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Assessing Eco-Efficiency and the Cost of Carbon Abatement in Wastewater Treatment: Evidence From Spain

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ABSTRACT

Wastewater treatment plants (WWTPs) play a critical role in protecting public health and the environment but are also contributors to carbon emissions. Improving the eco-efficiency of WWTPs is essential for advancing sustainability in the sector. This study proposes a parametric approach using stochastic frontier analysis to evaluate the eco-efficiency of 108 WWTPs in Spain and estimate the marginal cost of reducing GHG emissions. The eco-efficiency index (EcoEI) integrates operational costs, pollutant removal efficiency, and indirect carbon emissions. Results show an average EcoEI of 0.638, suggesting that WWTPs could improve performance by approximately 36%. The estimated marginal abatement cost of carbon emissions ranges from €0.010 to €1.240 per kg CO_2eq, with an average of €0.309/kg CO_2eq. Significant differences in marginal costs were found across secondary treatment technologies, though not in eco-efficiency scores. These findings have important implications for utilities and regulators aiming to enhance sustainability and meet the targets set by EU Directive 2024/3019.

1 | Introduction

Wastewater treatment plays a key role in protecting public health and preserving ecosystems, thereby contributing to both community well-being and planetary health (Shamshad and Rehman 2025). Its importance in advancing sustainable development is underscored by the United Nations sustainable development goals (SDGs) (United Nations 2015). Thus, Obaideen et al. (2022) demonstrated that effective wastewater treatment can contribute to achieving 11 of the 17 SDGs. From a sustainable development perspective, wastewater treatment represents a paradigmatic example of infrastructure systems operating at the intersection of environmental protection, economic viability, and climate mitigation. Achieving sustainability in this sector requires moving beyond compliance-based environmental regulations toward integrated performance frameworks that simultaneously address cost efficiency, resource use, and greenhouse gas (GHG) emissions. Wastewater treatment is neither economically nor environmentally neutral. Economically, water and wastewater service costs must be financed through user tariffs (Wareg 2023). According to IBNET (2024), wastewater tariffs vary significantly worldwide, ranging from 5.98 USD/m^3 in Japan to 0.26 USD/m^3 in Albania. In the European Union (EU), the average annual per capita investment in wastewater infrastructure was 31.4 EUR in 2024 (WISE 2025). From an environmental perspective, wastewater treatment plants (WWTPs) are notable sources of both direct and indirect GHG emissions. In the United States, WWTPs emit over 21 million metric tons of GHGs annually (Shen et al. 2015), while in the EU, carbon emissions from the wastewater treatment sector are estimated at approximately 34.45 million tonnes of CO_2 equivalent (CO_2eq) per year (WISE 2025). The reduction of carbon emissions has gained global momentum since the 2015 Paris Climate Agreement and has emerged as a pressing objective in the wastewater sector (Li et al. 2022; Ranieri et al. 2024). Within the EU, a major transformation in wastewater management is underway through the Directive 2024/3019 on urban wastewater treatment. This legislative initiative supports the EU's overarching goal of achieving climate neutrality by 2050, requiring a progressive reduction of GHG emissions from WWTPs (EU 2024). Although the mitigation of GHG emissions from WWTPs offers substantial environmental and societal benefits, it is crucial to recognize the economic trade-offs involved (Gillingham and Stock 2018; Laramee et al. 2018). While the concept of eco-efficiency was originally developed by Schaltegger and Sturm (1989), it has gained renewed relevance in light of the objectives set out in Directive 2024/3019.

