERNANCE (ESG) EVALUATION

The growing emphasis on sustainability in the construction industry necessitates a multidimensional approach to evaluating materials. The ESG framework—comprising Environmental, Social, and Governance dimensions—provides a holistic lens to assess the performance of Sustainable Construction Materials (SCMs). While prior research has often emphasized environmental and technical aspects, this section expands the scope by integrating governance and social sustainability to identify SCMs that are not only eco-efficient but also ethically managed and socially responsible.

7.1 Environmental Impact

The environmental dimension evaluates SCMs based on their life-cycle carbon footprint, potential for waste minimization, and environmental toxicity. Materials like hempcrete, cork, and recycled wood demonstrate excellent environmental performance due to their biodegradability, carbon sequestration capabilities, and minimal pollution footprint. Hempcrete, in particular, actively absorbs CO_2 during the curing process, contributing positively to net-zero goals. Conversely, materials like precast concrete, although beneficial in reducing site waste, still demand significant energy during production and often lack clear data on human toxicity.

7.2 Social Impact

Social sustainability considers how materials affect human well-being and contribute to local economies. Key indicators include thermal comfort, adaptability, employment generation, and housing affordability. Straw bales, sheep's wool, and bamboo score well due to their local availability, ease of handling, and positive impact on indoor air quality. These materials also support rural employment, thereby fostering inclusive development. However, several industrial by-product-based materials—such as ferrock and recycled steel—require additional research into their effects on indoor health and occupant safety.

7.3 Governance and Compliance

Governance refers to the existence of robust institutional frameworks and compliance with international standards such as LEED (Leadership in Energy and Environmental Design), ACI (American Concrete Institute), and ISO 14001. Materials with established standardization protocols, such as precast concrete, recycled steel, and plant-based polyurethane foams, benefit from widespread regulatory adoption. In contrast, mycelium and timbercrete remain under-regulated, hindering their scalability despite promising environmental and economic characteristics.

The following table presents a comprehensive ESG mapping of 15 commonly studied SCMs. A ✓ indicates substantial evidence of performance under the specified category, while an × signifies limited or insufficient data.

Table No: 5

ESG Mapping for 15 Sustainable Construction Materials (SCMs)

SCM	Environmental	Social	Governance	Remarks

Bamboo	✓✓	✓✓✓	✓	High renewability and local job creation; limited global standardization.
Straw Bales	✓✓	✓✓✓	×	Excellent thermal comfort; lacking formal compliance codes.
Sheep's Wool	✓✓✓	✓✓✓	✓	Great insulation; governed under green building standards in EU.
Cork	✓✓✓	✓✓	✓✓	Carbon sequestration and LEED-compliant.
Recycled Plastic	✓✓	✓	✓✓	Good for landfill reduction; toxicity concerns.
Recycled Wood	✓✓✓	✓✓	✓	Low-impact; widespread availability.
Recycled Steel	✓✓✓	✓	✓✓✓	Highly governed; reduces mining footprint.
Precast Concrete	✓✓	×	✓✓✓	Efficient for site work; needs health impact studies.
Hempcrete	✓✓✓	✓✓	×	Strong environmental potential; lacks standard code compliance.
Timbercrete	✓✓	✓✓	×	Innovative composite; not yet standardized.
Mycelium	✓✓	✓	×	Biodegradable but lacks structural certification.
Ferrock	✓✓✓	✓	×	Industrial waste reuse; more governance protocols needed.
Plant-Based Polyurethane	✓✓	✓	✓	Renewable alternative to plastic foams.
Rammed Earth	✓✓	✓✓	×	Strong thermal mass; governance weak in modern building codes.
Cork-Concrete Composite	✓✓	✓	×	Hybrid material; promising, but limited standardization exists.

✓ = Present; ✓✓ = Strong performance; ✓✓✓ = Very strong; × = Absent/limited data

7.4 Summary and Implications

This ESG evaluation underscores the critical need for integrated, multi-criteria research on SCMs. While many materials display strengths in individual categories, only a few—such as cork, sheep's wool, and straw bales—achieve balanced performance across all ESG dimensions. On the other hand, widely adopted materials like precast concrete and recycled plastic require deeper investigation into health and social dimensions.

To accelerate the mainstream adoption of SCMs, future research should focus on:

- Establishing standard regulatory benchmarks for emerging materials.
- Quantifying health and well-being metrics in real-life construction.
- Bridging knowledge gaps in lifecycle governance and public policy integration.

