Efficiency Changes of Urban Solid Waste Management in Chinese Coastal Cities along the Bohai Sea: A Super-SBM DEA Window Analysis

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Abstract

This study investigates the efficiency of municipal solid waste management in twelve coastal cities surrounding the Bohai Sea in China over the years 2019 to 2021, employing Data Envelopment Analysis (DEA). The selection of these cities is based on their substantial geographical and economic significance, as well as their impact on regional environmental quality. Using the super-SBM DEA window analysis approach, we analyze technical efficiency, pure technical efficiency, and scale efficiency to gain insights into the performance and challenges of municipal solid waste management.

The research findings unveil significant variability in technical efficiency scores across the cities, pointing to fluctuating levels of solid waste management efficiency attributed to changes in local policies, financial strategies, and external economic conditions. Pure technical efficiency scores also exhibit notable fluctuations, reflecting variances in administrative efficiency and the impact of policy changes. Scale efficiency analysis reveals an increase in 2020, implying enhanced economies of scale and resource utilization, followed by a decrease in 2021, indicating potential over-expansion or inefficiencies in waste processing.

This study concludes that achieving optimal efficiency in municipal solid waste management is not solely dependent on increasing investment or operational scale. It necessitates strategic planning, sustained policy support, effective management, and the integration of advanced technologies. The dynamic nature of environmental policies, technological advancements, and economic transformations requires adaptable municipal solid waste management approaches. Investing in smart waste management technologies and sharing successful practices among cities can significantly enhance efficiency. Future research should focus on detailed and advanced methods to dissect specific components of municipal solid waste management, thereby supporting the development of tailored strategies for sustainable and efficient waste management.

Keywords: *Data Envelopment Analysis (DEA) , Municipal Solid Waste Management, Slacks-Based Measure (SBM), Super-efficiency, Window Analysis*

1. Introduction

According to the 'Bohai Sea Region Cooperation and Development Outline' released by the National Development and Reform Commission of China, the Bohai Sea, being an integral part of China's maritime domain, plays a crucial role in the nation's economy and development. As one of the economic zones with the most comprehensive advantages and development potential, it holds a strategically significant position in terms of opening up to the outside world and modernization. The area around the Bohai Sea hosts a series of port cities primarily focused on marine resources, forming an economic zone that is both coastal and bordering. Cities like Tianjin, Qingdao, Dalian, and Yantai, serving as significant economic, trade, and industrial hubs in China, have propelled regional economic development. Ports such as Tianjin and Qingdao are not only vital for northern China's international trade but also indispensable components of global transportation.

However, rapid urbanization and industrial growth in these areas have posed increasingly severe environmental challenges. The massive production of municipal solid waste has become a major environmental problem for these coastal cities. The municipal solid waste management significantly impacts the region's marine ecosystem and the prospects for sustainable development. Currently, these cities face numerous challenges in municipal solid waste management and environmental protection, including waste classification, recycling, disposal, and reduction of waste production. Therefore, investigating and improving the efficiency of municipal solid waste management in the cities around the Bohai Sea is not only crucial for their sustainable development but also has a profound impact on environmental protection and ecological safety in the entire Bohai Sea region.

This study aims to evaluate the efficiency of municipal solid waste management in cities around the Bohai Sea, specifically focusing on coastal cities at the municipal level or above, utilizing the Data Envelopment Analysis (DEA) method. The goal is to provide a scientific basis for improving municipal solid waste management strategies and practices, thereby promoting the continuous and healthy environmental development of the region.

2. Literature Review

In recent years, measuring the efficiency of municipal solid waste management has become a research hotspot with the concept of sustainable development.

Albores et al. (2016) investigated the efficiency of waste-to-energy systems in municipal solid waste management using DEA method. The research emphasized the increasing generation of municipal solid waste globally, especially in OECD countries and four developing countries including China. Significant research gaps in analyzing the efficiency of these systems in developing countries were identified. Yang et al.

(2018) revealed regional disparities in municipal solid waste management efficiency across Chinese cities. They highlighted the need for improved management and technology, especially in western and central regions, and emphasized region-specific policies due to varying efficiency levels. Qian (2020) evaluated the efficiency of municipal solid waste management in China from 2007 to 2016 using the BCC-DEA model. The study found significant differences in waste management efficiency across regions, with some regions being more efficient while others lagging behind. Key factors affecting efficiency, including economic development, city size, waste management fees, and level of marketization, were identified. The study provided insights into policy implications, concluding that economic and technological investments are critical to improving waste management efficiency in Chinese cities.

