

An Integrated MCDM Framework for Provincial Wastewater Management Assessment in Türkiye

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Abstract

Municipal wastewater management is an essential component in public infrastructure planning and environmental sustainability. Although Turkey has increased wastewater treatment services in recent years, there remain significant differences between provinces in access to treatment, capacity for advanced treatment, and the volume of untreated wastewater. In this study, an integrated Multi-Criteria Decision-Making (MCDM) framework is proposed to evaluate the performance of municipal wastewater management of Turkish provinces using provincial level data retrieved from the Turkish Statistical Institute (TÜİK). The weights of objective criteria were determined by applying the CRITIC method and the performance levels of the provinces were ranked by using the TOPSIS, MARCOS and CoCoSo methods. To have a more comprehensive evaluation perspective, an integrated ranking structure based on average ranking scores was also developed. Furthermore, the consistency among the MCDM methods was verified by Spearman rank correlation analysis. The results show that the advanced treatment ratio is the most important evaluation indicator in the provincial wastewater management performance assessment. Performance levels were relatively high in provinces such as Kilis, İzmir, Kocaeli and Tekirdağ while Muş, Aksaray and Şanlıurfa showed relatively weaker performance. The correlation analysis showed a high level of consistency between the applied MCDM methods confirming the reliability of the ranking structure. The study provides a multidimensional assessment framework for municipal wastewater management and practical suggestions for environmental infrastructure investments, regional planning and sustainable wastewater management policies in Türkiye.

Keywords

Wastewater management; CRITIC; TOPSIS; MARCOS; CoCoSo.

1. Introduction

Rapid urbanization, industrialization and population growth have placed considerable pressure on urban environmental infrastructure systems, in particular municipal wastewater management services. Poor wastewater collection and treatment practices can lead to serious environmental and public health problems through the contamination of surface water, groundwater and soil resources (WWAP, 2017). Thus, upgrading wastewater treatment facilities and ensuring sustainable wastewater management have become a critical priority for both developed and developing countries.

Recently, studies on wastewater management have focused on environmental sustainability, treatment efficiency, and effectiveness of infrastructure (Molinos-Senante et al., 2010). Apart from the existence of wastewater treatment facilities, other criteria such as treatment accessibility, advanced treatment capacity, untreated wastewater burden, and environmental efficiency have emerged as key dimensions of municipal wastewater management assessment. Advanced wastewater treatment technologies are particularly important to reduce environmental pollution and to ensure long-term ecological sustainability.

Recent decades have seen significant progress in municipal environmental infrastructure development in Turkey. However, there are still notable inter-provincial differences in wastewater collection systems, access to treatment, capacity of advanced treatment, and volumes of untreated wastewater. While some provinces have relatively advanced wastewater management infrastructure and treatment systems, others still face infrastructural and environmental limitations. Therefore, it is necessary to create a multidimensional provincial-level evaluation to reveal regional disparities and to support the development of evidence-based environmental policy.

Evaluation of wastewater management systems inherently involves several, possibly conflicting criteria. In recent years, Multi-Criteria Decision-Making (MCDM) methods have been increasingly applied to environmental management, infrastructure planning, and sustainability assessment studies (Tzeng & Huang, 2011). Various MCDM approaches have been employed in prior studies to assess environmental performance, wastewater treatment alternatives, sustainability indicators, and infrastructure priorities (Zavadskas et al., 2014; Ulutaş et al., 2020). But, most of previous studies mainly focused on treatment technology selection, facility-level assessment or limited environmental indicators. There is a lack of comprehensive evaluations at the provincial level that integrate the indicators of infrastructural accessibility, treatment quality and environmental burden into a unified evaluation framework in the literature.

In this regard, this study proposes an integrated MCDM framework to evaluate the municipal wastewater management performance of Turkish provinces by using the indicators at the provincial level from the Turkish Statistical Institute (TÜİK, 2024). The CRITIC method was used to obtain the objective criterion weights. The TOPSIS, MARCOS and CoCoSo methods were used to rank the provincial performance levels. In addition, a composite ranking structure was developed based on average ranking positions to get a more comprehensive provincial assessment. Besides, the Spearman rank correlation analysis was carried out to analyze the consistency among the applied MCDM methods.

