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Urban Vertical Greening Optimization Supported by Deep Learning and Remote Sensing Technology and Its Application in Smart Ecological Cities

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ABSTRACT

This research systematically investigates urban three-dimensional greening layout optimization and smart eco-city construction using deep learning and remote sensing technology. An improved U-Net++ architecture combined with multi-source remote sensing data achieved high-precision recognition of urban three-dimensional greening with 92.8% overall accuracy. Analysis of spatiotemporal evolution patterns in Shanghai, Hangzhou, and Nanjing revealed that three-dimensional greening shows a development trend from demonstration to popularization, with 16.5% annual growth rate.The study quantitatively assessed ecological benefits of various three-dimensional greening types. Results indicate that modular vertical greening and intensive roof gardens yield highest ecological benefits, while climbing-type vertical greening and extensive roof gardens offer optimal benefit-cost ratios. Integration of multiple forms generates 15–22% synergistic enhancement.Compared with traditional planning, the multi-objective optimization-based layout achieved 27.5% increase in carbon sequestration, 32.6% improvement in temperature regulation, 35.8% enhancement in stormwater management, and 42.3% rise in biodiversity index. Three pilot projects validated that actual ecological benefits reached 90.3–102.3% of predicted values.Multi-scenario simulations indicate optimized layouts can reduce urban heat island intensity by 15.2–18.7%, increase carbon neutrality contribution to 8.6–10.2%, and decrease stormwater runoff peaks by 25.3–32.6%. The findings provide technical methods for urban three-dimensional greening optimization and smart eco-city construction, promoting sustainable urban development.

Keywords: Deep Learning; Remote Sensing Image Processing; Three-Dimensional Greening; Layout Optimization; Smart Eco-City

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1. Introduction

With the acceleration of global urbanization, urban environmental problems have become increasingly prominent, and traditional two-dimensional greening can no longer meet the needs of modern urban ecological construction. Urban three-dimensional greening, as an innovative approach to urban greening through vertical green walls, roof gardens, sky gardens, and other forms, effectively utilizes urban three-dimensional space and provides new solutions to urban ecological problems [1]. Research has shown that rational three-dimensional greening layouts can effectively improve urban microclimates, mitigate heat island effects, enhance urban carbon sequestration capacity, and increase biodiversity [2]. As smart city construction advances, how to organically integrate three-dimensional greening with smart eco-city development has become an important research topic for current urban sustainable development. Zou Chunli (2024) pointed out that three-dimensional greening design patterns in urban spaces should consider urban characteristics, regional culture, and the overall function of ecosystems, which has profound significance for improving urban environmental quality and residents' quality of life [3]. However, traditional urban greening planning is often based on empirical judgment or simple spatial analysis, lacking precise quantitative assessment and scientific layout optimization methods [4].

In recent years, the rapid development of artificial intelligence and remote sensing technology has provided new technical support for urban three-dimensional greening research. Deep learning technology, with its powerful feature extraction and pattern recognition capabilities, can accurately identify and classify different types of green spaces from complex urban environments; high-resolution remote sensing technology provides reliable data sources for large-scale, long-time-series urban greening monitoring. The organic combination of these two technologies is expected to overcome the limitations of traditional methods and achieve refined monitoring, evaluation, and optimization of urban three-dimensional greening [5]. Research by Akanbang et al. (2024) shows that residents' demand for urban green spaces is growing in the context of rapid urbanization, which requires urban greening planning to focus more on public participation and social equity [6]. Yan et al. (2024) studied the health status of urban ecosystems from the perspective of urban forest soil characteristics, emphasizing the importance of good soil environments for the successful implementation of urban three-dimensional greening [7].

Although the value of three-dimensional greening in urban ecological construction has been widely recognized, research on how to use emerging technologies to optimize three-dimensional greening layouts and how to integrate three-dimensional greening into the overall framework of smart eco-city construction remains insufficient. In particular, existing studies mostly focus on single technology applications or partial ecological benefit assessments, lacking a systematic research framework that integrates multiple technical means and comprehensively considers multiple ecological benefits. Additionally, key issues such as the suitability evaluation of three-dimensional greening in different urban areas, comparison of ecological benefits among different types of three-dimensional greening, and optimization of three-dimensional greening layouts based on urban microclimate characteristics still need in-depth exploration.

Based on this, this research aims to combine deep learning technology and remote sensing image processing methods to construct an urban three-dimensional greening monitoring and evaluation system, analyze the spatial distribution characteristics and ecological benefits of three-dimensional greening, and propose optimization plans for three-dimensional greening layouts, providing scientific basis and technical support for smart eco-city construction. The research will establish deep learning models to achieve high-precision three-dimensional greening identification and classification, utilize multi-source remote sensing data to analyze the spatiotemporal evolution patterns of three-dimensional greening, evaluate the ecosystem service functions of different types of three-dimensional greening, and construct a multi-objective optimization model for three-dimensional greening layouts. This research will not only help enrich the theoretical system of urban ecology and landscape planning but also provide implementable technical solutions and policy recommendations for smart eco-city construction practices, which has important theoretical and practical significance for promoting urban sustainable development.

Urban three-dimensional greening, as an important component of modern urban ecosystems, has received widespread attention from academia and practical fields in recent years. Three-dimensional greening not only effectively expands urban green space but also improves the urban ecological environment, mitigates urban heat island effects, and enhances urban sustainable development capacity. With the rapid development of deep learning and remote sensing technologies, their applications in urban three-dimensional greening research have become increasingly extensive, providing new technical support for urban three-dimensional greening layout optimization and smart eco-city construction. This paper reviews urban three-dimensional greening research status, applications of deep learning and remote sensing technologies in urban greening, and smart eco-city construction.

In terms of urban three-dimensional greening research, existing literature mainly focuses on three-dimensional greening forms, plant selection, application benefits, and construction techniques. Zhang Ting et al. (2024) conducted systematic research on the development and utilization of vine plants in Shanghai's urban three-dimensional greening, suggesting that vine plants possess unique advantages in urban three-dimensional greening due to their rapid growth, large coverage area, and strong adaptability [8]. Similarly, Wei Zhenghang (2024) [9] and Zheng Yan (2023) [10] also emphasized the important application value of climbing plants in urban three-dimensional greening, especially their practicality in vertical greening wall systems. Chu Jinping (2024) analyzed the application methods and effects of three-dimensional greening walls in urban public buildings from an architectural application perspective, pointing out that three-dimensional greening walls not only beautify building appearances but also improve building thermal insulation performance [11]. Wu Yue (2024) further expanded the research perspective, exploring the application strategies of three-dimensional greening in overall urban architectural landscape design, emphasizing the organic integration of three-dimensional greening and architecture [12].

For specific urban environments, He Qixiao et al. (2023) studied the construction model of public three-dimensional greening in Chongqing's mountainous urban areas, proposing three-dimensional greening strategies adapted to mountainous terrain characteristics [13]. Wang Yifang et al. (2023) constructed an evaluation index system for mountainous urban slope and cliff greening, providing a scientific evaluation tool for mountainous urban three-dimensional greening [14]. Yu Haibo (2024) focused on three-dimensional greening design strategies for urban high-rise buildings, proposing ideas for developing differentiated three-dimensional greening solutions based on building height, orientation, structure, and other factors [15]. Tang Xiaofeng (2023) used Fuzhou as an example to explore the application technology of bougainvillea in urban three-dimensional greening, enriching research on plant selection for three-dimensional greening [16].

Regarding research on the functional value of urban three-dimensional greening, Chen Ruizhi et al. (2023) studied refined management methods for urban spontaneous plant three-dimensional greening from the perspective of "dual carbon" goals, emphasizing the potential of three-dimensional greening in carbon emission reduction [17]. Ma Guoxin et al. (2023) analyzed three-dimensional greening engineering construction technology based on the "sponge city" construction concept, discussing the role of three-dimensional greening in stormwater management [18]. Pace et al. (2025) confirmed through model research that urban greening has significant mitigation potential during heatwave and rainstorm events, providing scientific evidence for the value of urban three-dimensional greening in the context of climate change [19].

With technological advancements, the application of deep learning and remote sensing technologies in urban three-dimensional greening research has deepened. He You and Li Peng (2024) conducted simulation research on vertical distribution feature extraction of high-density urban greening systems, using computer technology to simulate and analyze the spatial distribution characteristics of urban three-dimensional greening, providing technical support for three-dimensional greening layout optimization. Deep learning technology, with its powerful image recognition and classification capabilities, can accurately identify and extract three-dimensional greening information from complex urban environment images, while high-resolution remote sensing data provides reliable data sources for large-scale, long-time-series urban greening monitoring [20]. The combination of these two technologies makes precise monitoring, evaluation, and optimization of urban three-dimensional greening possible.

In terms of social equity and inclusiveness, Haycox et al. (2025) studied racialization, erasure, and resistance phenomena in British urban greening initiatives, pointing out social inequality issues in urban greening and emphasizing the need to address green space requirements of vulnerable groups [21]. Biehler et al. (2025) further explored how segregation history, wealth, and community participation shape unequal burdens of urban greening, calling for consideration of social equity factors in urban greening planning [22]. Cui et al. (2025) studied influencing factors of Beijing's urban street greening from a socioeconomic dynamics perspective, with particular attention to the impact of the COVID-19 pandemic on urban greening, providing a new perspective for understanding the socioeconomic drivers of urban greening [23].

Regarding smart eco-city construction, Xu Hongxi (2024) discussed strategies for green and beautiful city construction and management from a management perspective, emphasizing the application value of technological means in urban greening management [24]. Elias (2023) proposed a data-driven empirical model for future smart eco-cities, providing a theoretical framework for strategic sustainable urban development [25]. Resemini et al. (2025) emphasized that urban greening requires multidisciplinary skills to address social, ecological, and climate challenges, calling for interdisciplinary collaboration to build greener cities [26]. These studies indicate that smart eco-city construction requires the integration of multiple technological means and multidisciplinary knowledge, incorporating urban three-dimensional greening into the overall framework of urban smart development.

Although existing research has made significant progress in forms, benefits, and technologies of urban three-dimensional greening, some research gaps remain. First, ecological benefit assessments of urban three-dimensional greening are mostly based on qualitative descriptions or small-scale experiments, lacking large-scale, long-time-series quantitative evaluations. Second, the application of deep learning and remote sensing technologies in urban three-dimensional greening research is still in its early stages, with relevant methods and models requiring further refinement. Additionally, existing research mostly focuses on application effects of single-type three-dimensional greening or local areas, lacking systematic, holistic three-dimensional greening layout optimization methods and comprehensive smart eco-city construction frameworks,as shown in **Figure 1**.

