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ASSESSING ECO-EFFICIENCY OF WASTEWATER TREATMENT PLANTS: A CROSS-EVALUATION STRATEGY

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Abstract:

Evaluating the eco-efficiency of wastewater treatment plants (WWTPs) is crucial for enhancing environmental and economic performance in the water utility sector. Previous studies in this area estimated WWTP eco-efficiency through self-evaluation, which might have led to overestimation and biased policy recommendations. To address these issues, this study applies a cross-evaluation strategy, combining self-evaluation and peer-evaluation, to assess the eco-efficiency of WWTPs. The empirical application focuses on a sample of Spanish WWTPs, yielding the following key findings. Average eco-efficiency scores were 0.353 and 0.230, for self-evaluation and global peer-evaluation approaches, respectively, confirming the overestimation of eco-efficiency scores based on self-evaluation. If WWTPs were eco-efficient, they could potentially reduce greenhouse gas (GHG) emissions by up to 0.39 kg CO_{2eq}/year. The application of reliable methods, such as peer-evaluation, for eco-efficiency assessment of WWTPs provides water regulators with a comprehensive understanding of the environmental and economic performance of WWTPs. This knowledge guides decision-making, policy development, and resource allocation, facilitating sustainable and efficient wastewater management practices.

Keywords: performance; regulation; greenhouse gas emissions; benchmarking; data envelopment analysis.

1. INTRODUCTION

The primary objective of wastewater treatment is to enhance the quality of used water sources by reducing pollutant levels below sector-specific quality thresholds. This process is vital in minimizing the environmental impacts associated with the discharge of wastewater back into natural water bodies (Spellmann, 2013). Recent estimates indicate that the global volume of wastewater generated annually is approximately 359.4 x 10^9 cubic meters, out of which 52% (188.1 x 10^9 cubic meters) undergoes treatment (Jones et al., 2021) at wastewater treatment plants (WWTPs). WWTPs can be considered as productive units that utilize various resources such as energy, personnel, and materials to eliminate pollutants present in wastewater (Ren and Liang, 2017). However, it is important to note that the energy consumption associated with WWTP operations also contributes to the emission of greenhouse gases (GHGs), particularly in regions where non-renewable energy sources dominate (Huang et al., 2021). This highlights the need to address energy efficiency and GHG emissions in WWTPs, particularly in regions heavily reliant on non-renewable energy sources.

Eco-efficiency was initially defined by Schaltegger and Sturm (1989) as the ratio between value added and environmental impacts. In the context of wastewater treatment plants (WWTPs), eco-efficiency is measured by considering a comprehensive set of indicators that encompass pollutants removed from wastewater, economic costs, and greenhouse gas (GHG) emissions (Dong et al., 2017; Gemar et al., 2018; Mocholi-Arce et al., 2020; Xi et al., 2023). Eco-efficiency pertains to the ability of WWTPs to minimize greenhouse gas emissions and operational expenses while effectively eliminating pollutants from wastewater. Consequently, assessing the eco-efficiency of WWTPs requires the application of multi-criteria methods to account for these diverse factors.

Until now, only a limited number of studies have undertaken the evaluation of WWTPs' eco-efficiency, including works by Molinos-Senante et al. (2014, 2016), Dong et al. (2017), Gemar et al. (2018), Gómez et al. (2018), Mocholi-Arce et al. (2020), Ramirez-Melgarejo et al. (2021), Fallahiarezoudar et al. (2022), and Xi et al. (2023). To the best of our knowledge, all of these previous studies have utilized data envelopment analysis (DEA) techniques, which is a non-parametric method based on linear programming (Milanović et al., 2022). DEA enables the construction of an efficient production frontier by considering the inputs and outputs of the evaluated WWTPs as units (Cooper et al., 2011; Petrovic et al., 2016). The eco-efficiency index, representing the relative position of the WWTPs in relation to the production possibility frontier, is derived from DEA (Ramirez-Melgarejo et al., 2021). Furthermore, DEA allows for the integration of the three dimensions of eco-efficiency, which are service value (pollutants removed), resource consumption (economic costs), and environmental impacts (GHG emissions), as inputs, desirable outputs, and undesirable outputs, respectively (Dong et al., 2017; Gomez et al., 2018).

Notwithstanding the significant methodological advantages of the DEA method to assess eco-efficiency of WWTPs, previous studies on this topic presented a common limitation: they evaluated the eco-efficiency of WWTPs from a self-evaluation DEA perspective. This approach allows WWTPs to rate their own eco-efficiency using the most favorable weights, which can lead to overestimation of eco-efficiency. Additionally, self-evaluation DEA often results in multiple optimal solutions, further complicating the assessment process (Ning et al., 2023). From a policy perspective, self-evaluation DEA has two main limitations. Firstly, it lacks external validation by benchmarking against other WWTPs, which is crucial from a regulatory standpoint. Without comparing performance against other units, it becomes difficult to determine the true efficiency levels and identify areas for improvement. Secondly, overestimating eco-efficiency scores through self-evaluation may result in overlooking opportunities for enhancing the overall performance of the water industry.

