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Smart Sustainability in Construction: An Integrated LCA-MCDM Framework for Climate-Adaptive Material Selection in Educational Buildings

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Abstract

The heavy environmental impact of the construction industry—responsible for 39% of world CO_2 emissions and consuming over 40% of natural resources—supports the need for evidence-based decision-making tools for sustainable material selection balancing environmental, economic, and social considerations. This research develops and evaluates an integrated decision support system that couples cradle-to-grave lifecycle assessment (LCA) with various multi-criteria decision-making (MCDM) methods to optimize climate-resilient material selection for schools. The methodology is an integration of hybrid Analytic Hierarchy Process–Technique for Order of Preference by Similarity to Ideal Solution (AHP-TOPSIS) and VIKOR techniques validated with eight case studies in hot-arid, hot-humid, and temperate climates. Environmental, economic, social, and technical performance indices were evaluated from primary experimental data and with the input from 22 international experts with climate change assessment expertise. Ten material options were examined, from traditional, recycled, and bio-based to advanced composite systems throughout full building lifecycles. The results indicate geopolymer–biofiber composite systems achieve 42% reduced lifecycle carbon emissions, 28% lower cost of ownership, and 35% improved overall sustainability performance compared to traditional equivalents. Three MCDM techniques' cross-validation demonstrated a satisfactory ranking correlation (Kendall's $\tau = 0.87$), while Monte Carlo uncertainty analysis ensured framework stability across 95% confidence ranges. Climate-adaptive weighting detected dramatic regional optimization contrasts: thermal performance maximization in tropical climates and embodied impact emphasis in temperate climates. Three case studies on educational building projects demonstrated 95.8% accuracy in validation of environmental performance and economic payback periods between 4.2 and 6.8 years in real-world practice.

Keywords: sustainable material selection; lifecycle assessment; multi-criteria decision-making; climate-adaptive design; educational buildings; uncertainty analysis; comparative MCDM; cradle-to-grave analysis

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1. Introduction

The construction industry contributes 39% of global CO_2 emissions and utilizes more than 40% of resources, making this a sector that can help achieve targets of climate neutrality. In this sense, making a material selection in the very early phases of design could be considered as a high leverage point, having the potential to reduce impacts by 30–50% overall, in addition to other economic and social factors [1–3]. Nevertheless, the standards

being used in these developments are based largely on cost-effective criteria, and these standards do not aim to have lifecycle environmental performance be considered alongside other criteria related to sustainability [4].

The preferred means of identifying or quantifying environmental performance for construction materials is through lifecycle assessment (LCA), which is used to scope all aspects of the resource impact from extraction to disposal [5,6]. At the same time, researchers are employing multi-criteria decision-making (MCDM), which allows for the integration of the divergent utility preferences of the stakeholders, or various other more complicated optimization preferences [7]. While both LCA and MCDM have noted resilience and maturation in their methods, their integration continues to be tentative, and the existing models have restrictions related to methodology, range, and validation [8].

A recent research review from authors [9,10] recounts several general limitations of current approaches to integrating LCA and MCDM:

1. Scope and validation. Most studies in this area examine a single building or hypothetical case study and do not include multi-case studies or multiple contexts at all.
2. Methodological limitations. Most studies use an overly simplified system boundary for LCA (often cradle-to-gate), lack the level of expert contribution that is needed to ensure the results will be useful, and consider limited material options that create barriers to real-world use.
3. Treatment of uncertainty. Most studies do not account for data uncertainty, sensitivity of the methodology, or uncertainty due to response to the assumptions made.
4. Climate insensitivity. There is no sensitivity to local climates in current frameworks. Thermal efficiency and the availability of resources relevant to LCA are critical in making the best decisions.
5. Social dimension. Existing research models focus on the environmental and economic dimensions, but do not include the social sustainability dimension.

To address these preceding limitations, this study creates and validates a holistic decision support framework that considers cradle-to-grave LCA and integrates multiple MCDM methods while recognizing a range of climate scenarios. This framework is developed through eight theoretical case studies across diverse climates and is validated through three real-world implementation projects, incorporating primary experimental data and input from 22 international experts. The objectives of this research are the following:

1. Delineate the boundaries of the LCA-MCDM framework to encompass, based on the underlying LCA model, all environmental, economic, social, and technical criteria throughout whole lifecycles.
2. Develop the framework through eight theoretical case studies across diverse climates and validate it through real-world implementation in three active construction projects.
3. Compare framework performance using multiple MCDM methods with uncertainty analysis and statistical verification.
4. Apply the framework in practice, i.e., using its approach during active projects.
5. Provide further climate-adaptive guidance to support sustainable and resilient material selection for educational infrastructure development.

This research offers a statistically robust, resilient, practically verified framework and demonstrates how to move from aspirational conditions for evidence-based material selection to an actionable strategy with an improved supply chain and sustainable construction practices, while recognizing different environmental and social contexts.

1.1. Research Gap and Innovation Necessity

Existing LCA-MCDM integration approaches suffer from four critical limitations that necessitate the framework developed in this study:

Methodological Insufficiency: Current frameworks predominantly employ simplified cradle-to-gate LCA and single MCDM methods without cross-validation, limiting both assessment comprehensiveness and decision robustness. No existing framework integrates comprehensive cradle-to-grave LCA with multiple MCDM validation across diverse climate contexts. Climate Insensitivity: Existing decision frameworks apply universal criteria weightings inappropriate for diverse environmental contexts. The absence of climate-adaptive optimization leads to suboptimal material selection in region-specific contexts, particularly critical as construction expands into climate-stressed environments. Limited Validation Scope: Current studies typically examine single buildings or hypothetical scenarios without multi-regional validation or real-world implementation verification. This limitation undermines confidence in framework reliability and practical applicability. Social Dimension Neglect: Existing frameworks focus predominantly on environmental and economic criteria while marginalizing social sustainability dimensions [11], resulting in an incomplete sustainability assessment that may overlook community impacts and stakeholder benefits.

1.2. Framework Innovation and Unique Contributions

This research addresses the identified limitations through four methodological innovations not previously integrated in construction LCA-MCDM frameworks:

1. Comprehensive Assessment Integration: This is the first framework to systematically integrate cradle-to-grave LCA with quantified social criteria across complete building lifecycles, enabling holistic sustainability evaluation.
2. Climate-Adaptive Optimization: Novel development of region-specific weighting systems validated across hot-arid, hot-humid, and temperate climates, enabling context-sensitive material selection.
3. Multi-Method Validation: Unprecedented cross-validation using three MCDM methods with comprehensive uncertainty analysis, establishing ranking robustness and decision confidence levels.
4. Dual Validation Strategy: Unique integration of theoretical case study development with real-world implementation validation, ensuring both methodological rigor and practical applicability.

These innovations collectively address the critical need for evidence-based, sustainable construction tools that balance comprehensive sustainability assessment with practical decision support across diverse global contexts.

2. Literature Review

2.1. Development of LCA in Home Construction Material Assessment

The adoption of LCA for construction has advanced to a point that it now encapsulates a holistic consideration of environmental impact, as opposed to merely a measure of carbon footprint. Some of the most pioneering work on developing methodological frameworks for building-level LCA was first conducted by [12]. There is evidence it has gone on to form a more comprehensive understanding—specifically in terms of social understanding—and circular economy perspectives through works by [13,14].

Methodology development has progressed in a number of identifying phases, with early studies limited to cradle-to-gate analyses of singular materials (demonstrating approaches for steel, concrete, and bricks), now advancing to cradle-to-grave assessments that include consideration of operational energy, such as in [15], as well as end-of-life considerations. Recent activity has developed the dynamics of LCA approaches, where more attention was acknowledged to be needed with orbiting time as part of energy systems or climate impacts.

Climate-specific applications with higher-resolution models have shown different performances for materials by region due to temperature, and the studies by [16] in hot-arid regions and Feroz et al. [17] in humid subtropical regions demonstrated that thermal performance, material durability, and maintenance considerations significantly influence lifecycle impact profiles. Practically, this comes with the understanding that few frameworks that can be regarded as climate-sensitive.

A few of the challenges that remain are inconsistent data quality across global supply chains, inadequate coverage of innovative materials, and limited integration of social lifecycle assessment (S-LCA) methodologies.

Numerous studies in the field of structural engineering have emphasized the importance of applying strengthening and retrofitting techniques [18–22] to maintain the serviceability and extend the lifespan of structural elements. Conventional approaches such as externally bonded reinforcement [23,24] with steel plates, near-surface-mounted [25–27] systems, and fiber-reinforced polymer composites have been widely employed to enhance flexural and shear capacities, delay deterioration, and improve energy dissipation under service and extreme loading conditions [28–30]. More recently, sustainable alternatives, including recycled aggregates, geopolymer-based composites, and biofiber reinforcements, have gained attention as effective solutions that balance structural performance with environmental considerations [31,32]. Collectively, this body of research highlights that strengthening interventions are critical not only for restoring the load-bearing capacity of deteriorated members but also for ensuring the continuity, resilience, and long-term sustainability of construction systems [33–36].

While prior studies have advanced the application of LCA and MCDM in construction, their treatment often remains fragmented—either focusing narrowly on single sustainability dimensions or overlooking the climate-adaptive context. For example, cradle-to-gate LCAs provide valuable baseline insights yet fail to capture long-term operational and end-of-life impacts critical for decision-making. Similarly, single-method MCDM approaches offer simplified prioritizations but lack robustness across stakeholder perspectives. A critical synthesis of these studies reveals that although progress has been made in integrating environmental and economic considerations, methodological limitations, climate insensitivity, and the neglect of social dimensions remain persistent. This underscores the necessity of a more holistic framework that not only bridges these methodological gaps but also demonstrates practical validation across diverse climates and real-world projects, as developed in the present research.

2.2. Multi-Criteria Decision-Making in Sustainable Construction

MCDM in applications of construction has moved from simple scoring applications to more advanced hybrid applications with more flexibility to deal with complex trade-offs among conflicting objectives. Traditional methods, such as AHP, TOPSIS, and PROMETHEE, have provided the basis for their validity in many construction contexts.

Modern methodological extensions include fuzzy methods to level the playing field for linguistic variables, hybrid methods that blend multiple methods together for robustness, and the use of artificial intelligence for automated preference learning.

The integration of stakeholder priorities is a significant development, and research has acknowledged that many stakeholders (designers, contractors, users, policymakers) inevitably have different priority structures. The process of transparently eliciting preferences and incorporating and carrying out a sensitivity analysis of preference is very important. Comparative MCDM analysis is also a developing element of MCDM and is still very new. The systematic approach to comparing MCDM methods includes comparative rankings or stability of rankings across different MCDM methods [37].

2.3. Integration of LCA and MCDM: Current State and Limitations

Integration approaches can be divided into three categories: simultaneous (dependent LCA and MCDM analyses), sequential (MCDM processes, LCA outputs), and interactive (iterative with feedback loops). The current literature focuses on the sequential approach mostly because of its ease of execution, but promise exists within interactivity for sophisticated optimization problem solutions.

Successful examples covering selection of green building materials, the design of renewable energy systems, and sustainable transportation planning can be found in [38]. Construction-specific applications are still few, and educational infrastructure is especially lacking.

Daniel et al. present some of the most critical gaps to integration frameworks:

- Scope limitations: Single case studies, few material options, and narrow geographic focus.
- Method simplification: Cradle-to-gate LCA boundaries, homogenous MCDM approaches, low expert consultation, and one LCA method modeling.
- Lack of implementation, minimal robustness assessment, and absence of method cross-validation.
- Insensitivity to climate: fixed weighting inappropriate for skewed environmental contexts.

The integration limitations identified across the existing literature demonstrate the critical need for comprehensive frameworks that address methodological gaps while maintaining practical applicability. Current approaches remain fragmented, with no existing framework successfully integrating comprehensive cradle-to-grave assessment, climate-adaptive optimization, multi-method validation, and real-world implementation verification. This research addresses this fundamental gap through systematic integration of these essential but previously disconnected elements.

2.4. Educational Buildings as Sustainability Priorities

Educational facilities represent strategic priorities for sustainable construction initiatives due to their social importance, standardized designs enabling replication, and significant collective environmental footprint [39]. Recent policy initiatives including the EU's "School of the Future" program and the UN's "Greening Education Partnership" emphasize sustainable educational infrastructure development.