Originally, eco-efficiency refers to the ratio of economic value generated to the environmental burden imposed by a given activity. In practical terms, it entails producing more value with less environmental impact or maximizing the value obtained from a fixed level of ecological pressure (Mahlberg and Luptacik 2014). Applied to WWTPs, eco-efficiency has been commonly interpreted as the ability to remove larger amounts of pollutants from wastewater while minimizing both economic costs and GHG emissions (Dong et al. 2017; Mocholi-Arce et al. 2020; Sala-Garrido et al. 2023). According to this definition, improvements in WWTPs' eco-efficiency can lead to operational cost savings, which may be transferred to citizens in the form of lower tariffs, while simultaneously reducing GHG emissions supporting progress toward carbon neutrality (Ramírez-Melgarejo et al. 2021).

Eco-efficiency is inherently a multidisciplinary concept, and its assessment requires the integration of multiple criteria into a synthetic indicator (Lorenzo-Toja et al. 2015; Torregrossa et al. 2018). Accordingly, previous studies evaluating the eco-efficiency of WWTPs have commonly applied Data Envelopment Analysis (DEA)—a nonparametric, multi-criteria decision analysis method (Dong et al. 2017; Gómez et al. 2018; Mocholi-Arce et al. 2020; Sala-Garrido et al. 2023). DEA uses linear programming to construct an efficient frontier based on observed input and output data from the WWTPs under evaluation (Ferreira et al. 2023; Yin et al. 2024). One of DEA's main strengths lies in its ability to endogenously assign weights to eco-efficiency indicators, thereby maximizing the global eco-efficiency score for each facility. However, as a nonparametric method, DEA attributes all deviations from the efficiency frontier solely to inefficiency, without accounting for statistical noise. This makes the method sensitive to outliers and susceptible to overfitting, particularly in small or heterogeneous samples (Carvalho and Marques 2016; Maziotis and Molinos-Senante 2023). Additionally, DEA does not permit the estimation of the economic cost associated with improving eco-efficiency, which limits its utility in policy contexts. Thus, DEA-based studies on WWTPs do not estimate the marginal cost of reducing carbon emissions, despite this being a key objective of Directive 2024/3019. This gap is significant, as quantifying the cost of GHG reduction is essential for WWTPs aiming to generate carbon credits[1] and participate in voluntary carbon markets (Ji et al. 2024; Salvi et al. 2025).

Against this background, the objectives of this study are threefold. First, it aims to propose and estimate an eco-efficiency index (EcoEI) for WWTPs using a parametric frontier approach that accounts for both inefficiency and statistical noise. This index integrates operational costs, GHG emissions, and pollutants removed from wastewater into a composite performance metric. Second, the study seeks to estimate the marginal cost of reducing GHG emissions from WWTPs. Third, it aims to analyze the influence of the type of technology used for secondary treatment of WWTPs on its eco-efficiency and cost of reducing carbon emissions. These objectives are directly aligned with the goals of the EU Directive 2024/3019, which emphasizes the need to enhance both cost-effectiveness and climate performance in urban wastewater treatment.

The empirical analysis focuses on a sample of 108 WWTPs located in a region of Spain. This regional focus ensures a high degree of regulatory, institutional, and energy-market homogeneity, which facilitates meaningful comparisons of eco-efficiency and carbon abatement costs across facilities. While this approach strengthens internal consistency, the results should be interpreted with caution when extrapolating to regions or countries with different regulatory frameworks, energy mixes, or carbon pricing regimes.

Eco-efficiency has emerged as a central concept for operationalizing the economic–environmental interface of sustainable development by linking value creation to ecological burden and providing a measurable pathway for aligning operational performance with sustainability objectives (Caiado et al. 2017). However, much of the empirical literature has treated eco-efficiency primarily as a benchmarking tool rather than as a governance instrument embedded within broader sustainability transitions (Loorbach et al. 2017). Addressing this gap, the present study moves beyond a purely technical efficiency assessment toward a sustainability transition perspective in which economic and environmental performance are jointly evaluated within evolving climate governance frameworks. In doing so, it contributes to the wastewater treatment performance literature in several ways.

