



Evolution of Green Building Concepts: From Energy Saving to Net Zero – A Review

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Abstract:

The building sector accounts for a substantial share of global energy consumption, greenhouse gas emissions, and natural resource depletion, making it central to achieving international climate and sustainability objectives. Over the last five decades, the philosophy of building design has evolved considerably—from a narrow emphasis on reducing operational energy consumption following the 1970s energy crisis to the contemporary ambition of developing Net Zero Energy Buildings (NZEBS), Net Zero Carbon Buildings (NZCBs), and regenerative buildings that generate positive environmental impacts. This review examines the historical evolution of green building concepts, highlighting the technological, environmental, policy, and socioeconomic factors that have shaped successive generations of sustainable building development.

Drawing upon recent literature, international policy frameworks, and global green building practices, the paper critically analyses the transition from energy-efficient buildings to sustainable buildings, high-performance buildings, green-certified buildings, carbon-neutral buildings, and finally net zero and regenerative buildings. The review further explores the development of international building rating systems including LEED, BREEAM, GRIHA, IGBC, Green Star, and EDGE, demonstrating their role in accelerating sustainable construction worldwide. Recent advances in digital technologies, Building Information Modelling (BIM), Artificial Intelligence (AI), Digital Twins, Internet of Things (IoT), renewable energy integration, smart grids, embodied carbon assessment, and life-cycle thinking are also discussed as critical enablers of next-generation green buildings.

The paper proposes an integrated conceptual framework illustrating the evolutionary pathway from energy conservation to climate-positive buildings while identifying the principal technological, environmental, economic, and policy drivers influencing this transition. Finally, emerging research directions involving circular economy principles, regenerative architecture, climate resilience, carbon-negative materials, and AI-enabled autonomous building management are presented. The review provides researchers, practitioners, policymakers, and industry professionals with a comprehensive understanding of how green building philosophies have evolved and where future sustainable construction is likely to progress.

Keywords: Green Buildings, Sustainable Buildings, Net Zero Energy Buildings, Net Zero Carbon Buildings, Energy Efficiency, Carbon Neutrality, Regenerative Buildings, Smart Buildings, Sustainable Construction and Building Performance.

1. Introduction

Buildings have historically been designed to satisfy functional requirements such as shelter, comfort, and economic efficiency. During much of the twentieth century, architectural practice paid relatively little attention to environmental consequences, resulting in increasing dependence on fossil fuels, intensive resource consumption, and growing greenhouse gas emissions. As urbanization accelerated worldwide, the construction sector emerged as one of the largest consumers of energy and raw materials.

Today, the built environment is responsible for approximately one-third of global energy demand and a significant share of energy-related carbon emissions, emphasizing its critical role in achieving international climate targets. Consequently, sustainable building practices have become central to national decarbonization strategies and the implementation of the Sustainable Development Goals (SDGs).

The evolution of green building concepts has occurred through several distinct phases. The first generation emphasized reducing energy consumption in response to the oil crises of the 1970s. During the 1980s and 1990s, growing awareness of environmental degradation expanded the focus toward sustainable development, integrating resource conservation, pollution reduction, and occupant health. Subsequently, green building rating systems formalized sustainability assessment by introducing standardized performance criteria.

The twenty-first century witnessed further transformation through high-performance buildings, smart buildings, and nearly zero-energy buildings. More recently, increasing concern regarding climate change has shifted attention beyond operational energy toward whole-life carbon emissions, embodied carbon, renewable energy integration, and regenerative design principles. Contemporary buildings are increasingly expected not merely to reduce environmental impacts but to restore ecosystems, improve biodiversity, and contribute positively to surrounding communities.

Several international agreements including the Paris Agreement, the European Green Deal, and national net-zero commitments have accelerated this transformation by promoting ambitious carbon reduction targets for the building sector. At the same time, rapid advances in digital technologies such as Artificial Intelligence, IoT, Building Information Modelling, Digital Twins, and predictive energy management have enabled buildings to become adaptive, intelligent, and increasingly autonomous.

Although numerous studies have investigated specific aspects of green buildings including energy efficiency, renewable technologies, or carbon-neutral design there remains a need for an integrated review tracing the complete evolution of green building concepts from their origins in energy conservation to today's holistic net-zero and regenerative paradigms. Existing literature often addresses these concepts independently, making it difficult to understand their historical progression, conceptual relationships, and future trajectory.

This review addresses this gap by synthesizing contemporary research into a unified framework that examines:

- the historical evolution of green building concepts;
- technological innovations driving sustainable construction;
- international policy developments;
- green building certification systems;
- emerging trends including AI-enabled smart buildings, circular economy principles, embodied carbon assessment, and regenerative design.

The findings provide a comprehensive foundation for future research and policy development aimed at achieving climate-neutral and resilient built environments.

2. Literature Review

2.1 Introduction

The evolution of green building concepts has attracted increasing scholarly attention over the past four decades, reflecting the growing urgency to address climate change, resource depletion, and rapid urbanization. Initially, research focused primarily on reducing operational energy consumption in buildings. However, contemporary literature recognizes buildings as complex socio-technical systems that influence environmental quality, economic development, public health, and social well-being. Consequently, green building research has shifted from isolated energy-efficiency measures toward holistic frameworks encompassing lifecycle sustainability, carbon neutrality, climate resilience, circular economy principles, and regenerative design.

