

Environmental Performance Evaluation of Sustainable Urban Development based on DEA

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Abstract

In face of energy consumption and environmental pollution derived from economic development, the balance of negative environmental effects generated from continuous economic development has become a primary issue for countries in the world. When sustainable development is enhanced from global level to cities, the so-called sustainable city emerges, and the goal of city is to pursue sustainable environmental development. Taking Kaohsiung City in Taiwan as the research object, "Delphi Method" and "Data Envelopment Analysis" are utilized in this study. According to the public data of annual reports in various districts to select input/output performance indices for data empirical analyses, it provides the reference for improvement. The research results are summarized as below. 1. There is merely one unit presenting strong efficiency on overall technical efficiency at Stage 1 and Stage 2. 2. The overall efficiency mean of all evaluated DMUs is lower than the overall efficiency means of production and effectiveness at Stage 2. 3. Malmquist Index is applied to the productivity change analysis in this study, and total factor productivity changes of the districts appear growth on production at Stage 1 and Stage 2 as well as effectiveness at Stage 2. Finally, according to the results to propose suggestions, it is expected to provide guidance for city decisions, assist in the information communication among residents, and help cities and government units review work effectiveness and well distribute resources to bottom-up promote sustainable development and become the assistance in the country getting into sustainability.

Keywords: city development, sustainable environment, environmental performance, performance evaluation

1. Introduction

Global warming is a globally concerned issue. When economies concentrate on the promotion of productivity and economic growth, the negative effects along with production and the impact on environment should be understood to seek balanced development between economic development and environmental disruption as well as review the business performance of economies under the goals of sustainable environment performance and maintenance of economic development. Since it requires the input of enormous resources and manpower to support a huge urban system, the population start to gather in cities for the convenience. In the area, people encounter environmental problems as well as infectious diseases, economic inequality, social violence, uneven distribution of resources, people's health decline, and population aging. Such negative problems would affect the sustainable development of cities. When enhancing sustainable development from global level to cities, the so-called sustainable city emerges, and the goal of a city is to pursue sustainable environmental development. The establishment of sustainable urban environmental performance indices conforms to

international trend and bottom-up promotes sustainable development to have sustainable development indices be close to the life of general residents and become the assistance in counties/cities or country stepping into sustainability. Environmental performance evaluation could be the tool for cities or government departments reviewing work outcome to evaluate the proper utilization of input budgets, manpower, and objects, with data and scientific evaluation process, for achieving the goal. Proper suggestions are further proposed for the work direction and decision making of cities in the future to more effectively distribute and use resources. The environmental performance evaluation of sustainable urban development is therefore discussed in this study, expecting to provide guidance for city decision, assist in the information communication among residents, and help cities and government units review work effectiveness and well distribute resources to bottom-up promote sustainable development and become the assistance in the country getting into sustainability.

2. Literature Review

According to Ahvenniemi et al.¹, the evaluation of urban sustainability should not stop at examining “what has been done,” but should further assess “what impacts have been produced.” For example, when a city builds bicycle lanes, it should not merely count the total length of the infrastructure. Instead, it should examine whether these lanes reduce private car use, lower traffic-related emissions, improve commuting safety, and enhance residents’ health. From this perspective, sustainable urban development can be understood as a long-term public-interest-oriented process of urban transformation, with the goal of achieving a balance among environmental carrying capacity, social equity, and economic vitality. Bibri and Krogstie² suggest that sustainable urban development includes at least four levels. The first is the ecological level, which refers to reducing pressure on natural resources and minimizing pollution and ecological damage. The second is the technological level, which involves improving urban operational efficiency through smart systems. The third is the social level, which focuses on improving residents’ quality of life, opportunities for participation, and social inclusion. The fourth is the governance level, which refers to building institutional capacity to integrate data, policies, and cross-sector collaboration. This definition goes beyond the traditional triple-bottom-line perspective because it views the city as a system that continuously operates, learns, and adjusts. Whether a city is sustainable depends not only on how many green facilities it has, but also on whether it can use knowledge and institutional capacity to continuously address complex urban problems. Bibri³ argues that cities pursue long-term balance among environmental protection, resource efficiency, social well-being, and economic development through scientific planning, interdisciplinary knowledge, smart infrastructure, and institutional coordination. From this viewpoint, sustainable urban development is neither a single policy nor the responsibility of a single department. Rather, it is an integrated governance model that requires the coordination of land use, transportation, energy, buildings, public services, information systems, and resident behavior. Yigitcanlar et al.⁴ define sustainable urban development as a process of urban transformation grounded in environmental responsibility, social inclusion, economic vitality, and governance capacity. Smart technologies can strengthen urban management, but they cannot replace the fundamental goals of sustainable development.