Such a direction ensures SCMs evolve beyond environmentally friendly labels to become robust, socially just, and institutionally grounded choices in the construction industry.

8. Challenges and Future Outlook

Despite the promising potential of Sustainable Construction Materials (SCMs) to reduce environmental burden and promote socio-economic development, several challenges continue to hinder their mainstream adoption. As sustainability frameworks evolve, it is essential for researchers, industry stakeholders, and policymakers to address the systemic gaps that exist in the current body of knowledge and implementation practices.

8.1 Current Challenges

Limited Real-World Performance Data

A significant number of SCMs remain confined to laboratory settings or pilot-scale experiments. As a result, real-world performance data—particularly under diverse climatic, structural, and usage conditions—are scarce. This lack of field validation restricts industry confidence in adopting SCMs at scale and creates uncertainty in structural reliability, thermal performance, and long-term durability.

High Initial Costs

Although many SCMs exhibit long-term economic and environmental benefits, their upfront costs are often higher compared to conventional materials. The lack of large-scale production, supply chain limitations, and absence of economies of scale drive up material prices. This presents a financial barrier, especially in developing countries where cost-sensitive construction dominates.

Absence of Robust Policy and Incentive Mechanisms

The absence of strong policy frameworks and governmental incentives for SCM integration hampers market uptake. While certification systems such as LEED or BREEAM exist, most countries lack mandatory regulations or financial support mechanisms (like subsidies or tax rebates) to promote the use of SCMs. Moreover, regulatory ambiguity for newer materials further delays standardization and certification.

8.2 Future Research Directions

To ensure SCMs contribute effectively to global sustainability goals, future studies must broaden their scope beyond material innovation to address multi-dimensional performance issues:

1. **Human Toxicity Metrics**
   There is a critical need to assess how construction materials affect human health, particularly regarding off-gassing, indoor air pollutants, and chemical leachates. Materials like recycled plastics and plant-based foams should undergo comprehensive toxicity profiling, including long-term exposure studies.
2. **Lifecycle Economic Analysis**
   Current economic evaluations of SCMs mostly focus on initial costs, overlooking maintenance, operation, and disposal phases. A full lifecycle cost-benefit analysis, including considerations of maintenance savings, end-of-life recyclability, and operational energy reduction, will provide a clearer understanding of long-term economic viability.
3. **Community-Level Adaptability and Social Value**

SCMs must be evaluated in context-specific settings that factor in cultural, economic, and geographic variables. Understanding how local communities perceive and benefit from SCMs—such as through job creation, housing affordability, and thermal comfort—will allow for more inclusive and socially sustainable construction strategies.

4. **Integration of Adaptive Policy and Market Frameworks**

To scale SCM adoption, governments and institutions must develop adaptive policy mechanisms that evolve with market maturity and scientific advancement. Standardized certification, streamlined regulatory procedures, and investment incentives are crucial for reducing uncertainty and encouraging innovation.

Table No: 6

Comprehensive Performance Matrix of Select SCMs

Material	Engineering	Environmental	Economic	Social	Notes
Bamboo	✓✓✓	✓✓	✓✓	✓✓✓	Strong tensile strength; high local employment potential.
Straw Bales	✓✓	✓✓✓	✓✓✓	✓✓✓	Affordable and low-energy material with excellent thermal comfort.
Sheep's Wool	✓✓	✓✓✓	✓	✓✓✓	Biodegradable and highly effective insulator.
Cork	✓✓	✓✓✓	✓✓	✓✓	Renewable and lightweight; good market availability.
Hempcrete	✓✓✓	✓✓✓	✓	✓✓	High carbon sequestration; limited standardization.
Timbercrete	✓✓	✓✓	✓	✓✓	Environmentally sound; structural data still limited.
Recycled Steel	✓✓✓	✓✓	✓✓✓	✓	High load-bearing capacity; limited social adaptability.
Recycled Plastic	✓	✓✓	✓✓	✓	Reduces landfill use; health impact studies needed.
Precast Concrete	✓✓✓	✓✓	✓✓	×	Strong industrial compliance; lacks human health studies.
Mycelium	✓	✓✓	✓	✓	Innovative; lacks regulatory frameworks and durability data.

