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Research on the Coupled and Coordinated Development of Green Infrastructure and Urban Ecological Environment

Zhang Xin[1]

[1] Capital University of Economics and Business, Beijing, China

Correspondence: Zhang Xin, Capital University of Economics and Business, Beijing, China. E-mail: xinxinzhangzzz@outlook.com

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Abstract

Green infrastructure, as a nature-based solution, plays a key role in urban sustainable development. This paper focuses on the coupled and coordinated development of green infrastructure and urban ecological environment. It first defines the basic concepts of green infrastructure and urban ecological environment, and their interaction, establishing a theoretical framework for coupled and coordinated development and proposing an evaluation index system. Next, by analyzing the role of green infrastructure in improving the ecological environment, the paper explores its contribution to ecosystem services, urban climate resilience, and environmental governance. The study then uses the coupling coordination degree model and case study methods to evaluate the current status of green infrastructure construction and its coordination with ecological environment development in different cities, identifying key issues and challenges such as technological, policy, financial constraints, and ecological pressures brought about by urbanization. Finally, the paper suggests strategies for optimizing the construction of green infrastructure and its coordinated development with the ecological environment, including strengthening planning and policy guidance, improving multi-stakeholder collaborative governance mechanisms, and promoting green technological innovations to facilitate the sustainable development of urban ecological environments. The findings of this research can provide scientific evidence for urban planners and policymakers, promoting the rational layout and efficient application of green infrastructure in urban ecosystems.

Keywords: green infrastructure, urban ecological environment, coupled and coordinated development, ecosystem services

1. Introduction

With the accelerating process of global urbanization, urban ecological environments are facing increasingly severe challenges. The traditional urban development model, which primarily relies on "grey infrastructure," has led to the degradation of urban ecosystems, exacerbating climate change and environmental deterioration. To address these issues, Green Infrastructure (GI) has gradually been adopted in urban planning and construction across various countries as an eco-friendly urban infrastructure solution. Green infrastructure not only effectively improves urban environmental quality and enhances ecosystem services but also strengthens the resilience of cities in adapting to climate change and promotes the construction of ecological civilization. Green infrastructure includes natural ecosystems such as parks, green spaces, water bodies, and wetlands, as well as built elements that mimic natural processes and enhance ecological functions, such as green roofs, permeable pavements, and ecological corridors[1]. Compared with traditional grey infrastructure, green infrastructure is more flexible, sustainable, and cost-effective, making it a crucial approach to achieving sustainable urban ecological development. However, despite the widespread attention given to green infrastructure globally, its effectiveness in practical applications is still influenced by various factors. For example, urbanization, land use changes, outdated policies and regulations, and insufficient financial investments may all hinder the full potential of green infrastructure in urban ecological environments. Therefore, exploring the coupled and coordinated development relationship between green infrastructure and urban ecological environments and understanding how to achieve their positive interaction has become an important issue in current urban sustainability research. This paper aims to explore the mechanisms of coupled and coordinated development between green infrastructure and urban ecological environments. First, it defines the basic concepts of green infrastructure and urban ecological environments and analyzes their interrelationship. Then, based on the theory of coupled coordination, the paper constructs a theoretical framework and evaluation index system for the coordinated development of green infrastructure and urban ecological environments. Through case analysis and model evaluation, the paper investigates the practical role of green infrastructure in optimizing urban ecological environments and identifies development bottlenecks. Finally, strategies and recommendations are proposed to promote the coupled and coordinated development of green infrastructure and urban ecological environments. The results of this study not only provide theoretical support for the planning and design of green infrastructure but also offer valuable insights for policymakers in advancing urban sustainable development[2].

2. Basic Concepts of Green Infrastructure and Urban Ecological Environment

Green Infrastructure (GI) refers to an infrastructure system that enhances ecosystem services and improves environmental quality through natural processes or nature-based solutions. It encompasses natural elements such as forests, wetlands, green roofs, and ecological corridors, as well as artificial ecosystems designed to simulate natural processes using technological methods. The primary functions of green infrastructure include environmental regulation, ecological restoration, climate adaptation, and water resource management. During urbanization, green infrastructure plays a critical role in improving air quality, regulating water flow, and mitigating floods, thus enhancing the sustainability of the urban ecological environment. Figure 1 illustrates the relationship between green infrastructure and urban ecosystems, demonstrating that green infrastructure not only directly impacts urban environments by enhancing natural ecosystem functions (such as water source protection and sediment regulation) but also plays an essential role in mitigating climate change and reducing the effects of extreme weather events[3].