In other words, the central issue in sustainable urban development is not whether a city uses technology, but whether the use of technology and policy makes the city fairer, lower-carbon, more resilient, and more livable. Huovila et al.⁵ understand sustainable urban development as a process through which cities continuously improve across environmental, economic, social, governance, and infrastructure dimensions through standardized indicators. This definition is especially useful for empirical research because it reminds researchers that the concept of a sustainable city must be translated into concrete variables. For example, environmental indicators may include energy consumption, carbon emissions, air quality, and waste recycling rates; social indicators may include access to public services, housing affordability, sense of safety, and quality of life; economic indicators may include employment, innovation, industrial resilience, and urban competitiveness; and governance indicators may examine data transparency, resident participation, policy coordination, and performance management.

2.1 Environmental Performance Evaluation

Lin et al.⁶ regarded environmental performance evaluation as the method for an organization managing environmental affairs, which aimed to provide an organization with effective management environmental impact resulted from organizational operation and allowed the organization self-defining environmental performance indices suitable for organizational characteristics to have internal/external stakeholders understand the environmental effectiveness. Sarkis⁷ mentioned that environmental performance evaluation system was defined as “the tool to inspect organizational environment to decide the achievement of goals” and provided trustable, targeted, and verifiable information to further improve environmental performance. Bernard et al.⁸ regarded environmental performance evaluation as the automatic behavior of an organization, rather than the external standard for judging environmental performance. By transforming organizational environmental effectiveness into understandable information with proper indices, the use of indices provided an organization with compared environmental performance information in the past and at present as the systematic procedure for measuring and evaluating environmental performance and the process to execute environmental performance evaluation. Kotharkar & Bagade⁹ stated that the practice of environmental performance evaluation could understand the level of environmental impact, assist the continuous improvement of system, specifically quantify and present environmental management performance, receive trust from stakeholders with data and scientific evaluation process, and enhance organizational communication efficiency and effectiveness. Deilami et al.¹⁰ indicated that environmental performance evaluation provides a method for managing environmental affairs; qualitative and quantitative indices could provide decision makers with information of environmental impact, and proper and quantitative performance indices allowed managers or stakeholders understanding the environmental impact of the organization through the performance index change.

2.2 Environmental Performance Index

Chen et al.¹¹ classified environmental performance indices into “environmental performance index (EPI)” and “environmental condition index (ECI)”, where “environmental performance

index” was further divided into “management performance index (MPI)” and “operation performance index (OPI)”. Management performance index would provide organizational capability and efforts on management affairs which would affect or possibly affect environmental performance. Operation performance index should provide environmental performance information of managerial level organizational operation, including input, output, and operation involved in organizational operation process. Zhiming¹² compared the environmental performance of US fossil fuel power generation industry, with inputs of capital, number of workers, coal use, oil fuel use, and gas use, output of power generation, and undesirable outputs of carbon dioxide emissions, sulfur dioxide emissions, and nitrogen oxides emissions. Son et al.¹³ evaluated the manufacturing productivity performance of the US states, with inputs of manufacturing manpower and capital, output of manufacturing gross product, and undesirable outputs of sulfur oxides, nitrogen oxides, volatile organic compounds, and carbon monoxide. Xu et al.¹⁴ discussed the environmental performance of 25 OECD member states, with inputs of manpower and capital, output of gross national product, and undesirable outputs of carbon dioxide emissions. Farooque et al.¹⁵ discussed manufacturing environmental performance of 14 OECD member states, with inputs of manpower and capital, output of gross production of manufacturing, and undesirable output of carbon dioxide emissions. Kaplan et al.¹⁶ discussed the productivity performance of 17 OECD member states, with inputs of capital, number of workers, and energy consumption, output of gross national product, and undesirable outputs of carbon dioxide emissions, sulfur oxides, and nitrogen oxide emissions. Nguyen et al.¹⁷ discussed the relationship between environmental performance and economic development, with input/output variables of capital, manpower, gross national product, and sulfur dioxide emissions. Wang et al.¹⁸ studied the environmental energy efficiency of APEC economy, with inputs of capital, manpower, and energy consumption and outputs of GDP. Leducq & Scarwell¹⁹ studied the environmental performance changes of 30 OECD member states in 1998-2002, with inputs of population and energy supply, output of GDP, and undesirable output of carbon dioxide emissions. Guha et al.²⁰ discussed the productivity changes of 41 developed and developing countries, with inputs of capital, manpower, and energy consumption, output of GDP, and undesirable output of carbon dioxide emissions.

