

Climate-Resilient Building Construction Using Low-Carbon Structural Materials

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ABSTRACT

The drive to address climate change has grown the urgency of building methods that generate less greenhouse gas emissions and are more resilient to global changes. This paper explores the construction of climate-resilient buildings using low carbon structural materials, highlighting their environmental impact, structural strength, cost-effectiveness, and resilience to climate challenges. It takes into account resources including low-carbon concrete, recycled steel, engineered timber and supplementary cementitious materials, and considers their potential for reducing embodied carbon without compromising structural safety and the long-term performance of the structure. A comparative, literature-based method is used to assess material properties, life cycle carbon emissions, construction costs, and hazard resistance to flooding, extreme heat, heavy rainfall, and high winds. It also explores the integration of the elements of Climate Responsive Architecture, LCA, Digital Prototyping and Sustainable Finance in building development. Based on the research on sustainable materials, climate adapted infrastructure, and low carbon built environment, the study suggests an integrated framework for the selection of structural materials and design strategies based on carbon intensity, durability, hazard exposure, and life cycle costs. The study highlights the need for coordinated building policies, relevant material standards, build capacity of the industry and investment in sustainable construction technologies to reach the greater potential for effective implementation. In conclusion, the use of low-carbon materials in combination with a climate-resilient design approach can help to create more sustainable, safer, and resource-efficient buildings, as well as support long-term climate mitigation and adaptation goals.

Keywords: Climate-resilient construction, low-carbon structural materials, embodied carbon, sustainable building materials, climate adaptation, life-cycle assessment, structural durability, green construction, climate risk management, sustainable built environment.

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INTRODUCTION

The construction sector is a key driver of economic growth, urbanization and the delivery of critical infrastructure, but is also a major source of greenhouse gas emissions, resource depletion and environmental degradation. Meanwhile, buildings are being exposed to extreme heat, flooding, and heavy rainfall due to climate change, among other environmental challenges. The challenges point to the need for construction methods that lower carbon emissions and enhance the building's resistance to today's and future climate impacts. The Climate Resilient Building Construction with the use of less carbon intensive building materials therefore is an important strategy to move forward sustainable development, strengthen the durability of infrastructure and lower the environmental footprint of the built environment. The study by Shuvo (2021) underscores the significance of sustainable material characterization in the context of low-carbon construction and the durability of

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infrastructure in which environmental impacts and material performance need to be taken into account.

There are opportunities to reduce the embodied carbon throughout the building life cycle by using low-carbon structural materials such as recycled steel, low-carbon concrete, supplementary cementitious materials, engineered

timbers and locally sourced construction resources. But their choice should not just be limited to carbon reduction, but should also take into account structural strength, durability, availability, cost and resistance to climate-induced degradation. Bayeroju et al. (2023) offer a framework for resilient construction materials to inform climate adapted infrastructure development and further emphasize the need to select construction materials based on environmental exposures and performance requirements. Likewise, Bailey et al. (2021) pointed out lessons learnt from climate resilience and building materials in the Caribbean where climate adaptation aspects of material selection and construction procedures are of importance, especially in areas vulnerable to extreme weather events and other climate risks.

Moreover, the construction of climate-resilient buildings involves a holistic strategy that involves the use of innovative materials, structural design, architectural designs, as well as environmental planning. Low carbon materials are not enough to make a building resilient, if they are not combined with appropriate construction systems and complemented by suitable design and maintenance practices. Zahra and Islam (2023) review improvements in sustainable architecture and building materials for climate-resilient infrastructure, providing a basis for examining how material technologies and design approaches can support environmental sustainability. In warm and humid environments, climate-responsive building design is particularly important because heat, moisture, rainfall, and ventilation requirements influence building performance. Ajith et al. (2024) examine resilient design for climate-responsive buildings in the warm and humid terrain of India, emphasizing the relevance of adapting construction strategies to local climatic conditions. These considerations demonstrate that material selection and building design should respond to both the carbon footprint of construction and the specific hazards affecting a building's location.

Furthermore, the transition toward a low-carbon and climate-resilient built environment requires life-cycle assessment, appropriate investment, supportive regulations, and coordinated planning. Evaluating construction materials solely on their initial cost or production emissions may overlook transportation, maintenance, replacement, operational performance, and end-of-life impacts. Jain (2023) addresses the relationship between climate resilience, green construction, and low-carbon development, while He and Prasad (2024) examine pathways for delivering sustainable, resilient, and low-carbon built environments. Charoenkit and Kumar (2017) also demonstrate the importance of integrating climate mitigation and disaster resilience into housing design assessment. Collectively, these perspectives support an approach in which environmental performance, structural safety, and long-term adaptability are considered together rather than as separate construction objectives.

Technological innovation can further strengthen this integration. Digital prototyping and multi-risk assessment

can help designers evaluate alternative materials, anticipate environmental hazards, and identify design strategies that improve building performance. Lucanto et al. (2024) investigate digital prototyping and regenerative design in relation to carbon neutrality and climate-resilient built environments, highlighting the relevance of assessing environmental risks across multiple scales. At the urban level, Kim (2017) emphasizes integrated planning approaches for climate-resilient and low-carbon smart cities, while Cheshmehzangi and Chen (2021) discuss low-carbon and climate-resilient sustainability transitions. These perspectives suggest that individual building projects should be aligned with broader urban development objectives, infrastructure systems, and long-term climate strategies.

Financial and institutional support is equally important for implementing low-carbon, climate-resilient construction at scale. Higher initial costs, limited access to innovative materials, insufficient technical expertise, and fragmented building regulations can constrain adoption, even where long-term environmental and resilience benefits are substantial. Kennedy and Corfee-Morlot (2012) examine the mobilization of investment in low-carbon, climate-resilient infrastructure, while Meltzer (2016) discusses the role of climate finance and green financial systems in financing such infrastructure. The World Health Organization (2023) further emphasizes the importance of integrating climate resilience and low-carbon principles into health systems, demonstrating the relevance of resilient building infrastructure for essential public services. Addressing these financial and institutional barriers is therefore necessary to make sustainable construction practices more accessible and widely applicable.

Despite growing interest in sustainable materials and climate adaptation, an important challenge remains: identifying how low-carbon structural materials can simultaneously satisfy carbon-reduction objectives, structural performance requirements, economic constraints, and climate-resilience needs. Materials with lower embodied carbon may require additional protection or maintenance under particular environmental conditions, while highly durable conventional materials may have substantial production-related emissions. Consequently, construction decisions require a balanced assessment of life-cycle carbon, durability, hazard resistance, cost, and local suitability. A systematic framework can help designers, engineers, policymakers, and developers evaluate these trade-offs and select solutions appropriate to different climatic and economic contexts.