Table 1. Representative Literature on the Evolution of Green Building Concepts

S. No.	Author(s)	Year	Paper Title	Major Contribution	Research Gap
1	Kibert, C. J.	2016	<i>Sustainable Construction: Green Building Design and Delivery</i>	Established the theoretical foundation of sustainable construction by integrating environmental, economic, and social sustainability principles into building design.	Limited emphasis on digital technologies and net-zero carbon concepts.
2	Ding, G. K. C.	2008	<i>Sustainable Construction-The Role of Environmental Assessment Tools</i>	Reviewed environmental assessment tools and highlighted the importance of performance-based evaluation in sustainable construction.	Focused primarily on environmental assessment rather than whole-life carbon reduction.
3	Zuo, J., & Zhao, Z. Y.	2014	<i>Green Building Research-Current Status and Future Agenda: A Review</i>	Comprehensive review of global green building research trends and future directions.	Limited discussion on emerging AI and smart building technologies.
4	Darko, A., Chan, A. P. C., et al.	2017	<i>Drivers for Green Building: A Review of Empirical Studies</i>	Identified economic, environmental, policy, and social drivers influencing green building adoption worldwide.	Did not examine Net Zero Energy Buildings in detail.
5	Darko, A., Chan, A. P. C.	2018	<i>Review of Barriers to Green Building Adoption</i>	Synthesized barriers including high costs, policy limitations, technological constraints, and stakeholder awareness.	Limited discussion of developing countries and carbon-neutral construction.
6	Pombo, O., Rivela, B., & Neila, J.	2016	<i>The Challenge of Sustainable Building Renovation</i>	Discussed sustainability improvements in existing buildings through renovation and retrofitting.	Limited focus on lifecycle carbon assessment.
7	Lu, Y., Wu, Z., Chang, R., & Li, Y.	2017	<i>Building Information Modelling (BIM) for Green Buildings: A Critical Review</i>	Demonstrated BIM as a key technology for sustainable building design, simulation, and lifecycle management.	AI-enabled building automation remained largely unexplored.

8	Azhar, S.	2011	<i>Building Information Modelling (BIM): Trends, Benefits, Risks, and Challenges</i>	Established BIM as an essential platform for sustainable project delivery and energy-efficient design.	Focused more on project management than net-zero buildings.
9	Attia, S.	2018	<i>Net Zero Energy Buildings: Design and Evaluation Methods</i>	Provided comprehensive methodologies for designing and evaluating Net Zero Energy Buildings.	Limited consideration of embodied carbon emissions.
10	Sartori, I., Napolitano, A., & Voss, K.	2012	<i>Net Zero Energy Buildings: A Consistent Definition Framework</i>	Developed internationally accepted definitions and classification of Net Zero Energy Buildings.	Carbon neutrality and circular economy were not addressed.
11	Fufa, S. M., et al.	2018	<i>Zero Emission Buildings-A Review of Concepts and Definitions</i>	Compared zero-energy, zero-carbon, and zero-emission building concepts.	Regenerative building principles were absent.
12	Pomponi, F., & Moncaster, A.	2016	<i>Embodied Carbon in Buildings: Measurement, Management, and Mitigation</i>	Highlighted the growing importance of embodied carbon in sustainable buildings.	Operational carbon remained the primary research focus.
13	Cabeza, L. F., et al.	2014	<i>Life Cycle Assessment of Buildings: State of the Art</i>	Reviewed lifecycle assessment methodologies for evaluating environmental impacts of buildings.	Limited integration with smart technologies.
14	World Green Building Council	2019	<i>Bringing Embodied Carbon Upfront</i>	Established global strategies for reducing embodied carbon throughout the building lifecycle.	Did not address AI-enabled building management systems.
15	International Energy Agency (IEA)	2023	<i>Buildings Sector-Global Status Report</i>	Reported recent trends in building energy consumption, carbon emissions, and decarbonization pathways.	Focused on global statistics rather than conceptual evolution.
16	UNEP	2023	<i>Global Status Report for Buildings and Construction</i>	Presented updated global building-sector emissions and policy recommendations toward net zero.	Limited discussion on regenerative architecture.
17	Cole, R. J.	2012	<i>Transitioning from Green to Regenerative Design</i>	Introduced regenerative design as the next evolution beyond green buildings.	Lacked practical implementation frameworks.
18	Mang, P., & Reed, B.	2012	<i>Designing from Place: A Regenerative Framework</i>	Proposed ecological restoration as the future direction of sustainable buildings.	Limited empirical validation across different climatic regions.

19	Kibert, C. J.	2022	<i>Sustainable Construction: Green Building Design and Delivery (5th Edition)</i>	Updated sustainable construction concepts by integrating circular economy, resilience, and net-zero principles.	More practical case studies are needed from developing countries.
20	Chastas, P., Theodosiou, T., & Bikas, D.	2016	<i>Embodied Energy in Residential Buildings Towards Nearly Zero Energy Buildings</i>	Demonstrated the increasing significance of embodied energy in nearly zero-energy buildings.	Did not incorporate regenerative design or AI-based optimization.