The main contribution of this study is the construction of a multidimensional provincial evaluation framework that integrates the indicators of infrastructural accessibility, treatment quality and environmental burden into one MCDM structure. The proposed framework integrates CRITIC, TOPSIS, MARCOS and CoCoSo methods and analyzes the consistency of the ranking results by using Spearman correlation analysis unlike the studies that apply only one evaluation technique. Furthermore, the study offers one of the first comprehensive provincial-level assessments of municipal wastewater management performance throughout Turkey and discovers the relative importance of wastewater management indicators, emphasizing the prominence of advanced treatment capacity. The proposed framework allows for comparative provincial benchmarking and offers practical insights for environmental policymaking, municipal infrastructure planning and sustainable wastewater management strategies in Türkiye.

2. Literature Review

Municipal wastewater management has become a key element of sustainable urban infrastructure and environmental management systems. Rapid urbanization, population growth and industrial development have led to a sharp increase in wastewater generation and the environmental pressure on municipal treatment systems. Therefore, the efficient management of wastewater collection, treatment and disposal processes has attained significant importance in the context of environmental sustainability and protection of public health. Previous studies have highlighted the importance of treatment efficiency, infrastructure effectiveness and environmental aspects in wastewater management systems (Molinos-Senante et al., 2010).

Multi-Criteria Decision-Making (MCDM) methods have been widely used in environmental management, sustainability assessment and infrastructure evaluation studies in recent years due to their ability to consider multiple and possibly conflicting criteria simultaneously (Zavadskas et al., 2014). Various MCDM methods such as TOPSIS, VIKOR, PROMETHEE, MARCOS and CoCoSo have been used for environmental performance evaluation, sustainable infrastructure evaluation, energy planning, supplier selection and wastewater treatment system evaluation. MCDM methods have been applied in many wastewater management studies for treatment technology selection, environmental risk assessment, sludge management and infrastructure prioritization.

Among these methods, TOPSIS has been frequently preferred due to its relatively simple computational structure and its ability to evaluate alternatives based on their distances to the ideal and anti-ideal solutions (Hwang & Yoon, 2012). More recently, the MARCOS and CoCoSo methods have attracted increasing attention due to their ranking

mechanisms based on the compromise and their ability to produce stable ranking structures under complex decision environments (Yazdani et al., 2019; Stević et al., 2020).

Despite the growing literature of environmental MCDM applications, several significant limitations still exist. First, much of the previous studies mainly focus on facility-level assessment or technology selection problems rather than large-scale provincial performance evaluation frameworks. Second, the relatively limited number of environmental indicators used in several studies may have failed to capture the multidimensionality of municipal wastewater management systems. Third, the simultaneous application of integrated comparative MCDM methods is still limited, especially for municipal wastewater infrastructure evaluation.

There are limited studies to evaluate the provincial wastewater management performance in Türkiye by using integrated MCDM frameworks. Thus, this study contributes to the literature by developing a multidimensional provincial evaluation framework that combines infrastructural accessibility, advanced treatment capacity and environmental burden indicators into one MCDM structure. Moreover, the combination of TOPSIS, MARCOS and CoCoSo methods with integrated ranking and correlation based consistency analysis provides a more holistic evaluation framework for the assessment of municipal wastewater management performances.

3. Methodology

This study proposes an integrated multi-criteria decision-making (MCDM) framework for the evaluation of the municipal wastewater management performance of Turkish provinces. Wastewater management systems are multidimensional in terms of infrastructure, technology and environment, so it would be insufficient to assess provincial performance on the basis of a single indicator. Hence, a comprehensive multi-criteria decision making (MCDM)-based evaluation framework was employed to evaluate multiple and possibly conflicting criteria simultaneously.

The methodological framework of the research is based on three main stages. First, the objective criteria weights were determined by the CRITIC method. Second, the performances of the provincial wastewater management were evaluated by three different MCDM techniques, namely TOPSIS, MARCOS and CoCoSo. Finally, we tested the consistency and robustness of the obtained rankings performing a Spearman rank correlation analysis. The general methodology framework is shown in Figure 1.

