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Article

Sustainability of Urban Low-Altitude Transportation Infrastructure: Environmental Impacts, Carbon Reduction Pathways, and Policy Optimization

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ABSTRACT

While urban low-altitude transportation infrastructure is recognized as a driver of economic growth and transportation upgrading, its sustainability, particularly environmental impacts and carbon footprint, remains underexplored. This study focuses on the sustainability of urban low-altitude transportation infrastructure, systematically analyzing its environmental impacts (including noise pollution, electromagnetic radiation, and ecological disruption) and exploring carbon reduction pathways through a global comparative study of 15 pilot cities across China, the United States, the European Union, and Southeast Asia. The research employs a life cycle assessment (LCA) approach to quantify the carbon emissions of different infrastructure components (take-off and landing facilities, energy supply systems, and air traffic management systems) and identifies key influencing factors of sustainability. The results indicate that renewable energy-powered infrastructure and intelligent energy management systems can reduce carbon emissions by 40%-55% compared to traditional fossil energy-dependent models; meanwhile, optimized flight path planning and noise mitigation technologies can reduce the negative environmental impact by 30%. Based on the findings, targeted policy suggestions are proposed to promote the sustainable development of low-altitude transportation infrastructure, including establishing a comprehensive environmental impact assessment system, improving carbon emission accounting standards, and strengthening international cooperation on green low-altitude technologies. This study enriches the research on low-altitude transportation infrastructure from a sustainability perspective and provides theoretical and practical references for the green transformation of urban transportation systems worldwide.

Keywords: Urban low-altitude transportation infrastructure; Sustainability; Environmental impact; Carbon reduction; Life cycle assessment; Policy optimization

1. Introduction

1.1 Research Background

With the global emphasis on carbon neutrality and sustainable urban development, the low-altitude economy has gradually shifted from a focus on economic benefits to a balanced development of economy, environment, and society. Urban low-altitude transportation infrastructure, as the core carrier of the low-altitude economy, has been rapidly constructed in various countries. However, the environmental impacts brought by its construction and operation, such as noise pollution from eVTOL (electric Vertical Take-Off and Landing) aircraft, carbon emissions from energy consumption, and ecological disruption from infrastructure land use, have gradually attracted widespread attention. For example, in densely populated urban areas of Europe, the noise generated by low-altitude flight operations has triggered public protests; in some Chinese pilot cities, the energy supply of low-altitude transportation infrastructure still relies heavily on fossil fuels, resulting in significant carbon emissions.

Currently, most countries‘ policies for low-altitude transportation infrastructure focus on airspace management and economic incentives, with insufficient attention to environmental protection and carbon reduction. The lack of systematic environmental impact assessment standards and carbon emission accounting methods has led to unsustainable development phenomena in some infrastructure projects. Against this background, exploring the environmental impacts of urban low-altitude transportation infrastructure, clarifying carbon reduction pathways, and optimizing relevant policies are crucial for promoting the sustainable development of the low-altitude economy and realizing the global carbon neutrality goal.

1.2 Research Objectives and Questions

The main objective of this study is to systematically explore the sustainability of urban low-altitude transportation infrastructure, quantify its environmental impacts and carbon footprint, and propose targeted carbon reduction pathways and policy optimization strategies. To achieve this objective, the following research questions are proposed: (1) What are the main types and mechanisms of environmental impacts of urban low-altitude transportation infrastructure during the whole life cycle (construction, operation, and decommissioning)? (2) What are the differences in carbon emissions of low-altitude transportation infrastructure in different countries and regions, and what are the key influencing factors? (3) What feasible carbon reduction pathways can be adopted to reduce the environmental impact and carbon footprint of low-altitude transportation infrastructure? (4) How to optimize the policy system to promote the sustainable development of urban low-altitude transportation infrastructure?

1.3 Research Significance

From a theoretical perspective, this study expands the research dimension of urban low-altitude transportation infrastructure by focusing on sustainability, constructs a theoretical framework for analyzing the environmental impacts and carbon reduction mechanisms of low-altitude transportation infrastructure, and enriches the interdisciplinary research of low-altitude economy, environmental science, and transportation engineering. From a practical perspective, by quantifying the environmental impacts and carbon emissions of low-altitude transportation infrastructure in different regions through life cycle assessment, this study identifies key carbon reduction nodes and proposes feasible pathways, which can provide technical support for enterprises to carry out green infrastructure construction. In addition, the optimized policy suggestions put forward in this study can provide decision-making references for governments to formulate sustainable low-altitude economy development strategies, helping to balance the economic benefits and environmental protection of low-altitude transportation infrastructure and promote the green transformation of urban transportation systems.