Critical Analysis of Existing Literature

The reviewed studies reveal a clear evolution in green building research over the last four decades. Early research primarily focused on improving operational energy efficiency through passive design strategies, enhanced insulation, and energy-efficient building systems (Kibert, 2016; Ding, 2008). Following the emergence of sustainable development principles, researchers expanded the scope of building performance to include environmental protection, resource conservation, indoor environmental quality, and lifecycle sustainability (Zuo & Zhao, 2014).

The introduction of green building certification systems such as LEED, BREEAM, GRIHA, and IGBC accelerated global adoption of sustainable construction practices by providing standardized performance assessment frameworks. More recent studies have shifted toward high-performance buildings, emphasizing intelligent energy management, Building Information Modelling (BIM), Artificial Intelligence (AI), Internet of Things (IoT), and Digital Twins for optimizing operational efficiency (Lu et al., 2017; Azhar, 2011).

Contemporary literature increasingly recognizes that operational energy reduction alone is insufficient to achieve long-term climate goals. Consequently, embodied carbon, lifecycle carbon assessment, circular economy principles, and regenerative design have emerged as major research priorities (Pomponi & Moncaster, 2016; World Green Building Council, 2019). The latest studies advocate transitioning from minimizing environmental impacts to creating climate-positive and regenerative buildings that restore ecological systems while achieving net-zero carbon emissions (Cole, 2012; Mang & Reed, 2012).

Research Gap:

Despite significant progress, existing literature remains fragmented. Most studies examine energy efficiency, green certification, embodied carbon, or digital technologies independently. There is a lack of comprehensive reviews integrating the historical evolution from energy-saving buildings to net-zero and regenerative buildings within a single conceptual framework. This paper addresses that gap by synthesizing technological, environmental, policy, and lifecycle perspectives into a unified evolutionary model.

3. Evolution of Green Building Concepts: From Energy Saving to Net Zero

3.1 Introduction

The evolution of green building concepts reflects a continuous transformation in architectural philosophy, environmental awareness, technological innovation, and sustainability policy. During the past five

decades, the objectives of sustainable buildings have shifted from minimizing energy consumption to achieving carbon neutrality and environmental regeneration. This transformation has been influenced by global energy crises, environmental legislation, climate change commitments, rapid technological advancement, and increasing awareness of lifecycle sustainability.

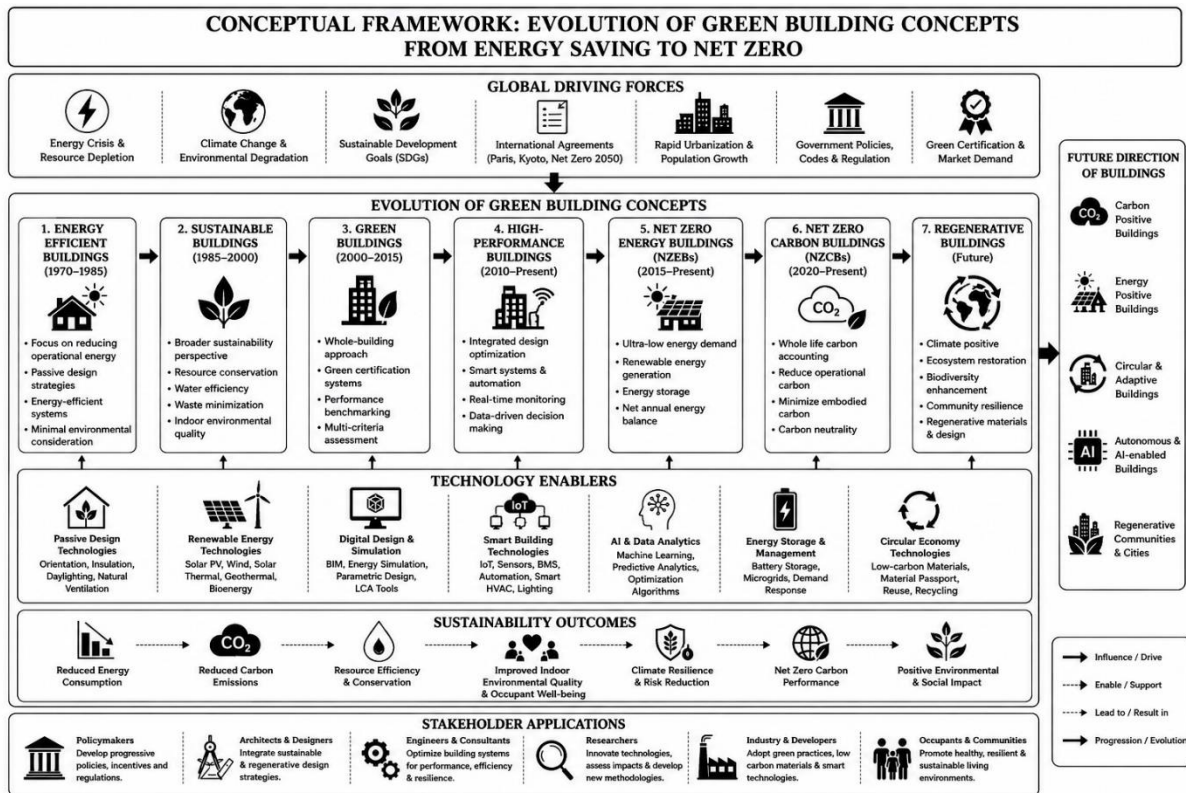
Initially, buildings were designed primarily to reduce operational energy demand through passive architectural strategies and energy-efficient technologies. However, growing recognition of resource depletion, greenhouse gas emissions, and climate change expanded the scope of sustainable construction beyond energy efficiency. Modern green buildings are now expected to minimize environmental impacts throughout their entire lifecycle while simultaneously improving occupant health, resilience, economic performance, and ecological restoration.