To address these limitations in assessing WWTPs' eco-efficiency, the use of the cross-efficiency DEA method is proposed. This approach combines self-evaluation with peer-evaluation, allowing for a more comprehensive and objective assessment. Cross-efficiency DEA takes into account the performance of all WWTPs in the analysis, enabling comparisons and identifying best practices across the industry (Walheer, 2022). By incorporating peer-evaluation, this method offers a more robust and realistic evaluation of eco-efficiency, providing valuable insights for policy-making and performance improvement in the water sector. Several cross-efficiency strategies have been proposed such as aggressive and benevolent (Doyle and Green, 1994), neutral (Wang and Chin, 2010), prospect (Liu et al., 2019) and regret-rejoice (Jin et al., 2022). However, none of them can accommodate undesirable outputs in performance assessment which is fundamental when assessing eco-efficiency of WWTPs because GHG emissions must be integrated in the evaluation (Dong et al., 2017). Hence, in this study, an alternative cross-efficiency DEA model recently developed by Liao et al. (2022) was utilized to assess the eco-efficiency of WWTPs. Another positive feature of this model, which is very relevant for the water industry, is its ability to estimate eco-efficiency scores following two strategies: i) global eco-efficiency priority (GEEP) and; ii) individual eco-efficiency priority (IEEP) (Liao et al., 2022).

GEEP and IEEP represent different preferences of decision makers, i.e., water regulators. GEEP considers all WWTPs as a whole and aims to optimize the eco-efficiency of the wastewater treatment industry as a collective. This strategy is suitable when the main purpose of the performance assessment is to identify potential improvements in GHG emissions for the entire industry or to establish environmental targets. IEEP, on the other hand, focuses on each individual WWTP and aims to maximize the eco-efficiency of each facility. This strategy is more applicable when the water regulator intends to assess the eco-efficiency of WWTPs for regulatory purposes or as input for setting tariffs. The choice between GEEP and IEEP depends on the specific objectives of the performance assessment as determined by the water regulator. By utilizing the cross-efficiency DEA model and considering both GEEP and IEEP, our study provides a comprehensive and flexible approach to evaluate the eco-efficiency of WWTPs, catering for different decision-making needs within the water industry.

The paper aims to achieve two main objectives. Firstly, it seeks to enhance the assessment of the eco-efficiency of WWTPs by combining self-evaluation and peer-evaluation methods. Secondly, it aims to provide valuable insights to water regulators for improving the economic and environmental performance of WWTPs. This will be achieved by calculating eco-efficiency scores based on GEEP and IEEP methodologies. It is worth noting that no previous research has been conducted in this particular area. Therefore, this paper makes a significant contribution to the existing body of literature by employing a cross-efficiency analysis framework to evaluate the eco-efficiency of WWTPs. Additionally, it addresses the issue of overestimating eco-efficiency that has been observed in traditional DEA methods due to self-evaluation in prior studies on this topic.

2. MATERIAL AND METHODS

2.1 Cross-efficiency DEA model to estimate eco-efficiency scores

The estimation of eco-efficiency scores based on cross-efficiency approach involves three stages which are described as follows (Liao et al., 2022):

Stage 1. Estimation of self-evaluation eco-efficiency scores

Assume that there are n WWTPs using x_{ij} $(i = 1, \dots, m)$ inputs to produce desirable outputs y_{rj} $(r = 1, \dots, s)$ and undesirable outputs z_{fj} $(f = 1, \dots, h)$, eco-efficiency scores for each WWTP are estimated by solving Model (1):

$$\theta_{dd}^{*} = Max \sum_{r=1}^{s} u_{rd} y_{rd} - \sum_{f=1}^{h} w_{fd} z_{fd} \tag{1}$$

$subject\ to$:

$$\sum_{i=1}^{m} v_{id} x_{id} = 1;$$

$$\sum_{r=1}^{s} u_{rd} y_{rj} - \sum_{f=1}^{h} w_{fd} z_{fj} - \sum_{i=1}^{m} v_{id} x_{ij} \leq 0, \quad j = 1, \dots, n;$$

$$\sum_{r=1}^{s} u_{rd} y_{rj} - \sum_{f=1}^{h} w_{fd} z_{fj} \geq 0, \qquad j = 1, \dots, n;$$

$$\nabla v_{id}, u_{rd}, w_{fd} \geq 0;$$

where v_{id}, u_{rd}, w_{fd} are the weights for inputs, desirable outputs and undesirable outputs, respectively.