This study contributes to the literature on sustainability performance in wastewater infrastructure in three main ways. First, it develops a multi-criteria EcoEI for WWTPs based on a stochastic frontier analysis (SFA) framework that simultaneously accounts for operational costs, pollutant removal, and GHG emissions. Unlike the nonparametric approaches commonly used in previous studies, the parametric frontier approach allows for the separation of inefficiency from statistical noise, providing a more robust assessment of plant performance. Second, the study estimates plant-level marginal costs of reducing GHG emissions, thereby quantifying the economic trade-offs associated with carbon mitigation in wastewater treatment operations. This provides new empirical evidence on the cost of carbon abatement in the sector. Third, the analysis investigates whether differences in secondary treatment technologies are associated with variations in eco-efficiency and carbon abatement costs. By combining these elements, the study offers an integrated analytical framework that links operational efficiency, environmental performance, and climate mitigation costs, providing relevant insights for utilities and regulators seeking to improve the sustainability of wastewater services.

2 | Material and Methods

2.1 | Eco-Efficiency Within Sustainability Governance

Sustainable development in infrastructure-intensive sectors, such as wastewater treatment, requires analytical frameworks that integrate economic performance, environmental impact,

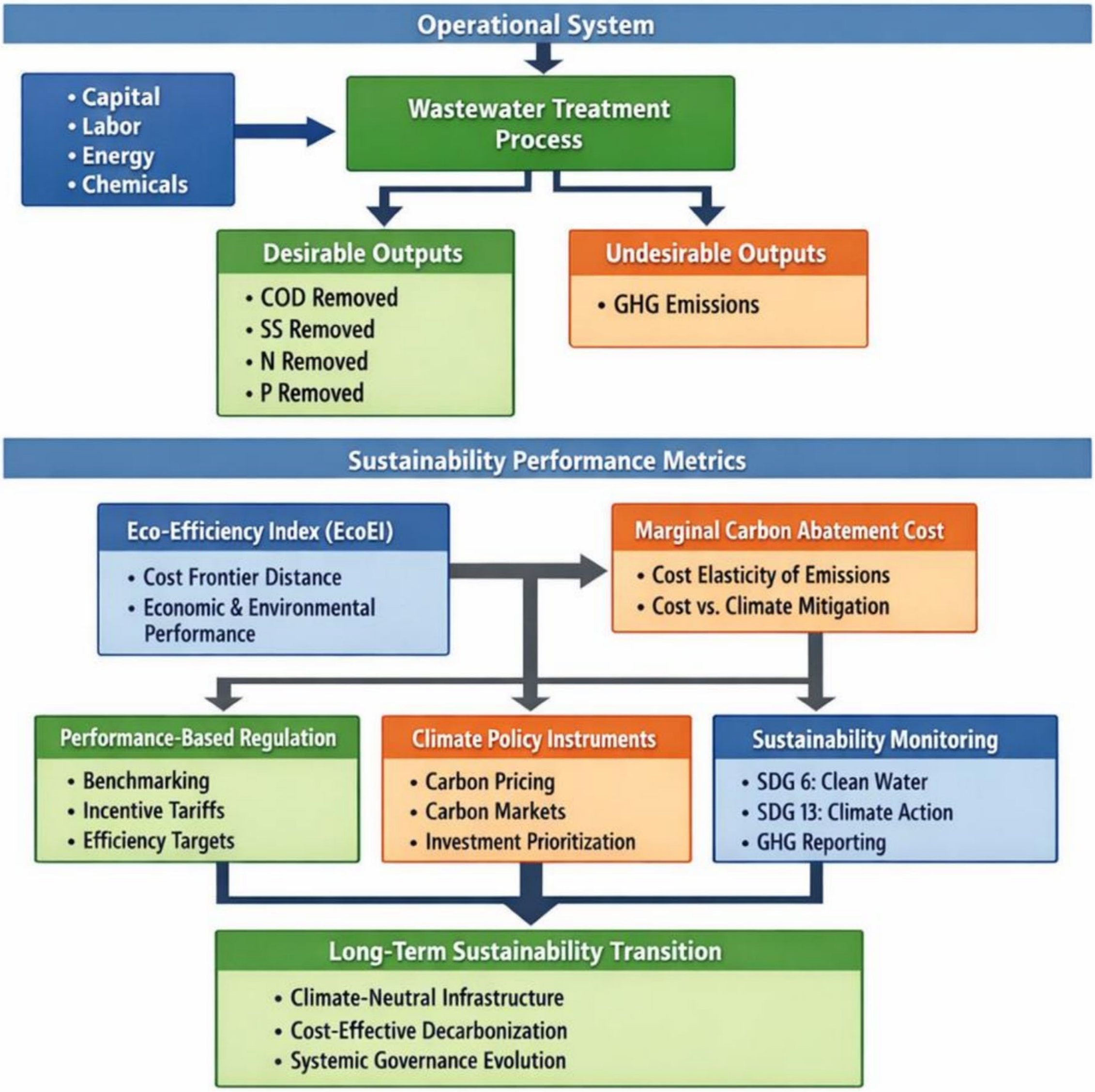

FIGURE 1 | Conceptual framework linking eco-efficiency, carbon abatement cost, and sustainability governance.

and governance mechanisms. To clarify the theoretical positioning of this study, Figure 1 and the accompanying discussion outline the analytical lens guiding the empirical analysis.

The conceptual framework (Figure 1) is structured around three interrelated layers. First, at the operational level, WWTPs transform inputs (capital, energy, labor) into desirable outputs (pollutant removal) and undesirable outputs (GHG emissions). These production relationships define the techno-economic boundary within which utilities