The evolutionary pathway of green buildings can be divided into seven major developmental phases (Table 2).

Table 2. Evolution of Green Building Concepts

Phase	Period	Primary Objective	Key Features	Representative Technologies
Energy-Efficient Buildings	1970–1985	Reduce operational energy	Passive solar design, insulation, daylighting	Thermal insulation, efficient HVAC
Sustainable Buildings	1985–2000	Balance environmental, social, and economic sustainability	Water conservation, waste reduction, lifecycle thinking	Sustainable materials, rainwater harvesting
Green Buildings	2000–2015	Improve overall environmental performance	Green certification, resource efficiency, IEQ	LEED, BREEAM, GRIHA, IGBC
High-Performance Buildings	2010–Present	Optimize operational performance	Smart systems, monitoring, automation	BIM, IoT, AI, Digital Twins
Net Zero Energy Buildings	2015–Present	Achieve energy neutrality	Renewable energy integration	Solar PV, geothermal, battery storage
Net Zero Carbon Buildings	2020–Present	Eliminate lifecycle carbon emissions	Embodied carbon reduction, circular construction	LCA tools, low-carbon materials
Regenerative Buildings	Emerging	Create positive environmental impacts	Ecosystem restoration, resilience	Carbon-sequestering materials, nature-based solutions

4. Conceptual Framework



4.1 Framework Overview

The proposed conceptual framework synthesizes the evolutionary progression of green building concepts from energy-efficient buildings to Net Zero and regenerative buildings. It integrates insights from the reviewed literature to explain how sustainability objectives have gradually expanded in response to technological innovations, environmental challenges, and policy developments. Unlike conventional frameworks that focus on a single aspect of sustainable construction, the proposed model presents a holistic view by illustrating the sequential transition of building philosophies over the past five decades. The framework assumes that each stage of development builds upon the achievements of the previous stage while introducing broader environmental objectives and more advanced technological solutions. Beginning with energy conservation, the framework progresses through sustainable and green buildings, followed by high-performance buildings, Net Zero Energy Buildings (NZEBS), Net Zero Carbon Buildings (NZCBs), and finally regenerative buildings. This progression reflects the transformation of the construction industry from minimizing environmental impacts to creating buildings that actively contribute to ecological restoration and climate resilience.

4.2 Driving Forces Behind the Evolution of Green Buildings

The evolution of green building concepts has been driven by several interconnected global forces. The energy crises of the 1970s initiated widespread efforts to improve building energy efficiency by reducing dependence on fossil fuels. Subsequently, increasing awareness of climate change, resource depletion, and environmental degradation broadened the sustainability agenda beyond operational energy savings. International agreements such as the Kyoto Protocol, the Paris Agreement, and the United Nations Sustainable Development Goals (SDGs) have further accelerated the adoption of sustainable building

practices by encouraging countries to reduce greenhouse gas emissions and promote low-carbon infrastructure. Rapid urbanization, increasing energy demand, and growing concerns regarding indoor environmental quality have also motivated governments and industry stakeholders to adopt more comprehensive green building strategies. Simultaneously, the development of green building certification systems, including LEED, BREEAM, GRIHA, and IGBC, has established standardized sustainability benchmarks, enabling organizations to evaluate and improve the environmental performance of buildings.

4.3 Technological Evolution Supporting Green Buildings

Technological advancement has been one of the most significant enablers of green building evolution. Early energy-efficient buildings primarily relied on passive architectural strategies such as building orientation, natural ventilation, thermal insulation, and daylight utilization. As sustainability objectives expanded, renewable energy technologies including solar photovoltaic systems, wind energy, geothermal heat pumps, and energy storage systems became integral components of sustainable buildings. The emergence of digital technologies has further transformed building performance by enabling intelligent monitoring and real-time optimization. Building Information Modelling (BIM), Artificial Intelligence (AI), Internet of Things (IoT), Digital Twins, smart sensors, and advanced building automation systems have significantly improved operational efficiency, predictive maintenance, and energy management. More recently, lifecycle assessment tools, embodied carbon analysis, and circular construction technologies have facilitated the transition from energy-efficient buildings to Net Zero Carbon Buildings. These technological innovations have collectively enabled buildings to become increasingly intelligent, adaptive, and environmentally responsible throughout their entire lifecycle.

4.4 Sustainability Outcomes Across the Evolutionary Stages

As green building concepts have evolved, the expected sustainability outcomes have become progressively broader and more comprehensive. Early building designs primarily targeted reductions in operational energy consumption and associated costs. Sustainable and green buildings subsequently expanded their focus to include water conservation, efficient material utilization, waste minimization, indoor environmental quality, and occupant health. High-performance buildings introduced continuous optimization through intelligent monitoring systems and data-driven decision-making. The emergence of Net Zero Energy Buildings shifted the emphasis toward balancing annual energy consumption with renewable energy generation, while Net Zero Carbon Buildings incorporated lifecycle carbon accounting by addressing both operational and embodied emissions. The most recent concept of regenerative buildings extends beyond minimizing environmental harm by promoting biodiversity restoration, ecosystem regeneration, carbon sequestration, climate resilience, and positive environmental impacts. Consequently, sustainability has evolved from a resource-efficiency perspective to a holistic framework integrating environmental, economic, social, and ecological dimensions.