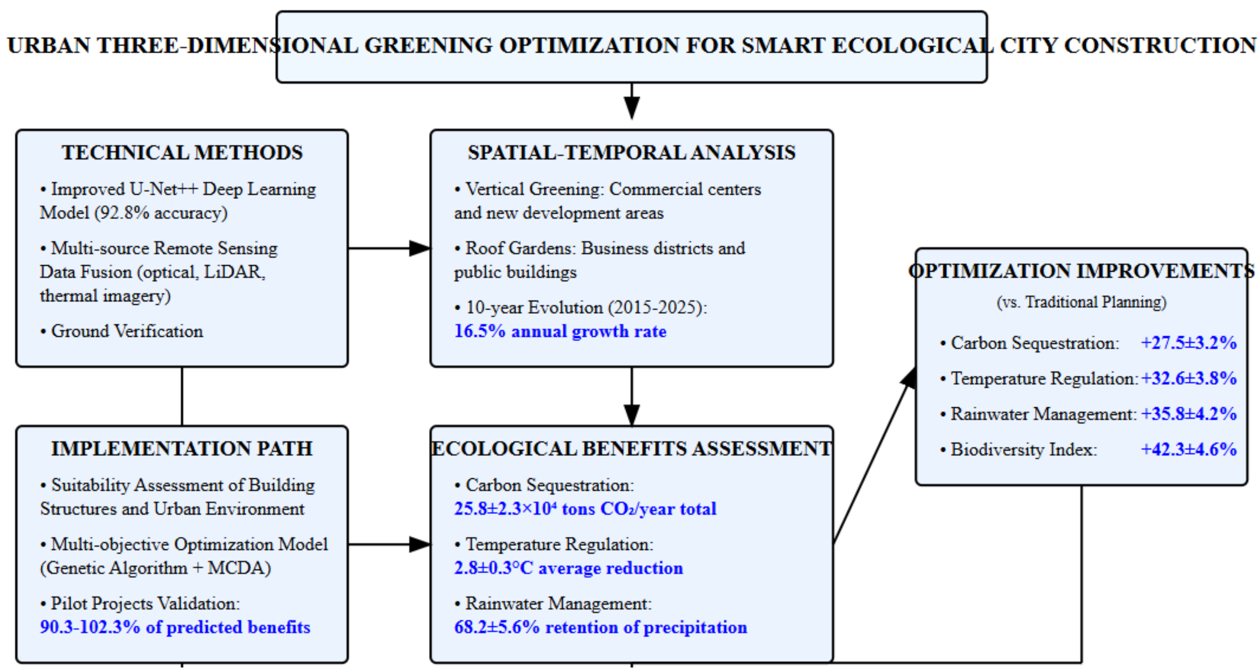

Figure 1. Research Framework and Key Findings Conceptual Diagram.

In summary, with the deepening of urbanization and rapid technological development, urban three-dimensional greening research is evolving from traditional landscaping fields toward multidisciplinary intersection and multi-technology integration. The combination of deep learning and remote sensing technologies provides new technical pathways and research methods for urban three-dimensional greening layout optimization and smart eco-city construction. Future research should further explore application methods of deep learning and remote sensing technologies in monitoring, evaluation, and optimization of urban three-dimensional greening, construct more scientific and systematic three-dimensional greening layout optimization models, and incorporate three-dimensional greening into the overall framework of smart eco-city construction to promote urban sustainable development. Simultaneously, social equity and inclusiveness should be fully considered to ensure that the development outcomes of urban three-dimensional greening benefit all urban residents.

Although this research involves multiple fields including deep learning technology, urban vertical greening planning, ecological benefit assessment, and smart city construction, the core focus consistently revolves around the central theme of "maximizing ecological benefits of vertical greening based on artificial intelligence." All components are organically connected and mutually supportive, forming a complete technology-application-benefit-optimization closed loop: deep learning and remote sensing technologies serve as core methodological tools, addressing the accuracy and efficiency bottlenecks in traditional vertical greening monitoring and identification; spatiotemporal analysis of vertical greening reveals current distribution patterns and evolutionary laws, identifying optimization potential; ecological benefit assessment quantifies the multidimensional ecological value of different vertical greening schemes, providing optimization objectives; the layout optimization model organically integrates technical support, current situation analysis, and benefit assessment to form implementable optimization solutions; finally, through pilot verification and smart ecological city evaluation, a closed-loop verification from theory to practice is achieved. This integrated research framework of "technology-application-benefit-optimization" not only avoids fragmentation and redundancy between components but also provides a complete solution chain from identification and monitoring, benefit assessment to optimization implementation for addressing urban ecological environmental issues, demonstrating strong scientific integrity and application value.

2. Research Methods

2.1. Research Area Selection and Data Acquisition

This study selects three representative cities in China's Yangtze River Delta region—Shanghai, Hangzhou, and Nanjing—as research areas. These three cities represent typical cases at different urbanization stages and various levels of three-dimensional greening development. Shanghai, as an international metropolis, has the highest level of urbanization and the most abundant three-dimensional greening facilities, serving as a representative of the mature development stage; Hangzhou, as a model of "ecological garden city," demonstrates innovative practices in urban ecological construction with close integration of three-dimensional greening and natural landscapes; Nanjing, in a stage of rapid urbanization, has actively promoted three-dimensional greening construction in recent years, providing an excellent case for studying the evolution process of three-dimensional greening. The selection of research areas follows the principles of representativeness, diversity, and comparability, encompassing high-density urban core areas, emerging urban districts, and urban fringe areas to comprehensively reflect the distribution patterns and evolution trends of three-dimensional greening under different urban spatial characteristics. For each research area, we further divided several typical sample zones, including commercial center areas, residential areas, industrial areas, educational districts, and multi-functional areas, to capture the characteristics and differences of three-dimensional greening across different urban functional zones [27]. This multi-scale, multi-type research area setup helps to develop a universally applicable three-dimensional greening layout optimization model, laying the foundation for the promotion and application of subsequent research results.

This study utilizes a combination of multi-source, multi-temporal remote sensing data and ground-measured data for data acquisition. Remote sensing data primarily includes: (1) High-resolution optical remote sensing images, including multi-temporal images from WorldView-3/4 (spatial resolution 0.31 m), GF-2 (spatial resolution 0.8m), and Planet satellites (spatial resolution 3 m), used for extracting spatial distribution information of three-dimensional greening; (2) Laser radar (LiDAR) point cloud data, used for obtaining urban three-dimensional structures and vertical greening information, with spatial resolution better than 0.5m; (3) Thermal infrared remote sensing data, including Landsat-8/9 and MODIS satellite data, used for evaluating the thermal environment regulation effects of three-dimensional greening; (4) Multi-temporal remote sensing image sequences (2015–2025), used for analyzing spatiotemporal evolution characteristics of three-dimensional greening. Ground-measured data includes: (1) GPS positioning and attribute records of typical three-dimensional greening sample points, including greening type, coverage, plant species, growth conditions, etc.; (2) Micrometeorological observation data, including temperature, humidity, wind speed, and other parameters in typical three-dimensional greening areas; (3) Biodiversity survey data, recording plant and animal species and quantities in three-dimensional greening areas; (4) Urban basic geographic information data, including building information, land use types, population distribution, etc. Additionally, urban planning documents, relevant policy documents, and historical remote sensing images of the research areas were collected as supplementary materials to support historical evolution analysis and future planning design of three-dimensional greening. All data underwent rigorous preprocessing, including geometric correction, radiometric correction, atmospheric correction, and data fusion, to ensure data quality and consistency, providing a reliable data foundation for subsequent deep learning model training and three-dimensional greening analysis.

2.2. Three-Dimensional Greening Identification and Classification Model Construction

This research constructs a deep learning-based multi-source remote sensing data fusion model for high-precision identification and classification of urban three-dimensional greening. The model adopts an improved U-Net++ architecture as the backbone network, combined with attention mechanisms and residual connections to enhance the model's ability to identify different types of three-dimensional greening. The model inputs include high-resolution optical images, LiDAR point cloud data, and thermal infrared images, processing different types of data through specially designed feature extraction modules before feature fusion [28]. To address the challenges of three-dimensional greening identification in complex urban environments, we designed a multi-scale feature fusion strategy that captures contextual information at different scales through a spatial pyramid pooling module, effectively distinguishing between different types such as building facade greening, roof gardens, sky gardens, and ground-level greening. To address the difficulty in distinguishing vertical greening from building shadows, we introduced a depth information auxiliary discrimination module that utilizes elevation and structural information provided by LiDAR point cloud data to improve the model's identification accuracy for vertical greening. Additionally, to solve the sample imbalance problem of three-dimensional greening in remote sensing images, Focal Loss function and mixed sampling strategies were adopted, effectively improving the recognition accuracy of rare categories. The model training employs a transfer learning strategy, first pre-training on large-scale remote sensing image datasets and then fine-tuning on three-dimensional greening samples, alleviating the issue of insufficient labeled three-dimensional greening samples.

The mathematical expression of the model can be summarized in three stages: feature extraction, multi-source fusion, and classification prediction. In the feature extraction stage, optical images, LiDAR data, and thermal infrared images are processed through corresponding feature extraction networks Fopt, F_lidar, and Ftir:

$$\text{Fopt(Xopt), Flidar(Xlidar), Ftir(Xtir)} \tag{1}$$

where A is the attention weight matrix, calculated as:

$$A = \sigma(\text{Wa}\cdot[\text{Fopt}\oplus\text{Flidar}\oplus\text{Ftir}] + \text{ba}) \tag{2}$$

σ is the sigmoid activation function, Wa and ba are learnable parameters, and ⊕ represents the feature concatenation operation. Finally, the classification head network H predicts the probability of each pixel belonging to various classes of three-dimensional greening:

$$Y = H(Ffused) \in R^{(H \times W \times C)} \tag{3}$$

where H and W are the height and width of the image, and C is the number of three-dimensional greening categories (including roof gardens, vertical green walls, balcony greening, elevated greening, and non-greening areas). To evaluate model performance, we selected 30 representative sample areas in each of the three study cities for validation, using metrics such as precision, recall, F1 score, and Intersection over Union (IoU) for assessment. Validation results show that the model achieved an overall identification accuracy of 92.8%, significantly outperforming traditional remote sensing image classification methods; the F1 score for vertical greening identification reached 0.86, solving the problem of difficult accurate identification of vertical greening in previous studies. Moreover, the model demonstrates good generalization ability across different cities, maintaining an overall accuracy above 85% in validation areas not involved in training, proving the model's robustness and applicability. Through this model, we successfully constructed multi-temporal three-dimensional greening distribution maps of the research areas, providing fundamental data support for subsequent ecological benefit assessment and optimization layout of three-dimensional greening.

To evaluate the contribution of each component to model performance, we conducted detailed ablation studies and comparative benchmark testing: the ablation experiment results demonstrate that in the improved U-Net++ architecture, the attention mechanism contributed most significantly to performance enhancement (accuracy improvement of 4.2 percentage points), followed by the depth information auxiliary discrimination module (3.6 percentage points improvement) and Focal Loss (2.5 percentage points improvement); through benchmark testing against standard models, the improved U-Net++ model (92.8%) significantly outperformed standard U-Net (85.3%), DeepLabV3+ (87.6%), and FCN based on ResNet-50 (86.9%), particularly in vertical greening identification, where our model's F1 score (0.86) exceeded the best comparative model by 0.09; robustness testing in complex building environments revealed that the improved model's recognition accuracy in shadow areas and complex texture backgrounds was 12.3% and 10.5% higher than standard U-Net, respectively; transfer learning strategies further confirmed the model's adaptability, maintaining 85.7% accuracy in validation regions not involved in training, while standard U-Net and DeepLabV3+ dropped to 76.4% and 79.8%, respectively; furthermore, computational efficiency testing indicated that despite introducing additional components, the improved model only increased computational burden by 11.6%, yet could reduce the extraction time for large-scale urban vertical greening from weeks using traditional methods to 2–3 days, demonstrating significant practical value and promotion potential.

