Research on Landscape Material Selection and Sustainable Design under Low-Carbon Principles

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Abstract: As global climate change issues grow increasingly severe, low-carbon principles have become a vital direction for promoting sustainable development in urban construction and landscape design. As fundamental elements of landscape design, the selection and application of horticultural materials not only impact carbon emissions during construction but also influence the overall ecological benefits and service life of landscapes. This paper systematically outlines principles and evaluation criteria for selecting landscape materials based on low-carbon concepts. It focuses on exploring application pathways for low-carbon materials in hardscape and softscape elements, while proposing design strategies for low-carbon landscapes by integrating emerging trends in green building materials. Through case studies and theoretical synthesis, the paper emphasizes the critical roles of life cycle assessment, localized material utilization, and green technological innovation in landscape design. Research findings indicate that rational material selection and scientific landscape design can effectively reduce carbon emissions, enhance ecological environment quality, and provide feasible pathways for the industry's green transformation. This study aims to offer references for landscape designers, relevant practitioners, and policymakers, promoting the sustainable development of landscape architecture under a low-carbon framework.

1. Introduction

Amidst intensifying global climate change and carbon emission pressures, low-carbon development has become an international consensus and action goal[1]. China's “carbon peak and carbon neutrality” strategy further charts the course for the landscape architecture industry[2]. As a vital component of urban development, landscape architecture not only serves ecological regulation, environmental beautification, and cultural preservation but also significantly impacts environmental sustainability through carbon emissions generated during material selection, construction, and maintenance[3]. Domestic and international scholars have explored sustainability in landscape design through research encompassing life cycle assessment, green material development, and energy-saving technology applications[4]. However, systematic research grounded in low-carbon principles—specifically how to achieve low-carbon material selection across different landscape types and integrate low-carbon concepts throughout the entire process of landscape design, construction, and maintenance—remains an area requiring deeper exploration.

Centered on low-carbon principles, this paper first outlines the fundamental principles and evaluation criteria for selecting landscape materials[5]. It then explores application pathways for low-carbon materials in landscape design by examining their practical use in hardscapes, softscapes, and novel green building materials. Finally, through case studies and strategy analysis, it proposes comprehensive methods and development directions for low-carbon landscape design[6]. This paper aims to provide theoretical references and practical insights for sustainable landscape construction while offering conceptual support for the industry's green transformation.

2. Principles for Selecting Landscape Materials Under Low-Carbon Concepts

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Guided by low-carbon principles, the selection of landscape materials should first adhere to the principles of Life Cycle Assessment (LCA) [7]. Materials generate carbon emissions across extraction, processing, transportation, construction, and maintenance phases, necessitating comprehensive consideration of their full lifecycle environmental costs. Compared to focusing solely on economics or aesthetics, lifecycle assessment provides a more scientific measure of a material's low-carbon value. Renewable timber and permeable pavers exhibit lower energy consumption during production and use while contributing to environmental regulation, making them highly suitable for low-carbon landscapes[8]. To evaluate the environmental impact of landscape materials, the carbon emission is calculated using the following formula:

$$C = \sum_{i=1}^{n}(E_i \times F_i) \quad (1)$$

The life-cycle carbon footprint of a material can be expressed as:

$$CF = \sum_{j=1}^{m}\left(M_j \times e_j\right) - R \quad (2)$$

To compare different materials, a normalized carbon intensity index is defined:

$$CI = \frac{C_{mat}}{A \times T} \quad (3)$$

Emphasis should be placed on utilizing locally sourced materials to reduce carbon emissions from transportation. Common landscaping materials like stone, timber, and soil, when procured locally, not only decrease energy consumption from logistics but also better align with regional environmental characteristics, achieving ecological and cultural harmony[9]. Furthermore, local materials offer greater adaptability during construction, shortening project timelines and reducing waste, thereby further enhancing low-carbon benefits.

The recyclability and circularity value of materials are fundamental principles in low-carbon design[10]. As solid waste accumulates during urban development, processing and reusing materials like waste concrete and scrap wood effectively reduces resource waste and environmental pollution. While such recycled materials may have limitations in aesthetic appeal and structural strength, technological innovation and thoughtful design enable their successful application in pathways, paving, and landscape features.