4.5 Future Direction of Green Building Development

The future evolution of green buildings is expected to be shaped by advances in digitalization, circular economy principles, climate adaptation, and regenerative design. Emerging research increasingly focuses on autonomous buildings capable of self-learning through Artificial Intelligence and Digital Twins, enabling real-time optimization of energy consumption, indoor environmental quality, and maintenance activities. Simultaneously, growing interest in carbon-negative materials, modular construction, material

passports, and circular resource flows is promoting the development of buildings with significantly reduced lifecycle environmental impacts. Future buildings are expected not only to achieve Net Zero Energy and Net Zero Carbon performance but also to generate surplus renewable energy, capture atmospheric carbon, restore biodiversity, improve local ecosystems, and strengthen community resilience. This transition signifies a paradigm shift from conventional sustainability approaches toward regenerative built environments that actively contribute to environmental restoration while supporting human health, economic prosperity, and long-term climate neutrality.

5. Methodology

5.1 Research Design

This study adopts a systematic narrative review approach to examine the evolution of green building concepts from energy-efficient buildings to Net Zero and regenerative buildings. The review integrates multidisciplinary literature from architecture, civil engineering, environmental science, construction management, energy engineering, and sustainability studies. Unlike empirical studies that rely on primary data collection, this research synthesizes existing knowledge to provide a comprehensive understanding of the historical development, technological evolution, policy influences, and future directions of green building concepts. The systematic review approach enables the identification of recurring themes, emerging trends, research gaps, and conceptual relationships across diverse scholarly publications.

5.2 Literature Search Strategy

A comprehensive literature search was conducted using internationally recognized scientific databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, Taylor & Francis Online, Wiley Online Library, IEEE Xplore, MDPI, and Google Scholar. These databases were selected because they contain high-quality peer-reviewed publications covering sustainable construction, energy-efficient buildings, environmental engineering, and smart building technologies. The search primarily focused on publications published between 2005 and 2026, while seminal studies published before 2005 were also included to capture the historical evolution of green building concepts.

A combination of Boolean operators and keyword strings was employed to maximize the retrieval of relevant studies. The principal search terms included *green buildings*, *sustainable buildings*, *energy-efficient buildings*, *high-performance buildings*, *Net Zero Energy Buildings*, *Net Zero Carbon Buildings*, *regenerative buildings*, *building sustainability*, *building lifecycle assessment*, *embodied carbon*, *renewable energy integration*, *Building Information Modelling*, *Artificial Intelligence in buildings*, *Digital Twins*, and *circular economy in construction*. Additional references were identified through backward and forward citation tracking of highly cited publications.

5.3 Study Selection and Eligibility Criteria

The retrieved publications were screened using predefined inclusion and exclusion criteria to ensure the relevance and quality of the reviewed literature. Only peer-reviewed journal articles, review papers, conference proceedings, international reports, and recognized policy documents published in English were considered. Particular emphasis was placed on studies discussing the evolution of green building concepts, sustainable building technologies, lifecycle assessment, energy performance, carbon neutrality, and regenerative design. Publications focusing exclusively on unrelated construction topics or lacking sufficient methodological rigor were excluded. Duplicated records retrieved from multiple databases were

removed during the screening process. After applying the eligibility criteria, the selected studies formed the basis for thematic synthesis and conceptual analysis.

5.4 Data Analysis and Synthesis

The selected literature was analysed using a thematic content analysis approach. Initially, each publication was examined to identify its primary research objectives, methodologies, major findings, technological focus, sustainability dimensions, and reported research gaps. Similar concepts were subsequently grouped into thematic categories representing successive stages in the evolution of green building concepts. These themes included energy-efficient buildings, sustainable buildings, green buildings, high-performance buildings, Net Zero Energy Buildings, Net Zero Carbon Buildings, and regenerative buildings. The synthesis process also examined cross-cutting technological developments, including renewable energy integration, Building Information Modelling, Artificial Intelligence, Internet of Things, Digital Twins, lifecycle assessment, embodied carbon evaluation, and circular economy principles. The resulting thematic relationships were integrated into the conceptual framework proposed in this review.

5.5 Reliability, Limitations and Framework Development

To enhance the reliability of the review, evidence was synthesized from multiple high-quality academic databases and internationally recognized reports published by organizations such as the International Energy Agency (IEA), United Nations Environment Programme (UNEP), World Green Building Council (WGBC), and the International Organization for Standardization (ISO). Cross-verification of findings across different sources helped reduce publication bias and improve the robustness of the proposed conceptual framework. Nevertheless, the review has certain limitations. The analysis is restricted to English-language publications and primarily relies on secondary literature, which may exclude valuable regional studies published in other languages. Furthermore, rapidly evolving technologies such as Artificial Intelligence, Digital Twins, and carbon-negative construction materials continue to develop, requiring periodic updates to maintain the framework's relevance. Despite these limitations, the adopted methodology provides a comprehensive and reliable synthesis of current knowledge and establishes a strong theoretical foundation for future empirical research on green building evolution.