operate. Second, at the performance level, eco-efficiency captures the joint evaluation of economic and environmental outcomes. The EcoEI measures the extent to which plants operate near the cost frontier, given their pollutant removal and emission levels. Simultaneously, the marginal cost of carbon abatement reflects the economic trade-offs associated with reducing undesirable outputs. Together, these indicators link operational performance to sustainability metrics. Third, at the governance level, performance metrics inform regulatory design, carbon pricing mechanisms, and investment allocation. In this layer, eco-efficiency functions not merely as a technical indicator but as a governance instrument supporting sustainability transitions. By revealing heterogeneity in abatement costs and performance gaps, the framework enables differentiated, performance-based regulation and climate-aligned incentives.

2.2 | Estimation of EcoEI and Marginal Cost of Reducing Carbon Emissions

The EcoEI for each WWTP is estimated using SFA, a parametric multi-criteria decision analysis method. Unlike DEA, SFA requires the a priori specification of a functional form to represent the production or cost technology. However, a key advantage of SFA is its ability to estimate performance indices—such as the EcoEI—while distinguishing between inefficiency and statistical noise, thereby offering a more robust assessment of plant performance under real-world conditions (Longo et al. 2023). As a parametric technique, SFA requires the estimation of a cost frontier whose general form is a follows (Mundaca 2025):

$$C_i = f(y_i, w_i; \alpha) + v_i + u_i \quad (1)$$

where C_i represents the operating costs incurred by WWTP i in delivering treatment services. These costs are modeled as a function of the output vector y_i and the corresponding input prices w_i. The parameter α are estimated though the specification of the cost function (see Equation 2). The term v_i captures statistical noise and is assumed to follow a normal distribution $v_i \sim N(0, \sigma_v^2)$, while u_i represents inefficiency and is assumed to follow a half-normal distribution, $u_i \sim N^+(0, \sigma_u^2)$ (Afsharian 2017; Carvalho and Marques 2016).