Stage 2. Estimation of peer-evaluation eco-efficiency scores based on GEEP

The GEEP means that the water regulator focuses on minimizing the emissions of GHG (undesirable output) for the whole wastewater treatment industry on the premise that the economic performance of the analyzed WWTPs keeps constant. Eco-efficiency scores are estimated by solving Model (2):

$$Min\ \sum_{f=1}^{h} w_{fd} \sum_{j=1}^{n} z_{fi} \tag{2}$$

$subject\ to$:

$$\sum_{i=1}^{m} v_{id} \sum_{j=1}^{n} x_{ij} = 1;$$

$$\sum_{r=1}^{s} u_{rd} y_{rj} - \sum_{f=1}^{h} w_{fd} z_{fj} - \sum_{i=1}^{m} v_{id} x_{ij} \leq 0, \quad j = 1, \ldots, n;$$

$$\sum_{r=1}^{s} u_{rd} y_{rj} - \sum_{f=1}^{h} w_{fd} z_{fj} \geq 0, \quad j = 1, \ldots, n;$$

$$\sum_{r=1}^{s} u_{rd} y_{rd} - \sum_{f=1}^{h} w_{fd} z_{fd} - \theta_{dd}^{*} \sum_{i=1}^{m} v_{id} x_{id} = 0,$$

$$\nabla v_{id}, u_{rd}, w_{fd} \geq 0;$$

where θ_{dd}^{*} is the eco-efficiency score of WWTP$_d$ obtained by model (1).

Stage 3. Estimation of peer-evaluation eco-efficiency scores based on IEEP

IEEP means that the decision maker focuses on the minimization of individual GHG emissions on the premise that the economic performance of WWTPs remains unchanged. Under this approach, the water regulator might identify the maximum eco-efficiency of each facility without considering the global performance of the wastewater treatment industry. Eco-efficiency scores imposing IEEP are estimated by solving the model (3):

$$Min\ \delta \tag{3}$$

$$subject\ to:$$

$$\sum_{i=1}^{m} v_{id}x_{id} = 1;$$

$$\sum_{r=1}^{s} u_{rd}y_{rj} - \sum_{f=1}^{h} w_{fd}z_{fj} - \sum_{i=1}^{m} v_{id}x_{ij} \leq 0, \quad j = 1, \ldots, n;$$

$$\sum_{r=1}^{s} u_{rd}y_{rj} - \sum_{f=1}^{h} w_{fd}z_{fj} \geq 0, \quad j = 1, \ldots, n;$$

$$\sum_{r=1}^{s} u_{rd}y_{rd} - \sum_{f=1}^{h} w_{fd}z_{fd} - \theta_{dd}^{*} \sum_{i=1}^{m} v_{id}x_{id} = 0,$$

$$w_{fd}z_{fd} \leq \delta, \quad f = 1, \ldots, h;$$

$$\nabla v_{id}, u_{rd}, w_{fd} \geq 0;$$

Models (2) and (3) are linear programming models that can be solved directly (Liao et al., 2022).

2.2 Case study

Eco-efficiency scores for a sample of 109 Spanish WWTPs are estimated. All facilities embrace pretreatment, primary treatment and secondary treatment removing suspended solids (SS), organic matter, nitrogen (N) and phosphorus (P) from wastewater according to the legal thresholds defined by the European Urban Wastewater Directive (91/271/ECC).

The evaluated facilities handle a wide range of wastewater volumes, ranging from 41,275 m^3/year to 121,095,795 m^3/year. However, the mathematical models employed to calculate eco-efficiency scores (models 1, 2, and 3) take into account variable returns to scale. This allows for the inclusion of potential economies of scale during the assessment process. The 109 WWTPs that were assessed employ a conventional activated sludge process for secondary treatment. Consequently, these WWTPs do not display significant technical differences from one another.

The variables considered to assess eco-efficiency were based on the literature review (e.g., Dong et al., 2017; Niu et al., 2019; Longo et al., 2019; Ramirez Melgarejo et al., 2021; Xi et al., 2023) and available statistical data. The specific variables are described as follows:

Inputs: annual operating costs expressed in €/year. It involves all costs incurred by the WWTP to treat wastewater.

Desirable outputs: annual quantities of SS, organic matter measured as carbon oxygen demand (COD), P and N removed from wastewater (kg/year). They were estimated based on Eq. (5):

$$O_{ij} = V_j * (P_{iij} - P_{eij}) \tag{5}$$

where O_{ij} denotes the output i for the WWTP j in kg/year; V_j is the volume of wastewater treated by the WWTP i in m^3/year; P_{iij} is the concentration of pollutant i in the influent for the WWTP j in kg/m^3 and; P_{eij} is the concentration of pollutant i in the effluent for the WWTP j in kg/m^3. i corresponds to SS, COD, P and N. Hence, the selected desirable outputs to assess the eco-efficiency of WWTPs consider the volume of wastewater treated by each facility and both the influent and effluent quality of wastewater.