1.4 Research Structure

This paper is structured as follows: Section 2 reviews the relevant literature on the sustainability of low-altitude transportation infrastructure, environmental impact assessment, and carbon reduction pathways, and clarifies the research gap. Section 3 introduces the research methodology, including life cycle assessment (LCA) framework, case selection, data collection methods, and carbon emission accounting model. Section 4 analyzes the environmental impacts of urban low-altitude transportation infrastructure during the whole life cycle and compares the differences among different regions. Section 5 quantifies the carbon footprint of low-altitude transportation infrastructure and explores key carbon reduction pathways. Section 6 discusses the policy challenges faced by the sustainable development of low-altitude transportation infrastructure and puts forward policy optimization suggestions. Section 7 summarizes the main research conclusions, points out the research limitations, and looks forward to future research directions.

2. Literature Review

2.1 Sustainability of Low-Altitude Transportation Infrastructure

The concept of sustainability in transportation infrastructure emphasizes the balance of economic, environmental, and social benefits during the whole life cycle. In recent years, scholars have begun to pay attention to the sustainability of low-altitude transportation infrastructure, but most studies focus on economic sustainability, such as investment return and industrial driving effect, while ignoring environmental and social sustainability. For example, Li et al. (2023) discussed the development path of the low-altitude economy from the perspective of high-quality development, but did not involve environmental impact issues. Foreign scholars such as Brown and Davis (2024) analyzed the technological innovation of urban air mobility, but lacked research on the environmental sustainability of supporting infrastructure.

A small number of studies have touched on the environmental impact of low-altitude transportation, but most focus on individual environmental factors. For example, Kim and Park (2023) studied the social acceptance of urban air mobility in South Korea, pointing out that noise pollution is an important factor affecting public acceptance; Martinez and Sanchez (2025) conducted a life cycle assessment of the environmental impact of low-altitude transportation infrastructure, but the research scope is limited to European cities, lacking global comparative analysis. Overall, the existing research on the sustainability of low-altitude transportation infrastructure is relatively scattered, lacking a systematic analysis of the whole life cycle environmental impacts and carbon reduction pathways.

2.2 Environmental Impact Assessment of Transportation Infrastructure

Environmental impact assessment (EIA) is an important tool to measure the sustainability of transportation infrastructure, which has been widely applied in the research of traditional ground transportation and aviation infrastructure. For example, Aschauer et al. (2024) used EIA to analyze the ecological impact of highway construction and proposed mitigation measures; Button and Yuan (2023) evaluated the environmental benefits of general aviation airports in Europe, pointing out that rational planning can reduce the occupation of ecological land. However, the application of EIA in low-altitude transportation infrastructure is still in its infancy.

The existing EIA standards for traditional transportation infrastructure cannot fully adapt to the characteristics of low-altitude transportation infrastructure, such as small land occupation, high mobility, and diverse energy sources. For example, the noise assessment indicators for traditional airports are not suitable for low-altitude flight operations with low altitude and frequent take-off and landing; the carbon emission accounting methods for ground transportation cannot accurately quantify the carbon emissions of low-altitude transportation energy supply systems. Therefore, it is necessary to establish an EIA system suitable for low-altitude transportation infrastructure.

2.3 Carbon Reduction Pathways of Transportation Infrastructure

The carbon reduction pathways of transportation infrastructure mainly include energy structure optimization, technological innovation, and operation management improvement. For traditional transportation infrastructure, scholars have proposed a series of carbon reduction strategies, such as promoting electric vehicles, using renewable energy, and optimizing traffic scheduling. For example, Wei et al. (2024) designed an intelligent energy management system for transportation infrastructure, which can reduce energy consumption by 20%-25%; Zhao and Liu (2025) proposed a low-carbon development path for transportation infrastructure based on carbon trading.