The primary aim of this study is to examine the application of low-carbon structural materials in climate-resilient building construction and develop an integrated perspective on their environmental, structural, and economic implications. Specifically, the study seeks to identify suitable low-carbon materials, assess their potential contribution to



climate adaptation and emissions reduction, examine the influence of climate hazards on material performance, and evaluate the design, financial, and policy measures needed to support adoption. Through a comparative, literature-based approach, the study considers how material selection, life-cycle assessment, climate-responsive design, and resilient construction practices can be coordinated to improve building performance.

Ultimately, climate-resilient building construction using low-carbon structural materials offers a pathway toward reducing the environmental impact of the construction industry while strengthening the durability and adaptability of buildings. Achieving these outcomes requires decisions that integrate material science, structural engineering, climate-risk assessment, economic evaluation, and sustainable development planning. By bringing these considerations together, the study aims to support more informed construction decisions and contribute to the development of a built environment that is both low-carbon and resilient to evolving climatic conditions.

LITERATURE REVIEW AND CONCEPTUAL FRAMEWORK

Concept of Climate-Resilient and Low-Carbon Building Construction

Climate-resilient building construction integrates greenhouse gas emission reduction with the capacity of buildings to withstand, adapt to, and recover from climate-related hazards. Conventional construction practices often prioritize initial cost and structural strength, while giving insufficient attention to embodied carbon, long-term material performance, and increasing exposure to extreme weather. A more integrated approach considers the environmental impacts of material extraction, manufacturing, transportation, construction, maintenance, and end-of-life management. Shuvo (2021) emphasizes the importance of characterizing sustainable construction materials to support low-carbon development and infrastructure durability.

Low-carbon construction aims to reduce emissions associated with building materials and construction processes through efficient resource utilization, recycled inputs, alternative binders, locally available materials, and improved design. Climate resilience complements these measures by ensuring that buildings maintain acceptable structural performance under conditions such as flooding, extreme heat, intense rainfall, strong winds, and humidity. Bayeroju et al. (2023) provide a framework-oriented perspective on resilient construction materials, highlighting their relevance to climate-adapted infrastructure development.

Consequently, climate-resilient, low-carbon construction should not be assessed through carbon reduction alone. Material selection must also account for structural safety, durability, moisture resistance, thermal performance, repairability, and suitability for local climatic conditions.

Jain (2023) situates these concerns within the broader development of green, low-carbon, and climate-resilient built environments.

Low-Carbon Structural Materials and Their Performance

Low-carbon structural materials are central to reducing the environmental footprint of buildings without compromising their load-bearing capacity or service life. Important alternatives include low-carbon concrete, recycled steel, engineered timber, and concrete incorporating supplementary cementitious materials. Their environmental and structural performance varies according to production methods, material composition, transport distances, design specifications, and maintenance requirements.

Low-carbon concrete can reduce embodied emissions when conventional clinker-intensive cement is partially replaced with suitable supplementary cementitious materials. However, its performance depends on mix design, curing, exposure conditions, and quality control. Recycled steel can support resource efficiency by incorporating recovered material into structural production, although its carbon footprint depends on the production route, electricity source, and recycling process. Engineered timber can store biogenic carbon during its service life, but its benefits depend on responsible sourcing, moisture protection, fire design, and end-of-life assumptions.

Shuvo (2021) supports the relevance of systematic material characterization to low-carbon construction and infrastructure durability. Material evaluation should therefore combine mechanical properties with environmental indicators, including embodied carbon and resource consumption. These assessments help designers identify materials that meet structural requirements while reducing whole-life environmental impacts.

Zahra and Islam (2023) discuss improvements in sustainable architecture and building materials for climate-resilient infrastructure. Their review provides a relevant basis for examining material innovation alongside building design strategies. In practice, no single material is universally optimal; performance depends on building function, local supply chains, exposure conditions, and the availability of skilled labor.

Climate Hazards, Material Durability, and Building Resilience

Climate change increases the importance of designing buildings for multiple hazards rather than relying exclusively on historical weather conditions. Flooding can cause foundation erosion, corrosion, water penetration, and deterioration of susceptible components. Extreme heat can affect thermal comfort, increase cooling demand, and accelerate the degradation of some construction materials. High humidity and intense rainfall can promote moisture

ingress, mold growth, and corrosion, while strong winds can impose substantial loads on roofs, connections, façades, and structural systems.

Bayeroju et al. (2023) emphasize resilient construction materials as part of climate-adapted infrastructure development. This perspective supports the use of performance-based material selection, in which construction materials are evaluated against the hazards expected during a building's service life. Bailey et al. (2021), in their report on building materials and climate resiliency in the Caribbean, provide a regional perspective on the relationship between material choices, low-carbon development, and exposure to climate-related risks.

Climate-responsive design must also consider interactions between materials and building systems. For example, a low-carbon structural frame may offer environmental advantages but still perform poorly if the building lacks adequate drainage, moisture barriers, roof protection, or appropriate ventilation. Ajith et al. (2024) examine resilient design for climate-responsive buildings in warm and humid Indian terrain, highlighting the relevance of climatic conditions to building design decisions.

Charoenkit and Kumar (2017) further connect low-carbon housing with disaster resilience by considering mitigation and adaptation within the assessment of self-help housing design. Their work supports an integrated approach in which affordability, construction feasibility, hazard resistance, and environmental performance are evaluated together.

Sustainable Architecture, Life-Cycle Assessment, and Digital Design

Sustainable architecture extends beyond the selection of individual materials to include building orientation, shading, natural ventilation, thermal mass, daylighting, insulation, and efficient structural layouts. These strategies can reduce operational energy demand and improve occupant comfort. When combined with low-carbon materials, they can contribute to reducing both embodied and operational emissions.

He and Prasad (2024) address the delivery of sustainable, resilient, and low-carbon built environments within broader urban sustainability transitions. Their perspective supports coordinated decision-making across building design, infrastructure planning, construction delivery, and environmental performance.

Life-cycle assessment (LCA) is particularly important because a material with lower initial embodied carbon may require more frequent maintenance or replacement. A fair comparison should therefore define a functional unit, reference service life, system boundaries, and assumptions concerning maintenance, transportation, replacement, and end-of-life treatment. These considerations help avoid selecting materials based on incomplete environmental comparisons.

Lucanto et al. (2024) examine digital prototyping and regenerative design in relation to carbon neutrality, climate resilience, and environmental multi-risk assessment. Digital design methods can support the evaluation of alternative materials and building configurations before construction. Building information modelling, digital prototypes, and climate-risk simulations can help project teams compare environmental impacts, test design alternatives, and identify potential vulnerabilities.

Similarly, Kim (2017) presents an integrated planning approach to climate-resilient and low-carbon smart cities. This broader planning perspective is relevant because building-level decisions are influenced by infrastructure networks, land-use patterns, drainage capacity, transportation, and urban heat exposure. Cheshmehzangi and Chen (2021) also connect low-carbon development with climate-resilient sustainability transitions, reinforcing the need to align individual building projects with wider decarbonization objectives.