Lo Storto (2021) used a non-parametric approach to investigate the efficiency of municipal solid waste management. Various factors that influence the efficiency of waste management, including socio-economic, socio-demographic, and institutional variables, were identified. The importance of DEA method in assessing the performance of waste management services was emphasized. Lo Storto (2021) analyzed the productivity of municipal solid waste collection in Italy from 2010 to 2019 using the SBM DEA Malmquist Index. The research shows that total factor productivity in the waste collection sector generally showed positive growth during this period. A significant correlation between waste production per capita and total factor productivity was found, emphasizing the importance of efficient waste management practices to achieve environmental sustainability goals.

Adeleke et al. (2021) The examination of the challenges and prospects for achieving sustainability in municipal solid waste management in South Africa highlighted the impact of factors such as population growth, urbanization, and literacy on waste generation and management. The main challenges to effective waste management were identified, and potential solutions, focusing on sustainable practices and energy recovery, were explored. Sala-Garrido et al. (2022) examined the efficiency of municipal solid waste management in Chile, focusing on technical, environmental, and eco-efficiency aspects. The research emphasized the impact of operational and environmental factors on waste management efficiency and discussed the implications of these findings for policymaking and operational practices in waste management. Directions for future research to expand the breadth and depth of analysis in this area were suggested.

Zhou et al. (2022) assessed the efficiency of municipal solid waste collection and disposal in the Yangtze River Delta region of China and found that efficiency varied significantly across cities, influenced by factors such as combined technical efficiency, pure technical efficiency, and scale efficiency. Chu et al. (2022) investigated the spatial and temporal differences in municipal solid waste carbon emission efficiency across Chinese provinces from 2010 to 2019. The research highlights the impact of various factors on municipal solid waste management efficiency, including regional differences and model limitations. Local governments were suggested to formulate municipal solid waste policies according to the specific conditions of their regions. Chu et al. (2023) assessed the effectiveness of the mandatory municipal solid waste classification policy in Shanghai.

It was found that the policy's implementation was significantly influenced by environmental factors and public budget allocation. A two-stage approach combining DEA and stochastic frontier analysis was used to assess the policy's impact on waste management efficiency. An increase in public budget revenues was found to positively affect the policy's effectiveness, suggesting that government funding plays a crucial role in successful waste management.

Unlike previous studies this study applies different approach in analyzing the efficiency of municipal solid waste management.

3. Research Design and Method

3.1. Data Sample and Variables Selection

The reasons for selecting the cities around the Bohai Sea as the research sample are the following. The cities around the Bohai Sea hold a significant position in China's geographical and economic landscape. Not only is the Bohai Sea an important marine ecosystem, but it also serves as a crucial water body connecting the northeastern, northern, and eastern regions of China. Economic activities in these cities, particularly port operations, industrial production, and marine resource development, contribute significantly to the regional economy while also generating a substantial amount of solid waste. Due to the rapid industrial and urban development of the urban agglomerations around the Bohai Sea, the management of solid waste has emerged as a key factor influencing regional environmental quality. Researching these cities can help evaluate the efficiency of municipal solid waste management, thereby providing valuable data support for the formulation of environmental protection and sustainable development strategies. The cities around the Bohai Sea, owing to their unique geographical location and economic status, could set a precedent in municipal solid waste management. Their successful practices may serve as a model for other coastal cities in China and globally, guiding them towards more efficient and sustainable waste management.

In summary, selecting the cities around the Bohai Sea as the research subject on the efficiency of solid waste management has clear geographical, environmental, social, and policy significance. The experiences of these cities can not only provide insights for environmental management in China but also serve as a reference for global cities facing similar challenges. Through in-depth research, it is possible to promote innovation in municipal solid waste management in these cities and contribute to advancing sustainable development strategies at the regional and national levels.