The estimation of the cost frontier model (Equation 1) requires the a priori specification of a functional form. In this study, a Cobb–Douglas cost function is adopted. This choice is motivated by several considerations. First, the sample size is relatively limited (108 WWTPs), and more flexible functional forms, such as the translog, would require estimating a large number of parameters, potentially leading to multicollinearity and imprecise estimates. The Cobb–Douglas specification offers a parsimonious structure that is particularly suitable for small and heterogeneous samples, ensuring econometric stability and reliable inference (Ferro and Mercadier 2016; Molinos-Senante et al. 2022). Second, detailed information on input prices is not available, which is a common limitation in empirical studies of WWTPs. In such cases, previous studies have successfully employed simplified Cobb–Douglas cost functions to estimate efficiency and marginal effects without compromising theoretical consistency. It should be emphasized that the primary objective of this study is not the estimation of detailed substitution elasticities, but the construction of an eco-efficiency indicator and the derivation of marginal costs of carbon emission reductions. In this context, the Cobb–Douglas specification provides a transparent, theoretically consistent, and econometrically reliable framework that is well suited to the study's aims (Jamasb et al. 2012; Mydland et al. 2019).

Accordingly, the following cost frontier model is defined and estimated:

$$\ln C_i = a_0 + \sum_{m=1}^{M} \alpha_m \ln y_{i,m} + \sum_{q=1}^{Q} a_q \ln q_{i,q} + v_i + u_i \quad (2)$$

where a_0 is the constant term. The model includes M outputs, representing in this study by the quantities of pollutants removed from the wastewater treatment (see Section 2.3). Equation (2) integrates an extra cost driver, q_i, which is the GHG emissions. The integration of this variable allows estimating the marginal cost associated with its reduction (see Equation 4).

Based on the estimated cost frontier model (Equation 2), the EcoEI of each evaluated WWTP i (EcoEI_i) is derived as follows:

$$\text{EcoEI}_i = \exp(-u_i) \quad (3)$$

EcoEI ranges from 0 to 1, where an index of 1 indicates that a WWTP is fully eco-efficient, while any value below 1 reflects some degree of eco-inefficiency and therefore potential room to improve in comparison to their peers.

The EcoEI measures the extent to which a WWTP operates close to the minimum-cost frontier, given its levels of pollutant removal and carbon emissions. An EcoEI value equal to one indicates that the plant is operating on the cost frontier and is therefore eco-efficient, whereas values below one reflect the presence of eco-inefficiency and potential scope for improvement relative to best-performing peers.

For practitioners and regulators, the EcoEI should be interpreted as a relative benchmarking indicator that identifies facilities with higher potential for cost savings and emission reductions, rather than as an absolute measure of performance. Unlike DEA-based eco-efficiency indices, which treat all deviations from the frontier as inefficiency, the stochastic frontier approach underlying the EcoEI explicitly accounts for statistical noise and measurement error. This feature makes the EcoEI particularly suitable for regulatory benchmarking and policy analysis, where operating conditions and data uncertainty may vary across facilities.

Based on the estimated parameters of the cost frontier model specified in Equation (2), the marginal cost of reducing GHG emissions for each WWTP i is calculated as follows (Sala-Garrido et al. 2021; Molinos-Senante et al. 2022):

$$\text{MCOST}_i = -\text{ELC}_i \times \frac{C_i}{q_i} \quad (4)$$

where ELC_i represents the elasticity of cost with respect to the cost driver q_i, that is, GHG emissions in this study. Notably, a negative sign is included in the marginal cost calculation because GHG emissions are treated as an undesirable output—that is, the aim of the WWTPs is reducing its emissions. A negative estimated coefficient for GHG implies that reducing emissions leads to higher operating costs, consistent with economic theory. Consequently, the marginal cost of reducing GHG is expected to be positive, reflecting the additional cost associated with improving environmental performance (Molinos-Senante et al. 2022).

