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Integration of Green Building Materials and Circular Design Principles for Sustainable Architectural Development

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ABSTRACT :

The growing environmental impacts associated with conventional construction practices have increased the need for sustainable architectural approaches that minimize resource depletion, waste generation, and carbon emissions. This study examines the integration of green building materials and circular design principles as strategies for promoting sustainable architectural development. Green building materials, including recycled, locally sourced, renewable, low-carbon, and responsibly manufactured materials, can reduce the environmental footprint of buildings while improving resource efficiency and indoor environmental quality. Circular design principles complement these approaches by emphasizing material durability, adaptability, reuse, repair, disassembly, and recovery throughout the building life cycle. The study evaluates how the combined application of these strategies can contribute to waste reduction, energy efficiency, embodied-carbon reduction, and improved material resource management in architectural practice. Particular attention is given to design strategies that facilitate material recovery and reuse at the end of a building's service life, thereby reducing dependence on virgin resources and minimizing construction and demolition waste. The study further highlights the importance of life-cycle assessment, material selection, modular construction, and design for disassembly in achieving circular and environmentally responsible buildings. The findings indicate that integrating green materials with circular design principles can provide a comprehensive framework for reducing environmental impacts while supporting economically and socially sustainable architectural development. The study concludes that architects, engineers, developers, manufacturers, and policymakers should adopt coordinated approaches that embed circularity and environmental performance into building design, construction, operation, renovation, and eventual deconstruction. Such integration can strengthen the transition toward resilient, resource-efficient, and low-carbon built environments.

Keywords: Green Building Materials; Circular Design; Sustainable Architecture; Life-Cycle Assessment; Resource Efficiency.

1. Introduction

The building and construction sector is increasingly recognized as a major contributor to global environmental degradation through its consumption of energy and raw materials, greenhouse-gas emissions, and generation of construction and demolition waste. The United

Nations Environment Programme (UNEP) reports that buildings and construction account for approximately *32% of global energy consumption and 34% of global carbon dioxide emissions*, while materials such as cement and steel contribute substantially to the sector's environmental burden (UNEP, 2025). These challenges have strengthened the need for architectural approaches that reduce resource consumption while maintaining functional, economic, and environmental performance throughout the building life cycle. One promising approach is the integration of *green building materials* with *circular design principles*. Green building materials include recycled, renewable, locally sourced, low-carbon, durable, and responsibly manufactured materials that can reduce environmental impacts associated with conventional construction. Recent research emphasizes that material selection should be assessed across the entire life cycle rather than solely according to initial cost or operational performance. Life-cycle assessment (LCA) provides an important framework for evaluating the environmental impacts of construction materials from raw-material extraction through production, construction, use, and end-of-life stages (2023). This approach is particularly relevant to sustainable architecture because it enables designers to compare material alternatives based on embodied energy, emissions, resource consumption, durability, and end-of-life recovery potential. Circular design extends this concept by seeking to maintain the value of building materials and components for as long as possible. Strategies include *design for disassembly, adaptability, repair, reuse, recycling, modular construction, and material recovery*. Santos et al. (2024) identify circular material-use strategies as important mechanisms for reducing raw-material extraction, greenhouse-gas emissions, and construction waste. Similarly, Finamore and Oltean-Dumbrava (2024) argue that effective circularity in the building sector requires a holistic approach involving the entire construction value chain rather than isolated interventions.

Design for disassembly is particularly significant because it enables building components to be separated and reused rather than becoming waste at the end of a building's service life. A recent systematic review found that design for disassembly is increasingly being investigated within architecture,

engineering, and construction, although challenges remain concerning standardization, connections, assessment methods, and integration into conventional design practice (2024). Recent research also emphasizes the importance of material information and traceability for achieving effective building-material circularity, particularly in supporting decisions concerning reclamation, reuse, and recycling (Ranasinghe et al., 2024). The energy dimension of sustainable architecture is equally important. Gelwasa and colleagues' recent research demonstrates the increasing relevance of *energy efficiency, renewable-energy integration, intelligent monitoring, and optimization* to sustainable technological development. For example, Gelwasa et al. (2025) examined energy efficiency and smart monitoring through the application of artificial intelligence, machine learning, digital twins, and Internet of Things technologies. Gelwasa's 2026 work with Rikoto further examines machine-learning-driven optimization of renewable-energy systems in relation to achieving Sustainable Development Goal 7. These contributions provide a useful technological perspective for architectural sustainability, where material efficiency and circularity can be complemented by intelligent energy systems and renewable-energy technologies.