Undesirable outputs: GHG emissions expressed in kilograms of CO_2 equivalent per year (kg CO_{2eq}/year). Statistical data about direct GHG emissions was not available for the analyzed WWTPs and therefore, according to past research (Molinos-Senante et al., 2016; Gemar et al., 2018; Gómez et al., 2018; Mocholi-Arce et al., 2020; Fallahiarezoudar et al., 2022), only indirect GHG emissions associated with the electricity consumption at WWTPs were considered. This is a limitation of the study which might be overcome in future studies if WWTPs monitor and collect data about direct GHG emissions.

Statistical information was provided by the Catalan Water Agency for 2021, which is shown in Table 1.

TABLE 1

3. RESULTS AND DISCUSSION

3.1 Eco-efficiency assessment based on self-evaluation and peer-evaluation.

The statistics of the eco-efficiency scores estimated for the 109 WWTPs are shown in Figure 1 (individual eco-efficiency scores for each WWTP are shown as supplemental material). The average eco-efficiency from the self-evaluation perspective is 0.353. Based on peer-evaluation perspective, average eco-efficiency scores are 0.230 and 0.219 for GEEP and IEEP approaches, respectively. Average eco-efficiency scores estimated illustrate the overestimation limitation when self-evaluation is considered, while the cross-efficiency methods (GEEP and IEEP) solve this limitation. To verify whether eco-efficiency differences among self-evaluation and peer-evaluation are statistically significant or not, the non-parametric Kruskall-Wallis test was applied. The null hypothesis tested is that eco-efficiency scores based on self-evaluation and GEEP and IEEP approaches are derived from the same population. If the *p*-value is equal or less than 0.05, then the null hypothesis could be rejected at a 95% of significance (Li et al., 2022). The estimated *p*-value is 0.04 which means that eco-efficiency scores estimated based on self-evaluation and peer-evaluation are statistically different.

The performance overestimation resulting from self-evaluation is also evidenced in the number of eco-efficient WWTPs (Figure 1). Based on self-evaluation approach, 6 out 109 WWTPs (5.5%) are eco-efficient, i.e., they are located on the efficient production frontier and therefore, are the best performers. On the contrary, when eco-efficiency scores are estimated based on peer-evaluation, both for GEEP and IEEP, only one facility is eco-efficient. Thus, this WWTP constitutes the reference for the other 108 WWTPs analyzed in this study. It is a small facility treating around 100,000 m^3/year whose operational costs are 0.75 €/m^3 which is slightly larger than average costs of the sample of analyzed WWTPs, i.e., 0.63 €/m^3. However, the mean GHG emissions of the eco-efficient WWTP are 0.094 $kgCO_{2eq}/m^3$ while the average for the 109 WWTPs is 0.299 $kgCO_{2eq}/m^3$. Thus, the excellent performance of the eco-efficient WWTP in terms of GHG emissions suggests that it is an eco-efficient plant.

FIGURE 1

Regardless of performance differences among self-evaluation and peer-evaluation, the eco-efficiency of the analyzed WWTPs is very poor. Average eco-efficiency scores estimated by previous studies presented a wide range between 0.240 and 0.929. In the case of Spanish WWTPs, Molinos-Senante et al. (2014), Gómez et al. (2018) and Mocholi-Arce et al. (2020) reported similar average eco-efficiency scores, i.e., 0.598, 0.454 and 0.480, respectively. On the contrary, Ramirez-Melgarejo et al. (2021) reported an average eco-efficiency score of 0.929 also for Spanish WWTPs. It should be noted that only seven WWTPs embraced the sample of this study, and 5 variables were integrated in the eco-efficiency model. Hence, DEA estimations present limited discriminatory power due to the lack of freedom degrees. In the case of Chinese WWTPs, variances in average estimated eco-efficiency are also evident. On the one hand, Dong et al. (2017) reported a mean eco-efficiency of 0.62 for a sample of 736 WWTPs. On the other hand, average eco-efficiency estimated by Xi et al. (2023) was 0.240 for 1044 WWTPs. It should be noted that all these previous studies estimated eco-efficiency scores based on self-evaluation and therefore, they were overestimated because the most favorable weights were allocated to each WWTP (Chen et al., 2020).