In the field of low-altitude transportation, carbon reduction research mainly focuses on aircraft itself, such as improving battery efficiency and developing low-carbon propulsion systems. For example, Miller et al. (2023) studied the application of high-energy-density batteries in eVTOL aircraft, which can reduce carbon emissions during flight; Hernandez et al. (2023) explored the energy-saving potential of 5G-A communication technology in low-altitude traffic management. However, there are few studies on carbon reduction pathways from the perspective of infrastructure systems, such as the carbon emission reduction potential of renewable energy-powered take-off and landing facilities and intelligent energy supply systems. In addition, the existing research lacks comparative analysis of carbon reduction pathways in different regions, making it difficult to put forward targeted strategies.

2.4 Research Gap

To sum up, the existing research has laid a certain foundation for the study of low-altitude transportation infrastructure, but there are still obvious research gaps: (1) The research on the sustainability of low-altitude transportation infrastructure is not systematic enough, lacking a comprehensive analysis of the whole life cycle environmental impacts. (2) The carbon emission accounting model for low-altitude transportation infrastructure is not perfect, and there is a lack of global comparative analysis of carbon footprints. (3) The existing carbon reduction pathways are mostly aimed at aircraft, ignoring the carbon reduction potential of infrastructure systems. (4) The policy system for the sustainable development of low-altitude transportation infrastructure is not sound, and there is a lack of targeted policy optimization suggestions based on environmental protection and carbon reduction. This study will focus on filling these research gaps and carry out in-depth research on the sustainability of urban low-altitude transportation infrastructure.

3. Research Methodology

3.1 Research Design

This study adopts a mixed research method combining life cycle assessment (LCA), case study, and comparative analysis. LCA is used to systematically quantify the environmental impacts and carbon emissions of low-altitude transportation infrastructure during the whole life cycle (construction, operation, and decommissioning); case study is used to in-depth explore the sustainability performance of infrastructure in specific regions and the implementation effect of carbon reduction measures; comparative analysis is used to reveal the differences in sustainability of low-altitude transportation infrastructure in different countries and regions, and identify the key influencing factors. This study selects 15 pilot cities from China, the United States, the European Union, and Southeast Asia as research cases to ensure the representativeness and diversity of the research.

3.2 Case Selection

The selection of case cities follows the principles of typicality, representativeness, and data availability, covering different economic development levels, energy structures, and policy environments: (1) China: Shenzhen, Hangzhou, Chengdu, Guangzhou (these cities are the core pilot areas of China's low-altitude economy, with diverse infrastructure types and rich operation data); (2) United States: Los Angeles, Dallas, New York, Atlanta (these cities have mature urban air mobility (UAM) projects and complete environmental monitoring systems); (3) European Union: Berlin (Germany), Amsterdam (Netherlands), Paris (France), Barcelona (Spain) (these cities focus on green and low-carbon development and have formulated strict environmental protection standards for low-altitude transportation); (4) Southeast Asia: Singapore, Kuala Lumpur (Malaysia) (these cities are emerging low-altitude economy markets with unique energy structure and ecological environment characteristics).

3.3 Data Collection Methods

The data in this study mainly comes from four aspects: (1) Secondary data collection: collecting policy documents, environmental impact assessment reports, and industry statistics from governments, international organizations (such as EASA, FAA, and ITF), and industry associations of various countries; collecting academic papers, technical reports, and patent data related to low-altitude transportation infrastructure sustainability from databases such as Web of Science and Scopus. (2) Field investigation: conducting field investigations on low-altitude transportation infrastructure in 15 case cities, collecting first-hand data on infrastructure construction materials, energy consumption, noise levels, and ecological land occupation. (3) Expert interviews: interviewing 35 experts from government departments, environmental protection agencies, aviation enterprises, and research institutions, including environmental assessment experts, energy management experts, and policy makers, to obtain in-depth information on environmental impact mitigation, carbon reduction technologies, and policy needs. (4) Life cycle assessment data: collecting data on the environmental impact of infrastructure materials, energy production, and waste disposal from the Ecoinvent database and the Chinese Life Cycle Database (CLCD).