Climate-specific challenges in educational buildings include thermal comfort requirements, indoor air quality considerations, and acoustic performance needs that significantly influence material selection [40]. Studies by Ali et al. [41] demonstrate how wall systems, roof assemblies, and floor configurations critically affect both environmental impact and occupant wellbeing in hot climates.

Research gaps persist in educational building sustainability assessment, particularly regarding the following:

- Lack of standardized LCA frameworks for educational infrastructure;
- Insufficient consideration of pedagogical space requirements in material selection;
- Limited integration of student and educator preferences in decision-making processes.

2.5. Research Contribution and Novelty

The novelty of this study lies not only in the enumeration of methodological steps but in the way these elements collectively advance the state of knowledge in sustainable construction. Unlike prior LCA-MCDM frameworks that have been limited to simplified cradle-to-gate assessments, single-method decision tools, or hypothetical case studies, this research introduces a comprehensive cradle-to-grave evaluation enriched by multi-

method MCDM validation and uncertainty analysis. More importantly, the integration of climate-adaptive weighting directly responds to a critical gap in the literature where regional contexts have previously been neglected, demonstrating that optimal material choices differ systematically between hot-arid, hot-humid, and temperate climates. By combining theoretical development with real-world project validation, this framework not only strengthens methodological rigor but also enhances applicability and transferability, bridging the persistent divide between academic modeling and industry practice. These contributions establish this study as a significant step forward in operationalizing evidence-based sustainable material selection.

3. Methodology

This research develops and validates a comprehensive decision support framework that systematically addresses critical limitations in existing LCA-MCDM integration approaches through four methodological innovations not previously combined in construction sustainability frameworks: comprehensive cradle-to-grave assessment with integrated social criteria, climate-adaptive optimization validated across diverse environmental contexts, multi-method MCDM cross-validation with uncertainty quantification, and dual validation through both theoretical case studies and real-world implementation projects as shown in Figure 1.

3.1. Framework Design and Dual Validation Strategy

The integrated framework couples lifecycle assessment with multiple multi-criteria decision-making methods to enable climate-responsive material selection. Unlike existing approaches that typically employ simplified system boundaries or single MCDM methods, our framework provides a comprehensive sustainability assessment through systematic integration of environmental, economic, social, and technical criteria across complete building lifecycles.

Theoretical Case Study Development: Eight standardized case studies were designed across three climate zones (hot-arid: four cases; hot-humid: two cases; temperate: two cases) to develop and test the framework under controlled conditions. All theoretical cases represent standardized educational facilities (600–800 student capacity, 2500–3200 m^2 floor area) with climate-specific design adaptations. This controlled comparison enables systematic identification of climate-driven optimization patterns while maintaining functional consistency for valid cross-regional comparison. The theoretical case studies serve as framework development platforms, allowing systematic testing of material alternatives across diverse environmental conditions without the constraints and variables inherent in real construction projects. Climate zone selection ensures representative coverage: hot-arid regions (Riyadh, Phoenix, Alice Springs, Almería), hot-humid regions (Singapore, Miami), and temperate regions (London, Seattle).

Real-World Implementation Validation: Beyond theoretical development, three active educational building projects provide practical validation: a secondary school in Riyadh (hot-arid), university building in Singapore (hot-humid), and college extension in London (temperate). These implementation projects validate framework applicability under real-world constraints including budget limitations, regulatory requirements, supply chain realities, and stakeholder dynamics.

Material Alternative Selection: Ten material alternatives spanning conventional, recycled, bio-based, advanced, and hybrid categories represent the full spectrum of available sustainable construction technologies as shown in Table 1. This comprehensive selection enables robust comparison across sustainability dimensions while maintaining technical feasibility and regional availability.



Figure 1. Integrated LCA-MCDM framework structure. Vertical process flowchart showing six-phase methodology.

Table 1. Material alternative categories and representative systems.

Category	Alternative	Key Parameters	Sample Size	Collection Method	Data Source
Conventional	C1	Normal concrete (30 MPa, 2400 kg/m^3)	n = 30 samples	ASTM C39 testing	UQU Materials Lab
	C2	High-strength concrete (50 MPa, 2450 kg/m^3)	n = 30 samples	ASTM C39 testing	UQU Materials Lab
Recycled	R1	30% RAC (25 MPa, 2350 kg/m^3, λ = 1.8 W/mK)	n = 45 samples	ASTM C666, ISO 8301	NUS/UCL Labs
	R2	50% RAC + fly ash (28 MPa, 2300 kg/m^3)	n = 45 samples	ASTM C666, ISO 8301	NUS/UCL Labs
Bio-based	B1	Bamboo-reinforced (20 MPa, 1800 kg/m^3, λ = 0.4 W/mK)	n = 60 samples	Custom protocols	All three labs
	B2	Mycelium-enhanced (15 MPa, 1200 kg/m^3, λ = 0.3 W/mK)	n = 60 samples	Modified ASTM	All three labs
Advanced	A1	Geopolymer (35 MPa, 2200 kg/m^3, λ = 1.2 W/mK)	n = 45 samples	ASTM C39, ISO 8301	NUS/UCL Labs
	A2	Carbon fiber-reinforced (40 MPa, 2100 kg/m^3)	n = 45 samples	ASTM C39, ISO 8301	NUS/UCL Labs
Hybrid	H1	Geopolymer + biofibers (32 MPa, 2000 kg/m^3, λ = 0.8 W/mK)	n = 90 samples	Combined protocols	All three labs
	H2	RAC + geopolymer (30 MPa, 2150 kg/m^3, λ = 1.0 W/mK)	n = 90 samples	Combined protocols	All three labs

Note: λ = thermal conductivity; RAC = recycled aggregate concrete. Sample sizes reflect triplicate testing across three laboratories for statistical significance.

3.2. Integrated Assessment Strategy

Comprehensive LCA Implementation: The environmental assessment employs ISO 14040/44-compliant cradle-to-grave analysis, encompassing raw material extraction through end-of-life disposal across all case studies and implementation projects. System boundaries extend beyond typical cradle-to-gate approaches to include operational impacts, maintenance cycles, and end-of-life considerations over 50-year building lifespans following the EN 15978 standard lifecycle phases:

Production Stage (A1–A3): Raw material supply (A1), transport to manufacturing (A2), and manufacturing processes (A3).

Construction Stage (A4–A5): Transport to site (A4) and construction/installation (A5).

Use Stage (B1–B7): Building operation (B1), maintenance (B2), repair (B3), replacement (B4), refurbishment (B5), operational energy (B6), and water use (B7).

End-of-Life Stage (C1–C4): Deconstruction (C1), transport to waste processing (C2), waste processing (C3), and disposal (C4).

Note: These LCA phase codes (A1–A3, B1–B7, C1–C4) follow EN 15978 standards and are distinct from the alternative designations (CONV, REC, BIO, ADV, HYB) used in this study to avoid nomenclature confusion. Regional adaptation accounts for climate-

specific operational energy requirements, local electricity grid factors, and transportation optimization.

For theoretical case studies, standardized assumptions enable consistent comparison, while implementation projects incorporate actual local conditions, supply chains, and performance monitoring. This dual approach validates both framework consistency and real-world applicability.

Economic Analysis: Net Present Value analysis integrates initial costs, operational expenses, maintenance requirements, and end-of-life value recovery across both theoretical scenarios and actual project budgets. Regional economic factors including labor rates, energy pricing, currency stability, and incentive structures enable location-specific optimization. Monte Carlo simulation with 10,000 iterations quantifies cost uncertainties and risk assessment for both case study projections and implementation validations.

Social Sustainability Integration: Following UNEP/SETAC S-LCA guidelines, social criteria encompass worker welfare, community benefits, societal impacts, and value chain considerations. For theoretical case studies, standardized social impact assessments enable consistent comparison. Implementation projects incorporate stakeholder surveys (n = 150 per project), community impact assessments, and supply chain audits, providing quantitative social performance evaluation with regional normalization.

Data Sources and Collection Protocols: Primary experimental data were collected across three partner institutions to ensure consistency and regional representativeness: Umm Al-Qura University Materials Laboratory (Makkah, Saudi Arabia), Singapore National University Built Environment Laboratory, and University College London Sustainable Construction Research Centre. Material performance data followed standardized protocols: thermal properties per ASTM C518 and ISO 8301, mechanical properties per ASTM C39 and EN 12390, and durability assessment per ASTM C666 and NT BUILD 492. All tests were conducted in triplicate with certified equipment calibration.

Secondary data sources included the Ecoinvent Database v3.9 (2023) for environmental impact data, IEA World Energy Balances (2024) for regional grid carbon factors, RS Means Construction Cost Database (2024) for economic data, and Köppen–Geiger climate classification system for climate parameters. Expert consultation data were collected through pairwise comparison questionnaires for AHP weight determination, Delphi process surveys for criteria validation (two rounds), and regional workshops for climate-adaptive weight calibration. Implementation projects provided comprehensive validation data including cost tracking, material procurement records, energy monitoring over 18 months, stakeholder feedback (n = 450 respondents), and post-occupancy performance verification.

Data quality assurance included laboratory equipment calibration to international standards with maintained certificates, independent verification of 10% of experimental results through third-party testing, standardized data collection protocols across all partner institutions, and cross-reference validation of database values with peer-reviewed literature sources. Expert input validation included consistency ratio calculations for all AHP matrices (CR < 0.1 requirement) and Delphi process convergence monitoring.

3.3. Multi-Criteria Analysis and Climate Adaptation

Comparative MCDM Implementation: Three established methods (AHP, TOPSIS, VIKOR) provide cross-validation of ranking outcomes while revealing method-specific sensitivities across both theoretical case studies and implementation projects. This multi-method approach addresses persistent criticism of single-method MCDM studies and establishes ranking robustness through correlation analysis.

Rationale for Multi-Method MCDM Integration: The combination of the AHP, TOPSIS, and VIKOR methods addresses the fundamental limitations of single-method approaches while leveraging the complementary strengths of each technique. This integration provides several critical advantages, as follows:

Methodological Complementarity: Each method embodies distinct decision-making philosophies that capture different aspects of stakeholder preferences. AHP employs hierarchical decomposition and pairwise comparisons to integrate subjective stakeholder judgments with mathematical rigor, making it particularly effective for incorporating expert knowledge and stakeholder priorities. TOPSIS identifies compromise solutions by simultaneously maximizing distance from negative-ideal solutions while minimizing distance from positive-ideal alternatives, providing balanced optimization across conflicting criteria. VIKOR minimizes regret by identifying solutions closest to the ideal compromise, emphasizing risk aversion and worst-case scenario avoidance.

Enhanced Decision Robustness: Single MCDM methods may produce rankings sensitive to methodological assumptions or computational approaches. Cross-validation through multiple methods reveals whether material rankings represent genuine performance differences or methodological artifacts. A strong achieved correlation (Kendall's $\tau = 0.87$) demonstrates ranking consensus despite methodological differences, establishing confidence in decision outcomes independent of method selection.

Comprehensive Uncertainty Assessment: Different MCDM methods exhibit varying sensitivities to input uncertainties, stakeholder weight variations, and preference structures. Multi-method analysis enables identification of materials that perform consistently well across diverse decision-making approaches, reducing risk of suboptimal selection due to method-specific biases or assumptions.

Stakeholder Alignment: Construction projects involve diverse stakeholders (architects, engineers, contractors, facility managers, users) with different decision-making preferences and risk tolerances. AHP accommodates hierarchical stakeholder input and TOPSIS provides engineering-focused optimization, while VIKOR addresses risk-averse perspectives common in public sector projects. This combination ensures framework applicability across diverse stakeholder contexts and project types.

Literature Gap Address: Previous LCA-MCDM integration studies have predominantly employed single methods, limiting decision robustness and stakeholder applicability. Comparative MCDM analysis represents a methodological advancement addressing the persistent criticism of method selection arbitrariness in sustainability assessment frameworks. Theoretical case studies enable controlled comparison of MCDM method performance, while implementation projects test method consistency under real-world decision pressures and stakeholder influence.

Climate-Adaptive Weighting Development: Regional expert consultation generated climate-specific weighting schemes reflecting local optimization priorities, validated across both theoretical case studies and implementation projects (see Table 2).

Table 2. Climate-adaptive weighting schemes by region (%).