This study employs the super-SBM DEA window model to analyze the urban solid waste management efficiency of 12 representative cities in the Bohai Sea region, as presented in table 1. The data for the 12 coastal cities of the Bohai Sea from 2019 to 2021 were collected and analyzed, with the information sourced from the 'China Urban Construction Statistical Yearbook' and other relevant statistical yearbooks.

Based on the aforementioned preliminary studies and brainstorming sessions with experts in the relevant fields, this paper ultimately identified 3 input indicators and 2 output indicators, as shown in Table 1.

Table 1. DMUs (decision-making units) and the Input and Output Variables

DMUs	Cangzhou, Dalian, Dongying, Huludao, Jinzhou, Panjin, Qinhuangdao, Tangshan, Tianjin, Weifang, Yantai, Yingkou
Input variables	Environmental Sanitation Fixed Asset Investment (10,000 RMB)
	Number of Harmless Treatment Plants/ Grounds (unit)
	Number of Vehicles and Equipment Designated for Municipal Environmental Sanitation (unit)
Output variables	Volume of Harmlessly Treated (10,000 ton)
	Harmless Treatment Capacity (ton/day)

3.2. DEA Window and Super-SBM Model

The conventional DEA model provides efficiency values for different cross-sections but only allows for static comparisons. This means that efficiency values from different frontiers are not comparable. To overcome this limitation, Charnes et al. (1985) proposed DEA window analysis. This methodology enables the comparison of the efficiencies of all decision-making units (DMUs) over time by combining each DMU with a frontier formed within a fixed-width window. The DEA window approach evaluates the efficiency of a specific DMU across different window periods as if they were separate entities. By averaging these efficiency values, one can obtain a representative efficiency value for the DMU for a given period.

In the field of efficiency and productivity assessment, the slacks-based measure (SBM) model (Tone, 2001) has been widely used to measure the relative efficiency of DMUs. However, the SBM model has limitations in dealing with efficient DMUs, as it cannot further distinguish differences in their efficiency. Tone (2002) developed the Super-efficiency SBM model, which can discriminate and rank the efficient DMUs in the SBM model. The specific formula for the Super-efficiency SBM model is as follows:

$$Min\,\delta = \frac{1 + \frac{1}{m}\sum_{i=1}^{m} \frac{s^-}{x_{ik}}}{1 - \frac{1}{S}\sum_{r=1}^{s} \frac{s^+}{y_{rk}}}$$

$$\text{s.t.} \quad \sum_{j=1, j\neq k} x_{ij}\lambda_j - s_i^- \leq x_{ik} \quad (i = 1,2,\ldots,m)$$

$$\sum_{j=1, j\neq k} y_{rj}\lambda_j + s_i^+ \geq y_k \quad (r = 1,2 \ldots,s)$$

$$\lambda_j \geq 0, j = 1,2,\ldots,n(j \neq k), s_i^- \geq 0, s_i^+ \geq 0$$

Here, the δ represents the efficiency value, and x and y are the input and output variables, respectively. s_i^- and s_i^+ respectively represent the slack of input and output variables, m

and s are the number of inputs and outputs, and λ_j denotes the weight. If the δ value is less than 1, it indicates that the DMU is inefficient; otherwise, it is efficient.

4. Results and Analysis

The selected 12 sample cities were evaluated using the super-SBM DEA window analysis approach, resulting in the calculation of technical efficiency, pure technical efficiency, and scale efficiency. Based on these calculated results, this paper will employ three methods to analyze the values obtained. This involves comparing the rate of change in scores for each city from 2019 to 2020 and from 2020 to 2021, as well as calculating the average rate of change across these years. By examining the trends of continuous growth or decline exhibited by the cities, potential influencing factors can be explored.

4.1. Analysis of Technical Efficiency Results

Dalian shows the highest average technical efficiency, exceeding 1.6, suggesting that over the three-year period, Dalian has demonstrated excellent performance in technical efficiency, likely due to effective waste treatment technologies and management. Weifang also has a high average technical efficiency, over 1.3, indicating that the city's waste treatment system operates efficiently. Dongying and Jinzhou have relatively low average technical efficiencies, at 0.6434 and 0.5239, respectively. This may indicate issues with efficiency in solid waste management within these cities, necessitating further analysis and improvement.