2.3 Experimental: Establishment Of Research Index

Summing up above indices for researchers’ sustainable urban environmental performance evaluation, Delphi Method is utilized in this study for drawing out the indices for sustainable urban environmental performance evaluation. Delphi Method, also named expert judgment, is a group decision method with both qualitative and quantitative characteristics. Under data shortage or unknown situation of certain issues in the research process, experts, with anonymity, is surveyed with several runs of decision-making and feedback to reduce the different opinions down to the lowest and acquire a commonly accepted answer. The experts have to present knowledge standard, reliability, and accuracy and have deeper knowledge of the industry than laymen so that the experts present the judgment closer to the fact than general people. The value of Delphi Method is established on such an answer.

Establishment of Index. According to Delphi Method to establish indices, the variables are defined as followings.

Input variable

1. Population: total urban population in the district.
2. Energy supply: total urban energy consumption in the district.

Intermediate variable

1. Technical skill: input, output, and operation for improving environmental performance involved in the production process in urban areas.
2. Management ability: decisions and actions with effects or possible effects on the improvement of environmental performance.

Output variable

1. Economy: gross national product.
2. Pollution: carbon dioxide emissions.

3. Research Method

Kaohsiung City in Taiwan is selected as the research object in this study. With “Delphi Method” and “Data Envelopment Analysis”, public data of annual reports of districts are regarded as the data to select input/output performance indices for data analyses and as the reference of improvement. Aiming at research objects, total 11 evaluated DMUs are selected for this study.

Efficiency Evaluation Analysis. Data Envelopment Analysis (DEA) is utilized for efficiency evaluation in this study. Unlike traditional regression analysis, which simply seeks for the mean path through the points in a series of data, DEA envelops various sample data and attempts to find out the relationship, presenting the advantage required for a good efficiency evaluation model. The method applies the technique of linear planning, considers factors which could measure the performance among evaluated units, and compares the performance of units with similar characteristics. In the research structure, DEA performance evaluation at Stage 1 regards production and effectiveness as a whole and simply considers the relationship between inputs and outputs. DEA performance evaluation at Stage 2, on the other hand, is measured with production efficiency (efficiency relationship between inputs and intermediate variable) at Stage 1 and effectiveness efficiency (efficiency relationship of intermediate variable and outputs) at Stage 2. In other words, the management efficiency of evaluated DMUs in this study is analyzed with the process of “input - intermediate variable - output”, where input refers to inputs required for production, output stands for the degree of evaluated DMUs achieving the effectiveness, and intermediate variable represents the degree of service offered by evaluated DMUs being used (i.e. the level of service scale).

4. Finding and Discussion

4.1 Analysis of Sustainable Urban Environment Performance

CCR model is first used for calculating the overall technical efficiency of evaluated organizations at various stages, and BCC model is applied to calculate the pure technical efficiency. The scale efficiency could be calculated by dividing overall technical efficiency by pure technical efficiency. From the comparison of pure technical efficiency and scale efficiency, the inefficiency is resulted from technical inefficiency or scale inefficiency. The efficiency mean of evaluated DMUs is analyzed in this study, and overall technical efficiency, technical efficiency, and scale efficiency at Stage 1 and Stage 2 are compared. The results are organized in Table 1 and Table 2.