Consequently, integrating green building materials with circular design principles provides a more comprehensive pathway toward sustainable architectural development. Such integration can reduce embodied environmental impacts, minimize construction waste, conserve natural resources, improve material recovery, and support energy-efficient buildings. Recent literature nevertheless indicates that barriers remain in material selection, information management, design practices, industry coordination, standards, and implementation. This study therefore examines the potential of integrating green building materials and circular design principles as a holistic strategy for developing resource-efficient, adaptable, resilient, and environmentally responsible architectural environments.

2. Materials and Methods

2.1 Research Design

This study adopts a *qualitative, descriptive, and analytical research design* to examine how green building materials can be integrated with circular design principles to support sustainable architectural development. The methodology combines systematic literature analysis, comparative assessment of material characteristics, and evaluation of circular design strategies. The approach is appropriate because the study focuses on identifying relationships between material selection, resource efficiency, environmental performance, adaptability, reuse, and end-of-life recovery rather than testing a single building product experimentally. The research process consists of four major stages: *literature identification, material classification, circular-design assessment, and synthesis of findings*. Recent scholarly publications and authoritative reports published between *2023 and 2026* are prioritized to ensure that the analysis reflects contemporary developments in sustainable construction and circular architecture.

2.2 Materials and Data Sources

The principal materials examined in the study are grouped into five categories: recycled materials, renewable/biobased materials, locally sourced materials, low-carbon materials, and reusable/recoverable building components. Examples include recycled aggregates, recycled metals, reclaimed timber, bamboo, compressed earth materials, low-carbon concrete, and modular building components. Secondary data are obtained from peer-reviewed journal articles, international sustainability reports, building-material databases, and relevant technical publications published from 2023–2026. Particular attention is given to studies addressing embodied carbon, material efficiency, construction and demolition waste, life-cycle assessment, design for disassembly, adaptability, material reuse, and circular economy principles.

Table 1. Categories of Green Building Materials Considered

Material category	Examples	Principal environmental benefit	Circular potential
Recycled materials	Recycled aggregate, recycled steel, recycled glass	Reduces demand for virgin resources	Recycling and material recovery
Renewable/biobased materials	Bamboo, certified timber, natural fibres	Renewable resource base and potential carbon storage	Reuse, repair and biological recovery
Locally sourced materials	Earth blocks, local stone, regional timber	Reduces transportation-related impacts	Local repair and reuse
Low-carbon materials	Low-carbon concrete, alternative binders	Reduces embodied carbon	Reuse and recycling potential
Reclaimed/reusable components	Reclaimed timber, doors, windows, structural components	Diverts materials from waste streams	Direct reuse and remanufacturing

2.3 Circular Design Framework

The study evaluates circularity through a building life-cycle perspective. Rather than treating a building as a final product, the methodology considers it as a system of materials and components capable of being maintained, adapted, reused and recovered. The assessment follows a hierarchy beginning with *material reduction and efficiency*, followed by durability and maintenance, adaptability, repair, component reuse, recycling and, where necessary, responsible disposal. Design for disassembly is considered particularly important because connections and components that can be separated without significant damage have greater potential for future reuse. The framework links material selection at the design stage with subsequent construction, occupation, adaptation, renovation and end-of-life processes. Environmental performance is assessed by considering resource consumption, embodied carbon, waste generation, durability and opportunities for material recovery.