By calculating the rate of change in technical efficiency scores for each city from 2019 to 2020 and from 2020 to 2021, it is evident that the average rate of change in technical efficiency from 2019 to 2020 was -11.47%, while it increased to 38.35% from 2020 to 2021. This suggests that certain policy factors post-2020 might have contributed to enhancing the cities' technical efficiency. Notably, Tangshan is the only city showing consistent growth. DL's technical efficiency score decreased by 57.85% from 2020 to 2021, representing the most substantial decline among all cities.

The continuous growth in TS could likely be attributed to consistent increases in funding, coupled with the adoption of new technologies and methods to improve efficiency. The significant improvements in DY and QHD (Qinhuangdao) after 2020 could be due to increased investment in environmental sanitation and enhancements in harmless treatment facilities. The decline in Dalian's technical efficiency score post-2020 is probably attributable to insufficient funding or inefficient utilization of resources.

Table 2. Technical Efficiency Results for Cities around the Bohai Sea

DMU	2019	2020	2021	Average
Cangzhou	1.1677	1.1191	1.1379	1.1416
Dalian	1.2367	2.5183	1.0609	1.6053
Dongying	0.4757	0.3095	1.0736	0.6196
Huludao	1.2538	1.3053	1.1777	1.2456
Jinzhou	0.7407	0.3794	0.4516	0.5239
Panjin	1.0880	1.0000	1.1271	1.0717
Qinhuangdao	0.6963	0.4312	1.1364	0.7546
Tangshan	0.8340	1.0477	1.1690	1.0169
Tianjin	0.7800	0.4344	0.7158	0.6434
Weifang	3.2048	0.3984	0.5439	1.3824
Yantai	1.0511	1.0329	1.1634	1.0825
Yingkou	0.5328	1.0002	0.5852	0.7061

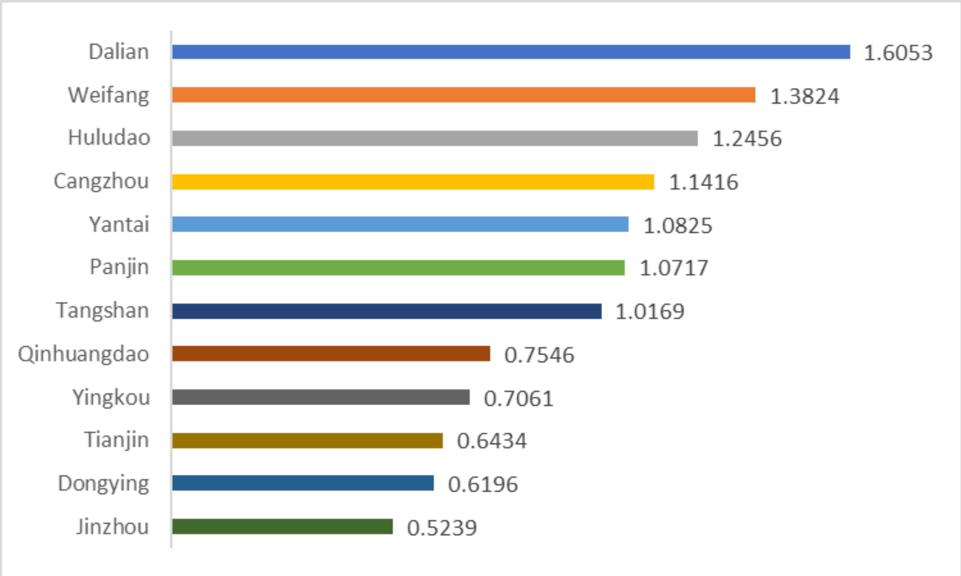

Figure 1. Average Technical Efficiency from 2019 to 2021

4.2. Analysis of Pure Technical Efficiency Results

The highest pure technical efficiency is observed in Tianjin, with an average score exceeding 2.0, suggesting exceptional management and operational efficiency over the three-year period. Dalian also shows strong performance, with a pure technical efficiency score above 1.7, indicating effective utilization of resources and managerial practices. Yingkou has the lowest average pure technical efficiency at just above 0.9, which might indicate room for significant improvement in operational efficiency. Similarly, Qinhuangdao has a pure technical efficiency score marginally above 1, suggesting that while it is managing operations at a basic level of efficiency, there could be potential for improvement.