The eco-efficiency is a synthetic indicator bounded between 0.0 and 1.0 (Ananda, 2019) and therefore, potential reductions in GHG emissions for each WWTP could be estimated based on actual GHG emissions and estimated eco-efficiency score[1] (Maziotis et al., 2023). Based on self-evaluation of eco-efficiency estimations, the emission of 17,921 tons CO_{2eq}/year could be avoided if analyzed WWTPs were eco-efficient. This figure increases up to 31,705 tons CO_{2eq}/year and 32,194 tons CO_{2eq}/year based on GEEP and IEEP eco-efficiency estimations, respectively. According to the Department for Business, Energy & Industrial Strategy (2022), in the European Union annual GHG emissions are around 7.5

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[1] $Potential\ reduction\ in\ GHG\ emissions = Current\ GHG\ emissions * (1 - Eco-efficiency\ score)$

tons of CO_{2eq} per person. Hence, potential savings in GHG emissions if the WWTPs assessed were eco-efficient would be equivalent to the annual GHG emitted by 2,389 (self-evaluation), 4,227 (GEEP) and 4,293 (IEEP) European people.

Beyond the result differences reported when eco-efficiency scores are quantified based on self-evaluation and peer-evaluation (Figure 1), estimated potential reductions in GHG emissions per cubic meter of wastewater treated (Figure 2) also worth discussion. Regardless of the methodological approach followed to estimate eco-efficiency scores, Figure 2 evidences that WWTP 102 is the facility with the largest potential to reduce GHG emissions, i.e., 0.39 kg CO_{2eq}/m^3 based on self-evaluation and 0.41 kg CO_{2eq}/m^3 according to peer-evaluation. Unlike what it is observed for this WWTP, in other facilities e.g., 13, 28, 67, 100, 101, the differences in potential GHG emission reductions based on self-evaluation and peer-evaluation are marked. It illustrates the relevance of using robust methods to assess eco-efficiency of WWTPs.

FIGURE 2

The resulting eco-efficiency overestimation from self-evaluation from a regulatory perspective can lead to several problems and challenges. Some of them are as follows: i) Inaccurate environmental impact assessment: overestimating eco-efficiency results in an incorrect assessment of the actual environmental impact of WWTPs. Regulatory decisions and policies based on overestimated eco-efficiency scores may fail to address the true level of GHG emissions; ii) Misguided resource allocation: If the eco-efficiency of WWTPs is overestimated, water regulators and WWTP managers may allocate insufficient resources or investments for improving infrastructure and upgrading treatment technologies; iii) Ineffective regulatory standards: Overestimating eco-efficiency may result in the establishment of lax regulatory standards. If WWTPs are perceived as being highly efficient, there may be less pressure to enforce stringent regulations, leading to suboptimal treatment practices and potential environmental risks; iv) Delayed technological advancements: When eco-efficiency is overestimated, there may be less incentive for innovation and the development of advanced treatment technologies. This can hinder progress in improving wastewater treatment processes, reducing energy consumption, and minimizing the environmental footprint of the plants and; v) Potential public health risks: If the actual performance of WWTPs is overestimated, it can undermine public health and safety.

3.2 Eco-efficiency assessment based on GEEP and IEEP

Comparing the eco-efficiency values between GEEP and IEEP, Figure 3 illustrates that scores under GEEP are always larger than IEEP for all analyzed WWTPs. Hence, maximizing the global eco-efficiency is also conducive to improvements in the eco-efficiency of individual WWTPs. This is because GEEP tries to achieve global eco-efficiency priority, and then the peer-evaluation eco-efficiency scores of the analyzed WWTPs from GEEP are often better than the ones from IEEP. Nevertheless, eco-efficiency scores obtained by cross-efficiency methods of GEEP and IEEP present a correlation coefficient of 0.99 which means that they are highly correlated.

FIGURE 3

In order to get a better understanding on how eco-efficiency scores are distributed across WWTPs, Figure 4 shows eco-efficiency distributions based on GEEP and IEEP scores. Because of the high correlation between GEEP and IEEP scores, the distribution of eco-efficiency scores based on both approaches is very similar. The majority of the analyzed facilities (78 out of 109 for GEEP and 79 out of 109 for IEEP) exhibit an eco-efficiency score lower than 0.3 which means that they can reduce by 70% or more their GHG emissions. Moreover, it also highlights that there is no WWTP with an eco-efficiency score ranging between 0.7 and 1.0. It confirms the poor performance of the analyzed facilities.

FIGURE 4

Based on the variables considered in this study to estimate eco-efficiency scores, some basic policies and actions that the regulator and WWTPs´ managers could adopt to enhance eco-efficiency are as follows.

- Energy use optimization: According to Gu et al. (2017) energy costs account for more than 60% of WWTPs' operating expenditure. Implementing energy-efficient technologies, such as energy-efficient motors and pumps, variable frequency drives, and energy recovery systems, can reduce energy consumption and therefore, operational costs and GHG emissions.
- Renewable energy integration: Installing renewable energy systems, such as solar panels or wind turbines, can help generate clean and sustainable energy to power the treatment processes. These installations can offset the energy demand from the grid and reduce the carbon footprint of the plant.