Economic, Policy, and Institutional Considerations

The adoption of low-carbon, climate-resilient construction materials depends not only on their technical performance but also on affordability, procurement practices, market availability, building codes, and financing mechanisms. Some materials may reduce life-cycle costs while requiring higher initial investment, specialized construction skills, or additional quality-control procedures. These factors can discourage adoption, particularly in projects with limited capital budgets.

Kennedy and Corfee-Morlot (2012) examine the mobilization of investment in low-carbon, climate-resilient infrastructure, providing a basis for considering the financial requirements of sustainable construction. Meltzer (2016) discusses the role of climate finance and green financial systems in financing low-carbon, climate-resilient infrastructure. Together, these works support the consideration of green lending, climate-related investment, incentives, and appropriate risk-sharing mechanisms.

Policy frameworks can further support implementation by establishing minimum performance standards, requiring life-cycle carbon reporting, encouraging resilient design, and promoting responsible material sourcing. Jain (2023) provides a broader foundation for understanding the relationship between green construction and climate resilience, while the World Health Organization (2023) demonstrates the importance of integrating climate resilience and low-carbon objectives into health-system infrastructure.

The literature therefore suggests that successful implementation requires coordination among material producers, engineers, architects, developers, regulators, financial institutions, and building occupants. Technical innovations are unlikely to achieve widespread impact without supportive procurement systems, consistent standards, and investment in professional capacity.



Conceptual Framework for Climate-Resilient, Low-Carbon Construction

The conceptual framework for this study integrates four principal dimensions: material characteristics, climate-risk exposure, building design and construction practices, and enabling institutional conditions. These dimensions interact to influence two primary outcomes: reduced life-cycle carbon emissions and improved building resilience.

The first dimension concerns material characteristics, including embodied carbon, strength, durability, recyclability, moisture resistance, and local availability. The second concerns climate-risk exposure, including flooding, heat, high winds, heavy rainfall, and humidity. The third concerns design and construction strategies, such as hazard-resistant structural systems, passive cooling, moisture management, efficient material use, and life-cycle assessment. The fourth concerns enabling conditions, including building codes, financing, technical capacity, procurement standards, and access to reliable material data.

These dimensions inform a decision-making process that evaluates alternative construction systems against environmental, structural, climatic, and economic criteria. He and Prasad (2024) support the broader integration of sustainability, resilience, and low-carbon development, while Lucanto et al. (2024) provide a basis for incorporating digital prototyping and multi-risk assessment. Kennedy and Corfee-Morlot (2012) and Meltzer (2016) further establish the relevance of investment and financing conditions to implementation.

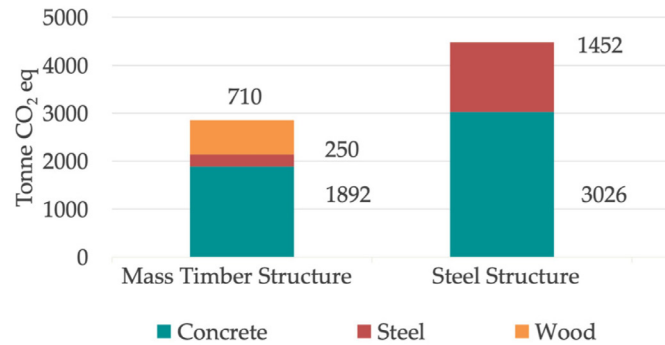


Fig 1: Values represent published median whole-life embodied carbon estimates for structural frame systems over a 50-year design life. The assessment covers life-cycle modules A–D and excludes operational energy and water use. Values are expressed per square metre of gross external area and should not be interpreted as totals for a complete building. Source: Hart, D'Amico, and Pomponi (2021).

The framework proposes that low-carbon materials produce the greatest overall benefit when they are selected according to local climate hazards, incorporated into appropriate building designs, and supported by life-cycle evaluation and effective institutional arrangements. Accordingly, the study assesses construction alternatives using the following criteria:

- Environmental performance: embodied carbon, resource efficiency, and whole-life emissions.
- Structural performance: load-bearing capacity, stiffness, strength, and code compliance.
- Climate resilience: resistance to relevant hazards, durability, and recovery potential.

Table 1: Comparative Evaluation of Low-Carbon Structural Materials for Climate-Resilient Building Construction

Structural material	Potential carbon-reduction pathway	Key structural or durability considerations	Climate-resilience considerations	Main limitations
Low-carbon concrete	Reduced clinker content and optimized cement use	Strength development, curing, permeability, and exposure-specific durability	Can be designed for demanding structural and environmental conditions; mix and detailing must suit exposure	Performance varies by mix design, material supply, and curing conditions
Recycled steel	Reuse of recovered steel and lower-emission production routes	Strength, ductility, connection quality, and corrosion protection	Suitable for engineered structural systems when protected against corrosion and designed for applicable wind and other loads	Carbon benefits depend on production route, energy source, and recycled content
Engineered timber	Renewable sourcing and potential biogenic carbon storage	Moisture control, connection performance, fire protection, and service-life management	Appropriate detailing can support durable construction; exposure to moisture and severe weather must be addressed	Sourcing, fire requirements, moisture exposure, and end-of-life assumptions affect suitability
Concrete with supplementary cementitious materials	Partial replacement of conventional cement constituents	Mix compatibility, curing, strength development, and long-term durability	Can provide suitable performance when formulated for local exposure conditions	Availability, material variability, and quality-control requirements
Locally sourced, lower-impact materials	Reduced transport impacts and more efficient use of regional resources	Quality consistency, code compliance, strength, and weathering resistance	Can improve contextual suitability when matched to local climate and hazards	Supply consistency, certification, and technical capacity may be limited

Source: Author's synthesis based on Shuvo (2021), Bayeroju et al. (2023), Bailey et al. (2021), Zahra and Islam (2023), Jain (2023), and Ajith et al. (2024). The table presents qualitative comparisons; actual performance must be verified for the specific material, project, and exposure conditions.

- Economic feasibility: initial cost, maintenance, replacement, and life-cycle cost.
- Implementation feasibility: local availability, construction skills, supply-chain reliability, and regulatory support.

This conceptual framework provides a structured basis for comparing materials and identifying construction strategies that balance decarbonization, structural reliability, climate adaptation, and affordability.

RESEARCH METHODOLOGY

Research Design

This study adopts a comparative, literature-based research design to examine how low-carbon structural materials can improve building sustainability while strengthening resilience to climate-related hazards. The methodology integrates environmental assessment, material-performance evaluation, climate-risk analysis, and life-cycle cost considerations. It draws on published research, technical reports, and established approaches to sustainable construction to identify material properties and design strategies that support carbon reduction, structural durability, and climate adaptation (Shuvo, 2021; Bayeroju et al., 2023).

The comparative approach considers materials such as low-carbon concrete, recycled steel, engineered timber, and concrete incorporating supplementary cementitious materials. These alternatives are assessed against conventional construction materials using consistent criteria, including embodied carbon, mechanical performance, resistance to moisture and heat, expected service life, availability, and maintenance requirements. The approach reflects the need to evaluate materials not only by their immediate environmental

benefits but also by their long-term contribution to resilient infrastructure development (Bailey et al., 2021; Jain, 2023).