By calculating the rate of change in pure technical efficiency scores for each city from 2019 to 2020 and from 2020 to 2021, it was found that the average rate of change in pure technical efficiency was -6.18% from 2019 to 2020 and -22.21% from 2020 to 2021. This indicates a general downward trend in the average pure technical efficiency for cities along the Bohai Sea coast from 2019 to 2021.

Dalian's pure technical efficiency score increased by 102.5% from 2019 to 2020 but then decreased by 64.66% from 2020 to 2021, indicating extreme instability in the city's pure technical efficiency. There should be a greater focus on management and decision-making levels, with particular attention to the efficiency of processes at various departmental levels. The performance of Weifang and Tianjin is also highly unstable, suggesting a need for a more thorough analysis of efficiency in daily operations and the efficiency of strategy formulation and implementation.

Table 3. Pure Technical Efficiency Results for Cities around the Bohai Sea

DMU	2019	2020	2021	Average
Cangzhou	1.2128	1.3704	1.3229	1.3021
Dalian	1.3182	2.6694	1.2933	1.7603
Dongying	1.0081	0.5316	2.5777	1.3725
Huludao	1.7093	1.7418	1.4072	1.6194
Jinzhou	1.4199	1.0318	0.5693	1.0070
Panjin	1.0892	1.1511	1.1515	1.1306
Qinhuangdao	1.0278	0.5638	1.1559	0.9158
Tangshan	1.0275	1.1393	1.1787	1.1152
Tianjin	2.0523	2.1249	2.0649	2.0807
Weifang	3.4977	0.4992	0.5500	1.5156
Yantai	1.0547	1.0449	2.2005	1.4334
Yingkou	1.0863	1.0294	0.6017	0.9058

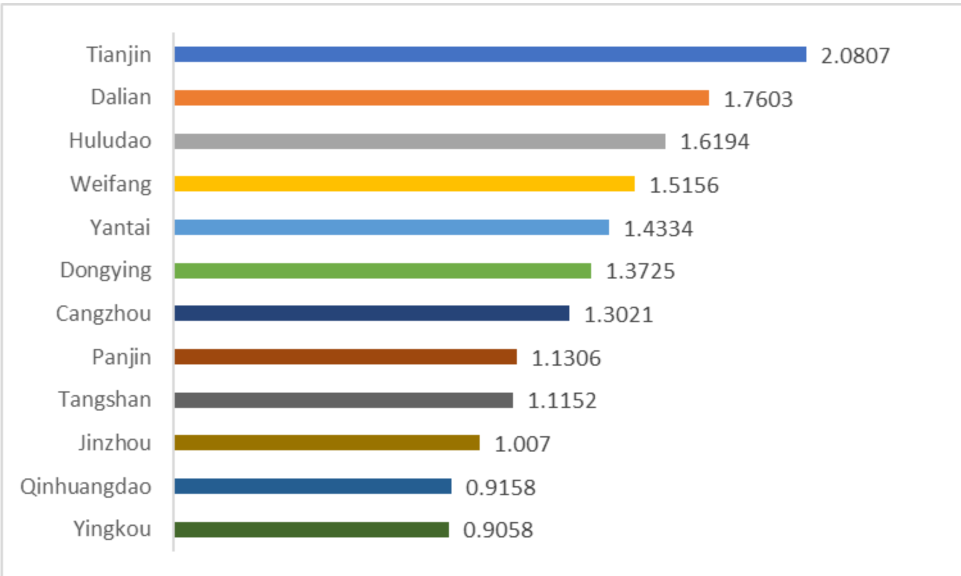

Figure 2. Average Pure Technical Efficiency from 2019 to 2021

4.3. Analysis of Scale Efficiency Results

Panjin has the highest average scale efficiency score, approximately 0.9488, suggesting that the city is operating near its most productive scale size. Tangshan and Dalian also exhibit high scale efficiency scores, indicating that these cities are likely benefiting from economies of scale in their waste management practices. Tianjin, on the other hand, shows a notably low scale efficiency score, just above 0.3, suggesting significant inefficiencies related to the city's scale of operations in waste management. Dongying and Jinzhou also have scale efficiency scores below 0.6, indicating room for improvement in scaling their waste management operations more effectively.