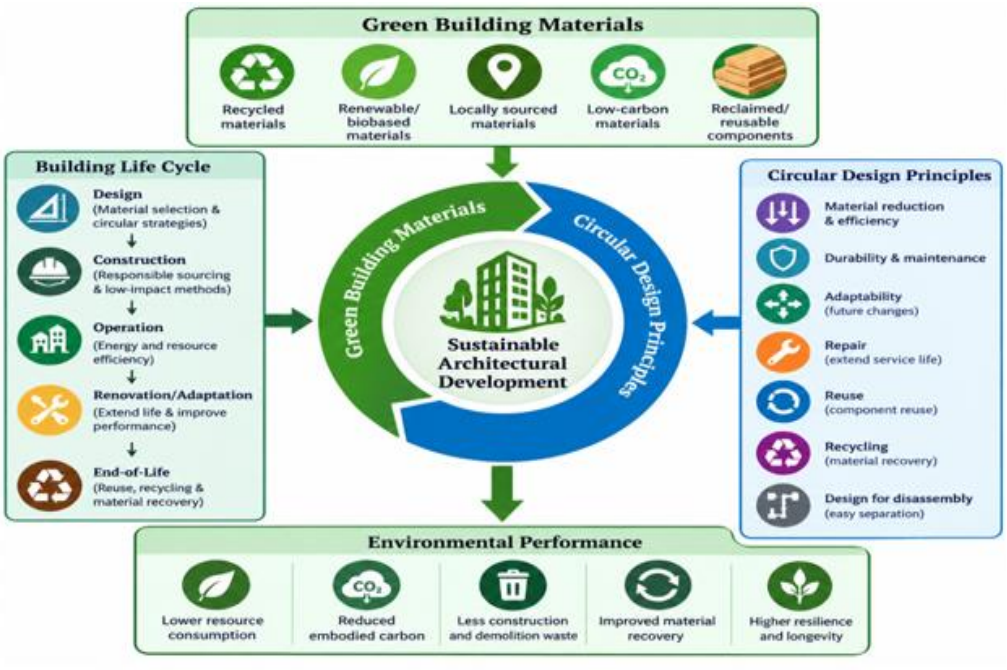


Figure 1. Conceptual framework for integrating green materials and circular design principles.

2.4 Assessment Criteria

A comparative assessment matrix is developed to evaluate the contribution of selected materials and design strategies to sustainable architectural development. Each criterion is considered in relation to the building life cycle. The assessment emphasizes environmental performance while also considering practical architectural requirements.

Table 2. Assessment Criteria for Green Materials and Circular Design

Criterion	Assessment focus	Measurement/indicator
Resource efficiency	Reduction in virgin material consumption	Relative resource demand
Embodied carbon	Environmental impact of material production	kg CO_2e or comparative carbon intensity
Waste reduction	Potential to minimize construction and demolition waste	Reuse/recycling potential
Durability	Expected service life and resistance to deterioration	Service-life assessment
Adaptability	Ability of spaces/components to accommodate future changes	Adaptability rating
Disassembly	Ease of separating components without damage	Disassembly potential
Reuse and recovery	Potential for direct reuse, remanufacturing or recycling	Recovery potential
Local availability	Availability and transportation requirements	Local/regional sourcing
Life-cycle performance	Environmental performance throughout the building life	LCA-based comparison

2.5 Data Analysis

The collected information is subjected to *comparative thematic analysis*. Findings from the selected literature are coded according to the major themes of green materials, circular design, embodied carbon, resource efficiency, waste minimization, adaptability, and material recovery. Materials and design strategies are then compared according to their environmental and circularity characteristics. Where quantitative environmental data are available, reported indicators such as embodied carbon, energy consumption, material recovery rates, and waste reduction are extracted and compared. Where numerical data are unavailable, qualitative ratings are used to identify relative strengths and limitations. This combined approach allows comparison across studies and material categories despite variations in research methods and geographical contexts.

2.6 Integration Model for Sustainable Architectural Development

The final stage develops an integrated model showing how material selection and circular design decisions can be incorporated into architectural practice. The model begins with *site and material assessment*, followed by selecting environmentally responsible materials and applying circular design strategies. The building is subsequently evaluated according to its operational performance, adaptability, maintenance requirements, and potential for component recovery.