Material safety and ecological adaptability are equally critical selection criteria. Low-carbon initiatives extend beyond carbon reduction to safeguarding human health and ecosystem stability. Landscape materials must be non-toxic, harmless, and biodegradable while fostering positive interactions with surrounding flora, water bodies, and soil environments. Permeable paving enhances rainwater infiltration, mitigates urban flooding risks, and improves microclimate quality. Only such safety- and ecologically-adaptive choices achieve true unity between low-carbon goals and sustainability.

3. Practical Application of Low-Carbon Materials in Landscape Design

Driven by low-carbon principles, landscape design now moves beyond traditional materials. It achieves dual goals of environmental friendliness and resource conservation through diversified material combinations and innovative technologies. The application of low-carbon materials in landscape design manifests primarily in three areas: Soft landscaping emphasizes low-carbon plant selections and optimized soil substrates to enhance carbon sequestration capacity and stormwater retention; with technological advancements, novel green building materials and energy-saving technologies are increasingly integrated into landscape design. Photovoltaic building materials and biodegradable composites offer expanded possibilities for sustainable garden design.

3.1 Application of Low-Carbon Materials in Hardscapes

In hardscape design, permeable paving materials exemplify the low-carbon philosophy. Permeable bricks, permeable concrete, and ecological sand-based materials not only effectively reduce stormwater runoff and alleviate urban flooding but also replenish groundwater through infiltration, improving microclimate conditions. These materials often utilize recycled aggregates or industrial byproducts in production, reducing resource consumption and carbon emissions while balancing functionality and environmental sustainability.

Renewable timber, a vital building material for hardscapes, finds extensive use in structures like boardwalks, pergolas, and seating. Compared to conventional wood, certified sustainably harvested timber or treated reclaimed wood alleviates pressure from overexploitation of forest resources while offering natural texture and ecological affinity during use. Strategic selection of wood species and treatment methods extends service life, significantly reducing the carbon footprint associated with frequent replacements.

The reuse of waste concrete and construction debris is gaining traction in hardscape construction. After mechanical crushing and screening, discarded concrete can be repurposed as roadbed fill or recycled aggregate, thereby reducing carbon emissions and ecological damage from natural sand and gravel extraction. The application of recycled concrete in landscape paving and retaining wall construction achieves resource recycling while providing low-cost, low-energy solutions for horticultural projects.

Innovative applications of metals and new composite materials in hardscapes also carry low-carbon significance. Metals like recyclable steel and aluminum gain attention for their reusability, while the introduction of biodegradable composites offers eco-friendly options for landscape features and structural components. These materials exhibit increasingly diverse properties, meeting comprehensive demands for strength, aesthetics, and environmental sustainability, thereby propelling hardscapes toward low-carbon and sustainable development.

3.2 Selection of Soft Landscaping and Ecological Substrates

Guided by low-carbon principles, plant selection—as the core element of soft landscaping—plays a vital role in enhancing the carbon sequestration capacity and ecological functions of gardens. Selecting native plants and low-maintenance varieties that tolerate drought and poor soil reduces resource consumption such as water and fertilizers while enhancing the ecological stability of plant communities. Multi-layered, diverse plant arrangements can elevate aesthetic value while boosting carbon dioxide absorption and sequestration, achieving dual benefits for low-carbon and ecological goals. In soft landscape design, the net carbon sequestration potential of vegetation is estimated as:

$$CS = \sum_{k=1}^{p} (B_k \times r_k) - M \qquad (4)$$

The rainwater regulation capacity of an ecological substrate is modeled as:

$$Q = P \times A \times \phi \qquad (5)$$

Replacing and optimizing lawns and groundcover plants is a key measure for reducing carbon emissions. Traditional expansive lawns require substantial irrigation, fertilization, and mowing during maintenance, resulting in a high carbon footprint. Substituting portions of lawn with low-carbon grass varieties, wildflower mixtures, or drought-tolerant groundcovers not only reduces energy consumption in maintenance but also increases biodiversity and enhances the overall functionality of the ecological landscape.

The rational selection and improvement of ecological substrates form a crucial foundation for soft landscaping. Soil amendments incorporating organic fertilizers, straw fibers, or industrial byproducts (such as fly ash) enhance soil permeability and nutrient retention while reducing carbon emissions from chemical fertilizer use. Local sourcing of substrate materials further lowers transportation energy consumption, advancing green and low-carbon practices in landscaping materials.