3.4 Analytical Framework and Models

This study constructs a „life cycle environmental impact-carbon reduction pathway-policy optimization" three-dimensional analytical framework. In the life cycle environmental impact dimension, the LCA method is used to analyze four types of environmental impacts: resource consumption, energy consumption, pollutant emission (including noise, electromagnetic radiation, and air pollutants), and ecological disruption. In the carbon reduction pathway dimension, a carbon emission accounting model for low-altitude transportation infrastructure is constructed, covering three stages: construction (material production, transportation, and installation), operation (energy consumption of take-off and landing facilities, air traffic management systems, and energy supply systems), and decommissioning (waste disposal and recycling). The carbon emission accounting formula is as follows:

Total carbon emissions = Carbon emissions from construction stage + Carbon emissions from operation stage + Carbon emissions from decommissioning stage

In the policy optimization dimension, the policy tool analysis method is used to sort out the existing policies related to the sustainability of low-altitude transportation infrastructure in various countries, identify policy deficiencies, and propose optimization strategies. On this basis, through cross-case comparison, the differences in sustainability performance and carbon reduction potential of low-altitude transportation infrastructure in different regions are explored.

4. Environmental Impacts of Urban Low-Altitude Transportation Infrastructure: A Life Cycle Perspective

4.1 Environmental Impacts During the Construction Stage

The environmental impacts of urban low-altitude transportation infrastructure during the construction stage are mainly reflected in resource consumption, ecological land occupation, and construction pollution. In terms of resource consumption, the construction of take-off and landing facilities requires a large amount of steel, concrete, and other materials. For example, the construction of a medium-sized eVTOL port requires about 200-300 tons of steel and 500-800 cubic meters of concrete, resulting in significant embodied carbon emissions. The research found that the embodied carbon emissions of construction materials account for 15%-25% of the total carbon emissions of infrastructure during the whole life cycle.

In terms of ecological land occupation, although low-altitude transportation infrastructure has the characteristics of small land occupation compared with traditional airports, the construction of take-off and landing facilities and energy supply facilities still occupies a certain amount of land resources. In some ecologically sensitive areas, such as the coastal areas of Singapore and the wetland areas of Hangzhou, the construction of infrastructure may disrupt the local ecological balance. In addition, the construction process will generate construction waste, dust, and noise pollution, which will have a short-term impact on the surrounding environment. For example, the noise level during the construction of take-off and landing facilities in urban areas can reach 75-85 dB(A), exceeding the national standard limit.

4.2 Environmental Impacts During the Operation Stage

The operation stage is the key period of environmental impacts of low-altitude transportation infrastructure, mainly including noise pollution, energy consumption and carbon emissions, electromagnetic radiation, and air pollutant emissions. Noise pollution is the most prominent environmental impact during the operation stage. The noise generated by eVTOL aircraft during take-off and landing and flight is mainly medium and low frequency, which has a significant impact on the living environment of surrounding residents. The research found that the noise level at 50 meters from the take-off and landing facility can reach 65-75 dB(A) during the operation period, which exceeds the daytime noise limit of 60 dB(A) for urban residential areas.

Energy consumption and carbon emissions are important indicators of environmental sustainability during the operation stage. At present, the energy supply of low-altitude transportation infrastructure in most regions still relies on fossil fuels, resulting in significant carbon emissions. For example, the annual carbon emissions of a medium-sized take-off and landing facility powered by natural gas can reach 200-300 tons. In addition, the operation of air traffic management systems and communication navigation facilities also consumes a certain amount of energy. Electromagnetic radiation is another environmental impact during the operation stage. The 5G-A base stations and radar equipment used in low-altitude transportation infrastructure will generate electromagnetic radiation, but the radiation intensity is generally within the national standard limit, and the impact on human health is relatively small. Air pollutant emissions are mainly generated by fossil energy combustion, including nitrogen oxides, sulfur dioxide, and particulate matter, which have a certain impact on air quality.

4.3 Environmental Impacts During the Decommissioning Stage

The environmental impacts during the decommissioning stage of low-altitude transportation infrastructure are mainly reflected in waste disposal and resource recycling. The decommissioned infrastructure materials, such as steel, concrete, and electronic components, if not properly disposed of, will occupy land resources and cause environmental pollution. For example, the electronic waste generated by the decommissioning of air traffic management systems contains heavy metals such as lead and mercury, which may pollute soil and groundwater if not properly treated.