- Enhanced treatment processes: Upgrading treatment processes with advanced technologies can improve the efficiency and effectiveness of pollutant removal. This can result in higher quality effluent contributing therefore to improvements in eco-efficiency.
- Sewage sludge management: Implementing anaerobic digestion, which produces biogas, allows reducing the volume of sludge to be managed. It further allows recovering energy reducing therefore the carbon footprint of the WWTP.
- Monitoring and optimization: Implementing real-time monitoring and process control systems can help optimize treatment processes, reduce energy and chemical usage, and minimize the environmental impact. It enables better tracking of performance indicators and facilitates proactive maintenance.

By implementing these strategies, WWTPs can improve their eco-efficiency, reduce their environmental footprint, and contribute to a more sustainable wastewater management system.

4. CONCLUSIONS

Evaluating the eco-efficiency of WWTPs is a useful task for water utilities to enhance their environmental and economic performance. Moreover, from a policy perspective, regulators can establish benchmarks and standards based on best practices and industry norms, enabling fair comparisons and setting performance targets for the facilities to achieve. Previous studies on this topic estimated eco-efficiency of WWTPs based on self-evaluation, i.e., allocating weights that maximize individual eco-efficiency scores which leads to performance overestimation. This could further lead to biased policy recommendations and lax regulatory standards. To overcome overestimation problems, this study applies a cross-evaluation strategy, which combines self-evaluation and peer-evaluation, to assess the eco-efficiency of WWTPs.

Eco-efficiency assessment of WWTPs using reliable methods can provide valuable insights and information to water regulators in several ways. First, eco-efficiency assessments enable water regulators to evaluate the overall performance of WWTPs in terms of their environmental and economic impacts. This information helps regulators identify areas for improvement and set benchmarks for performance. Second, eco-efficiency assessments can inform the development of policies and regulations related to wastewater treatment. This can include incentivizing the adoption of cleaner technologies, promoting resource recovery from wastewater, or setting specific targets for reducing energy consumption or carbon emissions. Third, eco-efficiency assessments provide a basis for monitoring the performance of wastewater treatment plants over time.

This study focuses on evaluating the eco-efficiency of a sample of Spanish WWTPs. However, it is important to acknowledge that the assessment of eco-efficiency only incorporates indirect GHG emissions due to the lack of comprehensive data on direct GHG emissions. To gain a more comprehensive understanding of the environmental performance of WWTPs, further analysis that includes direct GHG emissions is necessary. Furthermore, our study specifically examines WWTPs employing conventional activated sludge as a secondary treatment technology. However, there are alternative technologies such as trickling filters, membrane bioreactors, extended aeration, biofilters, and others that are utilized for pollutant removal from wastewater. Hence, to better support environmental policies, it would be valuable to compare the eco-efficiency among different wastewater treatment technologies.

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Author contributions statement

Ramón Sala-Garrido: Formal analysis; Methodology

Alexandros Maziotis: Conceptualization; Writting-Original Draft; Supervision

Manuel Mocholi-Arce: Methodology; Validation

María Molinos-Senante: Conceptualization; Writting-Original, Supervision

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

FIGURES

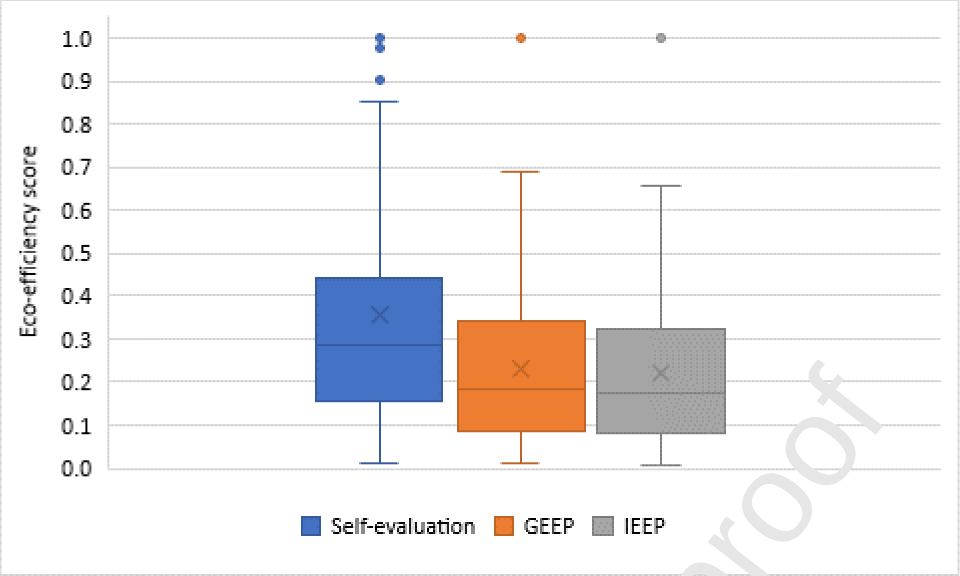

Figure 1. Statistics of eco-efficiency scores estimated based on self-evaluation and peer-evaluation[2].