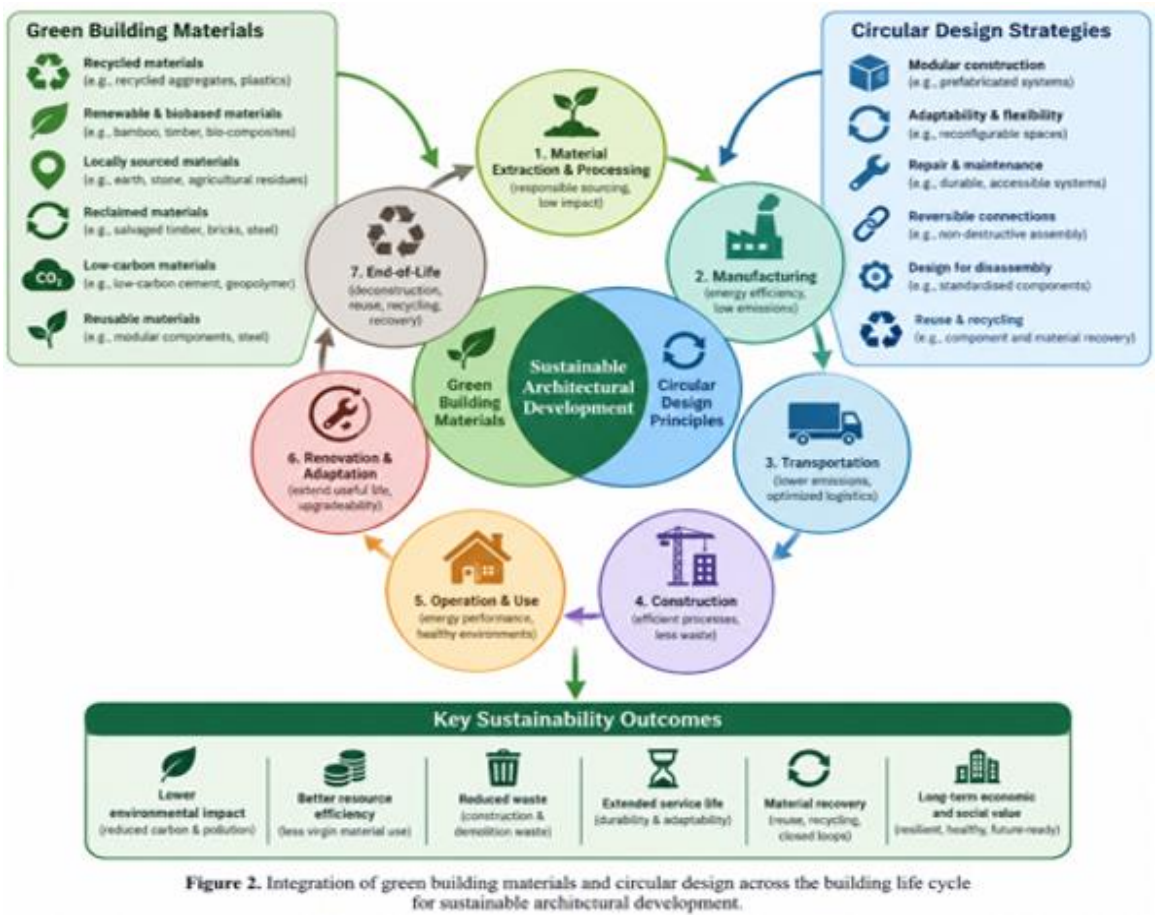


Figure 2. Integration of green building materials and circular design across the building life cycle for sustainable architectural development.

Figure 2. Proposed workflow for integrating green building materials and circular design in architectural practice.

3. Results

3.1 Integration of Green Building Materials and Circular Design

The analysis indicates that green building materials and circular design principles are most effective when applied as complementary strategies rather than as independent sustainability measures. Green materials primarily address the environmental impacts associated with material extraction, manufacturing, transportation, and construction, while circular design extends sustainability by preserving the value of materials and components throughout the building life cycle. The combined approach therefore addresses both *environmental impact reduction and resource-value retention*. The assessment identified five major pathways through which integration can improve sustainable architectural development: reduction of virgin-material demand, reduction of embodied carbon, minimization of construction and demolition waste, extension of component service life, and increased potential for material recovery. Materials such as recycled aggregates, recycled metals, reclaimed timber, bamboo, earth-based materials, and low-carbon concrete demonstrated different strengths depending on their application and life-cycle characteristics.

Table 3. Comparative Results of Green Materials and Circular Design Strategies

Strategy	Major environmental benefit	Circular-design opportunity	Overall contribution
Recycled materials	Reduces virgin-resource extraction and waste	Recycling and repeated material recovery	High
Renewable/biobased materials	Reduces dependence on non-renewable resources	Reuse, repair and potential biological recovery	High
Local materials	Reduces transportation requirements and supports local economies	Local repair, maintenance and reuse	Moderate–High
Low-carbon materials	Reduces embodied greenhouse-gas emissions	Potential for reuse/recycling depending on material type	High
Reclaimed components	Diverts usable materials from waste streams	Direct reuse and remanufacturing	Very High
Modular construction	Reduces construction waste and facilitates replacement	Disassembly, relocation and component reuse	Very High
Design for disassembly	Reduces damage during deconstruction	Direct component recovery	Very High
Adaptable design	Extends functional building life	Reconfiguration instead of demolition	Very High

The results further show that *reclaimed and reusable components, modular construction, design for disassembly, and adaptable design* provide particularly strong circularity potential because they retain material and component value beyond the first building application. This suggests that material sustainability should not be evaluated exclusively according to whether a material is recycled or renewable; its capacity to remain useful through subsequent building cycles is equally important.