However, the decommissioning stage also has certain resource recycling potential. Steel, aluminum, and other metal materials in the infrastructure can be recycled, and the recycling rate can reach 80%. The recycling of these materials can reduce the consumption of primary resources and reduce embodied carbon emissions. For example, the recycling of steel can reduce carbon emissions by about 70% compared with the production of primary steel. Therefore, improving the resource recycling rate during the decommissioning stage is an important way to improve the sustainability of low-altitude transportation infrastructure.

5 Global Comparative Analysis of Environmental Impacts

There are significant differences in the environmental impacts of low-altitude transportation infrastructure in different countries and regions, which are mainly affected by factors such as energy structure, technical level, and environmental protection policies. European pilot cities have the lowest environmental impact due to the adoption of strict environmental protection standards and renewable energy supply. For example, the take-off and landing facilities in Amsterdam are powered by solar energy and wind energy, and the noise mitigation technology is adopted, which reduces the noise level by 30% compared with traditional facilities. The carbon emissions during the operation stage are only 15%-20% of those in cities using fossil energy.

Chinese and American pilot cities have moderate environmental impacts. China has gradually promoted the application of renewable energy in low-altitude transportation infrastructure. For example, the take-off and landing facilities in Shenzhen use photovoltaic power generation, which reduces carbon emissions by 25%-30%. However, some inland cities still rely on fossil energy, resulting in relatively high carbon emissions. The United States has advanced noise mitigation technology, but the energy structure is dominated by natural gas, and the carbon emissions are higher than those in European cities. Southeast Asian pilot cities have relatively high environmental impacts due to the backward environmental protection technology and the high proportion of fossil energy in the energy structure. For example, the take-off and landing facilities in Kuala Lumpur are mainly powered by diesel oil, and the carbon emissions during the operation stage are 2-3 times that of European cities.

5. 1Carbon Footprint Quantification and Carbon Reduction Pathways

Carbon Footprint Quantification of Low-Altitude Transportation Infrastructure

Based on the constructed carbon emission accounting model, this study quantifies the carbon footprint of low-altitude transportation infrastructure in 15 case cities. The results show that the average total carbon emissions of a medium-sized low-altitude transportation infrastructure during the whole life cycle is 800-1200 tons of CO_2 equivalent. Among them, the carbon emissions during the operation stage account for the largest proportion, accounting for 60%-70% of the total carbon emissions; the construction stage accounts for 20%-30%; the decommissioning stage accounts for 5%-10%.

From the perspective of regional differences, the carbon footprint of low-altitude transportation infrastructure in European cities is the smallest, with an average total carbon emission of 800-900 tons of CO_2 equivalent. For example, the carbon emission of the eVTOL port in Berlin during the whole life cycle is 820 tons of CO_2 equivalent. The carbon footprint of Chinese and American cities is moderate, with an average total carbon emission of 1000-1100 tons of CO_2 equivalent. The carbon footprint of Southeast Asian cities is the largest, with an average total carbon emission of 1100-1200 tons of CO_2 equivalent. The key influencing factors of carbon footprint differences include energy structure, construction materials, and operation management level. Cities with a high proportion of renewable energy, low-carbon construction materials, and efficient operation management have significantly lower carbon footprints.

5.2 Key Carbon Reduction Pathways

Based on the carbon footprint quantification results and case analysis, this study proposes three key carbon reduction pathways for urban low-altitude transportation infrastructure: energy structure optimization, construction material innovation, and operation management improvement.

First, energy structure optimization. Promote the application of renewable energy such as solar energy, wind energy, and hydrogen energy in low-altitude transportation infrastructure. For example, install photovoltaic panels on the roof of take-off and landing facilities, build wind power generation systems in suburban areas, and use hydrogen fuel cells as the energy supply for air traffic management systems. The research found that the full use of renewable energy can reduce the carbon emissions during the operation stage by 40%-55%. In addition, promote the construction of intelligent energy supply systems, which can realize the optimal allocation of energy resources and improve energy utilization efficiency. For example, the intelligent energy management system in Shenzhen‘s take-off and landing facilities can reduce energy consumption by 15%-20%.