Figure 1. Methodological Framework of the Study

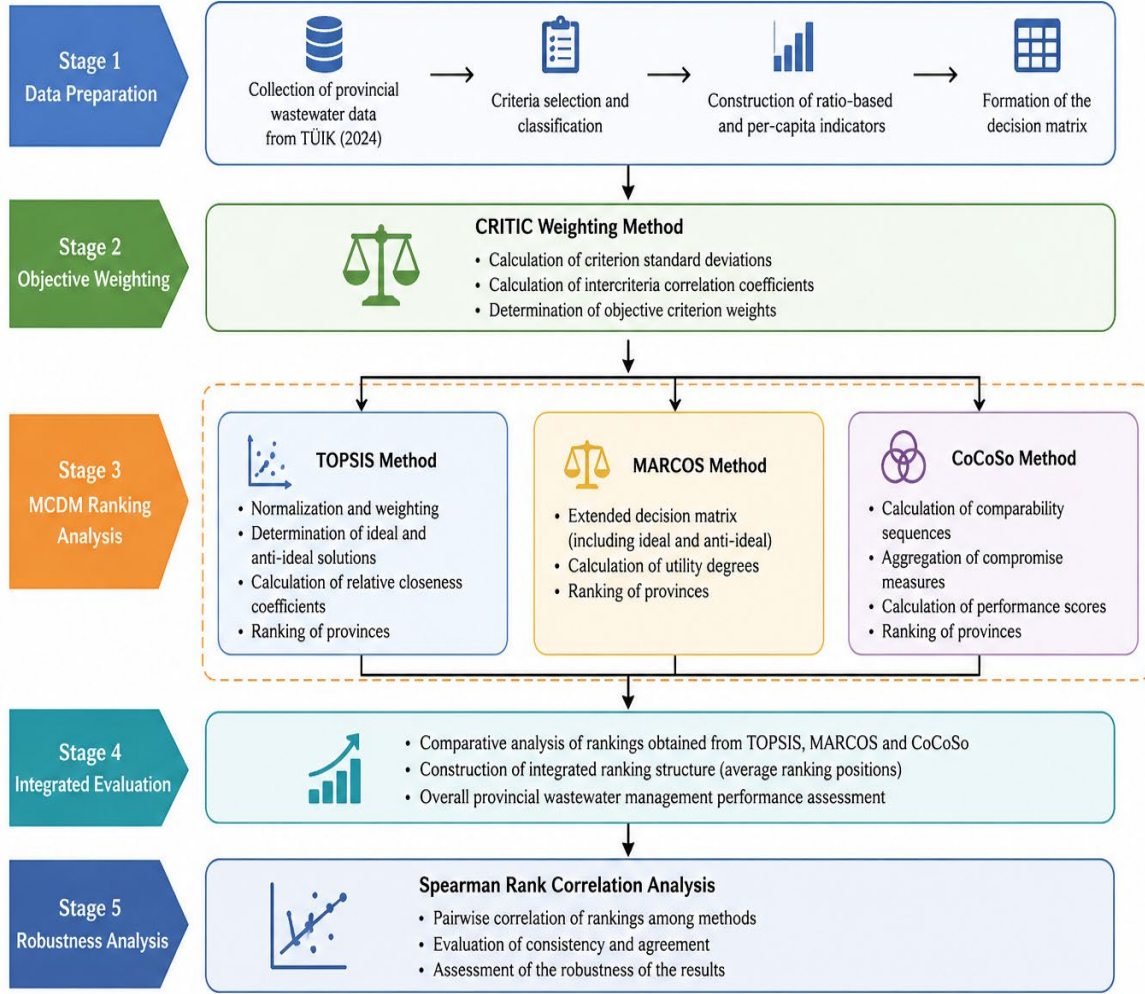


Figure 1. Methodological Framework of the Study

3.1. CRITIC Weighting Method

The objective criterion weights were determined by the CRITIC (Criteria Importance Through Intercriteria Correlation) method proposed by Diakoulaki et al. (1995). As opposed to subjective weighting methods, the CRITIC method takes into account the variation of criteria and the conflict structure between criteria. Therefore criteria with larger standard deviation and smaller correlation with other criteria get higher importance weights.

In the first step of the CRITIC procedure, the decision matrix was normalized. Then, the standard deviation of each criterion and correlation coefficients among criteria were calculated. Then, the information content of each criterion was calculated considering its variability and conflict level.

The CRITIC information measure is calculated as:

$$C_j = \sigma_j \sum (1 - r_{jk})$$

where C_j denotes the information content of criterion j , σ_j represents the standard deviation of criterion j , and r_{jk} refers to the correlation coefficient between criteria j and k .