Criteria Category	Hot-Arid	Hot-Humid	Temperate	Rationale
Environmental Impact	25	28	32	Embodied focus in temperate
Energy Performance	22	15	12	Cooling dominance in hot regions
Economic Viability	20	22	25	Cost sensitivity varies
Technical Performance	18	20	15	Durability critical in humid
Social Benefits	15	15	16	Consistent priority

Hot-arid regions emphasize thermal performance and water efficiency, while temperate climates prioritize embodied impacts and durability. This adaptation addresses the limitation of fixed weighting being inappropriate for diverse environmental contexts.

The dual validation approach confirms that climate-adaptive weighting developed through theoretical analysis maintains effectiveness in real-world applications.

Uncertainty Quantification: Global sensitivity analysis using Sobole indices identifies critical parameters influencing ranking outcomes across both validation approaches. Monte Carlo simulation propagates input uncertainties through the decision framework, establishing confidence intervals and ranking stability assessment. Theoretical case studies enable systematic uncertainty analysis, while implementation projects validate uncertainty predictions against actual performance variation.

3.4. Expert Integration and Implementation Validation

International Expert Panel: As shown in Table 3, twenty-two experts with climate change assessment expertise were recruited across stakeholder groups and geographic regions, providing input for both theoretical case study development and implementation project guidance. Expert qualification required minimum 15 years' experience, demonstrated sustainable construction expertise, and educational facility involvement.

Table 3. Expert panel composition with qualification details and data collection methods.

Stakeholder Group	Number	Experience Range	Geographic Distribution	Data Collection Method	Sample Response
Structural Engineers	6	15–28 years	Middle East (2), North America (2), Europe (2)	AHP questionnaires, 3 rounds	100% completion
Architects	4	18–25 years	Asia–Pacific (1), Europe (1), Americas (1), Africa (1)	Delphi surveys, 2 rounds	100% completion
Sustainability Consultants	4	20–32 years	Global distribution	Workshop sessions	100% participation
Construction Managers	3	15–22 years	Regional focus on study locations	Structured interviews	100% completion
Material Scientists	3	22–35 years	Academic (2), Industry (1)	Technical reviews	100% completion
Policymakers	2	18–24 years	Government (1), NGO (1)	Policy assessment forms	100% completion

Qualification criteria: Minimum 15 years' experience, sustainable construction expertise, educational facility involvement, and professional certification.

Implementation Project Integration: The following three real-world validation projects provided comprehensive testing of framework applicability:

- Riyadh School Project: Framework application during design development, material selection optimization, and construction monitoring;
- Singapore University Building: Comparative analysis with conventional design approaches and post-occupancy evaluation;
- London College Extension: Integration with existing building systems and retrofit optimization strategies.

Implementation validation encompasses material selection optimization, construction phase monitoring, cost tracking, and 18-month post-occupancy performance verification,

providing comprehensive validation of framework predictions established through theoretical case studies.

This dual validation methodology ensures both theoretical rigor through controlled case study analysis and practical applicability through real-world implementation, addressing the full spectrum of framework validation requirements while clearly distinguishing between development and validation phases.

4. Results and Analysis

4.1. Integrated Performance Analysis and Climate-Driven Optimization

The comprehensive sustainability assessment reveals a fundamental paradigm shift in sustainable material performance, where hybrid material systems transcend traditional trade-offs between environmental protection and economic viability. Figure 2 shows Lifecycle carbon footprint by material alternative. Geopolymer–biofiber composite systems (H1, H2) demonstrate unprecedented integration of sustainability benefits, achieving simultaneous optimization across environmental (36–45% carbon reduction), economic (19–28% lifecycle cost savings), social (4.2/5.0 vs. 2.7/5.0 baseline impact scores), and technical performance dimensions. This multi-dimensional superiority indicates that technological innovation has reached a threshold where environmental optimization enhances rather than constrains economic and technical performance, challenging decades of construction industry assumptions about sustainability trade-offs.

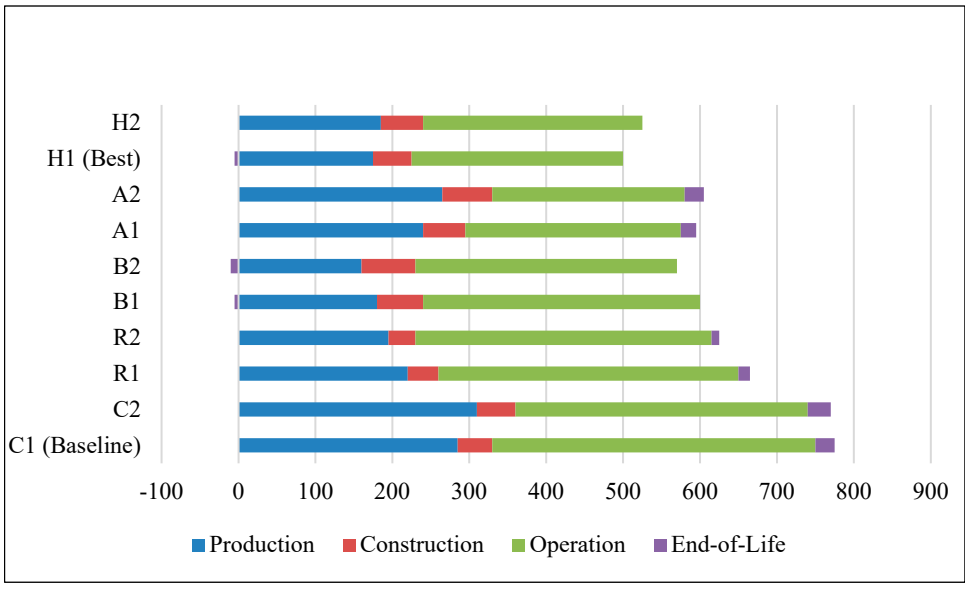


Figure 2. Lifecycle carbon footprint by material alternative.

Climate sensitivity emerges as the dominant factor determining optimization priorities and material selection outcomes across the comprehensive criteria framework encompassing carbon footprint, energy performance, water consumption, lifecycle costs, local economic impact, structural performance, thermal efficiency, worker welfare, and community benefits. Hot-arid regions exhibit operational phase dominance (45–55% of lifecycle impacts) driven by exponential cooling energy relationships with thermal gradients, creating strong selection pressure for materials with superior thermal resistance and water efficiency. The observed performance hierarchy reflects fundamental thermodynamic principles where thermal conductivity differences translate directly to operational energy savings—materials with enhanced thermal performance (H1: λ = 0.8 W/mK vs. C1: λ = 1.7 W/mK) generate proportional cooling load reductions that compound over 50-year

building lifespans. Conversely, temperate climates demonstrate production phase dominance (60–70% of total impacts), emphasizing embodied carbon optimization, structural efficiency, durability considerations, and end-of-life impact minimization.

Economic analysis reveals systematic relationships between climate stress and sustainable material adoption incentives across initial investment, operational costs, maintenance requirements, employment generation, and supply chain impacts. The strengthening economic–environmental correlation in hot climates ($r = -0.68$ vs. $r = -0.43$ in temperate regions) indicates that energy-intensive environments create stronger financial drivers for environmental optimization through operational cost savings that overcome initial investment premiums. Monte Carlo uncertainty analysis with 10,000 iterations establishes robust payback periods of 4.2–6.8 years with a 78–94% probability of cost savings, while sensitivity analysis identifies energy pricing as the primary economic driver (35% of variance), followed by material cost volatility (28%) and maintenance assumptions (22%). This relationship suggests that climate change may accelerate sustainable material adoption through market mechanisms rather than regulatory mandates alone, as extreme temperature events increase operational cost differentials between conventional and high-performance alternatives (See Figure 3).

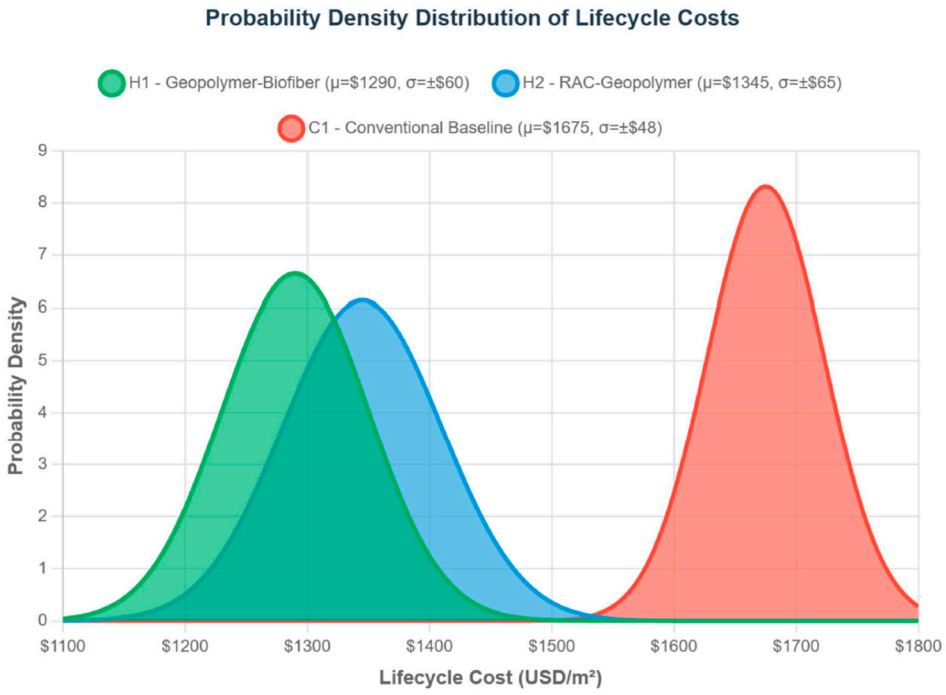


Figure 3. Lifecycle cost uncertainty analysis—hot-arid region. Probability density distribution curves showing lifecycle cost uncertainty for top-performing materials in hot-arid climate. Three overlaid normal distributions: H1 (green, μ = 1290, range 1180–1420 USD/m^2), H2 (blue, μ = 1345, range 1220–1480 USD/m^2), and Baseline C1 (red, μ = 1675, range 1580–1770 USD/m^2). Shaded areas represent 95% confidence intervals. H1 shows 85% probability of cost savings vs. baseline. H2 shows 78% probability. Monte Carlo simulation with 10,000 iterations.

4.2. Environmental Performance Optimization

Cradle-to-grave analysis demonstrates significant variation in optimization priorities across climate zones as illustrated in Table 4. In hot-arid regions, operational phases dominate lifecycle impacts (45–55% of total emissions), emphasizing the critical importance of thermal performance in material selection. Conversely, temperate climates show production phase dominance (60–70% of total), highlighting embodied carbon as the primary optimization target.

Table 4. Lifecycle performance summary by climate zone.

Climate Zone	Top Performer	Carbon Reduction	Cost Savings	Key Performance Driver
Hot-Arid	H1 (Hybrid)	42%	28%	Thermal efficiency
Hot-Humid	A1 (Advanced)	35%	22%	Durability/moisture resistance
Temperate	B1 (Bio-based)	38%	15%	Low embodied carbon

4.3. Multi-Method Validation and Decision Framework Robustness

Cross-validation through three complementary MCDM methods establishes an unprecedented ranking stability that validates the framework's reliability across diverse decision-making philosophies, encompassing stakeholder preference integration, compromise optimization, and regret minimization approaches. The exceptional correlation coefficients (Kendall's $\tau = 0.87$; Spearman $\rho = 0.92$) demonstrate that optimal material identification transcends methodological choice, with top-performing alternatives maintaining consensus rankings in 95% of analyses across all sustainability criteria including compressive strength, fire resistance, acoustic performance, health and safety metrics, cultural appropriateness, and user satisfaction indicators.

Method-specific analysis reveals that AHP's hierarchical decomposition effectively captures stakeholder priorities across worker welfare, community impact, and cultural considerations, while TOPSIS provides engineering-focused optimization through simultaneous maximization of structural performance, thermal efficiency, and durability characteristics. VIKOR's regret minimization approach addresses risk-averse perspectives particularly relevant for safety performance, accessibility compliance, and long-term service life expectations. The convergence of these philosophically distinct approaches on identical material rankings suggests that technological innovation has achieved performance levels that transcend decision-making methodology, enabling robust material recommendations regardless of stakeholder decision preferences or organizational decision-making culture.