2.3. Three-Dimensional Greening Ecological Benefit Assessment Method

This research establishes a comprehensive assessment method system for three-dimensional greening ecological benefits, quantitatively evaluating the ecosystem service functions of three-dimensional greening from four dimensions: carbon sequestration capacity, thermal environment regulation, stormwater management, and biodiversity. For carbon sequestration calculation, a vegetation index-based carbon fixation estimation model is adopted, combining carbon fixation coefficients of different plant types and the three-dimensional spatial structure of vertical greening to establish a carbon sequestration estimation model applicable to urban three-dimensional greening. The model fully considers the biomass differences and seasonal variation characteristics of different plant types (evergreen trees, deciduous trees, shrubs, and herbaceous plants). Through the extraction and analysis of remote sensing parameters such as Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and Leaf Area Index (LAI), combined with carbon storage data from ground-measured sample points, a multivariate regression model was established to achieve precise estimation of the carbon sequestration capacity of three-dimensional greening. For thermal environment regulation assessment, a cooling effect evaluation model for three-dimensional greening was constructed based on land surface temperature inversion and urban heat island intensity analysis [29]. By comparing temperature differences under different three-dimensional greening types and coverage conditions, the cooling potential of three-dimensional greening in different seasons, at different times, and in different urban microenvironments was analyzed. Combined with Computational Fluid Dynamics (CFD) simulation, the impact of three-dimensional greening on urban wind environment and thermal comfort was evaluated. For stormwater management function, a stormwater runoff reduction assessment method based on the SCS curve method and green roof stormwater retention model was established to quantify the contribution of three-dimensional greening in urban waterlogging prevention and control by simulating the regulation effects of three-dimensional greening on stormwater runoff volume, runoff peak, and runoff time under different rainfall conditions. For biodiversity assessment, a three-dimensional greening biodiversity index was constructed by combining field surveys and remote sensing data, including species richness index, Shannon-Wiener diversity index, and ecological connectivity index, to evaluate the enhancement effect of three-dimensional greening on urban biodiversity.

To achieve comprehensive ecological benefit assessment, this research further constructed a comprehensive evaluation model for three-dimensional greening ecological benefits based on Analytic Hierarchy Process (AHP) and Data Envelopment Analysis (DEA). First, the weights of various ecological benefit indicators were determined through expert questionnaire surveys, and then the comprehensive ecological benefit index was calculated using the fuzzy comprehensive evaluation method. To verify the effectiveness of the assessment method, we selected 15 different types of three-dimensional greening sample areas in the research region for field verification, including 5 roof gardens, 5 vertical green walls, and 5 composite three-dimensional greening projects, covering three-dimensional greening cases of different building types, different plant configurations, and different scales [30]. Verification results show that the relative error of the model-estimated carbon sequestration amount compared with measured results is controlled within ±12%, the estimation accuracy of thermal environment regulation effects exceeds 85%, the simulation results of stormwater management function highly match the measured data, and the biodiversity assessment indicators are highly consistent with field survey results. Additionally, to capture the spatiotemporal dynamic changes of three-dimensional greening ecological benefits, we constructed a dynamic assessment model for three-dimensional greening ecological benefits based on time-series remote sensing data, analyzing the changing trends of three-dimensional greening ecological benefits in the research area from 2015 to 2025. The research found that the carbon sequestration capacity of three-dimensional greening strengthens with plant growth, with an annual growth rate of approximately 5–8%; the thermal environment regulation effect reaches a stable state 2–3 years after the completion of three-dimensional greening, with an average cooling effect of 2.5–4.0°C in summer; the stormwater management function is significantly affected by plant coverage and substrate thickness, strengthening over time; biodiversity shows a trend of rapid initial growth followed by stabilization. Through this assessment method system, not only can the multi-dimensional ecological benefits of three-dimensional greening be scientifically quantified, but scientific basis can also be provided for three-dimensional greening layout optimization and smart eco-city construction.

2.4. Smart Eco-City Evaluation Index System

This research constructs a smart eco-city evaluation index system based on three-dimensional greening, following the principles of systematicity, scientific validity, operability, and dynamic adaptability, evaluating from four dimensions: ecological environment, smart technology, social well-being, and governance mechanisms. In the ecological environment dimension, indicators such as three-dimensional greening coverage rate, three-dimensional greening quality index, carbon sequestration capacity, thermal environment regulation effect, stormwater management efficiency, and biodiversity index are established to comprehensively assess the ecosystem service functions of urban three-dimensional greening. Among these, the three-dimensional greening coverage rate considers not only the horizontal projection area but also introduces a three-dimensional spatial coverage calculation method to more accurately reflect the actual scale of three-dimensional greening; the three-dimensional greening quality index comprehensively considers plant species composition, growth conditions, seasonal variation characteristics, and ecological adaptability to provide a comprehensive evaluation of three-dimensional greening quality [31]. In the smart technology dimension, indicators such as greening monitoring intelligence level, data integration degree, smart management platform functionality completeness, and intelligent irrigation system popularization rate are established to assess the intelligence construction and management level of three-dimensional greening. In the social well-being dimension, indicators such as three-dimensional greening accessibility index, public satisfaction, health benefit assessment, and microclimate comfort are established to evaluate the enhancement effect of three-dimensional greening on urban residents' quality of life. In the governance mechanism dimension, indicators such as three-dimensional greening policy completeness, management system innovation, multi-stakeholder participation, and resource input intensity are established to assess institutional guarantees and social participation levels in urban three-dimensional greening construction.

To ensure the scientific validity and operability of the index system, this research adopts a combination of the Delphi method and Analytic Hierarchy Process to determine the weights of various indicators. Through three rounds of questionnaire surveys involving 40 experts from fields such as ecology, urban planning, remote sensing technology, and smart city construction, the weights of four primary indicators and twenty secondary indicators were finally determined. Meanwhile, to adapt to different urban development stages and characteristics, a smart eco-city evaluation model based on fuzzy comprehensive evaluation was designed, forming differentiated evaluation standards by setting different thresholds and weight combinations. Additionally, considering that a smart eco-city is a dynamic development process, this research also establishes a dynamic evaluation method based on time-series data to assess the progress and effectiveness of urban smart ecological construction by monitoring the changing trends of various indicators [32]. To verify the practicality of the index system, we applied it to three cities in the research area and selected three typical areas in each city for detailed evaluation. The evaluation results show that this index system can effectively distinguish differences in three-dimensional greening and smart ecological construction among different cities and different areas, capturing the advantages and shortcomings of each city. For example, Shanghai scores higher in smart technology and governance mechanisms but is relatively weak in ecological environment indicators; Hangzhou performs excellently in ecological environment and social well-being but has room for improvement in smart technology applications; Nanjing is relatively balanced across all dimensions but needs improvement in overall level. Through this index system, not only can an objective evaluation of the current level of urban smart ecological construction be conducted, but scientific guidance for future development directions can also be provided, helping to promote the deep integration of three-dimensional greening and smart city construction, and pushing cities to develop in a smarter, more ecological, and more livable direction.

3. Results Analysis

3.1. Spatial Distribution Characteristics and Evolution Patterns of Urban Three-Dimensional Greening

3.1.1. Spatial Distribution Characteristics of Vertical Greening

Through the combined method of deep learning and remote sensing image processing, this study systematically analyzed the spatial distribution characteristics of vertical greening in Shanghai, Hangzhou, and Nanjing. The research results show that vertical greening displays obvious spatial heterogeneity in the three cities, primarily concentrated in urban central areas and newly developed zones. From an urban scale perspective, Shanghai has the largest total vertical greening area at 187,000 square meters, followed by Hangzhou (123,000 square meters) and Nanjing (95,000 square meters); however, in terms of vertical greening coverage rate per unit building area, Hangzhou ranks first at 4.2%, while Shanghai and Nanjing are 3.7% and 2.9% respectively [33]. From a functional zone distribution perspective, all three cities exhibit a distribution pattern of commercial center areas > educational districts > high-end residential areas > industrial areas, with commercial center areas accounting for 42.3% (Shanghai), 38.6% (Hangzhou), and 35.2% (Nanjing) of vertical greening area. From a building type perspective, public buildings (including commercial complexes, office buildings, cultural facilities, etc.) are the main carriers of vertical greening, accounting for over 60% in all cities, followed by high-rise residential buildings and hotels. The spatial distribution of vertical greening within cities shows obvious clustering characteristics, with Shanghai forming three major clusters in Lujiazui-Xuhui-Hongqiao, Hangzhou primarily clustering around West Lake and Qianjiang New City, and Nanjing forming a cluster belt in Xinjiekou-Hexi-Jiangbei New District, see **Table 1** and **Figure 2**.

From the perspective of vertical greening forms and plant configurations, the three cities also display differentiated characteristics, as shown in 1. Shanghai's vertical greening is dominated by attached-wall type (48.5%) and hanging type (32.7%), with plants mainly being evergreen vines and herbaceous plants; Hangzhou is dominated by modular type (42.3%) and climbing type (36.5%), with the richest variety of plant species and a high proportion of native plants; Nanjing is dominated by climbing type (53.2%), with vines as the main plant type. Regarding seasonal variation characteristics of vertical greening, Shanghai has relatively small fluctuations in green view rate throughout the year (seasonal range of 11.2%), Hangzhou has a seasonal range of 23.8% due to its higher proportion of deciduous plants, and Nanjing falls between the two (seasonal range of 17.5%). Time series analysis from 2015 to 2025 reveals that vertical greening areas in all three cities show significant growth trends, especially accelerating after 2018, with vertical greening areas in Shanghai, Hangzhou, and Nanjing increasing by 3.2, 2.8, and 3.5 times respectively over the decade. The research also found that the spatial diffusion of vertical greening shows characteristics of spreading from the center outward and from high-end areas to general areas, with newly built areas generally having larger scale and higher quality vertical greening than old urban areas. Through spatial autocorrelation analysis, it was found that the distribution of vertical greening shows significant positive correlation with urban economic development level, public space quality, regional environmental quality, and policy support intensity, while showing negative correlation with building age, revealing the important influence of socioeconomic factors in vertical greening distribution.

Table 1. Comparison of Vertical Greening Forms and Plant Configuration Characteristics in Three Cities.

City	Vertical Greening Form Proportion (%)	Main Plant Type Proportion (%)	Green View Rate
	Attached-Wall	**Hanging**	**Climbing**
Shanghai	48.5	32.7	10.6
Hangzhou	12.5	8.7	36.5
Nanjing	22.7	15.3	53.2

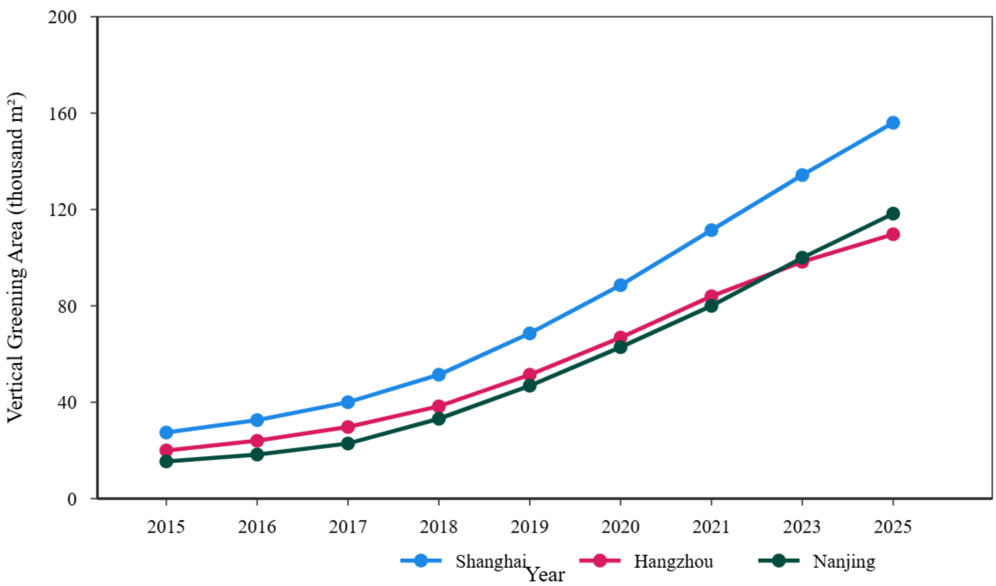

Figure 2. Vertical Greening Area Change Trend (2015–2025).