3.2 Resource Efficiency and Waste Reduction

The synthesis demonstrates that circular design can substantially strengthen the resource-efficiency benefits of green materials. Conventional material selection often focuses on the environmental characteristics of individual products, whereas circular design considers how materials are installed, maintained, replaced, dismantled, reused, and recovered. The integration of modular components, reversible connections, standardized dimensions, and accessible service systems creates opportunities to replace or upgrade individual components without destroying surrounding materials. Consequently, building renovation can shift from a demolition-intensive process toward *selective replacement and adaptation*. The results indicate that the greatest resource-efficiency gains occur when material reduction is considered before material substitution. In other words, using a greener material is beneficial, but reducing unnecessary material use and extending the service life of existing components can provide additional sustainability benefits.

3.3 Embodied Carbon Reduction

The analysis identifies embodied carbon as one of the principal areas in which material selection and circularity intersect. Conventional construction materials, particularly carbon-intensive materials, can contribute significantly to the environmental footprint of buildings before the building becomes operational. The results suggest that a combination of *low-carbon materials, recycled content, reclaimed components, material efficiency, and extended service life* provides a stronger pathway for embodied-carbon reduction than reliance on a single material substitution. Reusing an existing component can potentially avoid the environmental impacts associated with manufacturing a new replacement, although the actual benefit depends on transportation, refurbishment, remaining service life, and the environmental impact of alternative materials. Life-cycle assessment is therefore essential for preventing misleading sustainability claims. A material with recycled content or renewable characteristics should not automatically be considered environmentally superior without considering its complete life-cycle performance.

3.4 Adaptability, Durability and Building Longevity

A significant finding is that *building longevity is central to circular architectural development*. A building that remains functionally useful for a longer period can reduce the frequency of reconstruction and consequently reduce material demand and waste generation. Adaptable floor plans, flexible structural grids, accessible building services, demountable partitions, and replaceable components can enable buildings to accommodate changing user requirements. Similarly, durable materials can reduce the frequency of replacement and associated environmental impacts.

The findings therefore establish an important relationship:

Durability + Maintainability + Adaptability = Extended Building Service Life

Extended service life subsequently increases opportunities for repair, refurbishment, reuse and eventual recovery of materials.

3.5 Design for Disassembly and Material Recovery

Design for disassembly emerged as one of the most important principles in the integrated framework. Buildings designed with mechanical or reversible connections can potentially be dismantled systematically, allowing components to be reused or recycled rather than destroyed during demolition.

The analysis identifies several architectural characteristics that support disassembly:

- **i.** mechanical and reversible connections;
- **ii.** standardized component dimensions;
- **iii.** accessible joints and service systems;
- **iv.** modular structural and façade systems;
- **v.** separation of building layers;
- **vi.** identification and documentation of materials; and
- **vii.** avoidance of unnecessary permanent composite assemblies.

This finding indicates that *end-of-life recovery must be considered at the beginning of the design process*. Designing for future disassembly after the building has already been constructed is considerably more difficult than incorporating recoverability into the original design.

3.6 Integrated Sustainability Framework

The results support the development of an integrated framework in which sustainability is treated as a continuous process rather than a single design decision. The framework can be represented as:

Material Selection → Efficient Construction → Durable Building → Adaptable Use → Repair/Maintenance → Disassembly → Reuse/Recovery → Reduced Virgin Resource Demand

This framework demonstrates that green materials provide the material foundation for sustainability, while circular design provides the mechanisms through which those materials retain value over time.