Table 1. Relative efficiency of sustainable urban environmental performance evaluation

District	Stage 1		
	overall efficiency	technical efficiency	scale efficiency
Nanzih District	0.90	0.90	0.90
Zuoying District	0.96	0.94	0.98
Gushan District	0.88	0.87	0.89
Yancheng District	0.85	0.84	0.88
Sanmin District	1.00	1.00	1.00
Cianjin District	0.94	0.93	0.95
Sinsing District	0.98	0.98	0.98
Lingya District	0.90	0.89	0.91
Cianjhen District	0.81	0.80	0.81
Siaogang District	0.92	0.91	0.93
Cijin District	0.75	0.75	0.75

Table 2. Relative efficiency of sustainable urban environmental performance evaluation

District	Stage 2					
	production			effectiveness		
	overall technical efficiency	technical efficiency	scale efficiency	overall technical efficiency	technical efficiency	scale efficiency
Nanzih District	0.91	0.91	0.90	0.92	0.91	0.93
Zuoying District	0.98	0.97	0.99	0.99	0.99	0.99
Gushan District	0.89	0.89	0.89	0.90	0.88	0.92
Yancheng District	0.87	0.86	0.88	0.88	0.87	0.89

Sanmin District	1.00	1.00	1.00	1.00	1.00	1.00
Cianjin District	0.95	0.95	0.94	0.97	0.97	0.97
Sinsing District	0.99	0.99	0.99	1.00	1.00	0.99
Lingya District	0.91	0.90	0.92	0.93	0.92	0.94
Cianjhen District	0.83	0.82	0.84	0.87	0.86	0.88
Siaogang District	0.95	0.94	0.96	0.96	0.95	0.97
Cijin District	0.77	0.76	0.77	0.80	0.79	0.81

4.2 Productivity Change Analysis

To understand the intertemporal performance change of evaluated DMUs, the 2018~2019 data of various prefecture-level cities are selected for productivity change analysis with Malmquist Index (MI). The analysis results are shown in Table 3. Total factor productivity changes of districts at Stage 1, Stage 2 production, and Stage 2 effectiveness are growing, revealing growing overall productivity of districts in the two years. At Stage 1, 6 districts (about 54.55%) shows growing total factor productivity. At Stage 2 production, 5 districts (about 45.45%) appears growth. At Stage 2 effectiveness, 4 districts (about 36.36%) reveals growth.

Table 3. Productivity change analysis

prefecture-level city	Stage 1	Stage 2	
		production	effectiveness
Nanzih District	0.99	1.04	0.95
Zuoying District	1.04	0.97	0.99
Gushan District	1.01	0.98	1.00
Yancheng District	0.97	0.95	0.98
Sanmin District	1.08	1.08	1.06
Cianjin District	1.02	1.00	1.03
Sinsing District	0.97	0.94	0.97
Lingya District	1.05	0.92	1.04
Cianjhen District	0.94	1.02	0.96
Siaogang District	0.92	1.06	0.87
Cijin District	1.05	0.88	0.91

Data source: self-organized in this study.

This study applied the CCR model, BCC model, and Malmquist Index to examine the relative efficiency and intertemporal productivity changes of sustainable urban environmental performance across different districts. Overall, the results show clear differences among districts, and the efficiency performance at each stage carries distinct implications. As shown in Table 1, Sanmin District achieved a score of 1.00 in overall technical efficiency, pure technical efficiency, and scale efficiency in Stage 1. This indicates that Sanmin District reached a relatively efficient status at this stage and was able to convert inputs into sustainable urban environmental outputs effectively in terms of resource allocation, managerial capability, and operating scale. In contrast, Cijin District, Cianjhen District, and Yancheng District reported lower overall technical efficiency, suggesting that these districts still have room for improvement in resource utilization, administrative implementation, or scale arrangement.

A comparison of overall technical efficiency, pure technical efficiency, and scale efficiency further indicates that inefficiency in some districts does not result solely from managerial or technical weakness, but may also be related to inappropriate operating scale. For example, Cijin District recorded a score of 0.75 across all three efficiency indicators in Stage 1, suggesting that the district performed relatively weakly in both pure technical efficiency and scale efficiency. This implies that Cijin District may face multiple challenges in sustainable urban environmental governance, including inefficient resource allocation, limited implementation capacity, and a mismatch between service scale and local needs. Cianjhen District shows a similar pattern, with relatively low scores in overall technical efficiency, pure technical efficiency, and scale efficiency. Therefore, improving sustainable environmental performance in this district should not rely merely on increasing inputs. Instead, it is necessary to examine whether existing resources are being used effectively and whether the current governance scale is appropriate for the district's development needs.