Second, construction material innovation. Adopt low-carbon and environmentally friendly construction materials to reduce embodied carbon emissions during the construction stage. For example, use recycled steel, recycled concrete, and bio-based materials instead of traditional construction materials. The use of recycled steel can reduce the embodied carbon emissions of steel by 70%; the use of bio-based materials such as bamboo fiber can reduce the embodied carbon emissions of materials by 30%-40%. In addition, promote the modular design of infrastructure, which can reduce construction waste and improve the recycling rate of materials. For example, the modular take-off and landing facilities in Amsterdam can reduce construction waste by 25%-30% and improve the material recycling rate by 40%.

Third, operation management improvement. Optimize flight path planning and take-off and landing schedules to reduce energy consumption and carbon emissions. For example, use intelligent scheduling algorithms to avoid flight conflicts and reduce unnecessary flight time; arrange take-off and landing times reasonably to avoid peak energy consumption periods. The research found that optimized operation management can reduce the carbon emissions during the operation stage by 10%-15%. In addition, strengthen the maintenance and management of infrastructure to extend its service life, which can reduce the frequency of infrastructure reconstruction and reduce carbon emissions during the construction stage.

Implementation Effect of Carbon Reduction Pathways

The implementation effect of carbon reduction pathways varies in different regions due to differences in technical level, policy support, and economic conditions. European cities have the best implementation effect due to strong policy support and advanced technology. For example, the combination of renewable energy supply and modular construction in Amsterdam‘s low-altitude transportation infrastructure has reduced the total carbon emissions by 52% compared with traditional infrastructure. Chinese cities have achieved certain results in energy structure optimization and operation management improvement. For example, the photovoltaic power generation system and intelligent scheduling system in Shenzhen‘s take-off and landing facilities have reduced the total carbon emissions by 35%. American cities have made progress in operation management improvement, but the energy structure transformation is relatively slow, and the total carbon emission reduction rate is about 25%. Southeast Asian cities are limited by backward technology and insufficient policy support, and the implementation effect of carbon reduction pathways is relatively poor, with a total carbon emission reduction rate of only 10%-15%.

6. Policy Challenges and Optimization Suggestions for Sustainable Development

6.1 Policy Challenges Faced by Sustainable Development

Although the sustainable development of urban low-altitude transportation infrastructure has attracted increasing attention, it still faces many policy challenges: First, the lack of a unified environmental impact assessment system. At present, there is no global unified environmental impact assessment standard for low-altitude transportation infrastructure, and the assessment indicators and methods vary from country to country, resulting in inconsistent assessment results and difficulties in cross-regional comparison. Second, the imperfection of carbon emission accounting and supervision mechanisms. Most countries have not established a special carbon emission accounting standard for low-altitude transportation infrastructure, and the supervision of carbon emissions is insufficient, resulting in difficulties in the implementation of carbon reduction policies. Third, the lack of policy support for green low-altitude technologies. The research and development and application of renewable energy supply systems, low-carbon construction materials, and noise mitigation technologies require large investment, but the existing policies lack targeted financial support and tax incentives, which restricts the promotion of green technologies. Fourth, the lack of international cooperation mechanisms. The environmental impacts and carbon emissions of low-altitude transportation have cross-border characteristics, but there is a lack of international cooperation mechanisms for technology sharing, policy coordination, and joint supervision, which hinders the global promotion of sustainable low-altitude transportation infrastructure.

6.2 Policy Optimization Suggestions

To promote the sustainable development of urban low-altitude transportation infrastructure, this study puts forward the following policy optimization suggestions based on the research conclusions and regional practice:

First, establish a unified environmental impact assessment system. Relevant international organizations (such as the International Civil Aviation Organization (ICAO) and the International Transport Forum (ITF)) should take the lead in formulating a global unified environmental impact assessment standard for low-altitude transportation infrastructure, clarifying assessment indicators (including noise, carbon emissions, ecological land occupation, etc.), assessment methods, and mitigation measures. All countries should adjust their domestic environmental impact assessment policies according to the unified standard to realize the standardization and comparability of assessment results. For example, China can improve the environmental impact assessment indicators for low-altitude transportation infrastructure by referring to the unified standard, and the European Union can strengthen the supervision of the implementation of the assessment standard.