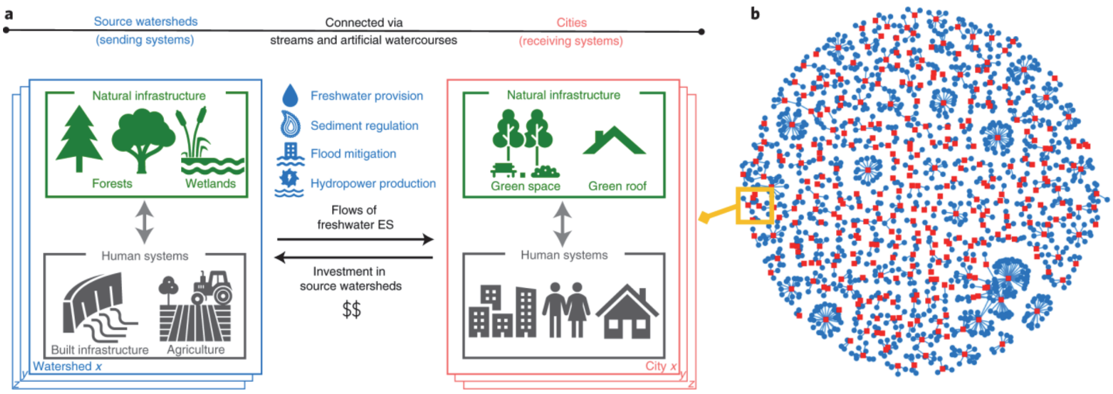

Figure 1. Coupling Model of Green Infrastructure and Urban Ecosystems

By developing green infrastructure, cities can provide essential ecological services while creating more livable environments for residents. For example, natural infrastructures such as wetlands and forests regulate water cycles, improve water quality, absorb carbon dioxide, and purify the air. Similarly, urban elements like green roofs and green spaces contribute to mitigating the urban heat island effect, increasing biodiversity, and providing recreational spaces, thereby enhancing residents' quality of life. The urban ecological environment refers to the ecosystem within and around urban areas, encompassing natural elements (such as air, water, soil, and vegetation) and human activities (such as construction, transportation, and agriculture) that influence these natural elements. As illustrated in Figure 1, source water areas (such as forests and wetlands) and urban reception systems (such as urban green spaces and building rooftops) are interconnected through the flow of ecological services, forming a complex ecological network. The urban ecological environment is characterized by its multi-layered structure, consisting of both natural ecosystems and artificial ecological systems created by human activities. The interactions between these systems determine the overall quality of the urban ecological environment. With the advancement of urbanization, the urban ecological environment faces challenges such as ecological degradation and excessive resource consumption[4]. In this context, green infrastructure plays a crucial role in ecological regulation. Strengthening the development of green infrastructure can effectively address ecological issues arising from urbanization, protecting and restoring damaged natural systems. The interaction and coupling relationship between green infrastructure and the urban ecological environment is significant. Natural infrastructures in source water areas (such as forests and wetlands) directly influence urban ecosystem functions through the flow of ecological services, particularly in water resource management and flood regulation. Urban green infrastructures (such as green spaces and green roofs) interact with natural systems by improving air quality, mitigating climate change, and enhancing biodiversity, collectively promoting improvements in the urban ecological environment. Green infrastructure not only enhances the quality of the natural ecological environment but also positively impacts human systems within cities. By providing ecological services such as air purification, water quality improvement, and temperature regulation, green infrastructure strengthens urban climate adaptability while also creating more habitats for biodiversity and improving human living conditions. Through this bidirectional interaction, the coordinated development of green infrastructure and urban ecological environments enhances ecosystem resilience and provides strong support for urban sustainability[5].