Table 3. Summary of the Review Methodology

Component	Description
Research Design	Systematic narrative literature review
Data Sources	Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley, Taylor & Francis, IEEE Xplore, MDPI, Google Scholar
Publication Period	Primarily 2005–2026 (with seminal earlier studies included)
Keywords	Green Buildings, Sustainable Buildings, NZEB, NZCB, Regenerative Buildings, BIM, AI, IoT, Embodied Carbon, Circular Economy
Document Types	Peer-reviewed journal articles, review papers, conference papers, international reports, policy documents
Selection Criteria	Relevance to green building evolution, sustainability, energy efficiency, lifecycle assessment, carbon neutrality, and regenerative design

Analysis Method	Thematic content analysis and conceptual synthesis
Outcome	Development of an integrated conceptual framework describing the evolution from energy-saving buildings to Net Zero and regenerative buildings

6. Discussion

6.1 Evolution of Green Building Concepts: A Paradigm Shift

The evolution of green building concepts demonstrates a significant paradigm shift in the philosophy of sustainable construction. The literature indicates that early building designs primarily focused on reducing operational energy consumption through passive architectural strategies and energy-efficient technologies. However, increasing concerns regarding climate change, environmental degradation, and resource depletion have progressively expanded the objectives of sustainable buildings beyond energy conservation. Contemporary green buildings are now expected to minimize environmental impacts throughout their entire lifecycle while simultaneously improving occupant health, economic performance, social well-being, and ecosystem resilience.

The review reveals that each evolutionary stage has introduced broader sustainability objectives rather than replacing previous concepts. Energy-efficient buildings laid the foundation for reducing operational energy demand, while sustainable buildings incorporated environmental, economic, and social dimensions. Green buildings subsequently introduced standardized certification systems that enabled objective performance assessment. More recently, high-performance buildings have emphasized intelligent operational optimization using digital technologies, whereas Net Zero Energy Buildings and Net Zero Carbon Buildings have expanded sustainability targets to include renewable energy generation, lifecycle carbon reduction, and climate neutrality. The emergence of regenerative buildings represents the latest stage in this evolution by promoting ecological restoration, biodiversity enhancement, and positive environmental contributions rather than simply reducing negative impacts.

6.2 Role of Technological Innovation in Green Building Evolution

One of the most significant findings of this review is the transformative role of technological innovation in advancing green building concepts. Earlier generations of sustainable buildings relied predominantly on passive architectural design, high-performance insulation, efficient lighting systems, and improved heating and cooling technologies. While these measures substantially reduced operational energy consumption, they were limited in their ability to continuously optimize building performance.

Recent advances in digital technologies have fundamentally transformed building operation and management. Building Information Modelling (BIM) has enabled integrated design and lifecycle management, while Artificial Intelligence (AI), the Internet of Things (IoT), Digital Twins, and smart sensors facilitate real-time monitoring, predictive maintenance, and intelligent energy optimization. These technologies allow buildings to respond dynamically to changing environmental conditions and occupant behaviour, thereby improving operational efficiency and reducing lifecycle costs. Furthermore, advances in renewable energy technologies, battery storage systems, and smart grids have made it increasingly feasible to achieve Net Zero Energy performance. Simultaneously, lifecycle assessment software and embodied carbon assessment tools have improved decision-making regarding low-carbon construction materials and circular resource utilization. Collectively, these technological innovations have accelerated

the transition from conventional green buildings to intelligent, autonomous, and climate-neutral built environments.

6.3 Transition from Operational Energy Efficiency to Lifecycle Carbon Neutrality

The review demonstrates that one of the most important conceptual developments in recent years has been the transition from operational energy efficiency to whole-life carbon neutrality. Earlier research largely evaluated building sustainability based on operational energy consumption, overlooking the environmental impacts associated with material production, construction processes, maintenance, renovation, and end-of-life demolition. However, recent studies emphasize that embodied carbon constitutes a substantial proportion of total lifecycle emissions, particularly in highly energy-efficient buildings where operational energy demand has already been minimized.

This realization has led to the emergence of Net Zero Carbon Buildings, which incorporate both operational and embodied carbon reduction strategies. The adoption of lifecycle assessment (LCA), Environmental Product Declarations (EPDs), low-carbon concrete, recycled steel, engineered timber, and circular construction principles reflects this broader perspective on sustainability. Consequently, the evaluation of building performance has shifted from annual energy balances to comprehensive lifecycle environmental assessments. This transition highlights the growing importance of integrating material selection, resource efficiency, and circular economy principles into sustainable building design and operation.

6.4 Emerging Trends and Future Opportunities

The literature suggests that the future of green building development will be characterized by increasing digitalization, climate resilience, and regenerative design. Artificial Intelligence and Digital Twins are expected to enable autonomous building management systems capable of continuously optimizing energy consumption, indoor environmental quality, predictive maintenance, and occupant comfort. Simultaneously, the integration of blockchain technology, cloud computing, and big data analytics may improve transparency in carbon accounting, material traceability, and sustainability reporting.