Data Sources and Literature Selection

Data are obtained from academic journal articles, conference proceedings, books, technical publications, and institutional reports relevant to sustainable materials, climate-responsive buildings, and low-carbon infrastructure. Priority is given to sources that discuss material characterization, life-cycle environmental impacts, climate hazards, construction practices, and resilience assessment.

The literature selection process follows four principal criteria:

- **Relevance:** Sources must address low-carbon construction materials, climate-resilient buildings, or related sustainability assessment methods.
- **Technical applicability:** Publications should provide information on material properties, structural performance, environmental impacts, or climate adaptation strategies.
- **Credibility:** Preference is given to peer-reviewed publications, recognized academic publishers, and institutional reports.
- **Comparability:** Sources should provide sufficiently clear evidence or documented assumptions to support meaningful comparisons across materials and construction systems.

Studies on climate-responsive architecture and sustainable building materials provide additional context for assessing the suitability of construction strategies under different climatic conditions (Zahra & Islam, 2023; Ajith et al., 2024). Research on integrated low-carbon and climate-resilient development further supports the inclusion of building-level and broader infrastructure considerations (He & Prasad, 2024).

Table 2: Comparative Evaluation Framework for Low-Carbon Structural Materials

<i>Evaluation criterion</i>	<i>Key indicators</i>	<i>Assessment approach</i>	<i>Expected contribution</i>
Embodied carbon	kg CO ₂ e per defined functional unit	Compare life-cycle assessment data using consistent system boundaries	Identify materials with lower carbon emissions
Structural performance	Strength, stiffness, load-bearing capacity	Review material test results and applicable engineering standards	Establish structural suitability and safety
Durability	Moisture resistance, corrosion, degradation, service life	Examine experimental findings and documented service-life evidence	Reduce premature deterioration and replacement
Climate resilience	Flood, heat, rainfall, and wind resistance	Match material and system performance to local hazard exposure	Improve building resilience under climate stress
Life-cycle cost	Initial cost, maintenance, replacement, end-of-life costs	Compare costs over a consistent analysis period	Identify economically feasible alternatives
Resource efficiency	Recycled content, local sourcing, reuse potential	Review material composition and supply-chain information	Reduce resource consumption and construction waste
Implementation feasibility	Availability, skills, standards, and supply-chain capacity	Assess local construction conditions and adoption barriers	Support practical implementation and scalability

Source: Researcher's synthesis based on Shuvo (2021), Bailey et al. (2021), Bayeroju et al. (2023), and Jain (2023). The table defines the proposed assessment framework; it does not present measured experimental results.



Material Characterization and Comparative Assessment

The selected materials are assessed according to their environmental, structural, and climate-resilience characteristics. Environmental assessment focuses on embodied carbon associated with material extraction, manufacturing, transportation, construction, maintenance, replacement, and end-of-life treatment, where data are available. A consistent functional unit and system boundary are required to ensure that comparisons are meaningful.

Structural evaluation considers compressive or tensile strength, stiffness, durability, moisture resistance, thermal performance, and suitability for the intended building application. Climate-resilience assessment examines the ability of material systems and structural designs to withstand relevant hazards, including flooding, extreme heat, heavy rainfall, and high winds. The specific performance indicators depend on the building type, local climate, exposure conditions, and applicable engineering standards.

Material characterization is particularly important because low embodied carbon does not automatically guarantee structural suitability or long-term durability. Therefore, environmental performance must be considered alongside engineering requirements and service-life expectations (Shuvo, 2021). Similarly, resilient material selection requires consideration of hazard exposure, local construction conditions, and the performance of the overall building system rather than isolated material properties (Bayeroju et al., 2023).

Climate-Risk and Life-Cycle Evaluation

The study evaluates the interaction between material characteristics and climate-related hazards. For example, flood-prone locations require attention to water absorption, moisture durability, corrosion resistance, and the consequences of prolonged inundation. Buildings exposed to extreme heat require consideration of thermal properties, material degradation, and the contribution of the building envelope to indoor comfort. Wind-prone areas require appropriate structural connections, impact resistance, and compliance with relevant structural design requirements.

The evaluation also incorporates life-cycle considerations to avoid selecting materials solely on the basis of initial cost or production-stage emissions. Materials that require frequent replacement or intensive maintenance may produce higher long-term environmental impacts than their initial characteristics suggest. The integration of mitigation and adaptation criteria is consistent with research examining low-carbon, disaster-resilient building and community design (Charoenkit & Kumar, 2017).

Where suitable data are available, digital prototyping and multi-hazard assessment can be used to examine alternative building configurations and identify potential environmental trade-offs (Lucanto et al., 2024). The assessment also considers whether low-carbon, climate-resilient strategies

can be implemented within broader urban planning and infrastructure development processes (Kim, 2017).

Evaluation Criteria and Analytical Framework

The comparative analysis uses a structured evaluation matrix to identify the relative strengths, limitations, and implementation requirements of different materials. Each material system is assessed against a common set of criteria, with documented measurements used wherever possible. Quantitative indicators, such as embodied carbon, strength, estimated service life, and life-cycle cost, are distinguished from qualitative indicators, such as local availability and implementation feasibility.

The framework emphasizes five dimensions:

- Environmental performance: Embodied carbon, resource efficiency, recyclability, and waste reduction.
- Structural performance: Strength, stiffness, durability, and compliance with engineering requirements.
- Climate resilience: Resistance to relevant hazards and suitability for local environmental conditions.
- Economic feasibility: Initial cost, maintenance expenditure, replacement requirements, and life-cycle cost.
- Implementation feasibility: Material availability, construction skills, supply-chain capacity, and compatibility with local building practices.

This multidimensional approach supports a balanced assessment of low-carbon and climate-resilient construction, consistent with broader approaches to sustainable built-environment development (Jain, 2023; He & Prasad, 2024). Financing and investment considerations are also recognized because the adoption of resilient infrastructure often depends on the availability of appropriate funding mechanisms and long-term investment planning (Kennedy & Corfee-Morlot, 2012; Meltzer, 2016).

Reliability, Limitations, and Ethical Considerations

To improve reliability, the study uses clearly defined assessment criteria, records the sources and assumptions underlying comparisons, and distinguishes measured findings from estimates and qualitative judgments. Where different studies use inconsistent functional units, geographical conditions, service-life assumptions, or life-cycle boundaries, their results are not treated as directly comparable without appropriate qualification.

A principal limitation of the literature-based approach is that published material-performance and carbon data may not represent every local climate, construction practice, or supply chain. Consequently, the findings should be interpreted in relation to the assumptions and geographical contexts of the underlying studies. Further field testing, structural analysis, and locally specific life-cycle assessment may be necessary before materials are selected for actual construction projects.