3. Theoretical Framework for the Coupled and Coordinated Development of Green Infrastructure and Urban Ecological Environment

The coupled and coordinated development of green infrastructure and the urban ecological environment is an interdisciplinary research field that integrates theories and methodologies from ecology, urban planning, sustainable development, and socioeconomics. Its theoretical foundation can be traced back to early 20th-century research in ecology and urban ecology, particularly the emergence of the Ecosystem Services (ES) theory, which deepened the understanding of the interactions between ecosystems and human activities. With the evolution of the green infrastructure concept, this theoretical framework has expanded to include the integration of natural and artificial systems and the impact of human activities on ecosystems. In recent years, as global challenges such as climate change and rapid urbanization have intensified, the role of green infrastructure in urban ecological environments has gained increasing attention, becoming a key strategy for promoting urban sustainability. Significant research advancements in this field include the introduction of the coupling degree model, which quantitatively assesses the interactions between natural and artificial ecosystems and their impacts on urban environments and human well-being[6]. Additionally, as theoretical development continues, researchers have proposed comprehensive evaluation methods for urban ecological sustainability to assess the effectiveness of green infrastructure under different urban development contexts.

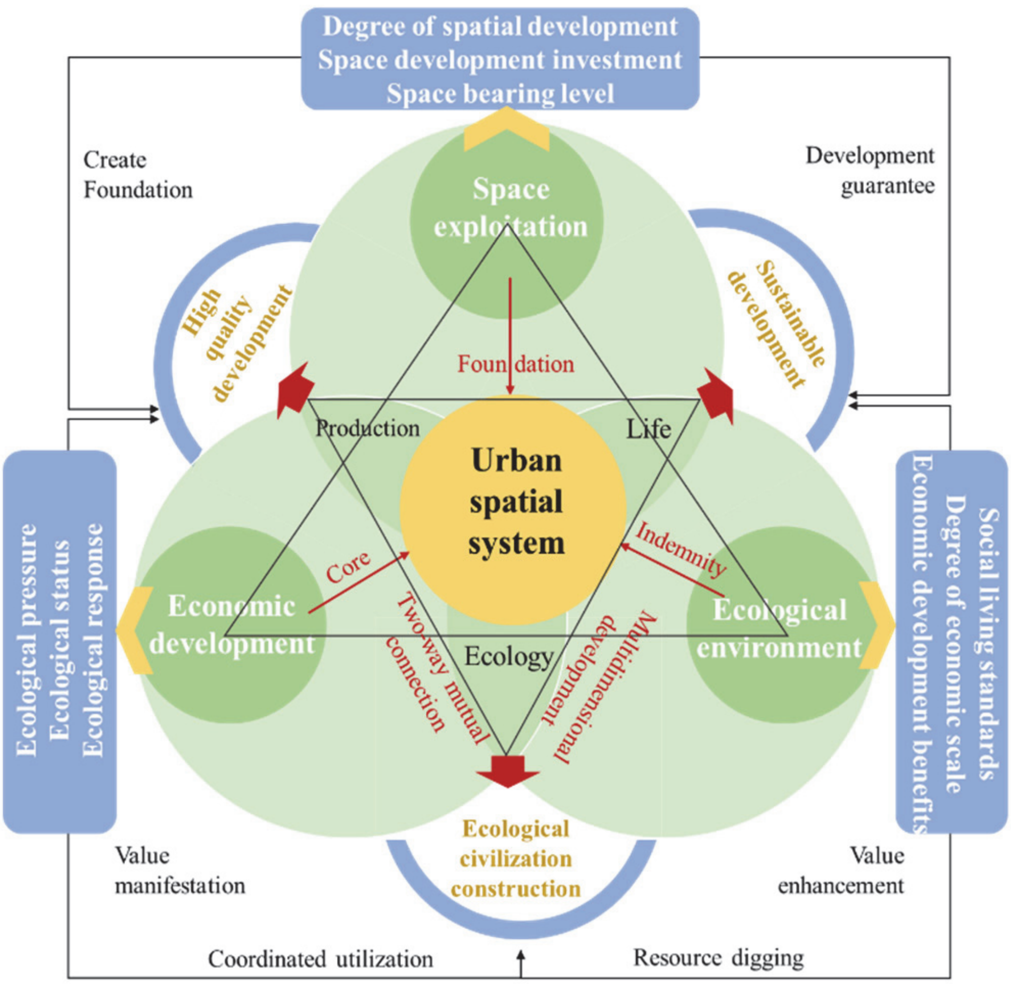

Figure 2. Framework for the Coordinated Development of Urban Spatial Systems and Ecological Environments