Another emerging trend involves the adoption of circular economy principles, which encourage material reuse, adaptive building design, modular construction, and waste minimization throughout the building lifecycle. Carbon-negative construction materials, bio-based composites, and nature-based solutions are also expected to play an increasingly important role in achieving climate-positive buildings. Beyond individual buildings, researchers are extending sustainability concepts toward regenerative communities, positive-energy districts, and smart sustainable cities where buildings interact intelligently with transportation systems, renewable energy networks, and urban ecosystems. These developments indicate that future green buildings will function as integrated components of resilient urban infrastructure rather than isolated structures.

6.5 Research Gaps and Future Research Directions

Despite substantial progress in green building research, several important knowledge gaps remain. First, there is no universally accepted definition or assessment methodology for Net Zero Carbon Buildings, leading to inconsistencies in carbon accounting across different countries and certification systems. Second, although Artificial Intelligence and Digital Twins have demonstrated considerable potential for optimizing building performance, empirical evidence regarding their long-term operational effectiveness

remains limited. Third, embodied carbon assessment methodologies require further refinement to improve consistency, comparability, and practical implementation during the early stages of building design. The review also identifies limited research on regenerative buildings, particularly regarding quantitative performance indicators, ecosystem service valuation, and biodiversity assessment. Additionally, most existing studies have been conducted in developed economies, whereas evidence from developing countries remains relatively scarce despite their rapidly expanding construction sectors. Future research should therefore focus on developing standardized assessment frameworks for regenerative buildings, integrating AI-driven decision-support systems with lifecycle sustainability assessment, investigating circular economy strategies in construction, and evaluating the long-term environmental, economic, and social impacts of Net Zero and regenerative buildings under diverse climatic and socio-economic conditions.

Table 4. Critical Discussion of the Evolution of Green Building Concepts

Evolutionary Stage	Primary Focus	Major Achievements	Remaining Challenges	Future Research Opportunities
Energy-Efficient Buildings	Operational energy reduction	Passive design, efficient HVAC, daylighting	Limited environmental perspective	Integration with renewable energy systems
Sustainable Buildings	Triple-bottom-line sustainability	Water conservation, material efficiency, lifecycle thinking	Lack of standardized performance evaluation	Holistic sustainability assessment
Green Buildings	Environmental certification	LEED, BREEAM, GRIHA, IGBC adoption	High certification costs and regional variation	Harmonization of certification systems
High-Performance Buildings	Intelligent operational optimization	BIM, IoT, AI, Digital Twins, automation	Cybersecurity, interoperability, implementation costs	AI-enabled autonomous building management
Net Zero Energy Buildings	Annual energy balance	Renewable energy integration, energy storage	Grid dependency and renewable intermittency	Smart grids and community energy systems
Net Zero Carbon Buildings	Lifecycle carbon neutrality	Embodied carbon reduction, lifecycle assessment	Lack of universal carbon accounting standards	Standardized carbon assessment frameworks
Regenerative Buildings	Positive environmental impact	Biodiversity restoration, ecosystem enhancement, carbon sequestration	Limited practical implementation and assessment metrics	Regenerative urban districts and climate-positive communities

7. Conclusion and Future Research Directions

7.1 Conclusion

The evolution of green building concepts reflects one of the most significant transformations in the construction industry's approach to sustainability over the past five decades. This review demonstrates that sustainable building philosophies have evolved progressively from an initial focus on operational energy conservation to comprehensive frameworks encompassing lifecycle sustainability, carbon neutrality,

digital intelligence, and environmental regeneration. Rather than representing isolated developments, each stage of evolution has expanded the scope of sustainable construction by integrating new environmental objectives, technological innovations, and policy interventions.

The review highlights seven major evolutionary stages: energy-efficient buildings, sustainable buildings, green buildings, high-performance buildings, Net Zero Energy Buildings (NZEBS), Net Zero Carbon Buildings (NZCBs), and regenerative buildings. Early research primarily emphasized reducing operational energy demand through passive design strategies and energy-efficient building systems. Subsequently, sustainable and green building concepts incorporated broader environmental considerations, including water conservation, material efficiency, indoor environmental quality, and lifecycle thinking. The introduction of internationally recognized certification systems such as LEED, BREEAM, GRIHA, and IGBC further accelerated the adoption of sustainable construction practices by providing standardized performance assessment frameworks.

The review also demonstrates that technological innovation has become a fundamental driver of green building evolution. Advances in Building Information Modelling (BIM), Artificial Intelligence (AI), Internet of Things (IoT), Digital Twins, smart sensors, renewable energy systems, and lifecycle assessment tools have enabled buildings to become increasingly intelligent, adaptive, and resource-efficient. These technologies have facilitated the transition from conventional energy-efficient buildings to high-performance buildings capable of real-time performance optimization and predictive energy management. One of the most significant findings of this review is the growing importance of lifecycle carbon assessment. While early sustainable building strategies primarily focused on operational energy consumption, contemporary research recognizes embodied carbon associated with construction materials as a major contributor to total building emissions. Consequently, Net Zero Carbon Buildings have emerged as a more comprehensive sustainability paradigm by integrating operational and embodied carbon reduction strategies. Furthermore, regenerative buildings extend beyond carbon neutrality by promoting biodiversity enhancement, ecosystem restoration, climate resilience, and positive environmental impacts, representing the next frontier in sustainable construction.