The normalized criterion weights are calculated as:

$$w_j = C_j / \sum C_j$$

where w_j represents the objective weight of criterion j .

3.2. TOPSIS Method

The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method, proposed by Hwang and Yoon (2012), ranks alternatives based on their relative distances from the ideal and anti-ideal solutions. The method assumes that the best alternative is the one that has simultaneously the minimum distance from the ideal solution and the maximum distance from the negative ideal solution.

After normalization and weighting the Euclidean distances to the ideal and anti-ideal solutions were calculated. Then the relative closeness coefficient was calculated in the following way:

$$C_i = D_i^- / (D_i^+ + D_i^-)$$

where C_i denotes the closeness coefficient of alternative i , D_i^+ represents the distance to the ideal solution, and D_i^- indicates the distance to the anti-ideal solution. Higher C_i values indicate superior wastewater management performance.

3.3. MARCOS Method

The MARCOS (Measurement of Alternatives and Ranking according to Compromise Solution) method, developed by Stević et al. (2020), assesses alternatives considering their utility degrees with respect to both the ideal and anti-ideal solutions simultaneously. The method is a generalization of the compromise solution framework with the use of utility functions in the ranking process.

First, for MARCOS a general decision matrix is constructed with the ideal and anti-ideal alternatives. Utility degrees are computed by comparing the performance of each alternative relatively after normalization and weighting. The utility degree is expressed as:

$$K_i = S_i / S_{AI}$$

where K_i denotes the utility degree of alternative i , S_i represents the weighted sum value of alternative i , and S_{AI} refers to the weighted sum value of the ideal alternative.

Higher utility values indicate better provincial wastewater management performance.

3.4. CoCoSo Method

The CoCoSo (Combined Compromise Solution) method was proposed by Yazdani et al. (2019) in which the strengths of multiple compromise MCDM methods are combined through the use of weighted sum and weighted product aggregation techniques. The method uses a structure of balanced evaluation considering different compromise mechanisms at the same time.

In the first step, the normalized decision matrices and weighted comparability sequences are computed. Finally, the performance scores are calculated using a combination of arithmetic and compromise aggregations.

The final CoCoSo performance score is calculated as follows:

$$K_i = \sqrt[3]{k_{ia} + k_{ib} + k_{ic}} + \frac{1}{3}(k_{ia} + k_{ib} + k_{ic})$$

where k_{ia} , k_{ib} , and k_{ic} represent different compromise aggregation measures associated with alternative i .

Higher K_i values indicate superior wastewater management performance.

3.5. Ranking Consistency Analysis

Spearman rank correlation coefficients were calculated between the TOPSIS, MARCOS and CoCoSo ranking results to test the consistency and robustness of the obtained rankings. Since the Spearman correlation analysis is based on the ranking positions, not the actual values, it is especially suitable for the comparison of alternative ranking structures derived from various MCDM methods.

The high positive correlation coefficients show a strong agreement among the methods, supporting the robustness of the proposed evaluation framework.

3.6. Dataset and Criteria Definition

In this study, the municipal wastewater management performance of Turkish provinces was evaluated by using the provincial-level data obtained from the Turkish Statistical Institute (TÜİK) for the year 2024. The dataset was constructed using three official TÜİK databases for municipal wastewater treatment statistics, municipal water withdrawal and discharge statistics and municipal environmental infrastructure services. These datasets include wastewater collection infrastructure, treatment access, treatment technology characteristics, and wastewater discharge conditions at the provincial level.

The initial dataset included all provinces, including the aggregate “Türkiye” observation. However, the national aggregate value was not included because the aim of the study is to compare provincial performance not national averages. In addition, Ağrı province was excluded from the analysis due to the undefined ratio value of the variable “advanced treatment ratio” since there were no advanced wastewater treatment activities in this province. The final data set thus consisted of 80 provinces.

The criteria selection process was designed to build a balanced framework able to reflect the operational, technological and environmental aspects of municipal wastewater management systems. In this context, the chosen indicators correspond to four complementary dimensions:

- infrastructure accessibility,
- waste water treatment coverage,
- technological treatment quality
- environmental pressure

Ratio-based and per capita indicators were preferred to absolute measures such as total treatment capacity or total wastewater volume to reduce the scale effect related to the highly populated metropolitan provinces. This approach is more equitable for interprovincial comparisons and improves the interpretability of MCDM rankings.