✓ = Satisfactory ✓✓ = Strong✓✓✓ = Very Strong × = Weak or lacking data

9. CONCLUSION

Sustainable Construction Materials (SCMs) represent a transformative opportunity to decarbonize the construction industry while fostering long-term ecological, economic, and social resilience. As this review demonstrates, SCMs offer a broad spectrum of engineering capabilities—such as strength, durability, and thermal insulation—alongside significant environmental benefits, including reduced CO_2 emissions, low embodied energy, and biodegradability. However, despite their proven laboratory performance, widespread adoption remains limited due to gaps in field data, standardization, and policy integration.

A notable shortcoming in current research lies in the inadequate exploration of economic and social dimensions. While some materials are cost-effective and leverage local resources, most lack comprehensive lifecycle cost assessments, maintenance evaluations, or indicators of social well-being such as housing affordability and employment generation. This imbalance hinders a full appreciation of SCMs' potential across the triple bottom line: environmental soundness, economic viability, and social equity.

To enable the mainstreaming of SCMs, future research must be both interdisciplinary and application-driven. Emphasis should be placed on real-world pilot projects, adaptive policy frameworks, and stakeholder-inclusive decision-making models. A collaborative approach between academia, industry, and government can facilitate the development of standards, subsidies, and certification systems that encourage innovation while ensuring safety and scalability.

Ultimately, the evolution of SCMs from experimental materials to industry-ready solutions will hinge on our ability to integrate sustainability into every stage of the construction lifecycle. Bridging the divide between innovation and implementation is not only a scientific imperative but a societal necessity. By doing so, SCMs can effectively contribute to climate resilience, resource efficiency, and inclusive urban development in the decades to come.

REFERENCES

1. Maraveas, C. (2020). Production of sustainable construction materials using agro-wastes. Materials, 13(2), 1–15. https://doi.org/10.3390/ma13020403
2. Son, S., Park, K., Fitriani, H., & Kim, S. (2021). Embodied CO_2 reduction effects of composite precast concrete frame for heavily loaded long-span logistics buildings. Sustainability, 13(3), 1074. https://doi.org/10.3390/su13031074
3. Chen, L., Chen, Z., Xie, Z., Wei, L., Hua, J., Huang, L., & Yap, P.-S. (2023). Recent developments on natural fiber concrete: A review of properties, sustainability, applications, barriers, and opportunities. Developments in the Built Environment, 16, 100255. https://doi.org/10.1016/j.dibe.2023.100255
4. Kc, S., & Gautam, D. (2021). Progress in sustainable structural engineering: A review. Innovative Infrastructure Solutions, 6(2), 68. https://doi.org/10.1007/s41062-020-00361-6
5. Liu, T., Chen, L., Yang, M., Sandanayake, M., Miao, P., Shi, Y., & Yap, P.-S. (2022). Sustainability considerations of green buildings: A detailed overview. Sustainability, 14(21), 14393. https://doi.org/10.3390/su142114393
6. Osman, A. I., Chen, L., Yang, M., Msigwa, G., Farghali, M., Fawzy, S., & Yap, P.-S. (2023). Cost, environmental impact, and resilience of renewable energy under a changing climate: A review. Environmental Chemistry Letters, 21(2), 741–764. https://doi.org/10.1007/s10311-022-01413-y