4. Discussion

The findings demonstrate that integrating green building materials with circular design principles provides a more comprehensive approach to sustainable architectural development than addressing material sustainability and building circularity separately. Green materials can reduce environmental impacts at the production stage, but their sustainability benefits may be diminished if buildings are subsequently demolished without recovering their components. Circular design addresses this limitation by considering what happens to materials during maintenance, renovation, adaptation, and end-of-life stages. One of the most important findings is that *material selection and design decisions are interdependent*. Selecting recycled, renewable or low-carbon materials does not automatically produce a circular building. The materials must also be incorporated into assemblies that permit maintenance, replacement, separation and recovery. Conversely, a highly disassemble building constructed entirely from environmentally intensive materials may achieve circularity without achieving optimum environmental performance. The strongest sustainability outcome therefore occurs when environmentally preferable materials are combined with circular assemblies and long-life design strategies. The findings concerning embodied carbon reinforce the importance of adopting a life-cycle perspective. Building sustainability has historically placed considerable emphasis on operational energy efficiency, but material production and construction can represent substantial environmental impacts. This makes early-stage architectural decisions particularly important because choices concerning structure, envelope, finishes, and construction systems can determine a building's embodied environmental footprint for decades. The results also emphasize the importance of *adaptability*. Buildings that can accommodate changes in occupancy, technology, spatial requirements or user needs without extensive demolition can remain functional for longer periods. Adaptability therefore represents both an architectural and environmental strategy. It reduces the need for replacement construction while preserving the embodied value of existing materials. Another important implication concerns construction and demolition waste. Conventional demolition frequently results in mixed waste streams that are difficult to recover efficiently. Circular design changes this approach by treating the building as a collection of recoverable materials and components. Material passports, component identification, and documentation can further support future decisions about reuse, recycling, and recovery. The findings are also consistent with the broader technological sustainability perspective represented in Gelwasa's recent work. The integration of intelligent monitoring, artificial intelligence, digital technologies and renewable-energy optimization provides opportunities to complement material circularity with improved operational performance. In architectural practice, this suggests that future sustainable buildings should not be viewed only as collections of environmentally preferable materials but as *integrated physical and digital systems* capable of monitoring performance, supporting maintenance and optimizing resource use. However, the implementation of circular architecture remains subject to practical limitations. Material availability, additional design requirements, construction skills, building regulations, market demand for reclaimed materials, quality assurance, and limited information about existing building components can constrain implementation. Furthermore, the environmental benefit of material reuse depends on factors such as transportation, processing, refurbishment requirements, and remaining service life. Circularity should therefore be evaluated through evidence-based life-cycle assessment rather than assumed solely from the presence of recycled or reusable materials.

5. Contributions to Knowledge

This study contributes to knowledge by establishing an integrated framework that connects *green building-material selection with circular architectural design* across the complete building life cycle. Rather than treating sustainable materials as isolated products, the study demonstrates that their environmental benefits can be strengthened when combined with durability, adaptability, repairability, design for disassembly, reuse, and material recovery. The study further contributes a comparative assessment framework for evaluating materials and design strategies according to resource efficiency, embodied carbon, waste reduction, durability, adaptability, disassembly, recovery, local availability and life-cycle performance. It also highlights the importance of shifting architectural decision-making from a linear *"take–make–use–dispose"* model toward a regenerative and circular model in which materials and components remain in productive use for as long as possible. In addition, the study provides an architectural basis for connecting material circularity with emerging digital technologies, intelligent energy systems and renewable-energy strategies. This provides a multidisciplinary perspective in which sustainable architecture encompasses not only material efficiency but also energy performance, technological intelligence, adaptability and long-term resource management. Overall, the study contributes a practical conceptual basis for architects, engineers, developers and policymakers seeking to incorporate circularity into contemporary sustainable building practice.

6. Further Directions

Future research should advance the integration of green building materials and circular design from predominantly conceptual assessments toward *empirical, quantitative, context-specific, and performance-based investigations*. Priority should be given to comprehensive life-cycle assessments (LCA) that compare conventional and circular building systems in terms of embodied carbon, embodied energy, water consumption, resource depletion, waste generation, durability, and end-of-life impacts. Further research should also establish regional databases of recycled, reclaimed, renewable, locally sourced, and low-carbon construction materials, incorporating information on material composition, environmental performance, cost, availability, durability, reuse potential, and recyclability. The application of *digital material passports, Building Information Modelling (BIM), digital twins, and Internet of Things (IoT)* should be investigated to improve material identification, documentation, traceability, maintenance, and recovery throughout the building life cycle. Within Nigeria, future studies should focus particularly on the technical, environmental, economic, and cultural suitability of locally available materials and circular construction practices under different climatic and regional conditions. Economic studies should quantify the long-term financial implications of circular construction by considering initial investment, maintenance, refurbishment, adaptability, residual material value, avoided demolition costs, and potential benefits from component recovery. In addition, post-occupancy evaluations should determine whether buildings designed