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[2] Dots represent the WWTPs with the best eco-efficiency, i.e., facilities whose eco-efficiency is larger than 0.9.

Figure 2. Potential reduction in greenhouse gas emissions if WWTPs were eco-efficient based on self-evaluation assessment and individual eco-efficiency priority (IEEP) approach.

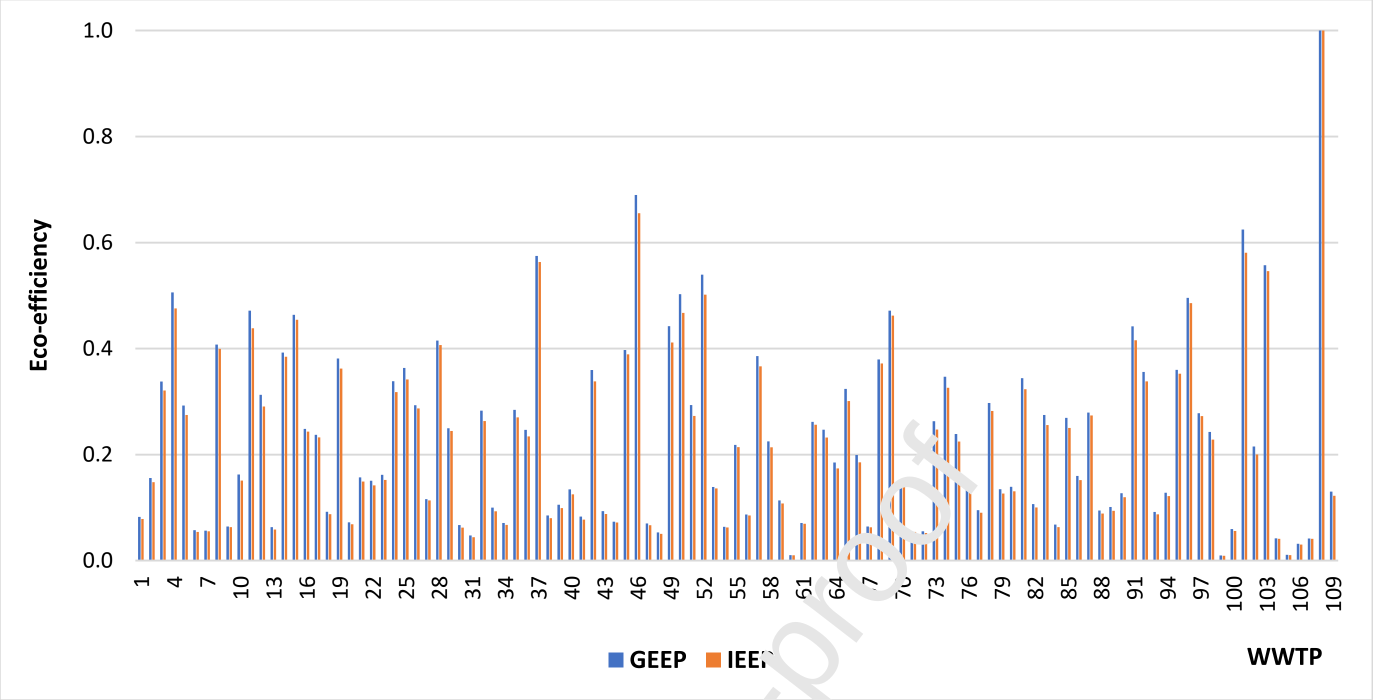


Figure 3. Eco-efficiency scores based on global eco-efficiency priority (GEEP) and individual eco-efficiency priority (IEEP) approaches.