Figure 2 illustrates the interconnections between urban spatial systems and ecological environments, forming a framework for their coordinated development. As shown in the figure, the role of green infrastructure in urban ecological environments is systematically categorized into multiple dimensions: spatial development, production, living, and ecology—key components of urban spatial systems. The urban spatial system itself is a highly interactive network, where various functional modules are interconnected and influence one another. Green infrastructure is closely linked to the socio-economic system, ecological environment system, and resource utilization system through ecological civilization construction, ecological stress regulation, and value enhancement. The coupling model emphasizes that green infrastructure is not only a part of the ecological system but also an integral component of the social system, with a mutually reinforcing and interdependent relationship. For example, urban green spaces, wetlands, and forests contribute to urban ecological improvement by providing ecosystem services such as water conservation, air purification, and temperature regulation. Meanwhile, the construction and maintenance of green infrastructure depend on economic investments, policy support, and active societal participation[7]. The coupled development of green infrastructure and the urban ecological environment enhances ecosystem quality while promoting socio-economic sustainability. Coordinated development ensures that the relationship between green infrastructure and urban ecological environments is optimized, allowing both functions to complement and reinforce each other, ultimately achieving sustainability goals. A key challenge in this coordination is balancing the supply of ecosystem services with the demands of socio-economic development, as well as integrating green infrastructure construction with environmental protection, social welfare, and economic growth. The evaluation indicator system plays a crucial role in quantifying the effectiveness of the coupled and coordinated development of green infrastructure and urban ecological environments. Typically, evaluation indicators include multiple dimensions:Ecological benefits, which assess the degree to which green infrastructure improves environmental quality. Social benefits, which focus on enhancements in residents' quality of life, particularly in terms of health, comfort, and safety. Economic benefits, which evaluate the cost-effectiveness of green infrastructure construction and maintenance, as well as its contributions to sustainable urban economic growth. Comprehensive benefits, which integrate ecological, social, and economic benefits to provide scientific decision-making support for policymakers. By establishing these theoretical foundations, coupling models, and evaluation indicator systems, the coupled and coordinated development of green infrastructure and urban ecological environments can be effectively guided and applied in both theory and practice. This not only provides valuable insights for urban planners but also offers a scientific pathway for advancing urban sustainability[8].