By calculating the rate of change in scale efficiency scores for each city from 2019 to 2020 and from 2020 to 2021, it was found that the average rate of change in scale efficiency was 108.36% from 2019 to 2020, while it was -22.21% from 2020 to 2021. This suggests that, in 2020, the majority of coastal cities achieved a higher level of resource utilization efficiency.

Table 4. Scale Efficiency Results for Cities around the Bohai Sea

DMU	2019	2020	2021	Average
Cangzhou	0.9628	0.8166	0.8601	0.8798
Dalian	0.9381	0.9434	0.8203	0.9006
Dongying	0.4719	0.5821	0.4165	0.4902
Huludao	0.7335	0.7494	0.8369	0.7733
Jinzhou	0.5217	0.3678	0.7933	0.5609
Panjin	0.9989	0.8688	0.9788	0.9488
Qinhuangdao	0.6775	0.7648	0.9831	0.8085
Tangshan	0.8116	0.9196	0.9918	0.9077
Tianjin	0.3801	0.2044	0.3466	0.3104
Weifang	0.9163	0.7981	0.9888	0.9011
Yantai	0.9966	0.9885	0.5287	0.8379
Yingkou	0.4905	0.9716	0.9727	0.8116

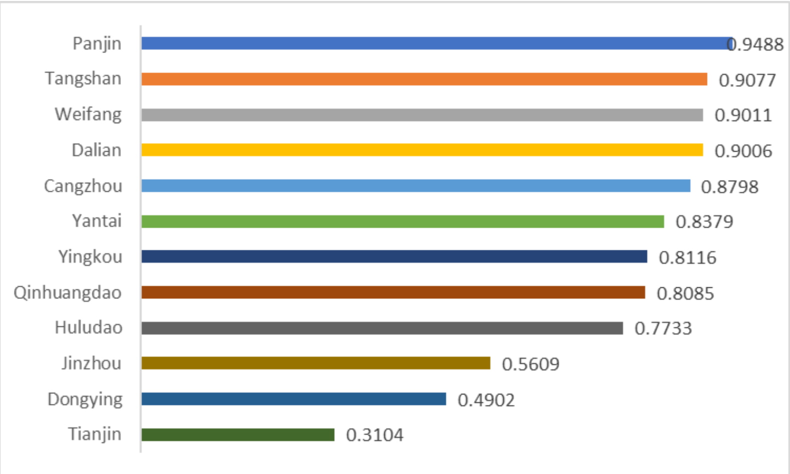

Figure 3. Average Scale Efficiency from 2019 to 2021

5. Discussion and Conclusion

Through an examination of the DEA results for 12 coastal cities around the Bohai Sea in China, we can gain insights into the efficiency of municipal solid waste management from 2019 to 2021. While variations exist among different cities and years, some conclusions can be drawn from the obtained results.

First, the technical efficiency scores indicate that although some cities have attained high efficiency in solid waste management, sustaining this level over the long term remains a challenge. This inconsistency reflects changes in local policies, financial investment strategies, or external economic conditions, all of which can impact a city's technical efficiency.

Second, the pure technical efficiency scores also exhibit fluctuations across many coastal cities. For instance, a city like Dalian experienced a substantial increase in pure technical efficiency in 2020 but faced a sharp decrease in 2021. This could be attributed to changes in administrative practices or the impact of short-term policy changes.

Third, scale efficiency exhibits a significant variation among the cities. The overall increase in scale efficiency in 2020 suggests that most cities expanded their economies of scale and made more full use of related resources. However, the subsequent decrease in 2021 indicates that these cities might have struggled to maintain economies of scale and full resource utilization, possibly due to over-expansion or inefficiencies in waste processing and disposal.

The comprehensive analysis of technical efficiency, pure technical efficiency, and scale efficiency suggests that achieving optimal efficiency in municipal solid waste management goes beyond mere increasing investment or expanding operational scale. It necessitates strategic planning, continuous policy support, robust management practices, and the integration of effective technologies. Given these findings, it is crucial for the coastal cities around the Bohai Sea to adopt dynamic solid waste management approaches capable of responding to constantly changing environmental policies, technological advancements, and economic transformations. Investing in smart waste management technologies, such as waste-to-energy plants or recycling facilities, can enhance efficiency. Moreover, cities can benefit by sharing and emulating successful practices to further improve municipal solid waste management efficiency.

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