The methodology also recognizes the importance of resilient and low-carbon design in buildings serving critical

public functions. The World Health Organization's (2023) Operational framework for building climate resilient and low carbon health systems provides a relevant institutional perspective on integrating climate resilience and emissions reduction into health infrastructure planning. Although its primary focus is health systems, its principles can inform consideration of building continuity, environmental performance, and resilience in appropriate applications.

Overall, this methodology provides a structured basis for comparing low-carbon structural materials and evaluating their suitability for climate-resilient building construction. By combining material characterization, environmental assessment, climate-risk evaluation, and life-cycle cost analysis, it supports construction decisions that balance emissions reduction, structural safety, durability, and long-term adaptability.

Proposed Framework for Climate-Resilient, Low-Carbon Construction

The proposed framework integrates low-carbon structural materials, climate-responsive building design, life-cycle assessment, and risk-based planning to support buildings that are environmentally sustainable, structurally durable, and capable of withstanding climate-related hazards. The framework emphasizes that material selection should not be based exclusively on initial cost or carbon emissions; it should also account for structural performance, local climate conditions, maintenance requirements, resource availability, and long-term resilience. Shuvo (2021) highlights the importance of sustainable material characterization for low-carbon construction and infrastructure durability, while Bayeroju et al. (2023) provide a basis for considering resilient construction materials in climate-adapted infrastructure development.

Low-Carbon Structural Material Selection

The first component of the framework involves identifying structural materials that reduce embodied carbon while satisfying engineering performance requirements. Potential options include low-carbon concrete incorporating supplementary cementitious materials, recycled steel, responsibly sourced engineered timber, and locally available materials with suitable structural properties. These materials should be assessed according to compressive and tensile strength, durability, moisture resistance, thermal performance, service life, and end-of-life recovery potential.

Material selection should follow a whole-life perspective. For example, recycled steel can reduce demand for virgin material production, while appropriately designed low-carbon concrete can reduce emissions associated with conventional cement use. Engineered timber may offer carbon-storage benefits when sourced responsibly, but its suitability depends on moisture exposure, fire protection, connection design, and local building regulations. Therefore, no material should be considered universally superior without

considering its intended application and environmental conditions.

Shuvo (2021) supports the importance of evaluating material characteristics in relation to low-carbon construction and infrastructure durability. Similarly, Jain (2023) emphasizes the broader relationship between climate resilience, green construction, and low-carbon built environments. These considerations establish a material-selection process that balances environmental performance with structural safety and long-term serviceability.

Climate-Responsive Building Design and Hazard Resistance

The second component integrates material selection with building designs that respond to local climate conditions and anticipated hazards. Climate-resilient construction requires the identification of relevant risks, including flooding, extreme heat, intense rainfall, high winds, coastal hazards, and changing humidity levels. The specific design response should reflect the building's location, occupancy, structural system, and projected climate exposure.

For flood-prone areas, appropriate strategies may include elevating critical building components, improving drainage, specifying water-resistant materials in exposed zones, and protecting foundations against erosion. In areas experiencing high temperatures, designers can combine suitable structural and envelope materials with shading, natural ventilation, reflective surfaces, and passive cooling. Buildings exposed to strong winds require appropriate structural connections, lateral stability, and envelope detailing.

Ajith et al. (2024) examine resilient design for climate-responsive buildings in warm and humid terrain, providing a relevant basis for incorporating regional climatic conditions into building design. Bailey et al. (2021) also address the relationship between climate resilience and building materials in the Caribbean context, highlighting the importance of considering regional hazards and material suitability. Furthermore, Zahra and Islam (2023) discuss improvements in sustainable architecture and building materials for climate-resilient infrastructure.

The framework consequently treats resilience as a combination of material properties, structural configuration, building-envelope performance, site planning, and maintenance rather than as an isolated characteristic of a particular material.

Life-Cycle Carbon Assessment and Durability Evaluation

The third component establishes a systematic method for comparing the environmental and technical performance of alternative building systems. Life-cycle assessment (LCA) should consider relevant stages, including raw-material extraction, manufacturing, transportation, construction, maintenance, replacement, demolition, and end-of-life recovery. Operational energy and emissions should also be



assessed when relevant to the study's system boundary.

The evaluation should distinguish embodied carbon from operational carbon to avoid overlooking important sources of emissions. For example, a structural material with relatively low manufacturing emissions may require frequent replacement under severe moisture exposure, potentially increasing its cumulative life-cycle impacts. Conversely, a more durable material may offer long-term benefits if its production emissions and maintenance requirements remain reasonable.

A comparative assessment should therefore examine:

- Embodied carbon per clearly defined functional unit.
- Structural capacity and compliance with applicable engineering standards.
- Durability under expected temperature, moisture, wind, and flood conditions.
- Maintenance frequency, replacement requirements, and anticipated service life.
- Material transportation, local availability, and construction waste.
- Potential for reuse, recycling, or other appropriate end-of-life recovery.

Lucanto et al. (2024) connect digital prototyping and regenerative design with carbon-neutrality objectives and the assessment of multiple environmental risks. Their work provides a relevant foundation for evaluating material and design alternatives through integrated environmental and risk analysis. Shuvo (2021) further supports the inclusion of durability within low-carbon material characterization.

Digital Prototyping and Integrated Risk Assessment

The fourth component incorporates digital tools to improve the reliability of design decisions before construction begins. Building information modelling (BIM), digital prototyping, energy simulation, structural analysis, and climate-risk mapping can help compare alternative structural systems and identify potential weaknesses during the design process.

These tools can be used to model the performance of different material combinations under projected temperature conditions, rainfall intensity, wind loading, and flood exposure. Where reliable data are available, digital assessments can also estimate embodied carbon, maintenance requirements, and life-cycle costs. This enables designers to compare alternatives before committing to material procurement and construction.

Lucanto et al. (2024) provide a relevant reference for digital prototyping, regenerative design, and multi-scale assessment of environmental multi-risks. Kim (2017) also addresses integrated planning approaches for climate-resilient and low-carbon smart cities, supporting coordination between building design and broader urban development strategies.

However, digital assessments should use documented assumptions, suitable climate scenarios, and validated models. Their outputs should inform, rather than replace,

professional engineering judgment, site investigations, and compliance with applicable building codes.

Policy, Financing, and Implementation

The fifth component addresses the institutional and financial conditions required to implement the framework. Even where low-carbon and climate-resilient materials offer long-term benefits, adoption may be limited by higher initial costs, limited supply chains, insufficient technical expertise, fragmented building regulations, and uncertainty about performance.

Implementation should therefore combine performance-based building standards, embodied-carbon assessment requirements, resilient-design guidance, professional training, and procurement practices that consider whole-life value. Public authorities and developers can also support demonstration projects and locally appropriate material testing to establish confidence in alternative structural systems.

Kennedy and Corfee-Morlot (2012) examine the mobilization of investment in low-carbon, climate-resilient infrastructure, while Meltzer (2016) considers the role of climate finance and green financial systems in financing such infrastructure. These references support examining financing mechanisms alongside technical design. Potential mechanisms include green building loans, concessional finance, climate-related investment funds, and incentives for verified emissions reductions and resilience improvements.