The proposed conceptual framework developed in this review integrates these evolutionary stages into a unified model, illustrating the relationships among global sustainability drivers, technological innovations, policy mechanisms, sustainability outcomes, and future building paradigms. By synthesizing fragmented literature into a coherent evolutionary framework, this study contributes to a deeper theoretical understanding of how green building concepts have developed and where future research and industry practices are likely to progress.

7.2 Theoretical Contributions

This review makes several important theoretical contributions to the green building literature. First, it presents a comprehensive evolutionary perspective by integrating diverse building concepts that have often been examined independently in previous studies. Second, it proposes a conceptual framework that illustrates the sequential progression from energy-efficient buildings to regenerative buildings, thereby providing a structured theoretical foundation for understanding sustainable building evolution. Third, the review highlights the increasingly interconnected roles of digital technologies, renewable energy systems, lifecycle assessment, and circular economy principles in shaping future building development. Finally, the study identifies emerging relationships between technological innovation and sustainability outcomes that may guide future conceptual and empirical investigations.

7.3 Practical Implications

The findings of this review offer several practical implications for policymakers, architects, engineers, construction professionals, and urban planners. Policymakers may use the proposed framework to develop progressive building regulations that encourage the transition toward Net Zero Carbon and regenerative buildings. Architects and designers can adopt integrated design strategies that combine passive architectural principles, renewable energy systems, and digital technologies throughout the building lifecycle. Engineers and facility managers may utilize Artificial Intelligence, Digital Twins, and smart building management systems to optimize operational efficiency, predictive maintenance, and carbon performance. Construction companies can support sustainable development through greater adoption of low-carbon materials, circular construction practices, and lifecycle carbon assessment methodologies. Collectively, these stakeholders play an essential role in accelerating the transformation of the built environment toward climate neutrality and long-term sustainability.

7.4 Limitations of the Review

Despite providing a comprehensive synthesis of current knowledge, this review has several limitations. The analysis was limited to English-language publications indexed in major academic databases and internationally recognized reports, which may have excluded valuable studies published in other languages or regional sources. Additionally, because this study relies exclusively on secondary literature, the proposed conceptual framework has not been empirically validated using primary data. Emerging technologies such as Artificial Intelligence, Digital Twins, blockchain-enabled building management, and carbon-negative construction materials continue to evolve rapidly, meaning that future technological developments may require refinement of the framework presented in this review. Furthermore, differences in national regulations, climatic conditions, and certification systems may influence the applicability of certain findings across different geographical contexts.

7.5 Future Research Directions

Although significant progress has been achieved in sustainable building research, numerous opportunities remain for future investigation. Future studies should focus on developing standardized international frameworks for assessing Net Zero Carbon Buildings and regenerative buildings, particularly with respect to lifecycle carbon accounting and ecosystem performance indicators. Greater empirical research is required to evaluate the long-term effectiveness of Artificial Intelligence, Internet of Things, Digital Twins, and autonomous building management systems under real operational conditions. Researchers should also investigate the integration of circular economy principles, modular construction, adaptive reuse strategies, and material passports into sustainable building practices.

Another promising research direction involves the development of carbon-negative construction materials capable of actively removing atmospheric carbon while maintaining structural performance. Additionally, future investigations should examine positive-energy districts, climate-resilient communities, and regenerative urban ecosystems rather than focusing solely on individual buildings. Comparative international studies involving developed and developing countries would further improve understanding of how regional policies, economic conditions, and climatic characteristics influence the successful implementation of Net Zero and regenerative building concepts. Finally, interdisciplinary collaboration among architects, engineers, environmental scientists, data scientists, and policymakers will be essential

for addressing the complex challenges associated with achieving climate-neutral and regenerative built environments.

Table 5. Summary of Key Findings and Future Research Agenda

Research Dimension	Key Findings	Future Research Priorities
Evolution of Green Building Concepts	Progression from energy-efficient buildings to regenerative buildings	Develop universally accepted conceptual models and assessment frameworks
Technological Innovation	BIM, AI, IoT, Digital Twins, and renewable energy systems are transforming building performance	Evaluate long-term operational effectiveness of intelligent building technologies
Carbon Management	Shift from operational energy efficiency to whole-life carbon neutrality	Standardize lifecycle carbon assessment and embodied carbon accounting
Sustainability Assessment	Green certification systems have improved environmental performance measurement	Harmonize international green building certification methodologies
Circular Economy	Material reuse, adaptive design, and low-carbon construction are becoming increasingly important	Integrate circular economy principles into mainstream building design and operation
Regenerative Buildings	Buildings are evolving toward positive environmental and ecological contributions	Develop measurable indicators for biodiversity, ecosystem restoration, and climate-positive buildings
Policy and Governance	International agreements have accelerated sustainable construction	Investigate policy mechanisms supporting Net Zero and regenerative built environments

This review provides a comprehensive synthesis of the historical evolution, technological advancements, policy drivers, and future trajectory of green building concepts. By integrating fragmented literature into a unified conceptual framework, it offers a valuable reference for researchers, practitioners, policymakers, and industry professionals seeking to understand the transition from energy-saving buildings to Net Zero and regenerative built environments. The proposed framework establishes a foundation for future theoretical development and empirical research while supporting the global transition toward resilient, intelligent, and climate-positive cities.

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