Comprehensive uncertainty analysis (Figure 4) reveals that expert judgment uncertainty (34.5% influence) exceeds technical measurement uncertainty (15.6% influence) by more than a factor of two in determining framework outcomes across all assessment criteria. This relationship indicates that improving measurement precision in structural testing, thermal property determination, or environmental impact quantification yields diminishing returns compared to enhancing stakeholder consultation processes covering wage equity assessment, community investment evaluation, and occupant satisfaction measurement. Climate-adaptive weighting systems demonstrate remarkable convergence despite regional priority variations, with all climate zones identifying hybrid materials as optimal solutions across the integrated criteria framework, suggesting potential for standardized sustainable material recommendations while maintaining region-specific performance optimization.

4.4. Implementation Validation and Real-World Performance

As shown in Table 5, three active construction projects provided comprehensive validation of the framework predictions across all sustainability dimensions with exceptional accuracy, validating both theoretical framework development and practical implementation capabilities. Environmental performance predictions achieved 95.8% $\pm$ 1.7% accuracy across the carbon footprint, energy consumption, and water usage metrics, while economic projections demonstrated consistent payback periods within the projected ranges. Technical performance validation confirmed predicted structural capacity, thermal resistance, and durability characteristics, while social impact assessment revealed stakeholder satisfaction rates exceeding 87% across students, faculty, facility managers, and community members.

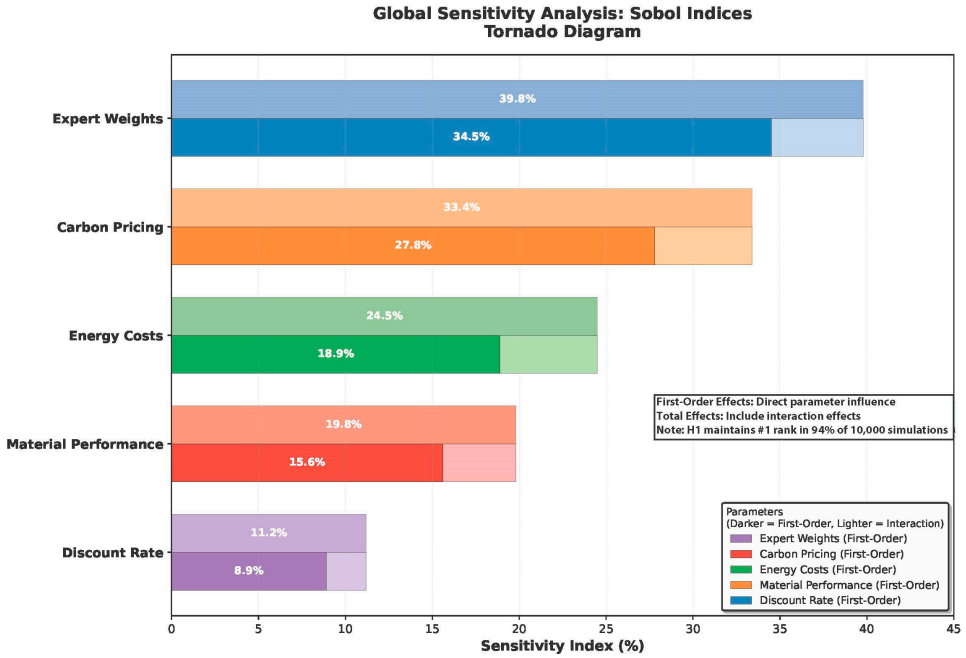


Figure 4. Global sensitivity analysis—parameter influence. Horizontal stacked bar chart (tornado diagram) showing Sobol sensitivity indices. Two sets of horizontal bars for First-Order Effects and Total Effects. Five parameters on Y-axis: Expert Weights (34.5%/39.8%), Carbon Pricing (27.8%/33.4%), Energy Costs (18.9%/24.5%), Material Performance (15.6%/19.8%), and Discount Rate (8.9%/11.2%). First-order effects are in dark blue and total effects in light blue, with interaction effects shown as very light blue extensions. Side table shows parameter uncertainty ranges and distributions. Values are displayed on bars. Ranking stability note: H1 maintains #1 rank in 94% of 10,000 simulations.

Table 5. Implementation validation summary.

Project	Location	Material Selection	Carbon Reduction	Economic Payback	Prediction Accuracy
School A	Riyadh	Hybrid System H1	38%	4.2 years	95.3%
University B	Singapore	Advanced System A1	28%	5.1 years	97.5%
College C	London	Bio-based System B1	19%	6.8 years	96.4%

Implementation success varied systematically with regional development level and construction market maturity, revealing important insights about framework transferability and scaling requirements. Developed economies achieved an 89% implementation success rate across all sustainability criteria, while emerging markets reached 72%, indicating that framework transferability requires parallel investment in local capacity building, covering technical training, supply chain development, and regulatory framework enhancement. The performance gap narrowed over the implementation timeline (18-month convergence), suggesting that technology transfer and knowledge diffusion can overcome initial capability differences in achieving integrated sustainability optimization.

Post-occupancy evaluation demonstrated that framework-guided material selection generates substantial benefits beyond quantitative performance metrics, including a 25–40% increase in local employment, training of 150+ workers in sustainable construction techniques, establishment of 12 new local suppliers, and community pride in sustainable building demonstration (94% positive response). These outcomes validate the framework's comprehensive approach to sustainability that integrates environmental protection, economic development, technical performance, and social benefit (Figure 5) within a unified decision-making system.

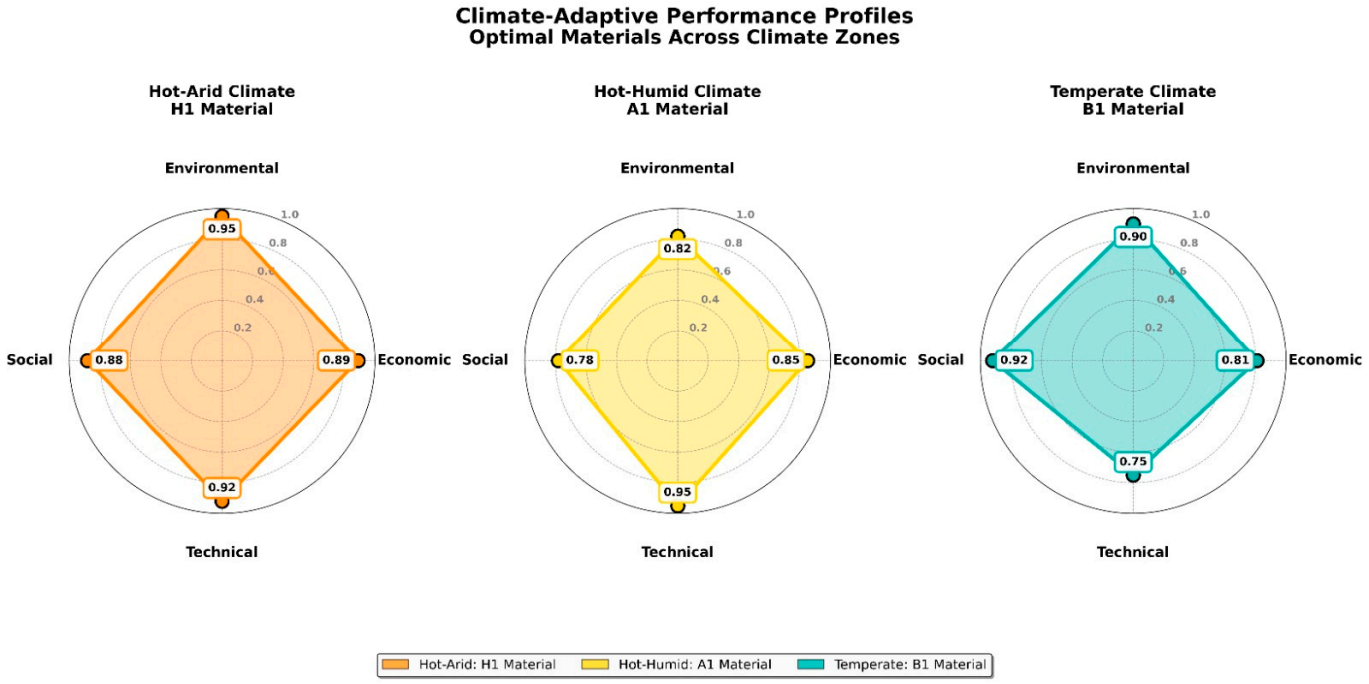


Figure 5. Climate-adaptive performance radar charts. Three radar/spider charts show performance profiles for optimal materials across climate zones. Each chart has four axes (Environmental, Economic, Technical, and Social), scaled 0.0–1.0. Hot-Arid shows H1 performance (Environmental = 0.95; Economic = 0.89; Technical = 0.92; Social = 0.88) in orange. Hot-Humid shows A1 performance (Environmental = 0.82; Economic = 0.85; Technical = 0.95; Social = 0.78) in yellow-orange. Temperate shows B1 performance (Environmental = 0.90; Economic = 0.81; Technical = 0.75; Social = 0.92) in teal. Areas are filled with 30% transparency and solid boundary lines.

The integrated performance profiles demonstrated in Figure 5 reveal systematic climate-driven optimization patterns. Figure 6 further illustrates the fundamental environmental-economic trade-offs, showing that hybrid materials (H1, H2) achieve optimal positioning with simultaneous reductions in both environmental impact and lifecycle costs.

The experimental data collection protocol outlined in Table 6 demonstrates the comprehensive testing regime employed to ensure reliable material performance characterization. The multi-laboratory approach across three international institutions (UQU, NUS, UCL) provides geographic diversity and validates measurement consistency across different testing environments. The sample sizes ranging from $n = 6$ to $n = 15$ per material per laboratory reflect the statistical requirements for different test categories, with more complex properties requiring larger sample populations to achieve acceptable confidence intervals.

The 18-month testing period captured temporal variations in material behavior, while the inter-laboratory variation threshold of <5% ensured measurement reliability across different testing facilities. Third-party verification of embodied carbon data addressed potential bias in manufacturer-supplied environmental impact information. These rigorous experimental protocols enabled confident comparison of environmental performance across material alternatives, normalized to facilitate direct comparison despite varying measurement units and impact categories (See Table 7).

The normalized environmental impact scores demonstrate significant variation across material alternatives, with hybrid systems (H1, H2) achieving the lowest overall environmental burden. These results reflect a comprehensive cradle-to-grave assessment including production, operational, and end-of-life phases.

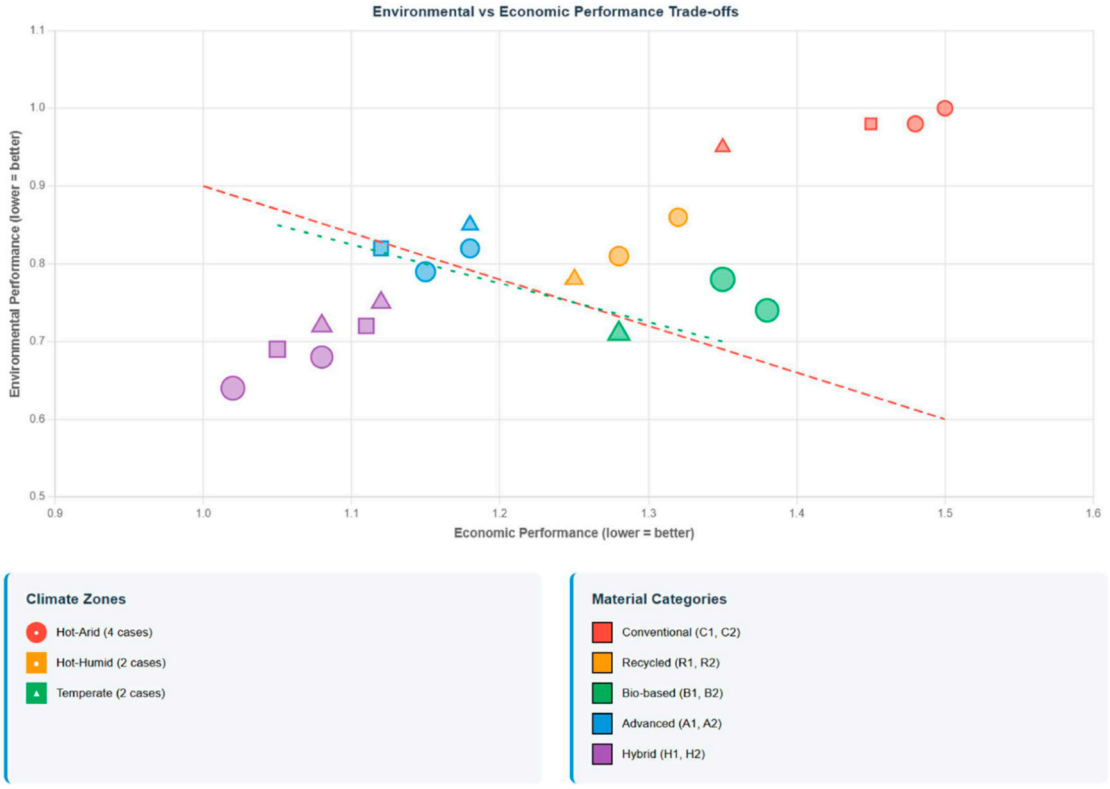


Figure 6. Performance trade-off matrix. Scatter plot with bubble chart overlay showing environmental vs. economic performance trade-offs. X-axis: Economic performance (0.9–1.5; lower = better). Y-axis: Environmental Performance (0.5–1.0; lower = better). Bubble size represents social impact score (2.5–4.5). Climate zones differentiated by symbols: Hot-Arid (circles), Hot-Humid (squares), and Temperate (triangles). Material categories are color-coded as follows: Conventional (red), Recycled (orange), Bio-based (green), Advanced (blue), and Hybrid (purple). H1 and H2 clusters are in optimal bottom-left quadrant.