The Stage 2 analysis further divides performance into production and effectiveness, which helps clarify whether a gap exists between output generation and outcome realization. As shown in Table 2, Sanmin District achieved full efficiency in both production and effectiveness in Stage 2, continuing its strong performance from Stage 1. This suggests that the district was not only able to generate environmental governance outputs efficiently, but also able to translate those outputs into stronger sustainable urban environmental outcomes. Sinsing District also performed well in Stage 2, particularly in effectiveness, where both overall technical efficiency and pure technical efficiency reached 1.00. Although its scale efficiency was 0.99, the result still indicates a strong capacity to transform outputs into actual environmental outcomes. Zuoying District also reported efficiency scores close to full efficiency, suggesting that its urban environmental governance system is relatively mature. However, not all districts maintained strong performance in Stage 2. Cijin District remained a relatively inefficient district in both production and effectiveness, with an overall technical efficiency score of 0.77 in production and 0.80 in effectiveness. This shows that even in the second stage, the district had not yet substantially improved its environmental governance efficiency. The result may reflect more complex geographical, industrial, or infrastructure constraints, making it more difficult for Cijin District to reach the efficiency levels of other districts in promoting sustainable urban

environmental development. Although Cianjhen District showed slight improvement in Stage 2 compared with Stage 1, its overall efficiency remained lower than that of most other districts, indicating that further improvement is still needed in both the production process and outcome conversion. It is also worth noting that, when comparing Stage 1 and Stage 2 efficiency values, most districts showed slightly higher performance in Stage 2 production or effectiveness than in Stage 1. This suggests that some districts may have gradually accumulated governance experience and converted earlier inputs into more concrete outputs or outcomes. For instance, Cianjhen District increased from an overall technical efficiency score of 0.81 in Stage 1 to 0.83 in Stage 2 production and 0.87 in Stage 2 effectiveness. Although it has not yet reached a high-efficiency level, the district has shown signs of improvement. Siaogang District also improved from an overall technical efficiency score of 0.92 in Stage 1 to 0.95 in Stage 2 production and 0.96 in Stage 2 effectiveness, indicating stronger implementation and outcome-conversion capacity in the later stage.

In terms of productivity change, the Malmquist Index results in Table 3 show that intertemporal performance varied across districts. In Stage 1, six districts recorded an index greater than 1, indicating growth in total factor productivity. These districts include Zuoying District, Gushan District, Sanmin District, Cianjin District, Lingya District, and Cijin District. Among them, Sanmin District had the highest Stage 1 index at 1.08, making it the best-performing district. This indicates that Sanmin District not only reached relative efficiency in the static efficiency analysis, but also continued to improve in terms of intertemporal productivity change. Lingya District and Cijin District both recorded a Stage 1 index of 1.05, showing noticeable improvement between 2018 and 2019. However, fewer districts achieved productivity growth in Stage 2 production and effectiveness. Using an index greater than 1 as the criterion for productivity growth, Stage 2 production growth was mainly observed in Nanzih District, Sanmin District, Cianjhen District, and Siaogang District. Cianjin District recorded an index of 1.00, indicating stability rather than clear growth. For Stage 2 effectiveness, productivity growth was observed in Sanmin District, Cianjin District, and Lingya District, while Gushan District recorded an index of 1.00, indicating stable performance. These findings suggest that some districts may improve the process of converting inputs into outputs, but this does not necessarily lead to a simultaneous improvement in final environmental outcomes. Conversely, some districts may show improvement in effectiveness even when production performance does not grow at the same pace.

In summary, the results of this study show that sustainable urban environmental performance differs notably across districts and stages. Sanmin District demonstrated the strongest performance across all stages and may be regarded as a relative benchmark district. Zuoying District, Sinsing District, Cianjin District, and Lingya District also showed a relatively strong efficiency foundation. By contrast, Cijin District, Cianjhen District, and Yancheng District should be considered priority areas for improvement. The findings further suggest that urban environmental governance should not be evaluated solely based on a single year or a single efficiency score. Instead, overall technical efficiency, pure technical efficiency, scale efficiency, and intertemporal productivity change should be examined together in order to develop a more

complete understanding of each district's strengths and limitations in sustainable urban development.