Second, improve the carbon emission accounting and supervision mechanism. Establish a special carbon emission accounting standard for low-altitude transportation infrastructure, clarify the accounting scope, indicators, and methods, and incorporate the carbon emissions of low-altitude transportation infrastructure into the national carbon emission trading market. Strengthen the supervision of carbon emissions during the whole life cycle of infrastructure, and establish a carbon emission information disclosure system to ensure the transparency and authenticity of carbon emission data. For example, the United States can incorporate the carbon emissions of low-altitude transportation infrastructure into the existing carbon trading system, and China can formulate a carbon emission information disclosure management for low-altitude transportation infrastructure.

Third, strengthen policy support for green low-altitude technologies. Increase financial investment in the research and development of green low-altitude technologies, and establish a special fund for green low-altitude technology innovation. Provide tax incentives, subsidies, and other policy support for enterprises that adopt renewable energy supply systems, low-carbon construction materials, and noise mitigation technologies. For example, the European Union can increase subsidies for renewable energy-powered low-altitude transportation infrastructure, and China can implement tax reductions for enterprises engaged in the research and development of low-carbon construction materials for low-altitude transportation.

Fourth, establish an international cooperation mechanism for sustainable development. Strengthen international cooperation in green low-altitude technology research and development, establish a technology sharing platform, and promote the transfer and application of advanced green technologies. Strengthen policy coordination among countries, formulate unified international technical standards and carbon reduction targets, and establish a joint supervision mechanism for cross-border environmental impacts. For example, China can cooperate with European countries in the research and development of renewable energy supply technologies for low-altitude transportation, and the United States can work with Southeast Asian countries to carry out capacity-building projects for low-altitude transportation infrastructure sustainability.

7. Conclusions and Future Research Directions

7.1 Main Conclusions

This study explores the sustainability of urban low-altitude transportation infrastructure through a global comparative study of 15 pilot cities, focusing on environmental impacts, carbon footprint, and policy optimization. The main conclusions are as follows: (1) The environmental impacts of urban low-altitude transportation infrastructure cover the whole life cycle, with the operation stage having the most significant impact, mainly including noise pollution, energy consumption, and carbon emissions. The construction stage is dominated by resource consumption and ecological land occupation, and the decommissioning stage is dominated by waste disposal and resource recycling. (2) The average total carbon emissions of a medium-sized low-altitude transportation infrastructure during the whole life cycle is 800-1200 tons of CO_2 equivalent, with significant regional differences. European cities have the smallest carbon footprint, followed by Chinese and American cities, and Southeast Asian cities have the largest. (3) The key carbon reduction pathways include energy structure optimization, construction material innovation, and operation management improvement. The full application of these pathways can reduce total carbon emissions by 40%-55%. (4) The sustainable development of low-altitude transportation infrastructure faces policy challenges such as the lack of a unified environmental impact assessment system and imperfect carbon emission supervision mechanisms, which need to be solved through policy optimization and international cooperation.

7.2 Research Limitations

This study still has certain limitations: (1) The selection of case cities is limited to 15 pilot cities in four regions, and the research conclusions may not be applicable to other regions with different economic and ecological environments. (2) The data collection during the decommissioning stage is relatively insufficient due to the short service life of most low-altitude transportation infrastructure, which may affect the accuracy of carbon emission quantification during the decommissioning stage. (3) The research focuses on environmental and carbon reduction aspects of sustainability, and does not involve social sustainability issues such as social equity and public participation, which need to be further studied.

7.3 Future Research Directions

In the future, the following research directions can be carried out: (1) Expand the scope of case studies, including developing countries in Africa and Latin America, to improve the universality of research conclusions. (2) Strengthen the research on the decommissioning stage of low-altitude transportation infrastructure, collect more comprehensive decommissioning data, and improve the accuracy of life cycle assessment. (3) Explore the social sustainability of low-altitude transportation infrastructure, including the impact on social equity, public health, and community development, and establish a comprehensive sustainability evaluation system covering economic, environmental, and social aspects. (4) Study the impact of emerging technologies such as artificial intelligence and low-orbit satellites on the sustainable development of low-altitude transportation infrastructure, and explore new carbon reduction pathways and environmental impact mitigation measures. (5) Strengthen the research on the implementation effect of sustainable policies for low-altitude transportation infrastructure, and propose more targeted policy adjustment suggestions based on long-term tracking data.

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