The development of rain gardens and green substrate systems is emerging as an innovative direction for low-carbon landscapes. By constructing rainwater retention ponds, infiltration ditches, and plant substrate layers, these systems not only reduce urban surface runoff but also improve microenvironment quality and habitat conditions for wildlife. Such ecological substrates integrate water storage, purification, and landscape beautification functions, offering urban landscaping a solution that combines low-carbon and ecological value.

3.3 Innovative Green Building Materials and Technologies

Advancements in materials science and ecological technology have positioned novel green building materials as a cornerstone for achieving low-carbon landscape design. The integration of photovoltaic (PV) materials enables landscape structures to simultaneously supply energy and serve ecological functions. PV pergolas and ground pavements not only provide clean energy for garden lighting and equipment operation but also enhance spatial functionality and technological aesthetics while reducing carbon emissions.

Biodegradable composite materials are increasingly applied in landscape ornaments and temporary structures. Typically made from bio-based polymers, biodegradable plastics, or agricultural byproducts, these materials decompose rapidly in natural environments, eliminating the environmental burden of traditional materials after disposal. Their lightweight and malleable properties also offer greater sculptural and innovative possibilities for landscape design. To compare the lifecycle carbon emissions of different green building materials, Figure 1 illustrates the distribution of emissions across several representative materials:

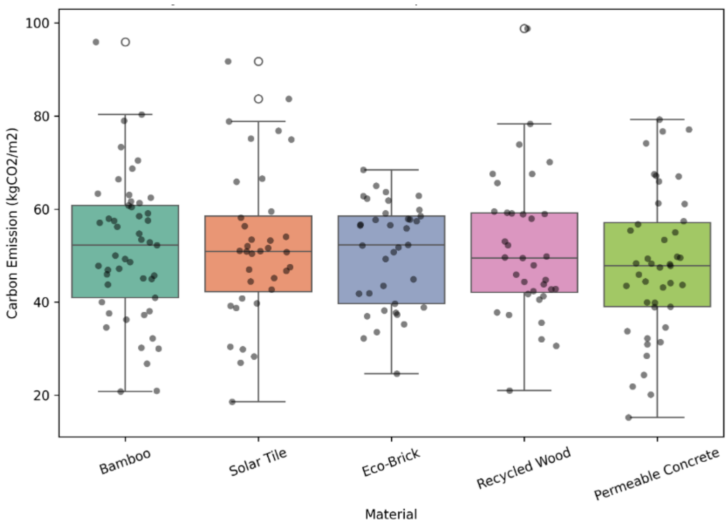

Figure 1 Lifecycle Carbon Emission Comparison of Green Materials

Advancements in green insulation and translucent materials offer fresh approaches to energy conservation in landscape design. Materials like low-emissivity glass (Low-E Glass), porous ceramics, and ecological translucent membranes effectively optimize thermal and lighting conditions, reducing reliance on artificial lighting and cooling systems. In greenhouse designs, leisure walkways, or urban public spaces, these materials enhance comfort while significantly lowering energy consumption.

The integration of smart materials and digital technologies is propelling landscape architecture into a smart, low-carbon era. Smart substrates that automatically adjust breathability and permeability based on temperature and humidity, along with composite building materials equipped with IoT sensors for energy monitoring, enable precise management of landscape environments. Through the application of these novel green building materials and innovative technologies, landscape design is progressively transitioning from traditional ecological aesthetics toward a comprehensive shift toward low-carbon, intelligent, and sustainable development.

4. Comprehensive Strategies and Case Studies in Low-Carbon Landscape Design

Landscape design under low-carbon principles demands energy conservation and emission reduction in material selection, alongside systematic sustainable strategies in overall planning and spatial construction. By integrating ecological, technological, and aesthetic elements, landscape design can fulfill functional requirements while minimizing negative environmental impacts, achieving harmonious coexistence between humans and nature, the overall sustainability index of a landscape project is expressed as a weighted sum of ecological, economic, and social benefits:

$$SI = \alpha E + \beta Ec + \gamma S \qquad (6)$$

The organic integration of low-carbon materials with holistic landscape design forms the foundation for sustainable development. Simply using low-carbon materials does not fully achieve green objectives. Design must integrate material properties with ecological functions through spatial organization, circulation planning, and functional zoning. For instance, in public plaza design, strategically placing permeable paving alongside green vegetation not only improves stormwater runoff but also enhances the site's ecological services. This integrated approach emphasizes a systems perspective, embedding low-carbon goals throughout the entire design process.