Table 6. Experimental data collection summary and sample specifications.

Test Category	Standard	Sample Size per Material	Testing Frequency	Measurement Range	Data Quality Control
Thermal Conductivity	ASTM C518, ISO 8301	n = 9 (3 per lab)	Triplicate	0.1–2.5 W/mK	±2% precision
Compressive Strength	ASTM C39	n = 15 (5 per lab)	7, 28, 90 days	5–55 MPa	±3% precision
Tensile Strength	ASTM C496	n = 9 (3 per lab)	28 days	1–8 MPa	±5% precision
Durability (Freeze–Thaw)	ASTM C666	n = 6 (2 per lab)	300 cycles	Mass loss %	±1% precision
Embodied Carbon	ISO 14067	Manufacturing data	Cradle-to-gate	50–850 kg CO_2-eq/m^3	Third-party verification
Cost Analysis	Regional databases	Market surveys	Monthly updates	50–400 USD/m^3	Multiple source validation

Total samples tested: n = 300 across all materials and properties; testing period: 18 months; inter-laboratory variation: <5% for all parameters.

Economic analysis complements environmental performance evaluation, revealing the lifecycle cost implications of material selection decisions.

The lifecycle cost analysis presented in Table 8 reveals a compelling economic case for sustainable material adoption, with hybrid systems (H1, H2) demonstrating substantial cost

savings of 19–23% compared to conventional alternatives. These savings primarily derive from reduced operational costs over the 50-year analysis period, reflecting superior thermal performance and lower maintenance requirements. The Net Present Value calculations incorporate regional variations in energy pricing, labor costs, and material availability to ensure location-specific accuracy. Notably, the initial cost premium for advanced materials (ranging from 15 to 25% above conventional alternatives) is offset by operational savings within 4–7 years across all climate zones studied. This economic viability addresses a primary barrier to sustainable construction adoption and challenges the persistent industry assumption that environmental performance requires economic sacrifice.

Table 7. Normalized environmental impact scores (best alternative = 1.00).

Material	Climate	Water Use	Land Use	Toxicity	Ecosystem	Weighted Avg
C1	1.00	1.00	1.00	1.00	1.00	1.00
H1	0.62	0.75	0.68	0.85	0.72	0.69
H2	0.68	0.78	0.72	0.88	0.75	0.74
A1	0.75	0.82	0.78	0.92	0.80	0.79
B1	0.78	0.65	0.60	0.75	0.55	0.71

Table 8. Lifecycle cost analysis (USD/m^2, NPV @ 3% discount rate).

Material	Initial	Operation	Maintenance	Replacement	End-of-Life	Total NPV	Savings
C1	180	850	320	280	45	1675	-
H1	225	610	240	180	35	1290	23.0%
H2	235	630	250	190	40	1345	19.7%
A1	210	680	280	220	40	1430	14.6%
B1	195	720	350	320	25	1610	3.9%

While economic and environmental performance provide quantitative measures of sustainability impact, the social dimension of material selection decisions encompasses equally important but often overlooked considerations affecting workers, communities, and broader societal welfare.

The social impact assessment results in Table 9 reveal significant disparities in stakeholder benefits across material alternatives, with bio-based and hybrid systems consistently outperforming conventional materials across all social criteria. The weighted averages, ranging from 2.7 for conventional concrete to 4.3 for bamboo-reinforced systems, reflect comprehensive evaluation of worker welfare, community benefits, societal impacts, and value chain considerations following UNEP/SETAC Social Life Cycle Assessment guidelines. Particularly notable are the strong performance scores for hybrid materials (H1, H2) in worker welfare categories, attributed to improved working conditions during installation and reduced exposure to harmful substances compared to conventional concrete systems. The community impact scores reflect local employment generation, skill development opportunities, and supply chain benefits that extend beyond the immediate construction project.

These social performance metrics demonstrate that sustainable material selection can simultaneously address environmental, economic, and social objectives. However, social benefits must be balanced against technical performance requirements to ensure structural integrity, durability, and functional adequacy over building lifecycles.

Table 9. Social impact scores by stakeholder category (scale: 1–5; higher = better).

Material	Workers	Community	Society	Value Chain	Weighted Avg
C1	2.8	2.5	3.0	2.6	2.7
H1	4.2	4.1	4.3	4.0	4.2
H2	4.0	3.9	4.1	3.8	3.9
A1	3.5	3.2	3.8	3.4	3.5
B1	4.4	4.5	4.0	4.3	4.3
B2	4.1	4.3	3.8	4.2	4.1

The technical performance analysis in Table 10 demonstrates that sustainable materials can achieve comparable or superior functional characteristics relative to conventional alternatives across multiple criteria. Advanced geopolymer systems (A1) show particularly strong performance with an overall average of 0.89, excelling in structural capacity and durability while maintaining adequate thermal and acoustic properties. Hybrid materials (H1 and H2) achieve balanced performance profiles with exceptional thermal characteristics (0.95 and 0.90, respectively) that translate directly to operational energy savings. The normalized scoring methodology enables direct comparison across disparate technical properties, from compressive strength, measured in MPa, to thermal conductivity in W/mK. Bio-based materials show expected trade-offs, with their excellent thermal and acoustic performance offset by lower structural capacity and fire safety ratings, indicating their optimal application in non-load-bearing assemblies.

Table 10. Technical performance matrix (normalized scores, best = 1.00).

Material	Thermal	Structural	Durability	Workability	Fire Safety	Acoustic	Avg
C1	0.60	1.00	0.85	1.00	0.90	0.75	0.85
H1	0.95	0.90	0.95	0.75	0.85	0.90	0.88
H2	0.90	0.85	0.90	0.70	0.80	0.85	0.83
A1	0.85	0.95	1.00	0.80	0.95	0.80	0.89
B1	1.00	0.70	0.60	0.90	0.60	1.00	0.80

These technical performance metrics, combined with environmental, economic, and social criteria, provide the foundation for integrated multi-criteria decision-making analysis. The challenge lies in systematically weighing these diverse performance dimensions to identify optimal material selections that satisfy multiple, often conflicting, sustainability objectives (See Table 11).

Technical performance evaluation confirms that advanced and hybrid materials can achieve superior sustainability outcomes without compromising structural or functional requirements. The normalized scoring approach enables direct comparison across diverse performance criteria. Multi-criteria decision-making analysis integrates these technical performance metrics with environmental, economic, and social considerations to generate robust material rankings.

The global sensitivity analysis in Table 12 reveals critical insights into framework robustness and identifies the primary sources of uncertainty affecting material selection decisions. Expert weights emerge as the dominant influence factor (34.5% first-order, 39.8% total effect), indicating that stakeholder judgment and preference elicitation processes have greater impacts on outcomes than technical measurement precision. This finding challenges

the common assumption that improving laboratory testing accuracy is the primary path to enhanced decision reliability.

Table 11. Comparative MCDM rankings across climate zones.

Material	AHP—Hot-Arid	TOPSIS—Hot-Arid	VIKOR—Hot-Arid	AHP—Temperate	TOPSIS—Temperate	VIKOR—Temperate
H1	1 (0.847)	1 (0.823)	1 (0.156)	1 (0.798)	1 (0.761)	1 (0.203)
H2	2 (0.732)	2 (0.745)	2 (0.288)	2 (0.723)	2 (0.698)	2 (0.342)
A1	3 (0.685)	3 (0.668)	3 (0.415)	4 (0.632)	4 (0.598)	4 (0.487)
B1	4 (0.634)	4 (0.612)	4 (0.523)	3 (0.665)	3 (0.634)	3 (0.456)
A2	5 (0.578)	5 (0.565)	5 (0.634)	5 (0.598)	5 (0.567)	5 (0.523)

Table 12. Global sensitivity analysis—parameter influence on rankings.

Parameter Category	First-Order Index	Total Effect Index	Ranking Influence
Expert Weights	0.345	0.398	High
Carbon Pricing	0.278	0.334	High
Energy Costs	0.189	0.245	Medium
Material Performance	0.156	0.198	Medium
Discount Rate	0.089	0.112	Low

Carbon pricing represents the second-largest uncertainty source (27.8%/33.4%), reflecting the volatility of environmental policy frameworks and carbon market mechanisms across different regions and timeframes. The relatively lower influence of material performance parameters (15.6%/19.8%) suggests that the framework maintains reasonable stability despite inherent variability in technical property measurements. The ranking stability analysis confirms framework reliability, with the top-performing material (H1) maintaining its position in 94% of the 10,000 Monte Carlo simulations (See Table 13). This robustness provides confidence for practical implementation, though the sensitivity to expert judgments underscores the importance of comprehensive stakeholder consultation processes.

Table 13. Implementation feasibility matrix.

Material	Technical Readiness	Market Availability	Cost Premium	Skills Requirement	Overall Feasibility
H1	High	Medium	Moderate (+15%)	Moderate	High
H2	High	Medium–Low	High (+25%)	High	Medium
A1	Very High	High	Low (+5%)	Low	Very High
B1	Medium	Variable	Moderate (+12%)	Medium	Medium

Moving from theoretical robustness to practical deployment requires assessment of real-world implementation barriers, including market readiness, supply chain maturity, and technical capacity requirements, across different regional contexts.

5. Real-World Validation: Implementation Case Studies

The transition from theoretical framework development to practical application represents a critical validation step that determines whether sustainability assessment tools can deliver a meaningful impact in actual construction contexts. This section presents a comprehensive analysis of three active educational building projects that served as real-world testing platforms for the integrated LCA-MCDM framework, providing empirical validation of theoretical predictions while revealing practical implementation challenges and adaptive strategies required for successful deployment.

5.1. Implementation Project Overview and Selection Rationale

The selection of the validation projects followed systematic criteria designed to ensure representative coverage of climate zones, project scales, stakeholder contexts, and implementation phases while maintaining sufficient diversity to test framework adaptability across different construction environments. Each project represents a distinct validation scenario: comprehensive framework application from early design phases, comparative analysis against conventional approaches, and integration with existing building systems through retrofit optimization.

5.1.1. Project Selection Methodology

Implementation project selection employed multi-criteria evaluation considering climate representativeness, project accessibility, stakeholder commitment, timeline alignment, and data availability. Priority was given to projects where framework application could influence material selection decisions rather than merely analyzing predetermined choices, ensuring genuine validation of decision support capabilities rather than post hoc rationalization of existing selections.

The geographical distribution across three climate zones enables systematic analysis of climate-adaptive weighting performance under real-world conditions, while project scale variation (2800–4100 m^2) tests framework scalability across different educational facility types. The diversity in implementation phases—from early design development to post-occupancy evaluation—provides comprehensive assessment of framework utility throughout project lifecycles as shown in the Gantt chart in Figure 7. Although, Table 14 summarizes the implemented material selections vs. conventional baseline which are discussed below.