according to circular principles achieve measurable improvements in energy efficiency, indoor environmental quality, maintenance, adaptability, material longevity, and occupant satisfaction. Future research should also examine the application of *artificial intelligence, machine learning, IoT, and digital-twin technologies* for predictive maintenance, building-performance optimization, material inventory management, and intelligent decision-making for repair, reuse, refurbishment, and recovery. Ultimately, research should translate these findings into *standardized circular-design indicators, assessment frameworks, architectural guidelines, BIM-based tools, and policy recommendations* that can be practically applied by architects, engineers, developers, contractors, manufacturers, and regulatory authorities throughout the design, construction, operation, renovation, and deconstruction stages of buildings.

7. Concluding Synthesis

This study demonstrates that the integration of *green building materials and circular design principles* provides a holistic pathway for improving the environmental, resource, and long-term performance of architectural development. While green building materials can reduce the environmental impacts associated with resource extraction, manufacturing, transportation, and construction, circular design strengthens these benefits by promoting durability, adaptability, maintenance, repair, disassembly, reuse, recycling, and material recovery. The findings indicate that sustainable architecture should therefore move beyond the conventional emphasis on operational energy efficiency and isolated material substitution toward a *whole-life-cycle approach* in which material selection, construction methods, building performance, adaptability, and end-of-life recovery are considered simultaneously. The study further establishes that design decisions made at the early architectural stage have significant implications for future resource consumption, embodied carbon, waste generation, and material recovery. In this regard, strategies such as modular construction, reversible connections, standardized components, adaptable spatial planning, reclaimed materials, low-carbon materials, and digital material documentation can contribute significantly to the transition from a linear construction model toward a circular built environment. For Nigeria and other developing economies, the approach offers additional opportunities to combine locally available resources, appropriate technologies, emerging digital systems, and context-sensitive architectural practices to achieve environmentally responsible and economically viable buildings. However, successful implementation will require stronger collaboration among *architects, engineers, researchers, manufacturers, contractors, developers, policymakers, and building users*, supported by appropriate standards, market mechanisms, technical capacity, reliable material information, and regulatory frameworks. Overall, the integration of green materials and circular design represents not merely a strategy for reducing environmental damage but a fundamental shift toward *resource-efficient, resilient, adaptable, regenerative, and future-oriented architectural development*.

Evidence Base of the Study

The evidence base for this study consists primarily of *recent peer-reviewed scholarly literature, authoritative international reports, technical publications, building-material information, and documented research on green building materials and circular design published between 2023 and 2026*. The selected evidence was examined thematically and comparatively according to the study's predefined assessment criteria: resource efficiency, embodied carbon, waste reduction, durability, adaptability, design for disassembly, reuse and material recovery, local availability, and whole-life-cycle performance. The analysis focused on reported evidence concerning recycled, renewable and biobased, locally sourced, low-carbon, reclaimed, and reusable building materials, together with circular strategies including modular construction, adaptable building systems, reversible connections, repair, reuse, recycling, and design for disassembly. Evidence from life-cycle assessment studies was considered where environmental indicators such as embodied carbon, energy consumption, resource use, and end-of-life impacts were reported, while qualitative evidence was used where studies did not provide directly comparable numerical data. The study therefore derives its conclusions from *secondary evidence synthesized across the identified literature and assessment framework*, rather than from primary laboratory experiments, surveys, post-occupancy measurements, or direct testing of individual building materials. This evidence base supports the conclusion that combining environmentally preferable materials with circular design strategies can improve resource efficiency, reduce waste and embodied environmental impacts, extend building and component service life, and increase opportunities for reuse and recovery. However, because the evidence is literature-based and the characteristics of materials and construction systems vary by location and application, the findings should be interpreted as a *comparative and conceptual synthesis rather than universally quantified performance results*. This distinction provides an appropriate basis for recommending future empirical studies, particularly life-cycle assessment, cost analysis, material-performance testing, post-occupancy evaluation, and context-specific investigation within the Nigerian construction sector.

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