The MCDM framework included five criteria. Three criteria were considered as benefit-oriented indicators and two criteria were considered as cost-oriented indicators. The first criterion, advanced treatment ratio, is the technology level and environmental level of wastewater treatment systems. The variable was calculated according to:

Advanced Treatment Ratio=Advanced Wastewater Treatment / Total Treated Wastewater

Higher values indicate broader sewerage network coverage and improved wastewater collection capacity. The second criterion is the population served by wastewater treatment plants. This criterion measures the share of the municipal population served by wastewater treatment services. This criterion reflects the accessibility and coverage of wastewater treatment services. The third criterion, population served by sewerage network, indicates the scale of wastewater collection infrastructure among provinces. Higher values indicate higher coverage of sewerage network and better capacity of waste water collection. The fourth criterion, average wastewater discharged per person, is indicative of the environmental and operational burden of wastewater generation. Higher levels of discharge can increase the environmental pressure and treatment requirements and therefore this variable was considered as a cost criterion. The fifth criterion is the ratio of untreated wastewater, which is the measure of untreated wastewater with respect to municipal population. Untreated wastewater ratio was calculated as follows:

Untreated Wastewater Ratio=Untreated Wastewater Amount/ Municipal Population

Higher scores indicate more environmental risk from untreated wastewater discharges and therefore have a negative impact on the provincial performance.

Physical, biological or natural treatment processes were not included in the model as separate indicators, as these variables are structurally dependent components of the same treatment system and may introduce redundancy within the MCDM framework. Instead, we used the advanced treatment ratio as a consolidated proxy for quality of technological treatment.

The variables used in the analysis are given in Table 1. Table 2 presents the descriptive statistics of the variables used in the analysis.

Table 1. Variables used in the MCDM model

Variable	Definition	Unit	Direction	Rationale
Advanced treatment ratio	Ratio of advanced wastewater treatment in total treated wastewater	Ratio	Benefit	Represents technological sophistication and treatment quality
Population served by wastewater treatment plants	Share of municipal population served by wastewater treatment plants	%	Benefit	Measures wastewater treatment accessibility and service coverage
Population served by sewerage network	Share of municipal population connected to sewerage infrastructure	%	Benefit	Represents wastewater collection infrastructure coverage
Average wastewater discharged per capita	Daily average wastewater discharge per capita	Liter/capita-day	Cost	Represents wastewater generation burden and environmental pressure
Untreated wastewater ratio	Untreated wastewater amount divided by municipal population	Ratio	Cost	Measures environmental risk associated with untreated discharges

Table 2. Descriptive statistics of the variables

Variable	Mean	Median	Std. Dev.	Min	Max
Advanced treatment ratio	0.514	0.581	0.416	0.000	1.000
Population served by wastewater treatment plants (%)	67.56	74.63	24.29	0.99	100.00
Population served by sewerage network (%)	92.17	94.44	7.10	65.00	100.00
Average wastewater discharged per capita (L/capita-day)	181.84	170.90	59.00	73.90	535.39
Untreated wastewater ratio	0.016	0.0108	0.0196	0.000	0.1259

The descriptive statistics show substantial inter-provincial heterogeneity in the performance of wastewater management in Türkiye. Specifically, the ratio of advanced treatment ranged widely from 0 to 1, reflecting substantial differences in the technological sophistication of provincial wastewater treatment systems.

There were also large differences between provinces in the percentage of wastewater treated, indicating different levels of environmental risk from the release of untreated wastewater. Average coverage of wastewater treatment services was around 67.6% and average coverage of sewerage networks was more than 92%. This finding shows that wastewater collection infrastructure is relatively widespread in the provinces, but treatment accessibility is still relatively scarce in some areas.

In addition, the average wastewater discharged per capita variable was relatively dispersed and positively skewed, indicating large differences in the intensity of wastewater generation across provinces. Such variability may be related to differences in urbanization, industrial activity, tourism intensity, climatic conditions and water consumption behavior.

Prior to the application of MCDM methods, a correlation analysis was performed to examine the internal relationship structure among the selected criteria. To avoid redundancy and instability of the ranking in the MCDM applications caused by too much correlation between indicators, the Spearman correlation coefficients were calculated.