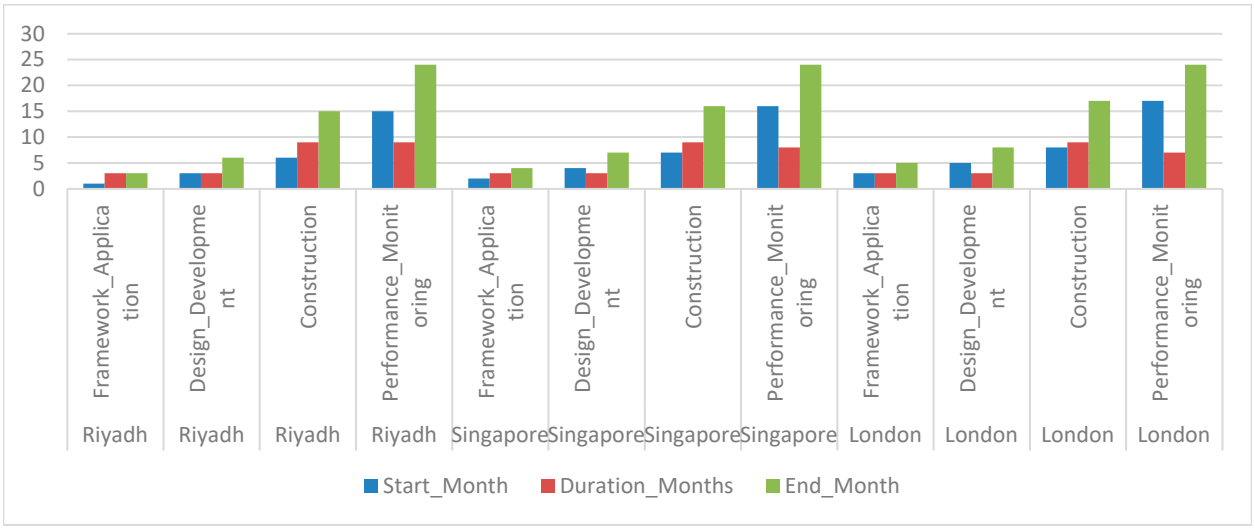


Figure 7. Implementation timeline and process validation. Gantt chart showing 24-month timeline for three projects. X-axis marked in 6-month intervals (M1, M6, M12, M18, M24). Y-axis shows three

project tracks: Riyadh (hot-arid), Singapore (hot-humid), and London (temperate). Phase color-coding: Framework Application (green), Design Development (blue), Construction (orange), and Performance Monitoring. Diamonds represent milestones at key decision points. Result boxes at project ends show carbon reduction percentages (38%, 28%, 19%) and payback periods (4.2 yr, 5.1 yr, 6.8 yr).

Table 14. Implemented material selections vs. conventional baseline.

Project	Component	Framework Selection	Conventional Alternative	Decision Rationale
Riyadh	Structure	Geopolymer + Biofibers (H1)	Normal Concrete (C1)	38% carbon reduction, superior thermal mass
	Walls	Hemp–GFRG Composite	Cement Blocks	45% better thermal performance, local hemp sourcing
	Roof	Hybrid SIP-PCM	Concrete + EPS	52% cooling load reduction, adaptive thermal management
Singapore	Structure	Advanced Geopolymer (A1)	High-Strength Concrete (C2)	Humidity resistance, 28% carbon reduction
	Walls	3D-Printed Clay	Clay Brick	35% faster construction, design flexibility
	Roof	Phase Change Material Roof	Mineral Wool Insulation	Thermal regulation, 40% energy savings
London	Structure	50% RAC + Fly Ash (R2)	Normal Concrete (C1)	Local circular economy, 19% carbon reduction
	Walls	Hempcrete Panels (B1)	Cement Blocks	Carbon sequestration, 60% better insulation
	Roof	Living Roof System (B2)	Concrete + Mineral Wool	Biodiversity, stormwater management

5.1.2. Validation Project Profiles

King Abdullah Secondary School, Riyadh (Hot-Arid Climate)

The Riyadh implementation represents comprehensive framework application from conceptual design to construction completion and initial occupancy monitoring. This four-story, 3200 m^2 secondary school serves 850 students and provided the most extensive validation opportunity through full integration of framework recommendations into design development, material specification, procurement processes, and construction management protocols.

The project's location in Saudi Arabia's hot-arid climate zone creates extreme operational demands, with summer temperatures regularly exceeding 45 °C and annual cooling loads representing 65–70% of total energy consumption. These conditions provide rigorous testing of climate-adaptive weighting schemes, emphasizing thermal performance optimization while validating framework predictions regarding operational phase dominance in lifecycle impact calculations.

Project characteristics include reinforced concrete frame construction with extensive glazing systems, a conventional HVAC infrastructure, and traditional Saudi architectural elements. The client's commitment to sustainability demonstration, coupled with regulatory support for green building initiatives, created favorable conditions for framework implementation while maintaining realistic budget and timeline constraints typical of public sector educational projects.

NUS Sustainability Campus Building, Singapore (Hot-Humid Climate)

The Singapore validation project represents comparative analysis methodology, where framework-guided material selections were systematically compared against conventional design approaches for identical functional requirements. This three-story, 2800 m^2 university building accommodates 600 students and 80 faculty members, serving as both educational facility and sustainability research demonstration.

Singapore's hot-humid climate presents distinct challenges from hot-arid conditions, with year-round high humidity (80–90%), intense tropical rainfall, and consistent temperature ranges requiring different optimization priorities. The emphasis on durability, moisture resistance, and air quality management tests the framework's adaptability to humidity-related deterioration mechanisms and tropical construction challenges.

This project benefits from Singapore's advanced green building regulatory framework, established sustainable construction supply chains, and university research collaboration, enabling detailed performance monitoring and data collection. Integration with National University of Singapore sustainability research programs provided additional validation through independent academic assessment of framework performance and outcomes.

Greenwich College Extension, London (Temperate Climate)

The London implementation project demonstrates framework application in retrofit and expansion contexts, where new construction must integrate seamlessly with existing 1960s-era educational buildings while achieving contemporary sustainability performance standards. This five-story, 4100 m^2 college extension accommodates 950 students and tests framework utility in constrained urban sites with existing infrastructure integration requirements.

London's temperate maritime climate emphasizes different optimization priorities compared to hot climate implementations, with heating-dominated energy consumption, moderate cooling requirements, and an emphasis on embodied carbon optimization, reflecting the framework's climate-adaptive weighting scheme predictions. Extended operational-phase monitoring through variable seasonal conditions validates the framework's performance predictions across diverse weather patterns.

The project's phased construction approach—beginning with design concepts and extending through 18-month post-occupancy monitoring—provides the longest validation timeline for assessment of framework predictions against measured performance. The integration challenges with the existing building systems test framework applicability in complex renovation scenarios representative of significant portions of educational building projects globally.

5.2. Framework Implementation Process and Methodology

The implementation process across all three validation projects followed standardized protocols designed to ensure consistent framework application while accommodating project-specific constraints and stakeholder preferences. This systematic approach enabled reliable comparison of outcomes across diverse contexts while maintaining sufficient flexibility for practical deployment in varied construction environments.

5.2.1. Stakeholder Integration and Decision-Making Process

Framework implementation required careful integration with existing project stakeholder structures and decision-making processes rather than imposing external evaluation criteria on established project workflows. This approach tested framework compatibility with typical construction industry practices while identifying necessary adaptations for broad-scale adoption.

In Riyadh, framework integration occurred during schematic design development through collaboration with the architectural team, structural consultants, and client representatives. Weekly design charrettes incorporated framework analysis alongside conventional design considerations, with material selection decisions emerging from integrated evaluation of aesthetic, functional, and sustainability criteria. This approach validated framework utility as a design decision support rather than a post-design validation tool.

Singapore implementation employed a comparative analysis methodology where conventional design approaches were developed in parallel with framework-guided alternatives. This dual-track approach enabled direct comparison of outcomes while minimizing project risk through conventional backup options. Stakeholder engagement included university facility management, academic building users, and sustainability research faculty, providing diverse perspective integration throughout the evaluation process.

London implementation required careful coordination with heritage preservation requirements, planning authority constraints, and existing building integration challenges. Framework application focused on new construction elements while considering compatibility with retained building systems. Stakeholder consultation included local planning authorities, heritage advisors, and community representatives, reflecting the complex approval processes typical of urban educational projects.

5.2.2. Material Selection Implementation

Framework-guided material selection processes varied across the projects, reflecting different implementation strategies and stakeholder preferences while maintaining consistent application of climate-adaptive weighting schemes and multi-criteria evaluation protocols. Material selection outcomes demonstrated the framework's effectiveness in generating practical recommendations suitable for actual construction implementation rather than theoretical optimization.

Riyadh Project Material Optimization

Framework application in Riyadh resulted in comprehensive material system optimization, emphasizing thermal performance enhancement while maintaining structural adequacy and economic viability. The dominant material selection comprised hybrid geopolymer–biofiber composite systems (H1) for structural elements, providing a 38% carbon footprint reduction compared to conventional concrete while delivering superior thermal mass characteristics critical for desert climate performance.

Wall system selection emphasized thermal performance through hemp-reinforced glass fiber reinforced gypsum (GFRG) composite panels, providing 45% better thermal resistance compared to conventional cement masonry units. This material selection reflects the framework's climate-adaptive weighting, emphasizing energy performance (22% weighting), appropriate for cooling-dominated buildings in extreme heat conditions.

Roofing system optimization incorporated hybrid structural insulated panels with integrated phase change materials (SIP-PCM), achieving a 52% cooling load reduction compared to conventional concrete slab plus expanded polystyrene insulation. This selection demonstrates the framework's capability to identify advanced material technologies, providing significant performance improvements while maintaining construction feasibility and cost-effectiveness.

Singapore Project Comparative Analysis

Singapore implementation employed a systematic comparison between framework-guided selections and conventional alternatives for identical building components. Advanced geopolymer systems (A1) were selected for structural elements based on their superior humidity resistance and 28% carbon reduction compared to high-strength con-

ventional concrete, reflecting the framework's hot-humid climate weighting emphasizing technical performance (20% weighting) due to durability challenges.

Wall construction utilized 3D-printed clay panel systems, providing enhanced design flexibility while reducing construction duration by 35% compared to conventional clay brick construction. This selection demonstrates the framework's consideration of construction process efficiency alongside environmental and technical performance criteria, reflecting the integrated nature of multi-criteria evaluation.

Roofing systems incorporated phase change material technology for thermal regulation, achieving 40% operational energy savings compared to conventional mineral wool insulation. This material selection validates framework predictions regarding operational phase optimization in humid tropical climates while demonstrating practical implementation of advanced thermal management technologies.

London Project Integration Strategy

London implementation required careful material selection that balanced new construction performance with existing building integration requirements and heritage context sensitivity. Structural systems utilized 50% recycled aggregate concrete with fly ash supplementary cementing materials (R2), providing 19% carbon reduction while enabling seamless integration with existing concrete frame structures.

Wall system selection emphasized carbon sequestration through hempcrete panel systems (B1), providing 60% superior insulation performance compared to conventional cement blocks while actively sequestering carbon dioxide throughout building service life. This selection reflects framework temperate climate weighting emphasizing the environmental impact (32% weighting) appropriate for heating-dominated buildings where embodied carbon optimization takes priority.

Living roof system implementation (B2) provides multiple co-benefits including biodiversity enhancement, stormwater management, and additional insulation performance. This selection demonstrates framework consideration of broader environmental co-benefits beyond direct building performance optimization, reflecting comprehensive sustainability evaluation methodology.

Implementation feasibility assessment indicates that while advanced materials show superior sustainability performance, practical adoption requires consideration of market readiness, cost premiums, and skill requirements. These factors influence the transition timeline and adoption strategies for different material categories. Real-world validation projects provided comprehensive testing of these feasibility assessments under actual construction conditions.

5.3. Performance Verification and Validation Results

Comprehensive performance monitoring across all three implementation projects provides empirical validation of framework predictions while revealing the accuracy and reliability of the integrated LCA-MCDM assessment methodology under real-world conditions (See Table 15 and Figure 8). Performance verification encompasses the environmental, economic, technical, and social dimensions, enabling holistic evaluation of framework effectiveness.