At the planning level, Charoenkit and Kumar (2017) link low-carbon and disaster-resilient community development, while He and Prasad (2024) address sustainable, resilient, and low-carbon built environments. Cheshmehzangi and Chen (2021) provide further context for integrating low-carbon development and climate resilience into broader sustainability transitions. For health facilities, the World Health Organization (2023) offers an operational framework specifically addressing climate-resilient and low-carbon health systems.

Proposed Framework and Performance Indicators

The framework combines five interdependent stages: material screening, climate-risk assessment, life-cycle evaluation, integrated design optimization, and implementation monitoring. Performance should be measured through indicators that reflect both mitigation and adaptation outcomes.

The framework should be applied iteratively. Material selection may need to be revised when hazard analysis reveals unacceptable vulnerability, while life-cycle assessment may identify alternatives with lower overall emissions or costs. The preferred solution is therefore the material and design combination that meets applicable safety requirements while achieving a defensible balance between carbon reduction, climate resilience, durability, and affordability.

Overall, the proposed framework establishes a practical basis for coordinating material innovation, climate-responsive design, life-cycle performance, digital assessment,

Framework component	Principal activities	Suggested performance indicators
Material selection	Compare low-carbon concrete, recycled steel, engineered timber, and suitable local materials	Embodied carbon, strength, availability, durability
Climate-risk assessment	Identify site-specific hazards and exposure	Hazard vulnerability, expected damage, resilience measures
Life-cycle evaluation	Assess carbon emissions, maintenance, and replacement	Whole-life carbon, life-cycle cost, service life
Design optimization	Integrate structural engineering, passive design, and digital modelling	Structural compliance, thermal performance, modeled risk reduction
Implementation and monitoring	Apply standards, financing, construction quality control, and maintenance plans	Cost performance, material compliance, maintenance outcomes, verified emissions reductions

Source: Proposed synthesis based on Shuvo (2021), Bayeroju et al. (2023), Bailey et al. (2021), Jain (2023), He and Prasad (2024), and Lucanto et al. (2024). The indicators are proposed evaluation criteria, not reported experimental results.

and enabling policies. Its central principle is that successful low-carbon construction must reduce environmental impacts without compromising structural safety or the ability of buildings to withstand evolving climate hazards.

RESULTS, DISCUSSION, AND RECOMMENDATIONS

Results of Low-Carbon Structural Material Assessment

The assessment of climate-resilient building construction focuses on the relationship between embodied carbon, structural performance, durability, climate hazard resistance, and life-cycle cost. Low-carbon structural materials, including recycled steel, low-carbon concrete, supplementary cementitious materials, and engineered timber, offer opportunities to reduce the environmental impacts of construction when appropriately selected and applied.

However, their suitability depends on material availability, building requirements, exposure conditions, maintenance needs, and the quality of construction practices. Shuvo (2021) emphasizes the importance of characterizing sustainable materials to evaluate their contribution to low-carbon construction and infrastructure durability.

The findings should be interpreted through a combined mitigation and adaptation perspective. A material with relatively low embodied carbon may not provide the best long-term outcome if it deteriorates rapidly under moisture exposure, extreme temperatures, or repeated flooding. Conversely, a durable material that reduces repair and replacement requirements may improve whole-life environmental performance, provided that its initial production impacts are also considered. Bayeroju et al. (2023) support the need for resilient construction materials that respond to climate-adapted infrastructure requirements.

The comparative assessment should therefore consider both environmental performance and structural reliability.

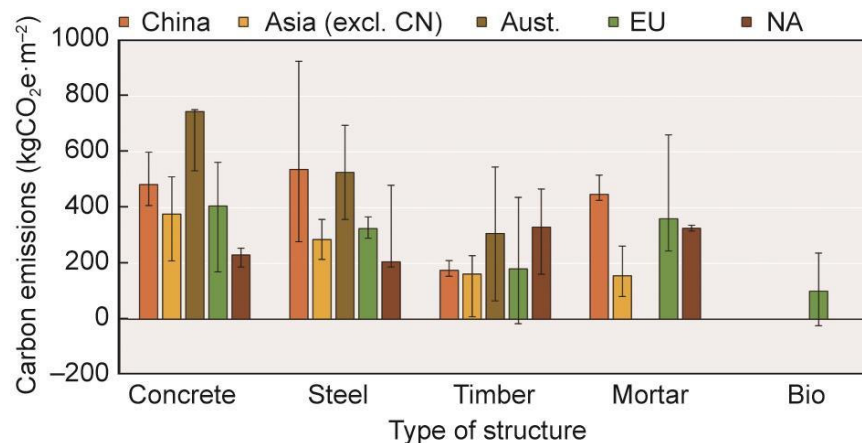


Fig 2: The graph presents published ranges of carbon-emission reductions for selected structural systems relative to the stated comparison systems. The reported ranges vary according to building design and height. Only carbon reduction is shown because comparable verified durability and climate-resilience scores were unavailable. Source: Building and Environment (2024), 251, Article 111195.



Table 4: Evaluation Matrix for Low-Carbon, Climate-Resilient Building Construction

Structural material or system	Embodied-carbon considerations	Structural performance and durability	Climate-resilience considerations	Implementation considerations
Low-carbon concrete	Potentially reduced emissions through cement substitution and optimized mix design	Requires verification of strength development, cracking, permeability, and long-term durability	Mix design and detailing should address flooding, moisture exposure, and temperature-related stresses	Availability of supplementary cementitious materials, quality control, curing, and applicable standards
Recycled steel	Potential emissions savings compared with primary steel, depending on production route and electricity source	High strength and potential for reuse; corrosion protection is important	Connections and protective systems should be designed for wind, moisture, and relevant hazard loads	Reliable recycled-steel supply, traceability, fabrication quality, and corrosion-control costs
Engineered timber	Potential carbon-storage benefits when sustainably sourced and assessed across the life cycle	Performance depends on product specification, connection design, moisture protection, and fire safety	Requires appropriate detailing against water ingress, humidity, severe weather, and fire exposure	Sustainable forestry, certification, specialist skills, treatment, and local supply chains
Reused or reclaimed structural components	May avoid some emissions associated with new material production	Suitability depends on verified condition, residual strength, and previous exposure	Components must be inspected and validated for the intended hazard conditions	Inspection, testing, certification, dimensional compatibility, and availability
Hybrid low-carbon structural systems	Potential to optimize carbon and resource use by combining complementary materials	Performance depends on compatibility, connection design, and coordinated maintenance	Can combine material strengths to address multiple hazards when properly engineered	More complex design coordination, lifecycle modelling, procurement, and construction oversight

Source: Author's synthesis based on Shuvo (2021), Bayeroju et al. (2023), Bailey et al. (2021), Jain (2023), and Zahra and Islam (2023). The matrix is qualitative; it does not represent measured comparative test results.