2.3 | Influence of Secondary Treatment on the Eco-Efficiency and Marginal Cost of Reducing Carbon Emissions

The eco-efficiency and marginal cost of reducing carbon emissions in WWTPs may be influenced by the type of secondary treatment technology employed (Dong et al. 2017). To assess whether technology plays a statistically significant role in this case study, the nonparametric test of Kruskal-Wallis was applied (Kruskal and Wallis 1952). In doing so, WWTPs are categorized according to the type of secondary treatment technology used, and the test is conducted to determine whether significant differences exist in their EcoEI and marginal cost of reducing carbon emissions.

The Kruskal-Wallis test evaluated whether the samples originate from the same distribution, and a statistically significant result indicates that at least one group exhibits stochastic dominance—suggesting heterogeneity in the variable assessed (eco-efficiency and/or marginal cost of reducing carbon emissions) across technologies. The hypotheses tested are:

TABLE 1 | Descriptive statistics of the variables used to estimate the EcoEI of WWTPs.

Variables	Unit of measurement	Mean	Standard deviation	Minimum	Maximum
Operational costs	€/year	756,318	1,415,486	18,976	9,915,457
Greenhouse gas emissions	$kgCO_{2eq}$/year	410,173	1,281,318	2338	10,039,318
CDO removed	kg/year	2,782,084	11,734,527	2567	106,021,387
SS removed	kg/year	1,497,863	6,964,340	893	67,171,650
N removed	kg/year	148,487	538,847	163	4,152,857
P removed	kg/year	35,444	165,045	16	1,506,131

Source: Own elaboration from public regulatory data.

H0. *The k samples come from the same population.*

H1. *Some samples come from the other population.*

The null hypothesis is rejected at the 95% confidence level when the $p \leq 0.05$, indicating that the treatment technology has a statistically significant influence on the eco-efficiency or marginal cost performance of the WWTPs.

2.4 | Case Study and Variables Description

The case study examines a sample of 108 WWTPs located in the northeast of Spain with annual treatment capacities ranging from 819,806 m^3/year to 10,508,061 m^3/year. All facilities employ secondary treatment processes designed not only to remove organic matter and suspended solids (SS), but also to eliminate nitrogen (N) and phosphorus (P). Regarding the type of technology adopted for secondary treatment,[2] the 108 WWTPs are distributed as follows: piston flow ($n=11$), concentric ($n=33$), biofilter ($n=32$), carousel ($n=22$), and complete mix ($n=10$). Each WWTP complies with the effluent discharge standards set by the European Urban Wastewater Directive 91/271/EEC, which was in force during the study year, 2022. The WWTPs are operated by both public and private utilities. However, they are all subject to the same regulatory framework to ensure compliance with European and national environmental standards.

According to the definition of eco-efficiency adopted in this study (Dong et al. 2017; Maziotis and Molinos-Senante 2023; Ramírez-Melgarejo et al. 2021), and considering both previous research and data availability, the EcoEI incorporates the following variables. The economic component is represented by the annual operational expenditure of each WWTP, expressed in €/year. Given that the primary function of a WWTP is the removal of pollutants from wastewater, the EcoEI also includes four key pollutants: SS, organic matter—measured as chemical oxygen demand (COD), N, and P. The removal of these pollutants was estimated according to Equation (5):

$$\mathrm{PLRV}_{ij} = \mathrm{WVL}_j * \left(\mathrm{Pollutant}_{iij} - \mathrm{Pollutant}_{eij}\right) \quad (5)$$

where PLRV_{ij} is the annual quantity of pollutants removed from wastewater for each pollutant j and WWTP i expressed in kg/year; WVL_i is the volume of wastewater treated by the WWTP i expressed in m^3/year; $\mathrm{Pollutant}_{iij}$ is the concentration of each pollutant j in the influent (i) of the WWTP i expressed in kg/m^3, and $\mathrm{Pollutant}_{eij}$ is the concentration of each pollutant j in the effluent (e) of the WWTP i expressed in kg/m^3.