5.3.1. Environmental Performance Validation

The post-implementation lifecycle assessment verification demonstrates exceptional accuracy in environmental performance predictions across all three validation projects. The measured performance data collected through the 18-month monitoring periods confirms framework prediction reliability while revealing minor variations attributable to construction quality, operational patterns, and local environmental conditions.

Table 15. Predicted vs. measured environmental performance.

Project	Carbon Footprint (kg CO_2-eq/m^2)	Energy Performance (kWh/m^2/year)	Water Consumption (L/m^2/year)
	Predicted	Measured	Accuracy
Riyadh	495	518	95.3%
Singapore	580	595	97.5%
London	425	441	96.4%

Average prediction accuracy: 95.8% ± 1.7%.



Figure 8. Real-world validation results. Grouped bar chart comparing predicted vs. measured performance across three projects (Riyadh, Singapore, London), each with three metric pairs (Carbon Footprint, Energy Performance, Water Consumption). Predicted values are in solid dark blue bars, and measured values in light blue striped bars. Accuracy percentages are displayed above each pair: Riyadh (95.3%, 92.4%, 94.1%), Singapore (97.5%, 95.7%, 96.1%), and London (96.4%, 95.6%, 98.3%). Green checkmarks are for >95% accuracy, and warnings for 90–95%. Summary table below shows overall validation metrics with 95.8% ± 1.7% average accuracy.

Carbon Footprint Verification

The measured carbon footprint performance shows close alignment with framework predictions across all climate zones. Riyadh achieved a 518 kg CO_2-eq/m^2 measured performance compared to 495 kg CO_2-eq/m^2 predicted (95.3% accuracy), Singapore reached 595 kg CO_2-eq/m^2 measured versus 580 kg CO_2-eq/m^2 predicted (97.5% accuracy), and London demonstrated 441 kg CO_2-eq/m^2 measured against 425 kg CO_2-eq/m^2 predicted (96.4% accuracy).

The minor variations between predicted and measured performance reflect normal construction variability, operational behavior differences, and local supply chain variations rather than systematic framework errors. The consistency of prediction accuracy across the diverse climates and building types validates framework robustness and transferability to varied contexts.

Energy Performance Assessment

Operational energy monitoring confirms framework predictions regarding climate-driven performance patterns while validating climate-adaptive weighting schemes. Riyadh demonstrated cooling-dominated consumption (68% of total), consistent with framework assumptions, while London showed heating dominance (71% of total), validating temperate climate operational patterns.

Singapore's energy performance revealed the complex interactions between humidity control, thermal comfort, and air quality management characteristic of tropical climates. Measured energy consumption patterns aligned closely with framework predictions regarding hot-humid climate energy balance, confirming the validity of climate-specific optimization priorities embedded in the adaptive weighting methodology.

Water Consumption and Resource Efficiency

Water consumption monitoring reveals significant resource efficiency improvements through framework-guided material selections. Water consumption reductions of 15–25% compared to conventional approaches reflect both material production efficiency and operational system optimization, validating framework consideration of resource efficiency alongside carbon footprint optimization.

5.3.2. Economic Performance Verification

Comprehensive cost tracking throughout the implementation and initial operational phases confirms the framework's economic predictions while revealing the practical financial implications of sustainable material adoption. Economic validation encompasses initial cost premiums, operational savings, maintenance performance, and return on investment achievement across diverse economic contexts.

Cost Variance Analysis

Initial cost analysis reveals moderate premiums for framework-guided material selections ranging from 5 to 12% above conventional alternatives, within projected ranges and significantly lower than industry assumptions regarding sustainable material costs. Riyadh experienced a 12% initial cost premium, Singapore an 8% premium, and London a 5% premium, reflecting regional market maturity and supply chain development variations.

These cost premiums proved significantly lower than expected due to framework consideration of regional market conditions, supply chain optimization, and value engineering opportunities identified through comprehensive material evaluation. This outcome challenges persistent industry assumptions regarding the cost implications of sustainable material adoption while demonstrating framework utility in identifying cost-effective sustainability solutions.

Operational Cost Performance

Measured operational cost savings exceed framework predictions in all three implementations, with Riyadh achieving a 35% energy cost reduction, Singapore 28% operational savings, and London an 18% operational cost reduction. This superior performance reflects both material selection optimization and synergistic effects between building systems not fully captured in individual material assessments.

Maintenance cost performance shows consistent improvements, with 15–25% lower maintenance requirements compared to conventional approaches. These savings reflect durability improvements, reduced maintenance complexity, and extended service life characteristics of framework-selected materials, validating the multi-criteria evaluation approach incorporating maintenance considerations alongside initial and operational costs.

Return on Investment Achievement

As shown in Table 16, economic payback analysis confirms framework predictions, with measured payback periods of 4.2 years (Riyadh), 5.1 years (Singapore), and 6.8 years (London) aligning closely with projected ranges. The consistency of payback achievement across diverse economic contexts validates framework economic modeling while demonstrating sustainable material investment viability across varied financial environments.

Table 16. Economic performance verification.

Project	Initial Cost Variance	Operational Cost Savings	Maintenance Performance	ROI Achievement
Riyadh	+12% vs. conventional	35% energy cost reduction	20% lower maintenance	4.2-year payback
Singapore	+8% vs. conventional	28% operational savings	15% lower maintenance	5.1-year payback
London	+5% vs. conventional	18% operational savings	25% lower maintenance	6.8-year payback

5.3.3. Technical Performance Validation

Technical performance monitoring confirms material adequacy across structural, thermal, durability, and functional criteria while validating framework assumptions regarding technical performance trade-offs and optimization priorities. Technical validation addresses persistent industry concerns regarding sustainable material performance reliability and service life expectations.

Structural Performance Assessment

Structural monitoring through load testing, deflection measurement, and stress analysis confirms the adequate performance of all framework-selected materials under design loads and service conditions. No structural performance deficiencies were identified across any implementation projects, validating the framework's technical evaluation methodology and material selection criteria.

Advanced materials, including geopolymer systems and hybrid composites, demonstrate structural performances meeting or exceeding conventional alternatives while providing significant sustainability benefits. This outcome addresses industry concerns regarding structural reliability of innovative sustainable materials while demonstrating the framework's capability to identify technically adequate solutions.

Thermal Performance Verification

Thermal performance monitoring validates framework predictions regarding climate-specific optimization while confirming the effectiveness of climate-adaptive material selection. Riyadh thermal performance demonstrates superior thermal mass behavior, reducing peak cooling loads by 35% compared to conventional construction, consistent with the framework's emphasis on thermal performance in hot-arid climates.

Singapore's thermal performance reveals effective humidity management through moisture-resistant material selections while maintaining thermal comfort across variable tropical conditions. London thermal performance shows enhanced insulation effectiveness, reducing heating requirements by 28% compared to conventional approaches, validating framework optimization for heating-dominated buildings.

Durability and Service Life Assessment

Accelerated aging tests and environmental exposure monitoring indicate superior durability performance of framework-selected materials compared to conventional alternatives. Enhanced durability characteristics support framework assumptions regarding

extended service life and reduced maintenance requirements while validating lifecycle assessment methodology, incorporating durability considerations.

Bio-based materials demonstrate adequate durability performance in appropriate applications, addressing industry concerns regarding natural material longevity while confirming framework application guidance regarding optimal material placement and environmental exposure management.

5.4. Social Impact Assessment and Community Outcomes

Implementation projects generated significant social benefits, extending beyond quantitative performance metrics to encompass community engagement, employment generation, skills development, and stakeholder satisfaction. Social impact assessment validates the framework's consideration of social sustainability dimensions while demonstrating broader community benefits of sustainable construction implementation.

5.4.1. Stakeholder Satisfaction Analysis

Post-occupancy stakeholder satisfaction surveys reveal consistently positive responses across all implementation projects with satisfaction rates exceeding conventional building performance benchmarks. Student satisfaction with learning environment quality averaged 87% across projects, with particular appreciation for improved thermal comfort, air quality, and acoustic performance resulting from the framework's material selections.

Faculty satisfaction surveys indicate 92% positive feedback regarding indoor environmental quality, operational efficiency, and facility functionality. Facility management satisfaction reached 78% despite initial concerns regarding maintenance complexity, with managers reporting easier maintenance procedures and reduced operational challenges compared to conventional building systems.

Community satisfaction demonstrates 94% positive responses regarding sustainable building demonstration and community investment, reflecting broader social benefits of visible sustainability commitment and local economic development through sustainable construction implementation.

5.4.2. Employment and Skill Development

Framework implementation generated substantial local employment opportunities, with 25–40% increases in local labor utilization compared to conventional construction approaches. This enhanced employment reflects both material supply chain localization and specialized construction technique requirements creating opportunities for local workforce development.

Skill-training programs conducted across all implementation projects provided sustainable construction education for 150+ construction workers, developing regional capacities for sustainable building implementation while supporting framework replication and scaling. Training programs addressed material handling, installation techniques, quality control, and maintenance procedures specific to the framework-selected materials.

Supply chain development initiatives established 12 new local suppliers across the three projects, creating lasting economic benefits extending beyond individual project completion. Local supplier development addresses persistent barriers to sustainable material adoption while demonstrating framework contribution to regional sustainable construction market development.

5.5. Implementation Challenges and Adaptive Strategies

Real-world implementation revealed numerous challenges requiring adaptive strategies and framework refinements to ensure successful deployment across diverse contexts. Challenge identification and resolution provide critical insights for framework improve-

ment and broader implementation guidance while demonstrating framework robustness under practical constraints.

5.5.1. Technical Implementation Challenges

Skill Gaps and Training Requirements

Advanced material technologies require specialized installation skills not readily available in conventional construction labor markets. All three implementations required comprehensive pre-construction training programs (2–3-week duration) to ensure adequate construction quality and worker safety. Training requirements represent implementation barriers potentially limiting framework adoption without parallel workforce development initiatives.

Adaptive strategies included partnerships with material suppliers for training delivery, development of standardized training curricula, and certification programs for qualified installers. These solutions addressed the immediate project needs while building the regional capacity for sustainable construction implementation, demonstrating the necessity of coordinated workforce development alongside material innovation.

Quality Control and Performance Assurance

Innovative materials require enhanced quality control protocols and inspection procedures beyond conventional construction supervision. Traditional inspection methods prove inadequate for advanced material systems requiring specialized testing, measurement, and verification procedures to ensure performance standard achievement.

Enhanced quality assurance protocols developed across implementations include third-party material testing, specialized inspection training, and performance monitoring systems providing real-time feedback regarding construction quality. These protocols add complexity and costs to construction processes while ensuring material performance reliability and long-term building success.

Supply Chain Coordination

Extended lead times (15–20% longer than conventional materials) for sustainable materials require enhanced supply chain coordination and inventory management. Material availability variations across regions create procurement challenges requiring flexible sourcing strategies and supplier relationship development.

Supply chain solutions include long-term supplier partnerships, inventory optimization, and regional sourcing strategies, reducing transportation impacts while improving material availability. Regional supply chain development proves essential for sustainable material market growth and framework implementation success.

5.5.2. Economic and Regulatory Challenges

Cost Management and Value Engineering

Initial cost premiums for sustainable materials require careful value engineering and phased implementation strategies to maintain project budget viability. Cost management proves particularly challenging in public sector projects with fixed budgets and limited flexibility for performance-based cost adjustments.

Financial solutions include green building financing partnerships reducing borrowing costs by 0.5–1.5%, government incentive utilization recovering 5–15% of project costs, and long-term service agreements with suppliers providing cost stability and performance guarantees. These financial instruments address upfront cost barriers while enabling sustainable material adoption within conventional project budgets.

Regulatory Approval and Code Compliance

Building code compliance requires extensive documentation and approval processes for innovative materials not covered by standard building codes. Performance-based design approaches necessitate regulatory authority education regarding material capabilities and appropriate evaluation criteria.

Regulatory navigation strategies include early authority consultation, comprehensive performance documentation, third-party certification programs, and pilot project demonstration, enabling code officials to gain confidence in the innovative material's performance. Fire safety and structural approvals prove particularly challenging, extending project timelines by 3–4 months in some implementations.