Table 3 shows the correlation matrix of the selected criteria. The results indicate that the variables are generally low to moderately correlated, implying that the selected indicators capture complementary rather than redundant dimensions of municipal wastewater management performance.

The population served by wastewater treatment plants had the strongest association with the ratio of untreated wastewater ($r=-0.796$). This inverse relationship is theoretically anticipated as more treatment service coverage is directly responsible for reducing untreated wastewater discharges. Nevertheless, the level of correlation was considered acceptable as both variables represent conceptually distinct dimensions of wastewater management performance.

In general, the correlation structure supports the adequacy of the criteria selected for the subsequent MCDM analysis.

Table 3. Spearman correlation matrix of the selected criteria

Variables	Advanced treatment ratio	Population served by wastewater treatment plants	Population served by sewerage network	Average wastewater discharged per capita	Untreated wastewater ratio
Advanced treatment ratio	1.000	0.053	-0.067	0.123	0.041
Population served by wastewater treatment plants	0.053	1.000	0.206	0.080	-0.796
Population served by sewerage network	-0.067	0.206	1.000	-0.078	0.104
Average wastewater discharged per capita	0.123	0.080	-0.078	1.000	0.332
Untreated wastewater ratio	0.041	-0.796	0.104	0.332	1.000

4. Results and Discussion

In this section the results obtained by the proposed MCDM framework are presented and discussed. First, we consider the objective criteria weights obtained from the CRITIC method. Then, a provincial wastewater management performance assessment is conducted by TOPSIS, MARCOS and CoCoSo methods, and the integrated ranking and robustness analyses are performed subsequently.

4.1. Weights of Criteria Based on CRITIC

The CRITIC method determined the objective importance levels of the selected criteria by taking into account both the variability of each criterion and the conflict structure among criteria. Table 4 presents the CRITIC weights computed for the five evaluation criteria.

Table 4. CRITIC weights of the evaluation criteria

Criterion	Weight
Advanced treatment ratio	0.412
Population served by sewerage network	0.187
Population served by wastewater treatment plants	0.176
Average wastewater discharged per capita	0.115
Untreated wastewater ratio	0.111

The results showed that the most weighted criterion was the advanced treatment ratio (0.412) and there was a significant gap between the other criteria. This outcome indicates that the quality of the technological treatment is the

most discriminating factor for the performance of municipal wastewater management among Turkish provinces. This variable is given much importance mainly because of the large inter-provincial heterogeneity in the practice of advanced treatment.

The second and third influential criteria were population served by sewerage network and population served by wastewater treatment plants, respectively. These findings underscore the importance of wastewater collection infrastructure and availability of treatment in the overall performance framework.

On the other hand, average wastewater discharged per capita and untreated wastewater ratio had comparatively less weights. These variables are still important from an environmental point of view, but their lower CRITIC weights show a comparatively lower discrimination power among the provinces.

Overall, the results of the weighting analysis indicate that the most crucial factors influencing the municipal wastewater management performance in Türkiye are technological sophistication and accessibility of infrastructure. This finding suggests that the investments based on the wastewater collection infrastructure alone may be not enough unless they can be complemented with advanced treatment technologies, which can improve treatment quality and reduce environmental burden.

4.2. Individual MCDM methods rankings of provinces

Provincial wastewater management performances were separately evaluated by TOPSIS, MARCOS and CoCoSo methods after the weighting stage. The best performing provinces extracted from each MCDM approach are presented in Table 5.

Table 5. Top 5 provinces according to different MCDM methods

Rank	TOPSIS	Score	MARCOS	Score	CoCoSo	Score
1	Kilis	0.947	İzmir	0.884	Kilis	2.649
2	Erzurum	0.946	Kocaeli	0.882	Kocaeli	2.633
3	Tekirdağ	0.935	Kilis	0.880	İzmir	2.630
4	Eskişehir	0.934	Tekirdağ	0.878	Eskişehir	2.562
5	İzmir	0.927	Erzurum	0.875	Bingöl	2.550

The results of the rankings show that some provinces were consistently ranked as the best alternatives by different MCDM methods. Kilis, İzmir, Kocaeli, Tekirdağ, Eskişehir and Erzurum also consistently ranked high indicating relatively good municipal wastewater management performance.