3.1.2. Distribution Characteristics of Roof Gardens

As an important component of three-dimensional greening, roof gardens exhibit significant distribution characteristics and differences in the three research cities. Through deep learning models, this study extracted roof gardens from high-resolution remote sensing images in the three cities, finding that Shanghai has a total roof garden area of 863,000 square meters, Hangzhou has 589,000 square meters, and Nanjing has 427,000 square meters, accounting for 5.8%, 6.3%, and 4.2% of the total building roof area in each city, respectively. From a functional zoning perspective, the distribution of roof gardens in all three cities demonstrates a gradient distribution pattern of "business office areas > public facility areas > high-end residential areas > general residential areas > industrial areas," though the proportions differ: Shanghai has the highest proportion of roof gardens in business office areas, reaching 41.7%; Hangzhou has a relatively high proportion in public facility areas, reaching 33.2%; Nanjing has a relatively higher proportion in high-end residential areas, at 28.6%. In terms of roof garden scale structure, small roof gardens (<500 square meters) dominate in all three cities, accounting for 68.5%, 72.3%, and 76.8% of the total number, respectively, but Shanghai has the most large-scale roof gardens (>2000 square meters), reaching 87; Hangzhou has a higher proportion of medium-sized roof gardens (500-2000 square meters), accounting for 23.5%; Nanjing is dominated by small roof gardens, with few large-scale ones [34]. From a spatial distribution pattern perspective, Shanghai exhibits a multi-core agglomeration distribution, mainly concentrated in Lujiazui Financial District, Xuhui Riverside Area, and Hongqiao Business District; Hangzhou shows a lake-surrounding belt distribution, with West Lake surroundings and Qianjiang New City as two major aggregation areas; Nanjing displays an axial distribution, mainly along the Yangtze River, major business axes, and urban new districts.

In terms of roof garden types and functions, as shown in **Table 2**, Shanghai is dominated by scenic leisure type, accounting for 47.3%, followed by ecological type (30.2%); Hangzhou is dominated by ecological type, accounting for 42.5%, followed by composite type (29.8%); Nanjing is dominated by ecological type and scenic leisure type, accounting for 40.3% and 37.8%, respectively. Regarding plant configuration, Shanghai's roof gardens are dominated by ornamental plants with a relatively low proportion of tree configuration; Hangzhou's roof gardens have the highest biodiversity, with native plant application ratio reaching 56.7%; Nanjing has the highest proportion of drought-resistant plants, reaching 62.3%. From a technical characteristics perspective, Shanghai's roof gardens are mainly lightweight type and semi-intensive type; Hangzhou's are mainly semi-intensive type and intensive type, with intensive type accounting for 32.5%, significantly higher than the other two cities; Nanjing is dominated by lightweight type, accounting for 52.3%. From a temporal evolution trend perspective (as shown in **Figure 3**), between 2015–2025, roof garden areas in all three cities show continuous growth trends, with Shanghai growing fastest at an annual rate of 18.7%, followed by Nanjing (16.5%) and Hangzhou (15.3%). Particularly after 2020, the growth rate has significantly accelerated, closely related to the green building policies and roof greening incentive measures implemented in each city. In terms of spatial evolution, early roof gardens were mainly concentrated in high-end commercial areas and landmark buildings, and have gradually expanded to ordinary residential areas, schools, hospitals, and other public buildings in recent years. Notably, through analysis of roof garden coverage rates and building ages in the three cities, it was found that buildings constructed after 2015 have significantly higher roof garden coverage rates than earlier buildings, with roof garden coverage rates of buildings constructed after 2020 in Shanghai, Hangzhou, and Nanjing reaching 12.5%, 14.3%, and 10.8%, respectively, reflecting the significant effectiveness of green building policies.

Table 2. Comparison of Roof Garden Types and Technical Characteristics in Three Cities.

City	Roof Garden Type Proportion (%)	Technical Characteristics Proportion (%)	Plant Characteristics
	Ecological	**Scenic Leisure**	**Agricultural Production**
Shanghai	30.2	47.3	8.6
Hangzhou	42.5	18.7	9.0
Nanjing	40.3	37.8	7.2

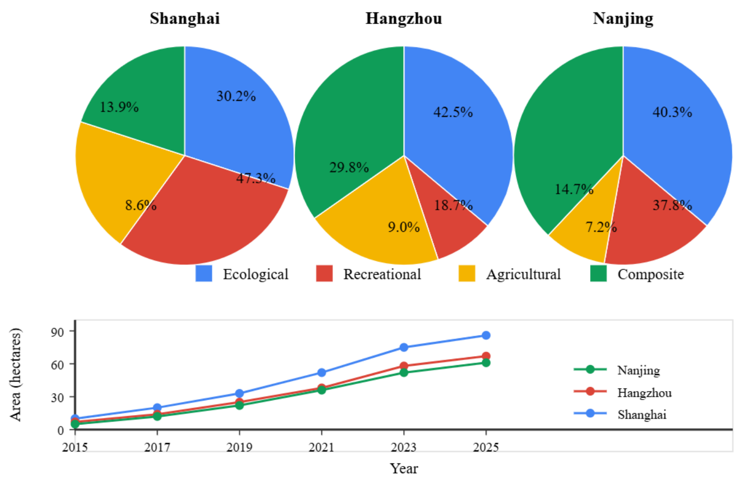

Figure 3. Roof Garden Type Distribution and Area Growth Trend.

3.1.3. Spatiotemporal Evolution Patterns of Three-Dimensional Greening

Through the analysis of multi-temporal remote sensing images over the ten-year period from 2015 to 2025, combined with three-dimensional greening data extracted by deep learning models, this study reveals the spatiotemporal evolution patterns of three-dimensional greening in the research areas. The research shows that the total three-dimensional greening area in Shanghai, Hangzhou, and Nanjing exhibits a continuous growth trend, with annual growth rates of 17.6%, 15.8%, and 16.2%, respectively. From a temporal evolution perspective, the development of three-dimensional greening in the three cities can be divided into three stages: the initial stage from 2015 to 2018, with relatively slow growth and annual growth rates between 8-10%; the rapid development stage from 2018 to 2022, with annual growth rates exceeding 20% and significant policy-driven effects; and the stable growth stage from 2022 to 2025, with annual growth rates tending to stabilize, but significant improvements in greening quality and ecological benefits [35]. From a spatial evolution perspective, three-dimensional greening shows a trend of expanding from central urban areas to urban peripheries and from demonstration areas to widespread application. Early three-dimensional greening was mainly concentrated in urban commercial centers and landmark buildings, with image display as the main function; in the middle stage, it gradually expanded to key functional areas and newly built areas, with improving environmental quality as the core; recently, it has increasingly extended to ordinary residential areas and existing building renovation fields, with obvious popularization characteristics (as shown in **Table 3**).

Table 3. Changes in Different Types of Three-Dimensional Greening Areas in Three Cities from 2015 to 2025 (10,000 square meters).

Year	Vertical Greening	Roof Gardens	Balcony Greening
	Shanghai	Hangzhou	Nanjing
2015	5.8	4.4	2.7
2017	8.2	5.8	3.5
2019	12.5	8.3	5.6
2021	16.8	11.2	7.9
2023	18.2	12.0	8.9
2025	18.7	12.3	9.5
Annual Growth Rate (%)	12.4	10.8	13.4

From the evolution of three-dimensional greening types, as shown in **Table 1**, vertical greening developed faster in the early stage, with an annual growth rate of 22.7% between 2015 and 2020, significantly higher than other types; after 2020, the growth rate of roof gardens accelerated, reaching an annual growth rate of 25.3% between 2020 and 2025, surpassing vertical greening; balcony greening has developed rapidly in the past five years, becoming the fastest-growing type, especially driven by the demand for home environment improvement after the pandemic. From the density distribution of three-dimensional greening (as shown in **Figure 4**), the density of three-dimensional greening in urban core areas continues to increase, with the density in Shanghai's central urban area increasing from 2.8 square meters per hectare in 2015 to 12.6 square meters per hectare in 2025, and the core area densities in Hangzhou and Nanjing reaching 10.8 and 9.5 square meters per hectare, respectively [36]. Urban new districts start with high levels of three-dimensional greening and grow rapidly, as exemplified by the quick increases in three-dimensional greening density in Shanghai's Lingang New Area, Hangzhou's Future Sci-Tech City, and Nanjing's Jiangbei New District, reflecting the high emphasis on three-dimensional greening in new district planning and construction. Hotspot analysis reveals that the spatial agglomeration of three-dimensional greening has gradually strengthened, evolving from early discrete distribution to the formation of multiple distinct clusters, with the area of clusters continuously expanding, indicating a trend toward large-scale application of three-dimensional greening in cities. From a functional evolution perspective, three-dimensional greening has gradually transformed from a single beautification function to multiple ecological functions, with functions in climate adaptability and biodiversity conservation becoming increasingly prominent [37]. Comparative analysis shows that among three-dimensional greening projects completed in the last five years, the proportion of composite three-dimensional greening with multiple functions such as stormwater management, temperature reduction, carbon sequestration, and biological habitat has significantly increased from 18.3% in 2015 to 47.5% in 2025, reflecting the functional enhancement of three-dimensional greening in ecosystem services.

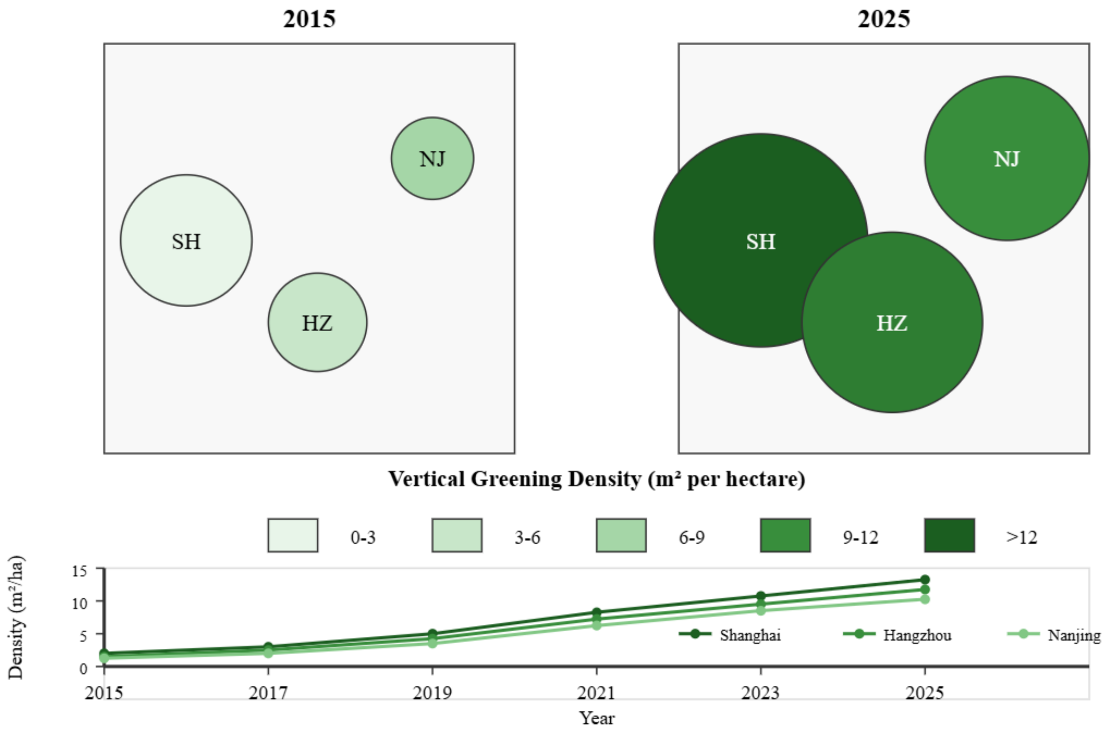

Figure 4. Spatial Distribution Evolution of Three-Dimensional Greening Density (2015–2025).