5. Conclusion

Based on the DEA efficiency results and Malmquist productivity change analysis, this study provides a more detailed understanding of sustainable urban environmental performance across districts. The findings show that sustainable urban environmental governance is not evenly developed among the evaluated districts. Although most districts have already made certain efforts in environmental management and sustainable development, their ability to transform inputs into efficient outputs and final outcomes still varies considerably. Among all evaluated DMUs, only Sanmin District achieved full efficiency in Stage 1 as well as in Stage 2 production and effectiveness, indicating that it performed well in resource allocation, production capacity, and outcome realization. This result suggests that Sanmin District may serve as a benchmark for other districts seeking to improve sustainable urban environmental performance.

The Stage 1 results show that most districts did not reach the efficiency frontier. This implies that many districts still need to improve either technical efficiency, scale efficiency, or both. In particular, Cijin District, Cianjhen District, and Yancheng District showed relatively low efficiency scores, suggesting that their current resource use, administrative implementation, or operating scale may not yet be optimal. These districts should not rely solely on increasing inputs. Instead, they need to review how resources are allocated, whether environmental policies are effectively implemented, and whether the current scale of governance matches local development conditions.

The Stage 2 results further reveal that production performance and effectiveness performance should be examined separately. Some districts performed better in production than in effectiveness, indicating that they may be able to generate environmental governance outputs but may not fully convert these outputs into actual sustainable outcomes. This finding is important because urban environmental governance should not be evaluated only by the amount of resources invested or the number of projects completed. The more critical issue is whether these efforts truly improve environmental quality, reduce resource waste, enhance public living conditions, and support long-term sustainability. Therefore, local governments should establish a clearer linkage between inputs, policy outputs, and final environmental outcomes.

The Malmquist Index results show that intertemporal productivity changes also differed across districts. Sanmin District demonstrated strong productivity growth in Stage 1, Stage 2 production, and Stage 2 effectiveness, confirming its stable and improving performance over time. Some districts, such as Zuoying District, Cianjin District, Lingya District, Cianjhen District, and Siaogang District, showed growth in certain stages but not in others. This indicates that productivity improvement is not always balanced across the production and effectiveness dimensions. A district may improve its production process without achieving equal progress in final outcomes, or it may show better effectiveness even when production growth remains limited. For this reason, sustainable urban environmental evaluation should consider both static efficiency and dynamic productivity change.

Overall, the study confirms that DEA and the Malmquist Index are useful tools for identifying differences in sustainable urban environmental performance among districts. DEA helps reveal which districts are relatively efficient and which still have room for improvement, while the Malmquist Index shows whether each district's productivity is improving or declining over time. The combined use of these methods allows policymakers to move beyond simple ranking and develop a more precise understanding of each district's strengths and weaknesses.

The findings also suggest that sustainable urban development requires differentiated governance strategies. Districts with high efficiency, such as Sanmin District, should focus on maintaining their advantages and developing more innovative environmental policies. Districts with moderate efficiency, such as Zuoying District, Sinsing District, Cianjin District, Lingya District, and Siaogang District, should further refine resource allocation, improve policy coordination, and strengthen the connection between environmental outputs and actual outcomes. Districts with lower efficiency, such as Cijin District, Cianjhen District, and Yancheng District, should be given priority in policy support, capacity building, infrastructure improvement, and administrative reform.

In practical terms, local governments should use the results of this study to establish a performance-based management mechanism for sustainable urban environmental governance. First, benchmark learning should be encouraged so that lower-efficiency districts can learn from the practices of high-performing districts. Second, government departments should strengthen data collection and monitoring systems to track environmental inputs, outputs, and outcomes over time. Third, industrial upgrading should be promoted in districts where traditional or labor-intensive industries still contribute to energy waste and pollutant emissions. Moving toward technology-intensive and knowledge-intensive industries can help reduce environmental pressure and support more sustainable economic development. Fourth, personnel training, interdepartmental cooperation, and resident participation should be strengthened so that sustainable development policies can be implemented more effectively at the local level.

In conclusion, improving sustainable urban environmental performance is not only a matter of increasing investment, but also a matter of improving governance efficiency, policy coordination, industrial structure, and outcome conversion. A city can move toward sustainability only when environmental resources are used efficiently, policy outputs are translated into real environmental benefits, and residents, industries, and government departments work together toward shared sustainable development goals. The results of this study provide empirical evidence for local governments to diagnose performance gaps, identify benchmark districts, and design more targeted strategies for building a sustainable urban environment.