Urban public spaces provide crucial settings for implementing low-carbon landscape concepts. In recent years, multiple cities have incorporated green building materials and ecological design techniques into parks, street green corridors, and waterfront spaces. Rain garden projects in certain cities, for instance, achieve natural rainwater infiltration and storage through drought-tolerant plants and permeable substrates, reducing pressure on municipal drainage systems. Similarly, some ecological parks utilize discarded concrete and recycled timber for landscape structures, lowering construction costs while demonstrating green, low-carbon design principles. These examples illustrate that low-carbon landscapes deliver ecological benefits while generating positive social demonstration effects. Figure 2 presents the comprehensive evaluation of low-carbon landscape design strategies across multiple dimensions, including carbon reduction, water conservation, thermal comfort, biodiversity, and economic benefits:

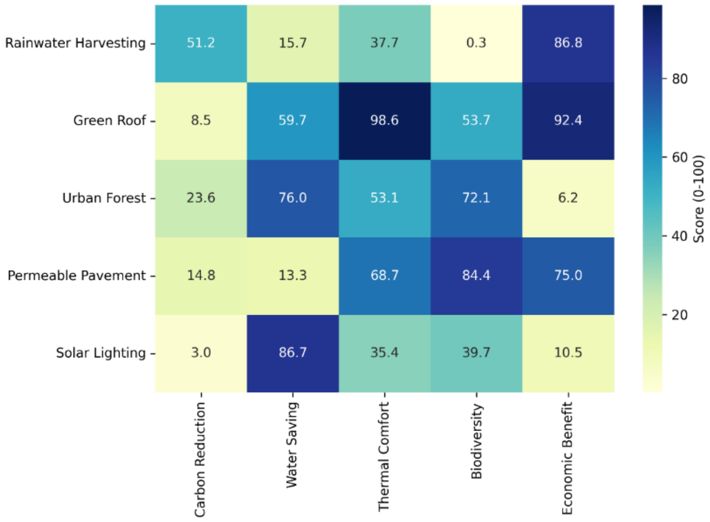

Figure 2 Comprehensive Benefits of Low-Carbon Landscape Strategies

From an industry development perspective, low-carbon landscape design presents new challenges and opportunities for designers and practitioners. Designers must possess interdisciplinary knowledge, integrating considerations of materials science, ecology, and engineering technology. The industry should also promote low-carbon materials through policy and standards, establishing carbon emission assessment systems and refining green building material certification mechanisms. Driven by both technological innovation and institutional frameworks, low-carbon landscape design will transition from isolated examples to widespread practice, thereby advancing the green transformation of the entire horticultural sector.

5. Conclusion

Against the backdrop of low-carbon development becoming a global consensus, landscape architecture faces new transformations and challenges. This paper systematically outlines principles for selecting landscape materials based on low-carbon concepts, analyzes specific applications of low-carbon materials in hardscape and softscape elements, and explores innovative development pathways for new green building materials and technologies. Research indicates that life cycle assessment, localized utilization, recycling, and ecological adaptability form the fundamental guidelines for low-carbon material selection. At the practical level, the judicious application of diverse low-carbon materials and technologies—such as permeable paving, native plants, recycled concrete, and photovoltaic building materials—can significantly reduce carbon emissions while enhancing the ecological benefits and social value of landscapes.

Case studies reveal that low-carbon landscapes hold environmental significance, demonstrating exemplary effects in urban public space development and promoting the broader dissemination and application of green concepts. Current low-carbon material adoption remains constrained by cost, technological limitations, and incomplete standard systems. Designers and industry practitioners urgently need to persist in interdisciplinary integration and innovative applications. The selection of horticultural materials and sustainable landscape design under low-carbon principles are not only crucial measures for addressing climate change but also an inevitable trend for the horticultural industry's green transformation. Further research and evaluation of low-carbon material performance should be strengthened, alongside improving policy support and industry standards. This will drive the deep integration of green building materials and smart technologies, thereby achieving the coordinated development of ecological value, social benefits, and economic efficiency in landscape architecture.

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