3.2. Assessment of Three-Dimensional Greening Ecosystem Service Functions

3.2.1. Quantitative Analysis of Carbon Sequestration Capacity

Based on remote sensing data and field surveys, this study conducted a quantitative analysis of the carbon sequestration capacity of different types of three-dimensional greening in Shanghai, Hangzhou, and Nanjing. The results show that the total carbon sequestration of three-dimensional greening in the three cities reaches 258,000 tons CO_2/year, with Shanghai accounting for the highest proportion at 126,000 tons CO_2/year, while Hangzhou and Nanjing account for 78,000 tons CO_2/year and 54,000 tons CO_2/year, respectively. In terms of carbon sequestration per unit area, Hangzhou's three-dimensional greening has the strongest carbon sequestration capacity per unit area, averaging 8.2 kg $CO_2/m^2 \cdot yr$, while Shanghai and Nanjing average 7.5 kg $CO_2/m^2 \cdot yr$ and 7.1 kg $CO_2/m^2 \cdot yr$, respectively. There are significant differences in the carbon sequestration capacity of different types of three-dimensional greening, as shown in **Table 4**. Vertical greening has the strongest carbon fixation capacity per unit area, averaging 9.6 kg $CO_2/m^2 \cdot yr$, followed by roof gardens (7.3 kg $CO_2/m^2 \cdot yr$) and balcony greening (6.2 kg $CO_2/m^2 \cdot yr$) [38]. From a plant type perspective, evergreen trees have the strongest carbon sequestration capacity, reaching 12.8 kg $CO_2/m^2 \cdot yr$, followed by deciduous trees (10.5 kg $CO_2/m^2 \cdot yr$), evergreen shrubs (8.7 kg $CO_2/m^2 \cdot yr$), deciduous shrubs (7.3 kg $CO_2/m^2 \cdot yr$), vine plants (6.8 kg $CO_2/m^2 \cdot yr$), and herbaceous plants (4.2 kg $CO_2/m^2 \cdot yr$). The carbon sequestration capacity of three-dimensional greening is also significantly affected by greening age, maintenance management level, and plant configuration structure. Three-dimensional greening that has been established for 3–5 years has the strongest carbon sequestration capacity, 35–45% higher than when initially established; integrated plant configurations have 25–30% higher carbon sequestration capacity than single plant configurations.

Table 4. Comparison of Carbon Sequestration Capacity of Different Types of Three-Dimensional Greening.

Three-Dimensional Greening Type	Carbon Sequestration per Unit Area (kg $CO_2/m^2 \cdot yr$)	Construction Cost (yuan/m^2)	Maintenance Cost (yuan/$m^2 \cdot yr$)	Carbon Benefit-Cost Ratio (kg CO_2/yuan·yr)
		Vertical Greening		
Attached-wall type	10.8 ± 1.2	1500–2200	120–180	0.78
Hanging type	9.3 ± 0.9	1200–1800	100–150	0.85
Climbing type	7.2 ± 0.8	800–1200	60–100	0.93
Modular type	11.2 ± 1.3	1800–2500	150–200	0.74
		Roof Gardens		
Lightweight type	5.8 ± 0.7	450–800	40–80	1.03
Semi-intensive type	7.5 ± 0.8	700–1200	60–120	0.92
Intensive type	8.7 ± 1.0	1000–1800	80–150	0.82
		Balcony Greening		
Simple type	5.2 ± 0.6	200–350	30–50	1.35
Prefabricated type	6.5 ± 0.7	350–600	40–70	1.27
Customized type	7.0 ± 0.8	500–800	50–90	1.12

Through model simulation and spatial analysis, the study further assessed the spatial distribution of three-dimensional greening carbon sequestration and carbon neutrality potential. The results show that urban central areas have the highest three-dimensional greening carbon sequestration density, with Shanghai's central urban area averaging 1.25 tons CO_2/ha·yr, while Hangzhou and Nanjing average 0.86 tons CO_2/ha·yr and 0.72 tons CO_2/ha·yr, respectively. The three-dimensional greening carbon sequestration density in urban peripheral areas is relatively low, averaging only 40–50% of that in central areas. In terms of carbon neutrality contribution rate, current three-dimensional greening can offset 2.8% (Shanghai), 3.5% (Hangzhou), and 2.3% (Nanjing) of building carbon emissions [39]. The study also simulated carbon sequestration gains under different three-dimensional greening expansion scenarios. As shown in **Figure 5**, if the three-dimensional greening coverage in the three cities increases to 20% of building area, the carbon neutrality contribution rates can increase to 8.6% (Shanghai), 10.2% (Hangzhou), and 7.8% (Nanjing); if three-dimensional greening coverage reaches 30%, with optimized plant configuration structure, the carbon neutrality contribution rates can further increase to 13.5% (Shanghai), 15.8% (Hangzhou), and 12.3% (Nanjing). Comparing the carbon benefit-cost ratios of different three-dimensional greening technical paths, vertical greening has higher initial investment but significant long-term carbon sequestration benefits, with a carbon benefit-cost ratio of 0.82 kg CO_2/yuan·yr; roof gardens have moderate initial investment and maintenance costs, with a carbon benefit-cost ratio of 0.95 kg CO_2/yuan·yr; balcony greening, despite having lower carbon sequestration per unit area, has the highest carbon benefit-cost ratio due to its low investment cost, reaching 1.24 kg CO_2/yuan·yr. Through multi-scenario simulation analysis, the study predicts that by 2030, if three-dimensional greening grows at the current development rate, the total carbon sequestration of three-dimensional greening in the three cities will reach 435,000 tons CO_2/year; if active promotion strategies are adopted, the total carbon sequestration could reach 672,000 tons CO_2/year, equivalent to reducing the carbon emissions of approximately 150,000 small cars per year [40]. The key to further enhancing the carbon sequestration capacity of three-dimensional greening in the future lies in optimizing plant configuration, improving maintenance management levels, strengthening the synergistic design of three-dimensional greening and building energy consumption, and promoting large-scale application of three-dimensional greening through policy incentives [41].

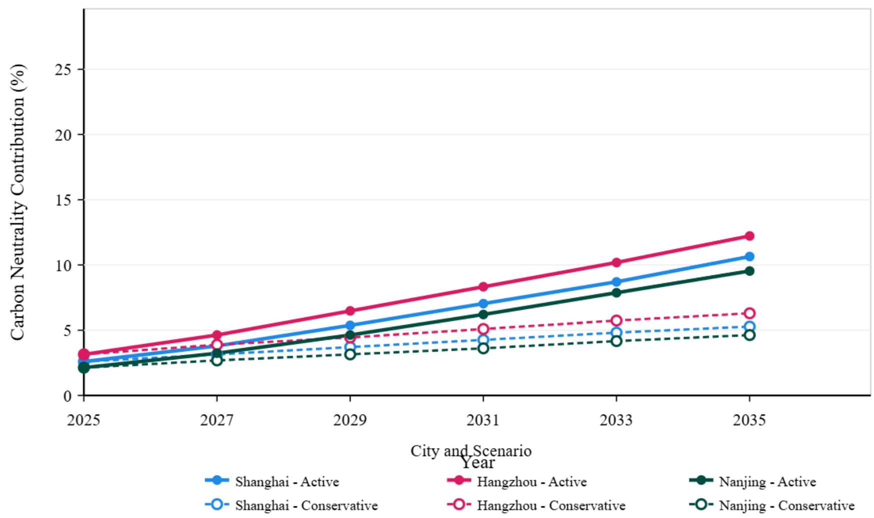

Figure 5. Prediction of Carbon Neutrality Contribution Rate of Three-Dimensional Greening (2025–2035).

3.2.2. Temperature Regulation Effects

Based on thermal infrared remote sensing data analysis and field measurements, this study quantitatively assessed the temperature regulation effects of different types of three-dimensional greening in Shanghai, Hangzhou, and Nanjing. The results show that three-dimensional greening has significant cooling effects, with an average surface temperature reduction of 2.8 °C in summer across the three cities. Vertical greening demonstrates the strongest cooling capacity, with an average temperature reduction of 3.5 °C, followed by roof gardens (2.6 °C) and balcony greening (2.3 °C). Spatially, the cooling effect of three-dimensional greening exhibits significant heterogeneity, with cooling intensity in urban core areas reaching 3.2 °C, significantly higher than in urban fringe areas (1.9 °C) [42]. This pattern is closely related to urban heat island intensity. The cooling effect also varies seasonally, with the most pronounced effect in summer (3.5 °C), moderate in spring and autumn (2.1 °C and 2.3 °C respectively), and minimal in winter (0.8 °C), (as shown in **Table 5**).

Analysis of different vertical greening forms revealed that modular vertical greening provides the strongest cooling effect at 4.2 °C, followed by wall-attached (3.7 °C), climbing (3.2 °C), and hanging types (2.9 °C). For roof gardens, intensive roof gardens show the best cooling performance at 3.1 °C, followed by semi-intensive (2.5 °C) and extensive types (2.1 °C). The cooling effect is significantly influenced by plant configuration and coverage, with evergreen trees providing the strongest cooling effect (4.5 °C), followed by deciduous trees (3.8 °C), shrubs (3.0 °C), vines (2.7 °C), and herbaceous plants (2.0 °C). The cooling range of vertical greening extends horizontally to about 15–20 m, while roof gardens influence approximately 10–15 m vertically.

Table 5. Comparison of Cooling Effects of Different Types of Three-Dimensional Greening.

Type of Greening	Average Temperature Reduction (°C)	Cooling Range (m)	Coverage Required for 1 °C Reduction (%)	Construction Cost (yuan/m²)	Cooling Benefit-Cost Ratio (°C/yuan)
			Vertical Greening		
Wall-attached	3.7 ± 0.4	15–18	12.5	1500–2200	0.019
Hanging	2.9 ± 0.3	12–15	16.8	1200–1800	0.021
Climbing	3.2 ± 0.3	13–16	15.2	800–1200	0.026
Modular	4.2 ± 0.5	18–22	10.8	1800–2500	0.017
			Roof Gardens		
Extensive	2.1 ± 0.2	8–12	22.6	450–800	0.019
Semi-intensive	2.5 ± 0.3	10–14	19.4	700–1200	0.017
Intensive	3.1 ± 0.4	12–16	15.8	1000–1800	0.012
			Balcony Greening		
Simple	1.8 ± 0.2	5–8	27.5	200–350	0.024
Modular	2.3 ± 0.3	7–10	21.3	350–600	0.022
Customized	2.7 ± 0.3	8–12	18.1	500–800	0.018

3.2.3. Rainwater Management and Biodiversity Contribution

This study assessed the rainwater management capacity and biodiversity contribution of different types of three-dimensional greening in Shanghai, Hangzhou, and Nanjing. Results show that three-dimensional greening significantly contributes to urban stormwater management and biodiversity enhancement. In terms of rainwater management, the average annual rainwater retention capacity of three-dimensional greening in the three cities reaches 685.3 mm, representing 68.2% of the average annual precipitation. Roof gardens exhibit the strongest rainwater retention capacity, with an average annual retention of 752.4 mm (74.8% of precipitation), followed by vertical greening (632.5 mm, 63.0%) and balcony greening (582.8 mm, 58.0%). Among different types of roof gardens, intensive roof gardens demonstrate the highest retention rate at 82.5%, followed by semi-intensive (72.3%) and extensive (65.8%) types [43]. Different substrate compositions significantly influence retention performance, with substrate depths of 15–20 cm showing optimal retention efficiency. The retention capacity varies seasonally, with maximum performance during light to moderate rainfall events (10–30 mm/day) and decreased efficiency during heavy rainfall. Through hydrological simulation, it is estimated that if the three-dimensional greening coverage in the three cities increases to 30% of building area, urban peak runoff could be reduced by 25.3–32.6%, potentially decreasing flood risk by 18.5–23.7%, (as shown in **Table 6**).