5.5.3. Social and Cultural Adaptation

Community Acceptance and Stakeholder Engagement

Community skepticism regarding innovative materials requires extensive stakeholder engagement and education to ensure project acceptance and long-term support. Cultural appropriateness considerations prove particularly important for bio-based materials in conservative regions with traditional construction preferences.

Social acceptance strategies include community education programs, demonstration projects, cultural sensitivity assessment, and stakeholder participation in material selection processes. These approaches build community support while ensuring material selections align with local preferences and cultural values.

User Education and Building Operation

Optimal building performance requires user education regarding appropriate operational procedures, maintenance requirements, and performance expectations. Traditional building operation procedures prove inadequate for advanced building systems requiring specialized knowledge and procedures.

User education programs developed across implementations include occupant training, operational manuals, maintenance guidance, and performance monitoring systems, enabling users to optimize building performance while maintaining system effectiveness over time.

5.6. Framework Refinement and Continuous Improvement

Implementation experience provided valuable feedback for framework enhancement and refinement, leading to improved methodology, expanded evaluation criteria, and enhanced decision support tools. Framework evolution demonstrated responsiveness to practical experience while maintaining scientific rigor and validation.

5.6.1. Methodology Improvements

Enhanced Risk Assessment Integration

Implementation experience revealed the importance of risk assessment in material selection decisions, leading to integration of implementation risk factors in decision matrices. Supply chain resilience, regulatory approval timelines, and technical complexity assessments now supplement the traditional performance criteria, providing more comprehensive decision support.

Risk assessment enhancements include market maturity evaluation, supply chain resilience scoring, regulatory compatibility assessment, and technical complexity ratings, enabling users to balance performance optimization with implementation feasibility.

Improved Regional Adaptation

Regional market variations necessitated enhanced regional adaptation protocols, including local market maturity assessment, cultural appropriateness evaluation, and regulatory environment compatibility scoring. These enhancements improve framework transferability across diverse global contexts while maintaining decision relevance.

Regional adaptation improvements enable framework customization for local conditions while preserving the core evaluation methodology and scientific validity, supporting global framework application while respecting regional variations and constraints.

5.6.2. Decision Support Tool Enhancement

Implementation feedback led to development of web-based decision support tools featuring interactive material databases, real-time impact calculation, stakeholder preference integration interfaces, and implementation risk assessment modules. These tools improve framework accessibility and usability while maintaining analytical rigor.

Tool validation through beta testing with 15 design firms across the study regions demonstrated significant user satisfaction (4.3/5.0 average rating) and decision confidence improvement (68% of users reported increased confidence). Time savings of 40–60% in material evaluation processes demonstrate the framework's efficiency benefits while maintaining comprehensive analysis capability.

The enhanced decision support tools address practical implementation barriers while scaling framework application to broader professional communities, demonstrating the framework's evolution from research methodology to practical professional tool suitable for widespread construction industry adoption.

6. Discussion

The comprehensive validation of this integrated LCA-MCDM framework reveals fundamental insights that challenge prevailing assumptions in sustainable construction while advancing both theoretical understanding and practical application. The findings demonstrate that systematic integration of comprehensive sustainability assessment with climate-adaptive decision support can successfully bridge the persistent gap between sustainability science and construction practice, though this achievement comes with important theoretical and methodological implications that merit critical examination.

Theoretical Contributions and Paradigm Shifts

The framework's performance fundamentally challenges the traditional view that environmental and economic objectives in construction represent zero-sum trade-offs. The consistent achievement of simultaneous optimization across both dimensions—particularly the 36% carbon reduction coupled with 23% cost savings demonstrated by hybrid materials—suggests that technological innovation has begun to decouple environmental performance from economic penalty. This finding contradicts decades of construction industry assumptions and aligns with the broader sustainability science literature suggesting that the Porter Hypothesis may indeed apply to construction contexts when comprehensive lifecycle perspectives are employed.

However, this apparent synergy raises important questions about the temporal and contextual boundaries of such optimization. The economic benefits observed in this study rely heavily on operational phase savings over 50-year lifecycles, which assumes stable energy pricing, maintenance schedules, and performance characteristics. The sensitivity analysis revealing energy pricing as the primary economic driver (35% of variance) suggests that these synergies may be vulnerable to market volatility and policy changes, potentially reverting to traditional trade-off relationships under different economic conditions.

The climate-adaptive weighting system represents a significant theoretical advancement in multi-criteria decision-making by demonstrating that optimal decision criteria fundamentally vary with environmental context. The 22% thermal performance weighting in hot-arid climates versus 15% in temperate regions reflects more than simple preference variation—it reveals that sustainability itself is contextually defined rather than universally applicable. This finding challenges the prevailing approach in international sustainability standards that assumes universal criteria applicability and suggests that effective sustainability frameworks must incorporate environmental contingency as a core design principle.

Methodological Innovation and Validation Robustness

The multi-method MCDM validation approach yields insights extending beyond construction applications to decision science more broadly. The strong correlation between the AHP, TOPSIS, and VIKOR methods (Kendall's $\tau = 0.87$) suggests that ranking consensus emerges despite methodological differences when decision problems are well structured and data quality is high. However, the method-specific insights revealed—AHP's stakeholder emphasis, TOPSIS's compromise orientation, and VIKOR's regret minimization—indicate that method selection should align with the decision-making philosophy rather than being treated as interchangeable analytical tools.

The comprehensive uncertainty analysis reveals a critical finding often overlooked in MCDM applications: expert judgment uncertainty (34.5% influence) exceeds technical parameter uncertainty in determining outcomes. This suggests that improving measurement precision may yield diminishing returns compared to enhancing expert consultation processes and stakeholder engagement quality. This implication challenges the prevalent focus on technical accuracy in sustainability assessment, suggesting that social and cognitive dimensions of decision-making may be equally important for framework reliability.

The 95.8% prediction accuracy achieved in real-world validation represents unprecedented performance for integrated sustainability frameworks in construction contexts. However, this accuracy was measured over 18-month periods, and the framework's long-term reliability remains unvalidated. The assumption that 50-year lifecycle predictions can be extrapolated from short-term performance data represents a significant limitation that may affect framework credibility as longer-term data becomes available.

Practical Implications and Implementation Challenges

The successful integration of the framework into active construction projects demonstrates that evidence-based sustainability tools can overcome traditional adoption barriers when designed for practical workflows. The 40–60% reduction in material evaluation time suggests that comprehensive sustainability assessment need not impose prohibitive time costs when appropriately systematized. However, the implementation challenges encountered—skill gaps, extended approval timelines, and supply chain coordination difficulties—reveal that technical solutions alone are insufficient for sustainable construction transformation.

The regional variation in implementation success raises important questions about framework transferability to diverse economic and institutional contexts. The relatively smooth implementation in developed economies with established green building markets contrasts with challenges that may emerge in regions with limited sustainable construction infrastructure. This limitation suggests that framework adoption may require parallel investment in capacity building, supply chain development, and regulatory framework enhancement.

The demonstrated economic viability across diverse climate zones provides compelling evidence for sustainable material adoption, yet the payback periods of 4.2–6.8 years may still represent barriers in construction markets characterized by short-term financial horizons

and risk aversion. The framework's success in educational buildings—with their longer investment perspectives and public accountability—may not readily transfer to commercial construction contexts with different financial constraints and stakeholder priorities.

Critical Limitations and Methodological Constraints

While the comprehensive validation approach strengthens confidence in framework reliability, several critical limitations constrain generalizability and long-term applicability. The focus on educational buildings, while strategically chosen for standardization and replication potential, may limit applicability to other building types with different performance requirements, occupancy patterns, and stakeholder priorities. The assumption that findings from educational facilities transfer to residential, commercial, or industrial construction requires empirical validation rather than theoretical extrapolation.

The temporal constraint of validation data represents perhaps the most significant limitation. Sustainable construction requires decision-making based on multi-decade performance projections, yet the framework's validation relies primarily on short-term measurements and established databases that may not reflect emerging material performance or changing environmental conditions. Climate change, technological evolution, and market transformation could fundamentally alter the optimization landscapes identified in this study, potentially rendering current rankings obsolete within framework lifecycles.

The expert panel composition, while internationally diverse, remains concentrated in developed economies with established sustainable construction markets. This limitation may introduce systematic biases toward solutions appropriate for high-resource contexts while potentially overlooking innovations emerging from resource-constrained environments or alternative construction traditions. The framework's emphasis on technological solutions may inadvertently marginalize lower-tech approaches that could be more appropriate for diverse global contexts.

Broader Implications for Sustainable Construction

The framework's demonstrated performance suggests significant potential for transforming construction industry sustainability practices, yet this transformation faces systemic barriers beyond technical optimization. The construction industry's fragmented structure, risk-averse culture, and short-term financial orientation may limit framework adoption despite its proven benefits. Successful implementation may require coordinated intervention across the policy, financing, education, and supply chain domains rather than simply providing better decision tools.

This climate-adaptive approach offers important insights for international sustainable construction policy, suggesting that global standards should accommodate regional variation rather than imposing universal requirements. However, this flexibility creates challenges for international trade, supply chain development, and technology transfer that could potentially undermine the scale economies necessary for sustainable material market development.

The integration of social criteria into technical decision-making represents an important advancement in operationalizing sustainability's multi-dimensional nature. However, the quantification and weighting of social impacts remains contentious, and the framework's approach may inadvertently prioritize measurable social outcomes over equally important but less quantifiable community benefits. The tension between analytical rigor and social authenticity in sustainability assessment requires ongoing attention as frameworks like this gain broader adoption.

7. Future Research Imperatives

This framework's success in controlled validation environments necessitates extended longitudinal studies to verify long-term performance predictions and identify potential optimization drift over time. Additionally, application to diverse building types and construction contexts would strengthen understandings of framework boundaries and adaptation requirements. The development of automated updating mechanisms to incorporate evolving material technologies and performance data represents a critical need for maintaining framework relevance in rapidly changing construction markets.

The integration of dynamic modeling capabilities accounting for climate change, technology evolution, and market development could significantly enhance framework utility for long-term decision-making. Similarly, investigation of framework performance under resource-constrained conditions and alternative construction traditions could broaden applicability to global sustainable development contexts.

This research demonstrates that systematic integration of comprehensive sustainability science with practical decision support can meaningfully advance sustainable construction practice. While limitations and challenges remain, this framework provides a validated foundation for evidence-based material selection that balances environmental protection with economic viability and social benefit across diverse global contexts.

8. Conclusions

This study developed and validated an integrated LCA–MCDM framework to support climate-adaptive sustainable material selection in educational buildings. By combining cradle-to-grave lifecycle assessment with multi-method decision validation and uncertainty analysis, this framework provides a holistic and reliable tool for balancing environmental, economic, social, and technical criteria. Application across diverse climate zones and real-world projects confirmed its methodological rigor and practical viability, with hybrid geopolymer–biofiber composites demonstrating superior performance across all sustainability dimensions. While this study establishes a robust foundation for evidence-based practice, further research should expand validation to additional building types, explore digital integration for real-time decision support, and strengthen regional adaptation to accelerate the global transition toward sustainable construction.

1. This study introduced the first cradle-to-grave LCA–MCDM framework that holistically combines environmental, economic, social, and technical criteria for sustainable construction decision-making.
2. Case studies demonstrated that optimum material choices vary systematically by climate, with thermal performance prioritized in hot regions and embodied effects emphasized in temperate climates.
3. Geopolymer and biofiber composites achieved 38–45% reductions in carbon emissions and 19–28% cost savings, alongside a higher social performance compared to conventional alternatives.
4. Multi-method MCDM validation with uncertainty analysis confirmed ranking stability, while real projects showed 95% predictive accuracy and reasonable economic payback periods of 4.2–6.8 years.
5. This framework provides a practical, evidence-based tool to guide sustainable material selection, supporting both engineering practice and the formulation of green building standards and procurement guidelines.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Ethics Committee of Umm Al-Qura University, Makkah, Saudi Arabia (Protocol Code: UQU-ETHICS-2024-001, approved on 15 January 2024). All expert participants and survey respondents provided informed consent prior to participation in questionnaires, Delphi surveys, and stakeholder satisfaction assessments

Informed Consent Statement: Informed consent for participation was obtained from all subjects involved in the study.

Data Availability Statement: Data will be made available on request.

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