Minor ranking discrepancies were observed between methods due to their different aggregation mechanisms, however overall ranking trends were very similar. Provinces with more advanced wastewater treatment infrastructure, better access to treatment and relatively lower loads of untreated wastewater generally had better performance scores. This pattern suggests that technological treatment capacity and effective infrastructure utilization may be more decisive than population size alone.

Results also show that high environmental performance is not only related to metropolitan scale. A number of smaller provinces such as Kilis and Bingöl showed strong performance levels despite relatively more limited demographic and infrastructural scales. This finding implies that good wastewater management performance is not only linked to metropolitan scale or economic size but may also correlate with efficient infrastructure utilization and relatively balanced service coverage.

4.3 Provincial Integrated Rankings

As the ranking structures generated by the three MCDM methods were quite similar, an integrated ranking framework was also developed on the basis of the average ranking positions obtained by the TOPSIS, MARCOS and CoCoSo methods. This allows for a more balanced and comprehensive evaluation, which reduces the potential effect of method-specific ranking changes. Table 6 presents the integrated provincial wastewater management performance rankings.

Table 6. Representative integrated provincial wastewater management rankings

Performance Category	Representative Provinces	Average Rank Range
Highest-performing provinces	Kilis, İzmir, Kocaeli, Tekirdağ, Eskişehir	2.67 – 5.33
Upper-middle-performing provinces	Bursa, Manisa, Kayseri, Erzurum, Bingöl	6.67 – 10.67
Lowest-performing provinces	Sinop, Şanlıurfa, Aksaray, Muş, Trabzon	77.67 – 79.67

Overall, the integrated ranking results were in line with the results derived from the individual MCDM methods. Provinces such as Kilis, İzmir, Kocaeli and Tekirdağ were consistently better ranked in all methods, which indicates that they have stable and strong wastewater management structures.

The findings also reveal major regional and infrastructural inequalities across Türkiye. In general, provinces in relatively industrialized and urbanized areas, especially those with more developed municipal infrastructure investment and stronger wastewater treatment capacities, performed better. In particular, provinces such as İzmir, Kocaeli, Tekirdağ and Bursa had relatively developed treatment infrastructure and advanced wastewater management practices.

On the other hand, the several poorer-performing provinces were characterized by poor treatment accessibility, limited capacity of advanced treatment and relatively higher burdens of untreated wastewater. Such results could be indicative of provincial differences in municipal infrastructure investments, institutional capacity and access to environmental services.

Also, the provinces in the industrialized western areas generally performed better in wastewater management, due to more developed treatment infrastructure and higher advanced treatment capacity. Interestingly, some relatively smaller provinces such as Kilis and Bingöl had remarkably strong ranking positions, which indicates that efficient environmental management practices and treatment quality might be more influential than demographic scale alone.

In general, the results emphasize the importance of the quality of technological treatment and effective infrastructure management for the improvement of provincial performance in wastewater management.

4.4. Comparative Analysis of MCDM Methods

To check the consistency and robustness of the obtained rankings, the Spearman rank correlation coefficients were calculated between the TOPSIS, MARCOS and CoCoSo ranking results. The correlation matrix is shown in Table 7.

Table 7. Spearman rank correlation matrix among MCDM methods

Methods	TOPSIS	MARCOS	CoCoSo
TOPSIS	1.000	0.970	0.970
MARCOS	0.970	1.000	0.956
CoCoSo	0.970	0.956	1.000

The results indicate very high positive correlations between the three MCDM methods. The highest correlation was between TOPSIS and CoCoSo ($r = 0.970$) and the lowest correlation was between MARCOS and CoCoSo ($r = 0.956$). However, all coefficients remained significantly high, with strong ranking consistency across methods.

The results indicate that the provincial performance rankings are very robust and not significantly affected by methodological differences of the selected MCDM techniques. Thus, the three methods resulted in very similar ranking structures, despite the different aggregation and compromise mechanisms used.

The high level of agreement across different MCDM approaches supports the stability of the selected criteria structure and minimizes the risk of method-dependent ranking bias. Thus, the integrated ranking results give consistent evidence regarding the relative levels of wastewater management performance of the Turkish provinces.