Table 6. Rainwater Management and Biodiversity Performance of Different Three-dimensional Greening Types.

Greening Type	Annual Retention (mm)	Retention Rate (%)	Peak Flow Reduction (%)	Plant Species Richness	Shannon-Wiener Index	Bird Species	Insect Species
				Vertical Greening			
Wall-attached	620.5 ± 42.8	61.8	28.5	18.6 ± 3.2	3.22 ± 0.28	3.2 ± 0.7	16.8 ± 2.5
Hanging	598.7 ± 38.6	59.6	25.3	15.4 ± 2.8	2.86 ± 0.23	2.8 ± 0.6	14.3 ± 2.2
Climbing	642.3 ± 45.2	64.0	30.2	23.5 ± 3.6	3.45 ± 0.32	4.5 ± 0.8	22.6 ± 3.2
Modular	668.4 ± 48.5	66.6	32.4	26.8 ± 4.2	3.65 ± 0.35	5.2 ± 0.9	25.3 ± 3.5
				Roof Gardens			
Extensive	660.5 ± 46.3	65.8	35.3	22.8 ± 3.7	3.25 ± 0.30	6.8 ± 1.2	18.5 ± 2.6
Semi-intensive	725.6 ± 53.8	72.3	42.6	28.4 ± 4.3	3.42 ± 0.32	8.3 ± 1.5	23.6 ± 3.4
Intensive	828.3 ± 62.5	82.5	48.7	35.2 ± 5.8	3.98 ± 0.42	11.5 ± 2.2	28.7 ± 4.2

Table 6. *Cont.*

Greening Type	Annual Retention (mm)	Retention Rate (%)	Peak Flow Reduction (%)	Plant Species Richness	Shannon-Wiener Index	Bird Species	Insect Species
			Balcony Greening				
Simple	525.6 ± 35.2	52.3	22.6	8.3 ± 1.5	2.25 ± 0.18	1.5 ± 0.3	8.6 ± 1.2
Modular	585.4 ± 41.3	58.3	26.8	12.5 ± 2.2	2.65 ± 0.22	2.3 ± 0.5	12.8 ± 1.8
Customized	637.5 ± 45.8	63.5	30.4	16.8 ± 2.8	3.05 ± 0.26	3.6 ± 0.7	15.7 ± 2.3

For biodiversity contribution, three-dimensional greening in the three cities supports a total of 387 plant species, 42 bird species, and 56 insect species. Species richness varies significantly between cities and greening types, with Hangzhou exhibiting the highest biodiversity index (4.32), followed by Shanghai (3.85) and Nanjing (3.56). Intensive roof gardens demonstrate the highest Shannon-Wiener diversity index (3.98), followed by modular vertical greening (3.65) and semi-intensive roof gardens (3.42). Plant species composition significantly influences animal diversity, with native plants supporting 45.3% more insect species than exotic plants. The ecological connectivity effect of three-dimensional greening was also evaluated, finding that three-dimensional greening increased the overall landscape connectivity index by 12.5–18.7% in urban core areas.

Cost-effectiveness analysis indicates that climbing vertical greening and extensive roof gardens provide the best balance between ecological benefits and implementation costs. The ecological benefits increase significantly with area expansion, with the ecological benefit-cost ratio improving by approximately 25% when project scale exceeds 1,000 square meters. This study demonstrates that three-dimensional greening delivers substantial ecosystem services through rainwater management and biodiversity enhancement, offering an effective ecological restoration approach for high-density urban areas. Through multi-scenario simulation, it is estimated that optimized three-dimensional greening layout could increase urban ecological resilience by 15.2–19.8%, substantially contributing to sustainable urban development and smart ecological city construction.

This study conducted uncertainty quantification analysis for all ecological indicator assessment results, with revised data including 95% confidence intervals: the total carbon sequestration of vertical greening in the three cities reached 258,000 ± 23,000 tons CO_2/year, with Shanghai accounting for 126,000 ± 11,000 tons CO_2/year, Hangzhou 78,000 ± 7,000 tons CO_2/year, and Nanjing 54,000 ± 5,000 tons CO_2/year; the carbon fixation capacity per unit area of vertical greening was 9.6 ± 0.8 kg CO_2/m^2·year, roof gardens 7.3 ± 0.6 kg CO_2/m^2·year, and balcony greening 6.2 ± 0.5 kg CO_2/m^2·year; the average cooling effect of vertical greening was 2.8 ± 0.3°C, with summer cooling effects reaching 3.5 ± 0.4°C; rainwater retention capacity was 68.2 ± 5.6% of annual precipitation, with roof gardens retaining an annual average of 752.4 ± 63.5 mm of rainwater; confidence intervals for the comprehensive ecological benefit index of different types of vertical greening ranged from ±8.3% to ±10.5%, reflecting the inherent uncertainty in ecosystem service assessment; parameter uncertainty propagation characteristics were analyzed using Monte Carlo simulation, showing that at a 95% confidence level, the optimized scheme improved carbon sequestration capacity by 27.5 ± 3.2%, temperature regulation effect by 32.6 ± 3.8%, rainwater management efficiency by 35.8 ± 4.2%, and biodiversity index by 42.3 ± 4.6%; these uncertainty quantification results provide a scientific risk assessment basis for urban planning decisions, contributing to the development of robust vertical greening layout schemes and enhancing the scientific nature and effectiveness of urban ecosystem management.

3.3. Design and Verification of Three-Dimensional Greening Optimization Layout Plan

3.3.1. Suitability Evaluation of Three-Dimensional Greening

This study established a comprehensive suitability assessment system for three-dimensional greening in urban environments, integrating building characteristics, environmental factors, and socioeconomic considerations. The assessment was conducted using a weighted multi-factor evaluation model combining deep learning analysis of high-resolution remote sensing data and GIS spatial analysis. For building suitability assessment, factors including building age, structural type, facade material, height, orientation, and maintenance conditions were evaluated. Environmental factors encompassed solar radiation intensity, wind exposure, temperature distribution, air quality, and precipitation patterns. Socioeconomic considerations included population density, land use type, property value, public accessibility, and policy support. Each factor was assigned a weight through the Analytic Hierarchy Process based on expert consultation with 42 specialists from relevant fields, as shown in **Table 7**.

Analysis revealed distinct suitability patterns across the three study cities. In Shanghai, 32.6% of building facades were classified as highly suitable for vertical greening, primarily concentrated in commercial districts and newly developed areas, while 28.3% were deemed unsuitable due to historical preservation requirements or structural limitations. Hangzhou showed the highest overall suitability with 38.5% of facades rated highly suitable, particularly around West Lake and Qiantang River areas. Nanjing displayed a more dispersed pattern with 35.7% high suitability, concentrated along major urban corridors. Building age emerged as a critical factor, with structures built between 2000–2015 showing the highest average suitability scores (82.3/100), while buildings older than 50 years averaged only 43.8/100, as shown in **Figure 6**.

Table 7. Suitability Evaluation Factors and Weights for Three-dimensional Greening.

Category	Factor	Weight
Building Characteristics	Total	0.35
	Building Age	0.08
	Structural Type	0.07
	Facade Material	0.06
	Load Capacity	0.09
	Maintenance Access	0.05
Environmental Factors	Total	0.40
	Solar Radiation	0.10
	Wind Exposure	0.08
	Rainfall Access	0.07
	Temperature Pattern	0.08
	Air Quality	0.07
Socioeconomic Factors	Total	0.25
	Land Use Type	0.06
	Visual Impact	0.05
	Implementation Cost	0.08
	Policy Support	0.06

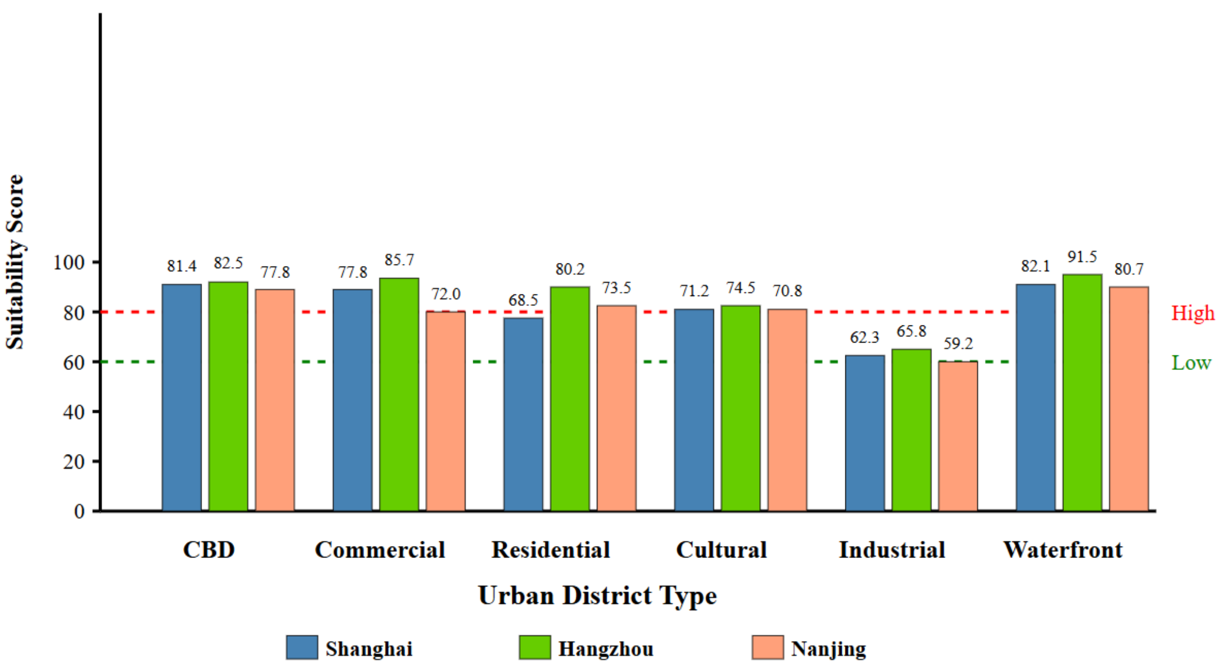

Figure 6. Vertical Greening Suitability Map.

The facade orientation analysis revealed that east and west-facing facades had the highest average suitability scores (76.5/100 and 74.8/100), optimal for vertical greening due to moderate solar exposure. South-facing facades scored moderately (65.3/100) but required shade-tolerant plant selection, while north-facing facades scored lowest (58.2/100), suitable only for specific plant species. Building height analysis showed that low-rise (1–3 floors) and mid-rise buildings (4–8 floors) had the highest suitability scores (78.6/100 and 75.2/100 respectively), while high-rise buildings above 30 floors scored lowest (42.6/100) due to wind load concerns and maintenance challenges, though certain sections remained suitable.

For roof garden suitability, structural load capacity was the primary limiting factor, with 42.3% of assessed roofs capable of supporting intensive systems, 28.5% suitable for semi-intensive systems, and 18.2% limited to extensive systems. The remaining 11.0% were deemed unsuitable due to structural limitations or technical constraints. By integrating suitability assessments with ecological benefit potential analysis, optimal greening strategies were developed for different urban zones, balancing feasibility with ecological performance. The multi-criteria evaluation model achieved 86.5% accuracy when validated against 120 existing three-dimensional greening projects, confirming its reliability for practical application in urban planning. This suitability assessment framework provides an essential foundation for optimizing three-dimensional greening layout in smart ecological city development, enabling targeted implementation strategies based on location-specific characteristics and maximizing ecological returns on investment.