4. The Role of Green Infrastructure in the Urban Ecological Environment

As a vital component of urban sustainability, green infrastructure plays a crucial role in improving the urban ecological environment, enhancing ecosystem services, increasing climate adaptability, and promoting human well-being. Green infrastructure not only provides diverse ecological services for urban ecosystems but also effectively mitigates ecological degradation caused by urbanization, thereby enhancing environmental resilience and sustainability. One of the primary functions of green infrastructure is water resource management. Urbanization often leads to issues such as water pollution, groundwater depletion, and frequent flooding. Green infrastructure addresses these challenges through measures like wetland restoration, rain gardens, and permeable pavements, which help regulate urban water cycles[9]. By reducing surface runoff, enhancing water retention, and improving water quality, green infrastructure strengthens urban water management. For instance, green roofs and rainwater harvesting systems alleviate urban flooding while improving rainwater storage and utilization efficiency, thereby easing water resource shortages. Green infrastructure also plays a vital role in improving air quality. Urbanization has led to increased industrial emissions, traffic pollution, and construction dust, all of which contribute to deteriorating air quality. Green infrastructure, particularly urban green spaces, forests, and vertical gardens, helps purify the air by absorbing carbon dioxide, releasing oxygen, and filtering harmful airborne particles. Additionally, vegetation in urban areas regulates humidity through transpiration, mitigating the urban heat island effect. Studies indicate that expanding urban green spaces can significantly enhance air quality and reduce health risks associated with air pollution. In addressing climate change, green infrastructure provides natural climate regulation, helping cities adapt to extreme weather events such as heatwaves, heavy rainfall, and droughts. Urban green spaces and forests offer shade, reduce heat accumulation, and lower city temperatures, thus mitigating the urban heat island effect and decreasing energy consumption. Furthermore, green infrastructure enhances stormwater infiltration and drainage, reducing flood risks associated with extreme rainfall. By increasing urban ecosystem resilience, green infrastructure enhances cities' capacity to respond to climate change[10]. Green infrastructure is also essential for protecting biodiversity. Urbanization often leads to habitat destruction and threatens species diversity. Green infrastructure restores and preserves urban ecosystems by providing diverse habitats for flora and fauna. Urban parks, green corridors, and wetlands support various species and offer city residents opportunities to connect with nature, fostering biodiversity within urban environments. Beyond its environmental benefits, green infrastructure also significantly contributes to social well-being. Urban green spaces, public gardens, and green roofs improve residents' quality of life and promote physical and mental health. Studies show that exposure to natural environments reduces stress, enhances psychological well-being, and supports overall health. Especially in post-pandemic urban recovery, green infrastructure plays a crucial role in improving living conditions and fostering social cohesion by encouraging community interaction. In summary, green infrastructure is essential for improving the urban ecological environment, enhancing ecosystem services, mitigating urbanization-induced ecological issues, and promoting social well-being. As urbanization continues, green infrastructure will play an increasingly central role in sustainable urban development, driving environmental, social, and economic progress[11].

5. Evaluation and Analysis Methods for Coupled and Coordinated Urban Ecological Development

Coupled and coordinated urban ecological development is a complex, multi-dimensional challenge that involves balancing ecological, economic, and social factors. Accurately assessing and analyzing the interaction between green infrastructure and urban ecological environments is a key research and practical concern. To systematically measure the coupling degree and coordinated development status between green infrastructure and urban ecological environments, researchers typically employ various quantitative evaluation methods and models. The coupling coordination degree model is widely used to evaluate the interaction between ecosystems and socio-economic systems[12]. This model quantitatively assesses the coupling degree between ecological and socio-economic systems and further analyzes their coordinated development status. The coupling degree (C) is calculated using the following formula 1:

$$C = \frac{1}{2}\left(\frac{A}{A_{max}} + \frac{B}{B_{max}}\right)$$

where C represents the coupling degree, indicating the interaction between the ecological and human systems. A and B are composite indicators representing the ecological environment and human system, respectively. If the coupling degree approaches 1, it indicates a high level of coordination between ecological and socio-economic systems. Conversely, if the value is close to 0, it suggests poor coordination, which may indicate ecological degradation or socio-economic instability.

The coordination degree (Q) evaluates the overall coordinated development of ecological and socio-economic systems and is calculated as shown in Formula 2:

$$Q = \frac{\sum_{i=1}^{n}(C_i \cdot W_i)}{\sum_{i=1}^{n} W_i}$$

where Q represents the coordination degree, reflecting the overall balance between ecological and socio-economic development. C_i denotes the coupling degree for the i-th indicator. W_i represents the weight of the i-th indicator, reflecting its relative importance in the overall coordination assessment. n is the total number of evaluation indicators. A high Q value suggests that green infrastructure and urban ecological environments are well-coordinated across multiple dimensions, while a low Q value indicates a need for intervention to improve coordination. To comprehensively assess the coupling coordination between green infrastructure and urban ecological environments, a well-structured evaluation indicator system is required, typically consisting of the following dimensions: Ecological Benefits – Evaluates improvements in environmental quality, including air quality, climate regulation, and water resource management. Common evaluation methods include monitoring pollutant concentrations, precipitation levels, and temperature variations. Social Benefits – Assesses the impact of green infrastructure on urban living quality, including the coverage of green spaces, accessibility to public parks, and improvements in residents' health and well-being. Survey questionnaires and satisfaction assessments are often used for quantification. Economic Benefits – Examines the cost-effectiveness of green infrastructure construction and maintenance, as well as its contribution to urban economic growth. Cost-benefit analysis (CBA) is commonly used to determine green infrastructure's role in productivity and innovation. Comprehensive Benefits – Integrates ecological, social, and economic dimensions to provide a holistic assessment. Weighted summation of various indicators produces a composite evaluation score, reflecting the overall level of coupled and coordinated urban ecological development. Accurate data collection is essential for evaluating and analyzing coupled and coordinated urban ecological development. Common data collection methods include: Remote Sensing Monitoring – Used to track urban green space distribution and changes. Geographic Information System (GIS) Analysis – Helps analyze spatial relationships between green infrastructure and other ecological elements. Field Surveys – Collects first-hand data on green infrastructure implementation and community feedback. Big Data Analytics – Integrates realtime monitoring of ecological, economic, and social parameters to provide insights into sustainable urban development trends. For example, a case study of a specific city can apply coupling coordination models to evaluate the effectiveness of green infrastructure development. Analysis results may reveal that the city performs well in water resource management and air purification but lags in social benefits. Such findings provide policymakers with actionable insights to enhance social well-being and overall ecological quality. The evaluation methods for coupled and coordinated urban ecological development provide urban planners and decision-makers with scientific tools to achieve balanced ecological and socio-economic progress. By utilizing coupling degree models, coordination models, and comprehensive evaluation systems, combined with advanced data analysis techniques, cities can accurately assess the impact of green infrastructure and formulate strategies for future sustainable urban development.

6. Evaluation and Analysis of Coupled and Coordinated Urban Ecological Development

Accurate evaluation and analysis play a crucial role in assessing the effectiveness of interactions between green infrastructure and urban ecological environments. To comprehensively evaluate the role of green infrastructure in urban ecosystems, data must be collected from multiple dimensions, including ecological, economic, and social benefits. These data are then systematically analyzed using tables and statistical tools to derive meaningful conclusions. Ecological benefits measure the impact of green infrastructure on environmental quality, including improvements in air quality, water resource management, and biodiversity. To evaluate these benefits, researchers collect environmental data such as urban air pollutant concentrations, precipitation levels, and temperature variations. The table below presents key ecological indicators over a three-year period:

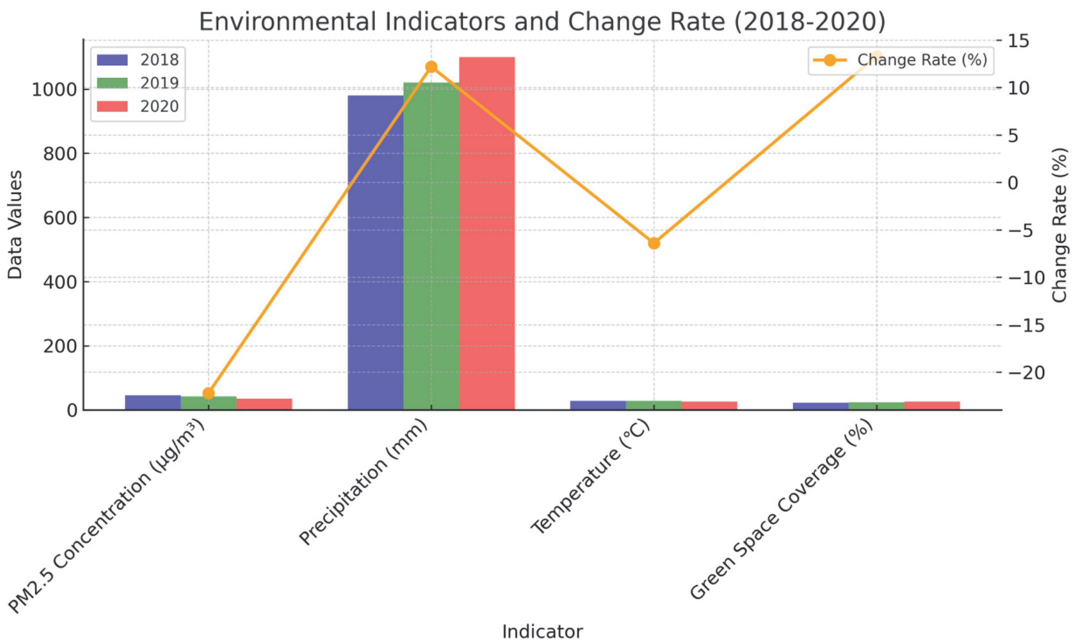

Figure 3. Environmental Indicators and Change Rate (2018-2020)