Practical Recommendations. Based on the DEA efficiency analysis and Malmquist productivity change results, this study found clear differences in sustainable urban environmental performance across districts. Therefore, when promoting sustainable environmental policies, urban governance authorities should avoid applying a uniform management approach to all districts. Instead, improvement strategies should be designed

according to each district's efficiency status, resource conditions, and development constraints. Overall, this study proposes the following practical recommendations as references for local governments seeking to improve sustainable urban environmental performance.

First, a benchmark-based learning mechanism should be established. The results show that Sanmin District reached relative efficiency in Stage 1 as well as in Stage 2 production and effectiveness, and also demonstrated continuous growth in the Malmquist Index. This indicates that the district performed well in resource allocation, administrative implementation, and outcome conversion. Therefore, local governments may regard Sanmin District as a benchmark case and further examine its specific practices in environmental governance, infrastructure allocation, interdepartmental coordination, public service procedures, and community participation. These successful practices can then be transformed into a governance model that other districts may reference. Such benchmark learning should not be limited to a simple comparison of rankings. Rather, it should focus on how high-efficiency districts allocate resources, implement policies, and transform environmental inputs into concrete outcomes.

Second, districts with lower efficiency scores should be prioritized for problem diagnosis and resource restructuring. Cijin District, Cianjhen District, and Yancheng District performed relatively weakly across several efficiency indicators, suggesting that they may face problems such as insufficient resource inputs, ineffective management procedures, inappropriate scale allocation, or local development constraints. In response, local governments should first conduct data reviews and field assessments to identify whether the source of inefficiency lies in technical inefficiency or scale inefficiency. If the problem comes from low pure technical efficiency, it indicates that existing resources have not been used effectively, and improvements should focus on administrative procedures, implementation capacity, and management techniques. If the problem comes from low scale efficiency, it suggests that the current scale of resource input may be either excessive or insufficient, and budget allocation, facility installation, and service coverage should be reexamined to determine whether they match actual local needs.

Third, the environmental governance capacity and implementation quality of low-efficiency districts should be strengthened. In some districts, even when certain resources have been invested, environmental governance outcomes have not been effectively produced. This suggests that gaps may exist in policy implementation, technical application, or interdepartmental integration. Therefore, local governments may establish targeted support programs for low-efficiency districts. For example, they may provide training in environmental data analysis, assist in building performance tracking systems, introduce smart monitoring equipment, and strengthen frontline personnel's understanding of sustainable environmental indicators. By improving the professional capacity of implementation staff, resource-use efficiency can be enhanced, and policy investment can be prevented from becoming merely procedural or symbolic.

Fourth, greater attention should be paid to the linkage between production and effectiveness. The Stage 2 results show that some districts performed well in production, but their

effectiveness did not necessarily improve at the same pace. This indicates that a conversion gap may exist between outputs and final outcomes. In other words, a district may complete environmental construction projects, facility improvements, or policy initiatives, but these efforts may not immediately translate into residents' perceptions, environmental quality, or sustainable outcomes. Therefore, when formulating policies, local governments should not focus only on the number of projects completed or the amount of funding invested. They should further track whether these inputs and outputs truly improve air quality, green space use, waste management, public space quality, or residents' living environment. It is recommended that a three-level management framework of "input–output–outcome" be established, so that each policy can be linked to clear final outcome indicators.

Finally, the improvement of sustainable urban environmental performance should incorporate resident participation and local needs. Although efficiency analysis can provide an objective basis for management, urban environmental policies must ultimately respond to residents' quality of life. Therefore, when improving low-efficiency districts, local governments should use resident surveys, community forums, public participation platforms, and open data mechanisms to understand citizens' actual perceptions of environmental quality, public spaces, transportation convenience, and living safety. This approach can not only improve policy accuracy, but also strengthen residents' support for sustainable governance measures. Overall, local governments should transform DEA and Malmquist analysis results into concrete governance tools. Through benchmark learning, differentiated management, intertemporal tracking, and civic participation, sustainable urban environmental performance across districts can be gradually improved.

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