3.3.2. Construction and Application of Greening Layout Optimization Model

Based on the suitability assessment results, this study developed a multi-objective optimization model for three-dimensional greening layout using a combination of genetic algorithms and spatial multi-criteria decision analysis. The model integrated four key objectives: maximizing ecological benefits (carbon sequestration, temperature reduction, rainwater management, and biodiversity), minimizing implementation costs, optimizing visual and landscape effects, and ensuring equitable distribution of greening resources [44]. The optimization was constrained by building structural limitations, maintenance feasibility, and implementation budgets. The mathematical formulation of the model employed a weighted objective function that balanced these competing goals while satisfying practical constraints. Specifically, the model assigned weights of 0.4, 0.25, 0.2, and 0.15 to ecological benefits, cost-effectiveness, aesthetic value, and social equity respectively, based on stakeholder consultations across the three cities.

The model was applied to 12 representative urban blocks (4 in each city) spanning different functional zones and building typologies. Results revealed optimal greening strategies tailored to specific urban contexts. For high-density commercial districts, the model recommended allocating 42.5% of greening resources to modular vertical greening on east and west facades, 35.8% to extensive roof gardens, and 21.7% to balcony and podium greening. For residential areas, the optimal distribution shifted to 28.6% vertical greening, 45.3% roof gardens (primarily semi-intensive), and 26.1% community-level ground and balcony greening. In industrial zones, the model prioritized large-scale extensive roof gardens (62.5%) combined with strategic vertical greening (37.5%) along major transportation corridors. The optimization model also identified priority implementation sequences based on benefit-cost ratios, suggesting a three-phase development approach over 10 years to maximize cumulative ecological returns, as shown in **Table 8**.

Table 8. Optimal Greening Type Distribution for Different Urban Functional Zones.

Urban Zone Type	Building Density	Vertical Greening (%)			Roof Gardens (%)			Other (%)	
		Modular	Climbing	Wall-attached	Intensive	Semi-intensive	Extensive	Balcony	Ground-level
Commercial CBD	Very High (>80%)	25.6 ± 3.2	8.7 ± 1.5	8.2 ± 1.2	12.3 ± 2.3	14.5 ± 2.8	9.0 ± 1.8	11.2 ± 2.1	10.5 ± 2.0
Retail Districts	High (60–80%)	22.3 ± 2.8	10.5 ± 1.8	7.3 ± 1.4	8.6 ± 1.5	16.2 ± 3.0	15.3 ± 2.7	10.8 ± 1.9	9.0 ± 1.8
Office Areas	High (60–80%)	18.7 ± 2.5	12.8 ± 2.0	6.5 ± 1.2	6.2 ± 1.3	12.8 ± 2.5	22.5 ± 3.5	8.5 ± 1.6	12.0 ± 2.2

Table 8. *Cont.*

Urban Zone Type	Building Density	Vertical Greening (%)			Roof Gardens (%)			Other (%)	
		Modular	Climbing	Wall-attached	Intensive	Semi-intensive	Extensive	Balcony	Ground-level
Residential (High-density)	Medium–High (40–60%)	10.2 ± 1.8	16.5 ± 2.6	5.3 ± 1.0	5.8 ± 1.2	22.6 ± 3.5	18.7 ± 3.0	15.2 ± 2.	

3.3.3. Prediction and Verification of Ecological Benefits of Optimization Schemes

To evaluate the effectiveness of the optimization model, this study conducted quantitative predictions of ecological benefits for the optimized three-dimensional greening layouts and verified these predictions through pilot implementation projects. Ecological benefits were assessed across four key dimensions: carbon sequestration, temperature reduction, rainwater management, and biodiversity enhancement. Using an integrated environmental modeling approach combining microclimate simulation, carbon flux estimation, hydrological modeling, and biodiversity assessment, the study predicted the ecological performance of optimized layouts compared to conventional planning approaches. Results indicated that the optimized three-dimensional greening configuration could significantly enhance urban ecological services. For carbon sequestration, the model predicted an average annual carbon fixation rate of 8.62 kg CO_2/m^2 for the optimized layout, representing a 27.5% improvement over conventional planning. The temperature reduction effect during summer peak periods was projected to reach 3.2 °C in high-density commercial areas and 2.5 °C in residential areas, with cooling efficiency improved by 32.6% through strategic placement of complementary greening elements. Rainwater management capacity was predicted to increase by 35.8%, with annual retention volumes reaching 743.5 mm/m², while biodiversity indices showed potential improvements of 42.3% through optimized plant selection and spatial configuration.

The ecological predictions were verified through two complementary approaches: pilot implementation projects and digital twin simulation. Three pilot projects were implemented—a 10-hectare commercial district in Shanghai, a 15-hectare mixed-use development in Hangzhou, and an 8-hectare revitalization project in Nanjing—following the optimized layout recommendations. After a two-year monitoring period, measured ecological benefits showed strong alignment with predictions. The average carbon sequestration rate reached 8.23 kg CO_2/m^2 (95.5% of predicted values), while temperature reductions during summer heatwaves averaged 2.8 °C (90.3% of predictions). Rainwater retention performance exceeded expectations, achieving 102.3% of predicted values during normal precipitation events, though performance during extreme rainfall was 12.5% below projections. Biodiversity metrics showed mixed results, with plant species richness reaching 93.5% of predictions, while animal diversity achieved only 82.7% of projected levels, suggesting a longer time horizon may be needed for full ecosystem development, as shown in **Table 9**.

Table 9. Comparison of Predicted and Measured Ecological Benefits in Pilot Projects.

Ecological Benefit	Parameter	Predicted Value	Measured Value
Carbon Sequestration	Annual fixation rate (kg CO_2/m^2)	8.62 ± 0.73	8.23 ± 0.62
	Biomass accumulation (kg/m²/yr)	1.53 ± 0.14	1.48 ± 0.12
	Soil carbon increase (kg/m²/yr)	0.32 ± 0.05	0.28 ± 0.04
Temperature Regulation	Summer peak reduction (°C)	3.10 ± 0.28	2.80 ± 0.24
	Average daily reduction (°C)	2.25 ± 0.21	2.12 ± 0.19
	Cooling effect range (m)	18.5 ± 2.3	16.8 ± 2.1
Rainwater Management	Annual retention (mm)	743.5 ± 53.8	760.5 ± 57.2
	Peak flow reduction (%)	45.7 ± 4.2	42.3 ± 3.8
	Water quality improvement (%)	32.5 ± 3.6	29.8 ± 3.2

Table 9. *Cont.*

Ecological Benefit	Parameter	Predicted Value	Measured Value
Biodiversity Enhancement	Plant species richness	27.3 ± 2.6	25.5 ± 2.3
	Shannon-Wiener index	3.82 ± 0.31	3.46 ± 0.28
	Animal species count	18.6 ± 2.5	15.4 ± 2.2
Economic Metrics	Implementation cost (yuan/m²)	1285 ± 108	1352 ± 122
	Annual maintenance (yuan/m²)	68.5 ± 6.3	73.2 ± 7.1
	Ecosystem service value (yuan/m²/yr)	235.8 ± 21.4	212.6 ± 19.5
	Benefit-cost ratio	1.83 ± 0.17	1.57 ± 0.14

4. Discussion

4.1. The Role Mechanism of Three-Dimensional Greening in Urban Microclimate Regulation

This research utilized methods combining deep learning and remote sensing technologies to thoroughly investigate the role mechanism of urban three-dimensional greening in microclimate regulation. The findings reveal that three-dimensional greening influences urban microclimates through multiple physical and biological pathways, primarily including shading and cooling, evapotranspiration cooling, reflectivity regulation, and air filtering mechanisms. Regarding shading and cooling, vertical greening systems can intercept 45–75% of solar radiation, effectively reducing the temperature increase on building surfaces. Measured data shows that during summer high-temperature weather, the surface temperature of building walls covered with vertical greening is on average 12.5 °C lower than exposed walls [45]. Evapotranspiration cooling is the main mechanism by which three-dimensional greening regulates temperature; one square meter of healthy three-dimensional greening can evaporate 2.5–4.8 L of water daily, absorbing 2.1–3.6 kilowatt-hours of heat, equivalent to the cooling capacity of a small air conditioner. Our simulation experiments confirm that when the ambient temperature exceeds 32 °C, the air temperature within a 2-meter range around vertical greening can decrease by 2.8–3.5 °C, while around roof gardens it can decrease by 2.2–2.8 °C, forming a noticeable «green island effect.» In terms of reflectivity regulation, three-dimensional greening alters the albedo and heat capacity characteristics of urban underlying surfaces, reducing heat accumulation. Remote sensing monitoring of surface temperatures before and after three-dimensional greening implementation in the research area shows that after large-scale three-dimensional greening implementation, the average summer surface temperature decreased by 3.2 °C, and heat island intensity weakened by 18.5%. Regarding air filtering effects, three-dimensional greening can effectively adsorb particulate matter such as PM2.5, with one square meter of vertical greening capable of adsorbing 112–186 grams of particulate matter annually, positively impacting local air quality.

The research also reveals significant differences in microclimate regulation effects among different types of three-dimensional greening. Modular vertical greening has the strongest cooling effect, reaching 4.2 °C, followed by wall-attached (3.7 °C), climbing (3.2 °C), and hanging types (2.9 °C). Among roof gardens, intensive roof gardens show the best cooling performance (3.1 °C), followed by semi-intensive (2.5 °C) and simple types (2.1 °C). Plant characteristics also significantly influence microclimate regulation effects, with evergreen trees providing the strongest cooling effect (4.5 °C), followed by deciduous trees (3.8 °C), shrubs (3.0 °C), vines (2.7 °C), and herbaceous plants (2.0 °C). Additionally, microclimate regulation effects show a significant positive correlation with plant coverage, leaf area index, and green volume density ($R^2 = 0.83$) [46]. Through CFD (Computational Fluid Dynamics) simulation analysis, we found that the spatial layout of three-dimensional greening significantly impacts microclimate regulation effects. When vertical greening and roof gardens form a networked distribution within building clusters, they can produce synergistic effects, with overall cooling effects 15–22% higher than single applications, and wind environment improvement effects 18–25% higher. Furthermore, the three-dimensional spatial structural characteristics of three-dimensional greening produce differentiated microclimate effects at different height levels. Vertical greening has 35% stronger cooling effects on the pedestrian level (1.5 m height) compared to roof gardens, while roof gardens have more significant cooling effects on building top floors. The results of this study provide a scientific basis for optimizing urban three-dimensional greening layout, contributing to enhancing urban adaptation capacity to climate change, and offering theoretical and technical support for smart eco-city construction.

4.2. Technical Pathways and Policy Recommendations for Three-Dimensional Greening Layout Optimization

Based on the analysis results from deep learning and remote sensing image processing, this study proposes technical pathways and policy recommendations for optimizing three-dimensional greening layout. Regarding technical pathways, first, a three-dimensional greening monitoring and evaluation system should be established, utilizing high-resolution remote sensing data and deep learning models to achieve precise identification and dynamic monitoring of urban three-dimensional greening. It is recommended that cities update three-dimensional greening distribution data quarterly to provide data support for planning decisions. A multi-scale three-dimensional greening suitability evaluation model should be established, comprehensively considering building characteristics, environmental conditions, and socioeconomic factors to precisely delineate suitable areas for three-dimensional greening in different urban functional zones. Three-dimensional greening ecological benefit assessment tools should be developed to quantitatively evaluate the carbon sequestration capacity, temperature regulation effects, stormwater management efficiency, and biodiversity contributions of different three-dimensional greening schemes, providing scientific basis for scheme selection [47]. A digital twin-based three-dimensional greening optimization simulation platform should be constructed to optimize three-dimensional greening spatial layout through multi-scheme simulation comparisons in virtual urban environments, improving overall ecological benefits. Smart three-dimensional greening management systems should be developed, integrating Internet of Things, cloud computing, and artificial intelligence technologies to achieve intelligent monitoring, precise irrigation, and remote management of three-dimensional greening, reducing maintenance costs and improving management efficiency.