Low-carbon concrete formulations may reduce cement-related emissions, depending on their composition and production process, while recycled steel can reduce demand for primary steel production when recycling and manufacturing systems are appropriately managed. Engineered timber may offer carbon-storage benefits, but these depend on responsible sourcing, service life, fire safety, moisture control, and end-of-life treatment. These considerations align with the broader principles of climate-resilient and low-carbon built environments discussed by Jain (2023) and He and Prasad (2024).

Discussion of Climate Resilience and Material Performance

Climate resilience requires structural materials and building systems to withstand or recover from climate-related stresses without unacceptable loss of safety, functionality, or service life. Flooding can expose foundations and structural components to prolonged moisture, erosion, and contamination. Extreme heat can affect thermal comfort and the performance of some building materials, while intense rainfall and high winds can increase demands on roofs, connections, façades, and drainage systems.

Climate-responsive construction must consequently combine appropriate material selection with building orientation, passive cooling, moisture management, effective drainage, and hazard-specific structural detailing. Ajith et al. (2024) examine resilient design for climate-responsive buildings in warm and humid terrain, highlighting the relevance of climatic conditions to building design. Similarly, Bailey et al. (2021) address the relationship between climate resilience and building materials in the Caribbean, a context in which extreme weather exposure makes material durability and hazard resistance particularly important.

Sustainable architecture also requires the coordination of material innovation and design strategies. Zahra and Islam (2023) discuss improvements in sustainable architecture and building materials for climate-resilient infrastructure. These developments support an integrated approach in which material selection is not treated as an isolated decision but as part of a wider building-performance strategy. Charoenkit and Kumar (2017) further connect low-carbon construction with disaster-resilient community development, reinforcing the importance of considering emissions reduction and adaptation together.

Digital prototyping and environmental risk assessment can strengthen this integration by enabling designers to compare material combinations, test design alternatives, and identify potential vulnerabilities before construction. Lucanto et al. (2024) explore digital prototyping and regenerative design in relation to carbon neutrality and environmental multi-risk assessment. Such approaches can support evidence-based decisions, although their reliability depends on the quality of input data, modelling assumptions, and validation against actual material and building performance.

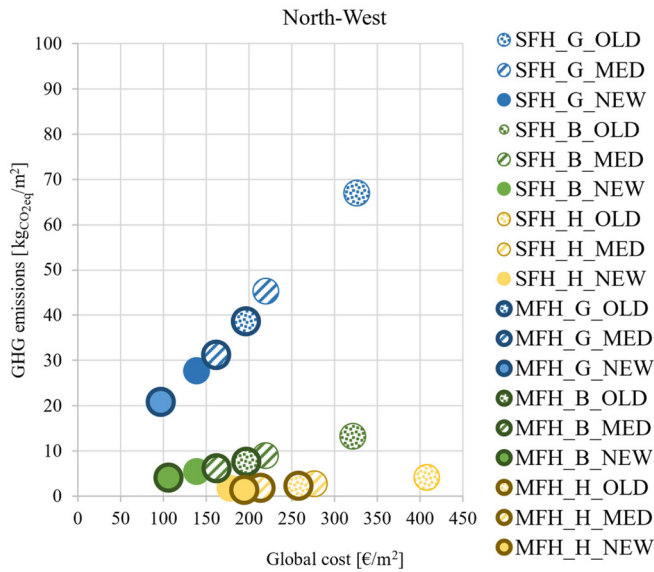


Fig 3: The graph presents the published life-cycle cost and global warming potential reported for a laminated veneer lumber (LVL) structural system in an Australian multi-storey apartment study. Error bars indicate the reported uncertainty. Because comparable data for other structural systems were unavailable, the result does not establish a comparative ranking. Source: Journal of Cleaner Production (2018), comparative life-cycle assessment of alternative structural frame materials.

The evaluation matrix indicates that no single material is universally optimal for all building types and climate conditions. Low-carbon concrete may be appropriate for foundations and other components requiring specific durability characteristics, while recycled steel may provide structural efficiency where reliable corrosion protection is available. Engineered timber and reclaimed components may offer additional environmental benefits when their technical suitability and sourcing can be demonstrated. Material decisions should therefore be based on verified performance requirements rather than environmental labels alone.

Life-Cycle Costs, Investment, and Implementation Barriers

The adoption of low-carbon, climate-resilient construction materials may involve higher initial costs associated with specialist design, material certification, testing, skilled labour, and supply-chain limitations. Nevertheless, an assessment limited to initial construction costs may overlook potential long-term savings from reduced maintenance, lower replacement frequency, improved energy performance, and reduced exposure to climate-related damage.

Kennedy and Corfee-Morlot (2012) examine investment mobilization for low-carbon, climate-resilient infrastructure, while Meltzer (2016) considers the role of climate finance and green financial systems. Their work provides a basis for

examining how financing mechanisms can help address the initial investment barriers associated with resilient and low-carbon infrastructure. Potential approaches include green lending, concessional finance, climate-related investment facilities, and procurement incentives tied to measurable environmental and resilience outcomes.

At the planning level, Kim (2017) presents an integrated approach to climate-resilient and low-carbon smart-city planning. Cheshmehzangi and Chen (2021) discuss low-carbon and climate-resilient sustainability transitions, providing a broader policy context for coordinating building-level interventions with long-term development goals. For healthcare buildings, the World Health Organization (2023) provides a framework linking climate resilience and low-carbon health systems, emphasizing the importance of protecting essential services while reducing environmental impacts.

Implementation should be supported by transparent performance standards, reliable material supply chains, professional training, and monitoring systems. Building owners and policymakers should also consider local climatic conditions, construction capacity, affordability, and maintenance resources when establishing material specifications.

RECOMMENDATIONS

The following recommendations emerge from the comparative assessment and literature review:

1. Adopt whole-life carbon assessment. Evaluate emissions from material extraction, manufacturing, transportation, construction, maintenance, replacement, and end-of-life treatment rather than relying exclusively on initial embodied carbon.
2. Integrate climate hazard assessment into material selection. Specify materials and structural systems according to site-specific risks, including flooding, extreme heat, heavy rainfall, high winds, and moisture exposure.
3. Strengthen material testing and quality assurance. Require appropriate verification of structural strength, durability, fire performance, corrosion resistance, and other relevant characteristics before deployment (Shuvo, 2021; Bayeroju et al., 2023).
4. Promote climate-responsive building design. Combine low-carbon structural materials with passive cooling, effective drainage, moisture management, and hazard-resistant detailing (Ajith et al., 2024; Zahra & Islam, 2023).
5. Expand green financing and incentives. Encourage financing mechanisms that recognize both emissions reductions and avoid climate-related losses, while ensuring that environmental claims are supported by credible evidence (Kennedy & Corfee-Morlot, 2012; Meltzer, 2016).
6. Use digital assessment tools. Apply digital prototyping and multi-risk modelling to compare design alternatives, evaluate lifecycle impacts, and identify potential performance weaknesses before construction (Lucanto et al., 2024).