7. Ricciardi, P., Belloni, E., Merli, F., & Buratti, C. (2021). Sustainable panels made with industrial and agricultural waste: Thermal and environmental critical analysis. Applied Sciences, 11(2), 706. https://doi.org/10.3390/app11020706
8. Aneke, F. I., & Shabangu, C. (2021). Green-efficient masonry bricks produced from scrap plastic waste and foundry sand. Case Studies in Construction Materials, 14, e00515. https://doi.org/10.1016/j.cscm.2020.e00515
9. Chen, L., Huang, L., Hua, J., Chen, Z., Wei, L., Osman, A. I., & Yap, P.-S. (2023). Green construction for low-carbon cities: A review. Environmental Chemistry Letters, 21(3), 1627–1657. https://doi.org/10.1007/s10311-023-01541-9
10. Zamora-Castro, S. A., Salgado-Estrada, R., Sandoval-Herazo, L. C., Melendez-Armenta, R. A., Manzano-Huerta, E., Yelmi-Carrillo, E., & Herrera-May, A. L. (2021). Sustainable development of concrete through aggregates and innovative materials: A review. Applied Sciences, 11(2), 499. https://doi.org/10.3390/app11020499
11. Chen, L., Chen, Z., Zhang, Y., Liu, Y., Osman, A. I., Farghali, M., & Yap, P.-S. (2023). Artificial intelligence-based solutions for climate change: A review. Environmental Chemistry Letters, 21(5), 2525–2557.
12. Chen, L., Msigwa, G., Yang, M., Osman, A. I., Fawzy, S., & Yap, P.-S. (2022). Strategies to achieve a carbon neutral society: A review. Environmental Chemistry Letters, 20(4), 2277–2310.
13. Farghali, M., Osman, A. I., Mohamed, I. M. A., Chen, Z., Chen, L., Ihara, I., & Yap, P.-S. (2023). Strategies to save energy in the context of the energy crisis: A review. Environmental Chemistry Letters, 21(4), 2003–2039.
14. Yang, M., Chen, L., Wang, J., Msigwa, G., Osman, A. I., & Yap, P.-S. (2023). Circular economy strategies for combating climate change. Environmental Chemistry Letters, 21(1), 55–80.
15. Hamada, H. M., Thomas, B. S., Yahaya, F. M., Muthusamy, K., Yang, J., Abdalla, J. A., & Hawileh, R. A. (2021). Sustainable use of palm oil fuel ash: A comprehensive review. Journal of Building Engineering, 40, 102286.
16. Tahmasebinia, F., Ma, Y., Joshua, K., Sepasgozar, S. M., Yu, Y., Li, J., & Marroquin, F. A. (2021). Sustainable architecture creating arches using a bamboo grid shell structure. Sustainability, 13(5), 2870.
17. Manjunatha, M., Preethi, S., Malingaraya, H. G., Mounika, H. G., Niveditha, K. N., & Ravi. (2021). Life cycle assessment of concrete prepared with sustainable cement-based materials. Materials Today: Proceedings, 47, 3637–3644.
18. He, Z., Shen, A., Wu, H., Wang, W., Wang, L., Yao, C., & Wu, J. (2021). Recycled clay brick waste as an alternative to cement. Construction and Building Materials, 274, 122113.
19. Borlea, S. I., Tiuc, A.-E., Nemes, O., Vermesan, H., & Vasile, O. (2020). Innovative use of sheep wool for improved sound-absorbing properties. Materials, 13(3), 581.
20. Karrech, A., Strazzeri, V., & Elchalakani, M. (2021). Improved thermal insulance of cement stabilised rammed earth. Construction and Building Materials, 268, 121075.
21. Althoey, F., & Hosen, M. A. (2021). Physical and mechanical characteristics of sustainable concrete. Sustainability, 13(8), 4306.
22. El-Chabib, H. (2020). Properties of SCC with supplementary cementing materials. In R. Siddique (Ed.), Self-Compacting Concrete: Materials, Properties and Applications (pp. 283–308). Woodhead Publishing.
23. Dey, D., Srinivas, D., Panda, B., Suraneni, P., & Sitharam, T. G. (2022). Use of industrial waste materials for 3D printing of sustainable concrete. Journal of Cleaner Production, 340, 130749.

24. Abbasi, S., Jannaty, M. H., Faraj, R. H., Shahbazpanahi, S., & Mosavi, A. (2020). Silica stone waste in sustainable concretes. Sustainability, 13(17), 3832.

25. Alex, J., Dhanalakshmi, J., & Ambedkar, B. (2016). Rice husk ash as cement replacement. Construction and Building Materials, 127, 353–362.

26. Siddika, A., Mamun, M. A. A., & Ali, M. H. (2018). Study on concrete with rice husk ash. Innovative Infrastructure Solutions, 3, 1–9.

27. Noaman, M. A., Islam, M. N., Islam, M. R., & Karim, M. R. (2018). Mechanical properties of brick aggregate concrete containing rice husk ash. Journal of Materials in Civil Engineering, 30(6), 04018086.

28. Zareei, S. A., Ameri, F., Dorostkar, F., & Ahmadi, M. (2017). Rice husk ash as a partial replacement of cement. Case Studies in Construction Materials, 7, 73–81.

29. Bie, R.-S., Song, X.-F., Liu, Q.-Q., Ji, X.-Y., & Chen, P. (2015). Effects of burning conditions and rice husk ash on cement. Cement and Concrete Composites, 55, 162–168.

30. Yang, M., Chen, L., Msigwa, G., Tang, K. H. D., & Yap, P.-S. (2022). Implications of COVID-19 on global environmental pollution. Science of the Total Environment, 809, 151657.