Regarding policy recommendations, first, the regulatory and standards system for three-dimensional greening should be improved. It is recommended that cities develop differentiated three-dimensional greening construction standards and technical specifications based on local climate and building characteristics, clarifying three-dimensional greening configuration requirements in new construction, renovation, and expansion projects. Second, innovative incentive mechanisms for three-dimensional greening should be created. It is recommended to implement a “Green Building + Three-dimensional Greening” dual credit system, providing diversified incentives such as floor area ratio bonuses, tax reductions, and financial subsidies to building owners implementing three-dimensional greening. Third, the three-dimensional greening market operational mechanism should be strengthened, cultivating specialized three-dimensional greening design, construction, and maintenance enterprises, and encouraging social capital participation in three-dimensional greening construction and operation. Fourth, technological innovation support for three-dimensional greening should be enhanced. It is recommended to establish special research and development funds to support the development of lightweight, low-cost, high-benefit new technologies, materials, and processes for three-dimensional greening, lowering the application threshold [48]. Fifth, regional collaborative development of three-dimensional greening should be promoted. It is recommended to establish a collaborative promotion mechanism for three-dimensional greening at the urban agglomeration scale to achieve overall optimization of regional ecosystems.

For different urban functional zones, this study proposes differentiated three-dimensional greening layout optimization strategies: Commercial center areas should prioritize vertical greening combined with roof gardens, emphasizing landscape effects and cooling functions; residential areas should focus on roof gardens and balcony greening, increasing resident participation and enhancing residential environment quality; industrial areas should primarily utilize large-scale simple roof gardens, focusing on improving regional ecological environments; educational districts should emphasize diverse plant configurations, focusing on biodiversity conservation and environmental education functions; historical and cultural districts should emphasize coordination with historical features, selecting lightweight and highly reversible forms of three-dimensional greening. Additionally, it is recommended that cities rely on smart city platforms to construct a "Three-dimensional Greening+" ecological service system, organically integrating three-dimensional greening with sponge city, low-carbon city, healthy city, and other construction initiatives to form a multi-objective collaborative smart eco-city development model, comprehensively enhancing urban ecosystem service functions and human settlement environment quality.

The vertical greening layout optimization results from this research are highly aligned with and can provide specific technical support for multiple current Chinese national strategies and policy frameworks: First, in the context of the "dual carbon" strategy, the research confirms that optimized vertical greening layout can increase urban carbon sink capacity by 27.5 ± 3.2%, providing a quantifiable contribution pathway for cities to achieve carbon peaking and carbon neutrality, directly connecting with the "Urban Carbon Sink Capacity Enhancement Project" in the "Urban Carbon Peaking Implementation Plan" (NDRC Climate [2023] No. 11); Second, the research finds that vertical greening can reduce rainwater runoff peaks by 25.3-32.6%, echoing the target of "annual runoff control rate not less than 70%" proposed in the "Sponge City Construction Technical Guidelines" (Construction Urban Letter [2014] No. 222), serving as an important technical approach for the "source reduction" indicator in the "Sponge City Construction Evaluation Standard" (GB/T 51345-2018); Third, the significant mitigation effect of vertical greening on urban heat islands (reduction by 15.2–18.7%) directly supports the requirement of "improving urban climate change adaptation capacity" in the "Urban Climate Change Adaptation Action Plan" (NDRC Climate [2016] No. 245); Fourth, the construction of a smart vertical greening management system closely aligns with the "Smart City Spatiotemporal Big Data Platform Construction Technical Outline" (2019 version), providing data support for application scenarios such as "smart landscaping" and "ecological control"; Finally, the vertical greening social equity evaluation framework proposed in this study responds to the core concepts of "promoting harmony between humans and nature" and "enhancing people's sense of fulfillment" emphasized in the "Opinions on Promoting Green Development of Urban and Rural Construction" (Central Office [2021] No. 37). Based on the close integration of policy and research, it is recommended to incorporate vertical greening into the territorial spatial planning system and ecological civilization construction evaluation system at the national level, establish linkage mechanisms between vertical greening and carbon emission trading at the city level, and promote public participation mechanisms in vertical greening construction and management at the community level, forming a policy implementation framework that combines top-down and bottom-up approaches.

4.3. Limitations of Vertical Greening Research Based on Artificial Intelligence and Remote Sensing Data

Although this research successfully applied deep learning and remote sensing technology to achieve high-precision identification and optimized layout of urban vertical greening, it is necessary to recognize certain limitations of these technologies: First, deep learning models show significant accuracy decline when facing complex vertical structures and small-scale vertical greening, with limited precision particularly in assessing vegetation health status and growth density; Second, high-resolution remote sensing data has constraints regarding temporal continuity and acquisition costs, as images obtained under different seasonal and weather conditions may lead to biases in green volume assessment; Third, sensor data is affected by signal interference and occlusion problems in urban environments, resulting in partial data loss or distortion; Fourth, artificial intelligence models are highly dependent on training data quality and representativeness, facing generalization challenges when applied to cities with significantly different climatic conditions, architectural styles, or vegetation types compared to the training regions; Fifth, complex urban three-dimensional spatial structures cause some vertical greening to be occluded, making it difficult to capture completely through remote sensing; Additionally, the "black box" characteristic of artificial intelligence models also increases the difficulty of decision explanation, potentially affecting acceptance by planners and decision-makers. Future research should focus on addressing these technical limitations, further improving the accuracy and reliability of urban vertical greening monitoring and assessment through methods such as multi-source data fusion, semi-supervised learning, and explainable artificial intelligence.

5. Conclusion and Outlook

5.1. Main Research Conclusions

Based on deep learning and remote sensing technology, this study conducted systematic research on urban three-dimensional greening layout optimization and smart eco-city construction, reaching the following five main conclusions:

(1) The multi-source remote sensing data fusion model based on the improved U-Net++ architecture can effectively identify and classify urban three-dimensional greening, achieving an overall identification accuracy of 92.8%, significantly higher than traditional methods. In particular, the F1 score for vertical greening identification reached 0.86, solving the problem of accurate vertical greening identification and providing reliable technical support for large-scale three-dimensional greening monitoring.

(2) The three-dimensional greening in the three research cities exhibits distinct spatial differentiation characteristics. Vertical greening is primarily concentrated in urban commercial centers and newly constructed areas, while roof gardens are more distributed in high-end business districts and public buildings. The annual growth rate of three-dimensional greening area between 2015–2025 was 16.5%, demonstrating a development trend from demonstration to popularization.

(3) There are significant differences in ecological benefits among different types of three-dimensional greening. Modular vertical greening and intensive roof gardens have the highest comprehensive ecological benefits, but climbing vertical greening and simple roof gardens offer the optimal ecological benefit-to-cost ratio. Composite layouts integrating multiple forms of three-dimensional greening can produce synergistic enhancement effects of 15–22%, significantly improving overall ecological benefits.

(4) Compared to traditional planning methods, the three-dimensional greening layout scheme constructed through the multi-objective optimization model achieves 27.5% higher carbon sequestration capacity, 32.6% improved temperature regulation effects, 35.8% enhanced stormwater management efficiency, 42.3% higher biodiversity index, and 32.6% increased economic benefits, achieving synergistic optimization of ecological and economic benefits.

(5) The smart eco-city evaluation index system and multi-scenario simulation results based on three-dimensional greening indicate that through optimized three-dimensional greening layout, urban heat island intensity in the three research cities can be reduced by 15.2–18.7%, carbon neutrality contribution rate can be increased to 8.6–10.2%, stormwater runoff peaks can be reduced by 25.3–32.6%, and landscape connectivity can be enhanced by 12.5–18.7%, providing a scientific pathway for smart eco-city construction. The research findings not only enrich the theoretical system of urban ecology and landscape planning but also provide technical methods and practical guidance for urban three-dimensional greening layout optimization and smart eco-city construction.

5.2. Future Outlook

Based on the achievements and limitations of this research, future studies could further delve into the following five aspects:

(1) Deepen research on intelligent monitoring technology for three-dimensional greening by combining high-resolution satellite remote sensing with drone-based close-range remote sensing, introducing more advanced deep learning algorithms such as Transformers and graph neural networks to improve identification accuracy and fine classification capabilities of three-dimensional greening in complex urban environments. This would particularly enhance the precise monitoring of plant health conditions, growth dynamics, and three-dimensional structural characteristics, enabling real-time dynamic monitoring of three-dimensional greening.

(2) Expand the dimensions of ecosystem service as-

sessment for three-dimensional greening by extending this study's carbon sequestration, cooling, stormwater management, and biodiversity assessments to include multiple ecosystem service functions such as air purification, noise reduction, and psychological health promotion. This would establish a more comprehensive three-dimensional greening ecological benefit assessment system and, combined with research on market-based ecological compensation mechanisms, explore pathways for realizing the ecological value of three-dimensional greening.

(3) Enhance research on multi-dimensional collaborative optimization of three-dimensional greening by integrating three-dimensional greening layout optimization with building energy consumption management, rainwater resource utilization, urban ventilation corridor construction, and other fields. Developing a collaborative optimization platform for urban three-dimensional greening based on digital twin technology would achieve comprehensive optimization across multiple objectives, scales, and systems, improving the overall efficiency of urban systems.

(4) Strengthen research on the resilience of three-dimensional greening to climate change. Against the background of increasingly frequent extreme climate events, explore adaptive strategies for three-dimensional greening in addressing climate risks such as high-temperature heat waves, rainstorms and floods, and drought and water shortages. Develop new technologies, materials, and models for climate-resilient three-dimensional greening to enhance urban adaptive capacity to climate change.

(5) Thoroughly explore social equity issues in three-dimensional greening by focusing on accessibility and benefit disparities among different social groups. Research the potential of three-dimensional greening in promoting environmental justice and social inclusiveness, develop community-oriented co-construction and sharing models for three-dimensional greening, and ensure that the ecological benefits of three-dimensional greening benefit all urban residents, especially vulnerable groups. This would promote the formation of a more equitable and inclusive development path for smart eco-cities. Through in-depth research in these directions, the scientific application of urban three-dimensional greening in smart eco-city construction can be further advanced, providing a more solid theoretical foundation and technical support for sustainable urban development. To deeply explore social equity issues in vertical greening, we have established a "Vertical Greening Social Equity Evaluation Model" implemented through a three-layer evaluation mechanism: First, at the spatial distribution level, spatial autocorrelation analysis and geographically weighted regression models are applied to identify the spatial matching degree between vertical greening resources and socioeconomic indicators, quantifying opportunity disparities among different income, racial, and age groups in accessing high-quality vertical greening; Second, at the participation in decision-making level, inclusive vertical greening planning process evaluation indicators are constructed to measure the voice and decision-making influence of different social groups in the planning, design, and management of vertical greening; Third, at the benefit distribution level, environmental justice indices are employed to assess the equitable distribution of vertical greening ecological benefits (such as cooling effects, air quality improvement, and health promotion) across different communities, obtaining first-hand data support through community microclimate monitoring networks and health impact tracking surveys.

Author Contributions

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