The Figure 3 shows that an increase in urban green spaces significantly contributed to improving air quality, as evidenced by the noticeable reduction in PM2. 5 concentrations. Additionally, increased green coverage helped mitigate the urban heat island effect, leading to lower temperatures. Economic benefits focus on how green infrastructure supports urban economic growth by increasing land value, reducing healthcare costs associated with pollution, and enhancing residents' overall quality of life. Cost-benefit analysis (CBA) quantifies the economic returns of green infrastructure investments. The Figure 4 presents an economic benefits assessment:

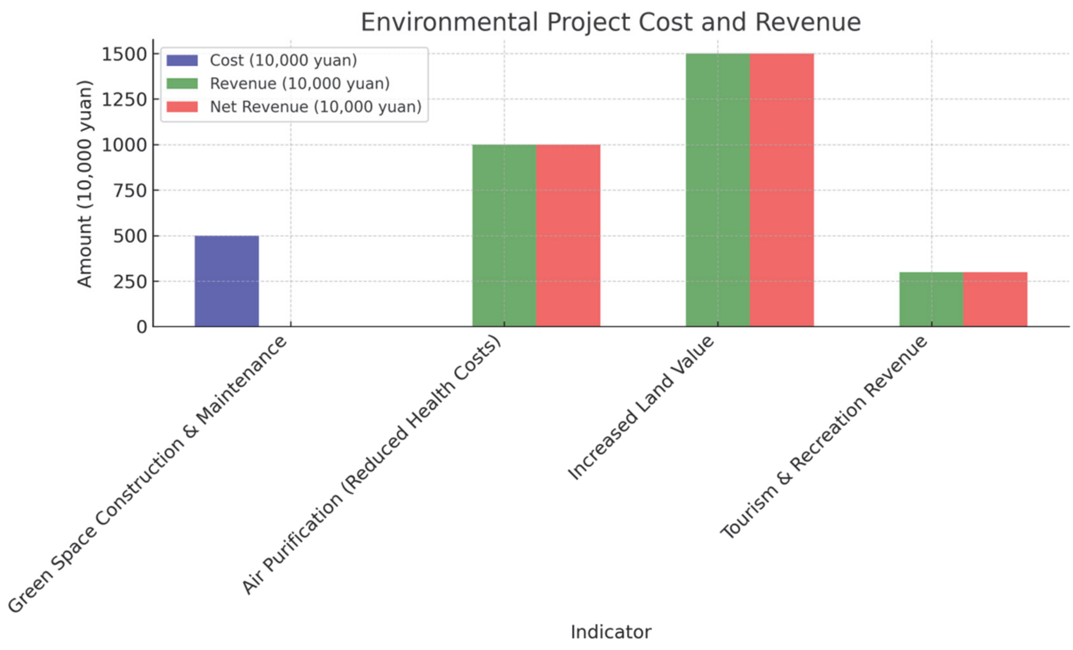

Figure 4. Environmental Project Cost and Revenue

Despite initial investment costs, the table shows that green infrastructure generates significant economic returns, particularly in terms of air purification and land value appreciation. By reducing health-related expenses and increasing property values, green infrastructure provides substantial financial benefits to urban economies. Social benefits focus on how green infrastructure enhances urban residents' quality of life, health, and social engagement. By conducting surveys and satisfaction assessments, researchers can quantify the impact of green spaces on mental health, social participation, and public engagement. The table below presents key social indicators:

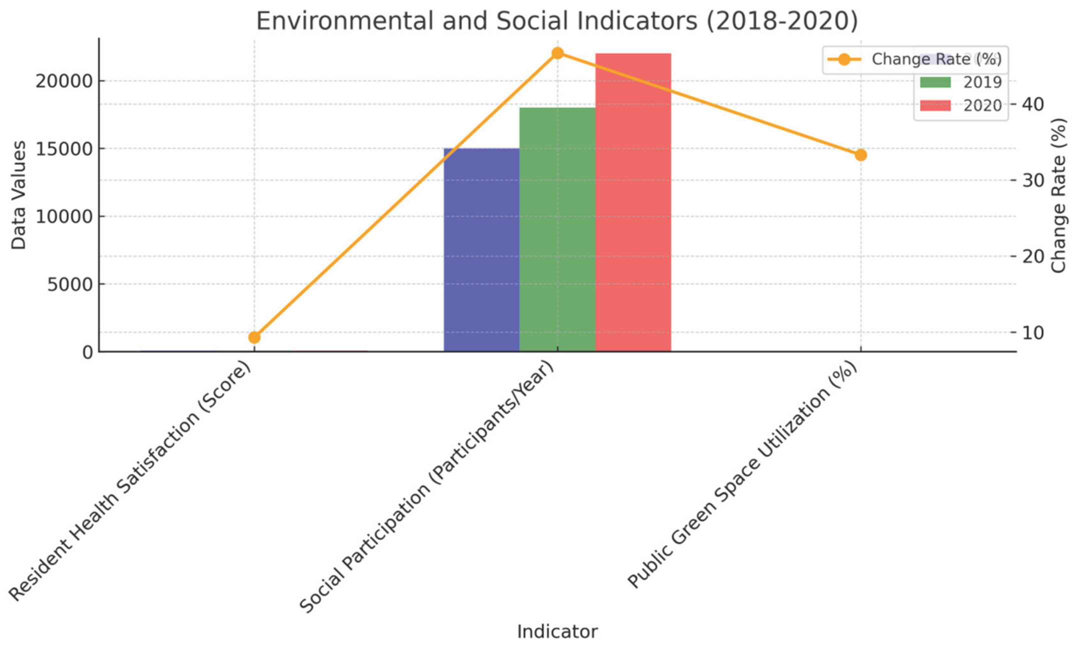

Figure 5. Environmental and Social Indicators (2018-2020)

The Figure 5 demonstrates that increasing green infrastructure significantly improved residents' health satisfaction and overall well-being. Additionally, greater social engagement and higher green space utilization rates indicate that green infrastructure enhances community cohesion and promotes active lifestyles. To further validate the role of green infrastructure in urban ecological development, multiple experimental analyses were conducted, including: Before-and-after comparisons of urban green space expansion. Assessment of green roofs in mitigating the urban heat island effect. Long-term impact of ecological planning on public health. Results confirm that increasing green infrastructure not only improves the urban environment but also strengthens economic and social benefits. Based on the data and analyses, key conclusions include: Significant Ecological Improvements: The expansion of urban green spaces and wetlands effectively reduced PM2. 5 concentrations, improved air quality, and alleviated the urban heat island effect. Strong Economic Returns: While green infrastructure requires initial investments, its long-term benefits—such as air purification and increased land value—far exceed its costs, making it an economically viable strategy for sustainable urban development. Enhanced Social Well-being: Green infrastructure investments led to improvements in residents'health, social participation, and quality of life, fostering stronger community cohesion. These findings highlight the essential role of green infrastructure in promoting coupled and coordinated urban ecological development. By integrating environmental, economic, and social benefits, green infrastructure contributes to a more sustainable and livable urban future.

7. Conclusion

This study examined the theoretical framework and evaluation methods for the coupled development of green infrastructure and urban ecological environments, highlighting its ecological, economic, and social benefits. The findings confirm that green infrastructure mitigates heat island effects, improves air quality, and boosts economic growth by increasing land value and reducing health costs. Applying coupling and coordination models, the study validates its essential role in sustainable urban development. Despite challenges like funding shortages and policy delays, future efforts should prioritize planning, investment, and multi-stakeholder collaboration. Green infrastructure remains a key driver of balanced urban development, ensuring long-term environmental and social well-being.

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