The very high Spearman rank correlations indicate a strong consistency across the applied MCDM methods, but such consistency can not be considered as direct proof of ranking accuracy. The correlation analysis only shows that the different ranking methods yield similar ordering structures with respect to the selected criteria and weight scheme. The rankings obtained should be viewed as a benchmarking tool for comparison rather than an absolute measure of wastewater management performance. No external validation indicators such as environmental outcome measures, regulatory compliance indicators or operational wastewater treatment performance data were available at the provincial level. Future studies could include external validation variables to further assess the practical validity of provincial rankings.

5. Conclusion and Implications

In the study, a comprehensive Multi-Criteria Decision-Making (MCDM) framework was proposed to evaluate the performance of municipal wastewater management of Turkish provinces with provincial-level environmental infrastructure indicators obtained from TÜİK. The study integrated the CRITIC weighting method with TOPSIS, MARCOS and CoCoSo ranking methods to develop a multi-dimensional provincial performance assessment framework incorporating indicators of infrastructural accessibility, technological treatment quality and environmental burden.

The results showed that the advanced treatment ratio was the most significant criterion in the appraisal process. This finding highlights the importance of technological treatment quality rather than simply expanding access to wastewater collection or treatment services. In other words, these findings suggest that the quality and technological sophistication of treatment infrastructure play a critical role in sustainable wastewater management performance. From a policy perspective, the proposed framework can assist decision-makers to identify priority provinces for investment in environmental infrastructure and track regional disparities in performance in wastewater management. Future investment programmes should target especially those provinces with low capacity for advanced treatment and high loads of untreated wastewater. The results also show that improving quality of treatment is as important as increasing service coverage in achieving sustainable objectives of wastewater management.

The ranking results revealed that there were significant inter-provincial differences in Türkiye. Provinces such as Kilis, İzmir, Kocaeli, Tekirdağ and Eskişehir, were among the top performers by different MCDM methods. These provinces generally exhibited higher advanced treatment capacity, broader treatment coverage and lower untreated wastewater loads. The significant performance of the industrialized and urbanized provinces, such as İzmir, Kocaeli and Tekirdağ, in particular, shows that infrastructural investment capacity and municipal environmental management capacity might have a major role in wastewater management performance.

However, the results also pointed out that metropolitan scale does not guarantee better environmental performance. Some relatively smaller provinces like Kilis and Bingöl scored surprisingly good rankings despite their smaller population and economic scales. This suggests that effective environmental management practices, technological efficiency and quality of infrastructure may be more important than the mere size of the population.

On the other hand, provinces with lower performance generally had lower levels of treatment accessibility, less infrastructure for advanced treatment and relatively higher loads of untreated wastewater. These results can indicate regional differences in the investments in environmental infrastructure and the capacities of municipal services. The results therefore indicate the need to improve advanced treatment systems and strengthen wastewater management infrastructure especially in relatively disadvantaged regions.

Another important finding of the study is the high consistency observed between TOPSIS, MARCOS and CoCoSo methods. The very high Spearman rank correlation coefficients achieved between methods indicated that the ranking

structures were highly robust and not significantly influenced by method variations. Such consistency improves the interpretability and reliability of the proposed evaluation framework.

However, the study also has several limitations. First, the analysis was limited in terms of the number of provincial level indicators due to data availability constraints. The evaluation framework could be further improved in terms of its comprehensiveness by including additional variables related to financial investment capacity, operational efficiency, energy consumption or treatment plant performance. Second, the study had a cross-sectional evaluation structure by using a one-year dataset. Future studies may develop dynamic or longitudinal evaluation frameworks to investigate temporal changes in wastewater management performance. Third, the integrated MCDM framework provides a comprehensive comparative evaluation, however, the results obtained are still contingent on the chosen criteria and weighting method. Additionally, the study did not explicitly consider spatial interactions or regional spillover effects among provinces.

For future work, additional environmental, economic and social sustainability indicators can be added to provincial wastewater management assessments. Moreover, hybrid approaches that include MCDM methods in the efficiency analysis, spatial analysis or machine learning techniques might provide further insights on the drivers of environmental infrastructure performance. Moreover, no formal sensitivity analysis was carried out on the criterion weights obtained from CRITIC. Although the high agreement among various MCDM methods indirectly supports the stability of ranking, the robustness of the provincial rankings could be explored by doing sensitivity analyses under different weighting schemes in future studies.

Overall, the study provides a multidimensional assessment framework for evaluating municipal wastewater management performance in Türkiye and contributes to evidence-based environmental infrastructure planning and sustainable wastewater management policies.

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