7. Improve policy coordination and monitoring. Align building codes, procurement requirements, urban development plans, and sustainability objectives to support measurable progress toward climate-resilient, low-carbon construction (Kim, 2017; He & Prasad, 2024).

The overall assessment suggests that climate-resilient building construction requires coordinated decisions concerning materials, structural design, lifecycle performance, financing, and policy. Low-carbon materials can reduce construction-related emissions, but their contribution to resilience depends on appropriate specification, engineering, installation, and maintenance. The literature supports an integrated approach that evaluates both climate mitigation and adaptation rather than treating them as separate objectives (Charoenkit & Kumar, 2017; Jain, 2023; He & Prasad, 2024).

The proposed evaluation matrix and scatter graph provide a structured basis for comparing alternative material systems. However, quantitative conclusions about the magnitude of carbon savings, cost differences, and resilience improvements should be drawn only after collecting and analysing comparable empirical or published data. This approach supports more defensible material choices and strengthens the practical application of low-carbon, climate-resilient construction principles.

CONCLUSION

Climate-resilient building construction using low-carbon structural materials provides an important approach to reducing the environmental impacts of the built environment while strengthening buildings against climate-related hazards. The integration of materials such as low-carbon concrete, recycled steel, engineered timber, and supplementary cementitious materials can help reduce embodied carbon while maintaining structural safety, durability, and long-term performance. However, the suitability of each material depends on local climatic conditions, structural requirements, material availability, maintenance needs, and life-cycle environmental impacts. Shuvo (2021) emphasizes the importance of characterizing sustainable materials to support low-carbon construction and infrastructure durability, while Bayeroju et al. (2023) highlight the need for resilient construction materials that support climate-adapted infrastructure development.

The study further establishes that material selection alone is insufficient to achieve climate resilience. Effective outcomes require the integration of low-carbon materials with climate-responsive architectural design, hazard-resistant structural systems, moisture control, passive cooling, and appropriate site planning. These measures are particularly important in regions exposed to flooding, extreme heat, heavy rainfall, and strong winds. Bailey et al. (2021) demonstrate the relevance of integrating climate resilience and building-material considerations into efforts to develop lower-carbon and more resilient infrastructure. Similarly, Ajith et al. (2024) highlight

the importance of climate-responsive building design in warm and humid environments, while Zahra and Islam (2023) examine improvements in sustainable architecture and building materials for climate-resilient infrastructure.

Furthermore, whole-life assessment is essential for evaluating the actual sustainability of construction materials. Although some materials may have higher initial costs, their durability, reduced maintenance requirements, and lower environmental impacts over the building life cycle may provide long-term benefits. Digital prototyping and multi-scale environmental risk assessment can strengthen design decisions by helping construction professionals evaluate carbon emissions, material performance, and exposure to multiple environmental hazards (Lucanto et al., 2024). The broader integration of climate mitigation and adaptation into building development also supports the creation of sustainable communities and more resilient built environments (Charoenkit & Kumar, 2017; Jain, 2023).

Ultimately, climate-resilient construction requires a coordinated approach involving material innovation, structural engineering, environmental assessment, building regulation, financing, and professional collaboration. Integrating these elements can support safer, more resource-efficient, and lower-carbon buildings while contributing to wider sustainability and climate adaptation objectives (He & Prasad, 2024).

RECOMMENDATIONS

1. Promote the adoption of low-carbon structural materials. Governments, construction companies, and building professionals should encourage the use of low-carbon concrete, recycled steel, responsibly sourced engineered timber, and suitable supplementary cementitious materials. Selection should be based on verified embodied-carbon data, structural performance, durability, and local availability (Shuvo, 2021; Zahra & Islam, 2023).
2. Integrate climate-risk assessment into building design. Building projects should evaluate exposure to flooding, extreme temperatures, high winds, and heavy rainfall before selecting materials and structural systems. Climate-responsive design strategies should be adapted to local environmental conditions to improve building safety and long-term functionality (Bayeroju et al., 2023; Ajith et al., 2024).
3. Adopt whole-life carbon and cost assessment. Construction stakeholders should evaluate emissions from material production, transportation, construction, maintenance, replacement, and end-of-life management. Economic assessments should also consider long-term operational and maintenance costs rather than relying exclusively on initial construction expenditure (Jain, 2023; He & Prasad, 2024).
4. Strengthen building standards and sustainability policies. Regulatory authorities should incorporate measurable requirements for embodied carbon, structural durability, climate-hazard resistance, and resource efficiency into

building codes and procurement policies. These requirements should encourage construction practices that integrate climate mitigation with disaster preparedness (Charoenkit & Kumar, 2017; Kim, 2017).

5. Expand green financing and investment. Governments, financial institutions, and development partners should improve access to green loans, climate finance, and other appropriate financing mechanisms for low-carbon and climate-resilient construction. Financial support should prioritize projects that demonstrate credible emissions reductions and measurable resilience benefits (Kennedy & Corfee-Morlot, 2012; Meltzer, 2016).

6. Invest in research, innovation, and digital technologies. Universities, research institutions, and construction companies should conduct further studies on the long-term performance of low-carbon materials under changing climatic conditions. Digital prototyping, life-cycle assessment, and multi-hazard modelling should be used to compare alternative material systems and identify design weaknesses before construction begins (Lucanto et al., 2024).

7. Improve professional capacity and industry collaboration. Architects, engineers, contractors, material suppliers, policymakers, and sustainability specialists should receive training in low-carbon material selection, climate-responsive design, and resilient construction techniques. Collaboration across these groups can improve knowledge sharing and accelerate the adoption of sustainable construction practices (Bayeroju et al., 2023; He & Prasad, 2024).

8. Prioritize context-specific and socially inclusive construction. Material and design strategies should reflect local climatic conditions, affordability, construction skills, and access to resources. Lessons from climate-resilient infrastructure planning in the Caribbean and sustainable urban transitions should inform locally appropriate approaches rather than the indiscriminate adoption of standardized solutions (Bailey et al., 2021; Cheshmehzangi & Chen, 2021). For health facilities, these strategies should also support continuity of essential services under climate stress, consistent with the World Health Organization's (2023) Operational framework for building climate resilient and low carbon health systems.

FUTURE RESEARCH DIRECTIONS

Future research should prioritize empirical comparisons of low-carbon structural materials under different climatic conditions, particularly their long-term strength, durability, moisture resistance, and performance under repeated extreme-weather exposure. Further studies should also investigate the relationship between embodied-carbon reduction, life-cycle costs, and climate resilience across different building types. Comparative case studies, material testing, and digital simulations could help establish practical selection criteria for construction projects. In addition, research should examine how building regulations, green financing, local supply chains, and construction-industry capabilities influence the implementation of low-carbon

and climate-resilient solutions. These efforts would support more reliable evidence-based decisions and accelerate the transition toward a built environment that combines environmental responsibility, structural safety, and long-term resilience.

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