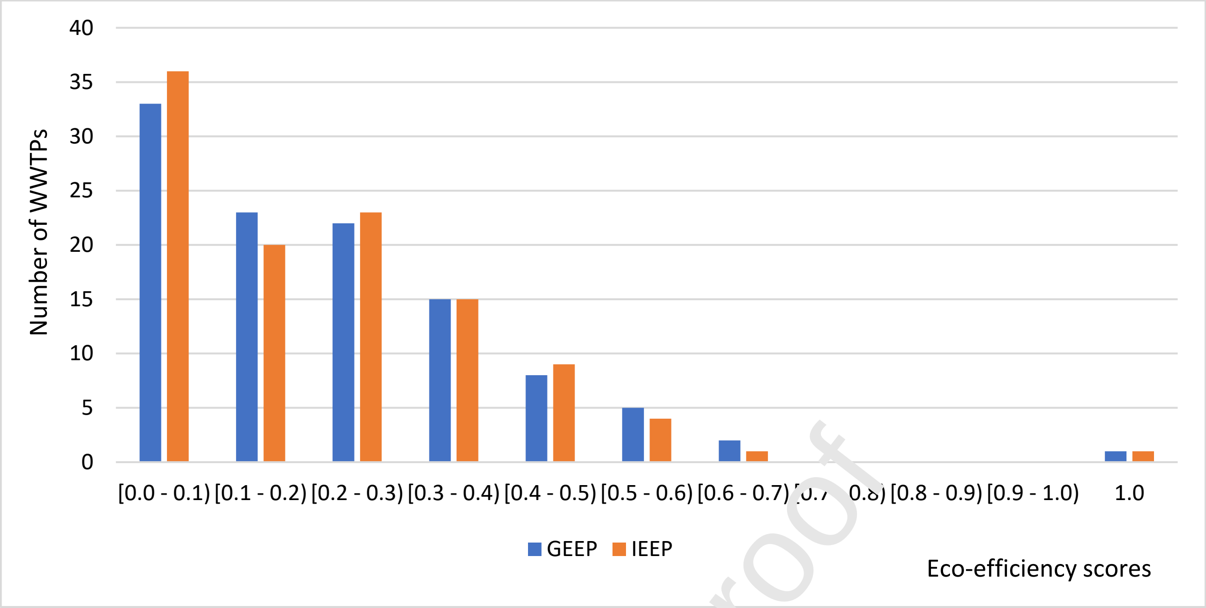


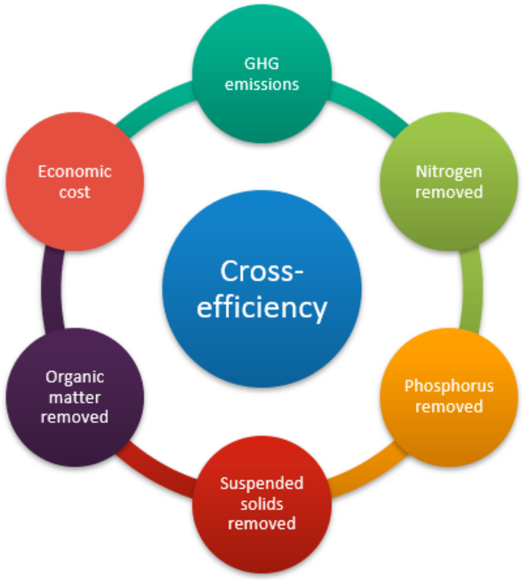
Figure 4. Distribution of eco-efficiency scores across WWTPs.

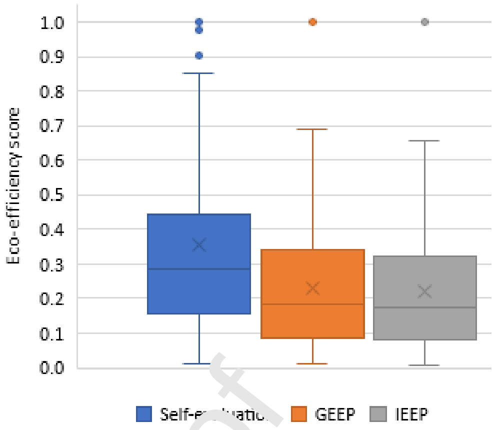
TABLES

Table 1. Descriptive statistics of the analyzed Spanish WWTPs.

Variables	Unit of measurement	Average	Std. Dev.	Minimum	Maximum
Operational costs	Euros/year	758,298	1,409,069	18,976	9,915,457
SS removed	kg/year	1,504,366	6,932,355	893	67,171,650
COD removed	kg/year	2,791,539	11,680,492	2,567	106,021,387
N removed	kg/year	149,680	536,491	163	4,152,857
P removed	kg/year	35,558	164,284	16	1,506,131
Greenhouse gas emissions	$kgCO2_{eq}$/year	411,307	1,275,4[illegible]8	2,338	10,039,318

GRAPHICAL ABSTRACT





HIGHLIGHTS

Eco-efficiency of wastewater treatment plants was evaluated based on cross-efficiency

Self-evaluation overestimates eco-efficiency scores of wastewater treatment plants.

Average eco-efficiency ranges between 0.219 and 0.353 based on the method used.

Potential reductions in greenhouse gas emissions are up to 0.39 kg CO_{2eq}/year.

Based on peer-evaluation only one wastewater treatment plant was eco-efficient.