From an environmental perspective—and aligned with the objective of estimating the marginal cost of reducing GHG emissions—GHG emissions are included as an additional indicator within the EcoEI (Ananda 2019; Ananda and Oh 2023). In this study, data on direct GHG emissions were not available; therefore, we considered indirect GHG emissions associated with electricity consumption during wastewater treatment. An emission factor of 273 gCO_2eq/kWh was applied, based on data from the Catalan Office of Climate Change (2022). GHG emissions are expressed in kilograms of CO_2eq per year.

Table 1 presents the descriptive statistics of the variables used in this study which were obtained from the regional public regulators.

3 | Results and Discussion

The empirical results presented in this section are interpreted in light of the conceptual framework outlined in Section 2.1. In particular, the analysis examines how plant-level operational performance, captured through eco-efficiency scores and marginal carbon abatement costs, relates to the broader sustainability governance perspective proposed in this study. Thus, the results provide insights into how benchmarking and carbon cost information can support climate-oriented regulation and investment decisions in the wastewater sector.

3.1 | Parameters of the SFA Model

To estimate the EcoEI for each WWTP included in the evaluation, the cost frontier defined in Equation (3) was modeled, with its estimated parameters presented in Table 2. The coefficients associated with the four variables representing pollutant removal—SS, COD, N, and P—are all positive and statistically significant. From a modeling perspective, this indicates that greater pollutant removal is associated with higher operational costs. In contrast, the coefficient for GHG emissions is negative, suggesting a positive marginal cost of emission reduction (Jamasb et al. 2012). This finding confirms that reducing carbon emissions entails additional costs. These results, while seemingly intuitive, provide evidence for the robustness of the SFA model used to estimate the EcoEI. This robustness is further supported by the statistical significance of the inefficiency variance component (σ_u^2).

The sum of the estimated coefficients for the four pollutants is 1.027, which is close to one. This suggests that, on average, the WWTPs operate under conditions of constant returns to scale. Among the pollutants, COD and SS have the greatest impact on operational costs. Specifically, a 1% increase in COD and SS removal leads to average cost increases of 0.536% and 0.314%, respectively. This result reflects the fact that these pollutants are removed in the largest quantities from wastewater (Table 1). The evidence on returns to scale in WWTPs is mixed in the literature. Several studies have reported constant or near-constant returns to scale (Yang and Chen 2021; Jiang et al. 2020). In contrast, other studies have identified increasing returns to scale (Castellet and Molinos-Senante 2016; Maziotis and Molinos-Senante 2023). These differences suggest that scale properties in wastewater treatment are highly context- and sample-dependent. Therefore, the finding of constant returns to scale in this study should be interpreted as specific to the sample analyzed and not as a general characteristic of all WWTPs.

TABLE 2 | Estimated parameters from the cost frontier.

Parameter	Coefficient	Standard error	*Z*-stat	*p*
Constant	3.763	1.170	**3.217**	0.001
COD removed	0.536	0.145	**3.694**	0.000
P removed	0.085	0.035	**2.416**	0.017
N removed	0.092	0.024	**3.849**	0.000
SS removed	0.314	0.110	**2.855**	0.005
GHG	−0.083	0.025	**−3.306**	0.000
σ_u^2	0.592	0.168	**3.530**	0.000
σ_v^2	0.587	0.066	**8.900**	0.000
λ	1.008	0.215	**4.680**	0.000

Note: The Log-likelihood is −113.4. Operating costs is the dependent variable. Bold indicates that coefficients are statistically significant at 5% significance level.
Source: Own elaboration.

3.2 | EcoEI Estimation

The main statistics of the estimated EcoEI for the 108 WWTPs evaluated in this study are presented in Figure 2. The average, median, and mode of the EcoEI are 0.638, 0.648, and 0.653, respectively. Given that the maximum achievable EcoEI is 1.0, these results suggest that, on average, the WWTPs assessed could improve their eco-efficiency by approximately 36.2%. The lowest-performing plant reported an EcoEI of 0.148, indicating a potential for improvement greater than 85%. Notably, none of the WWTPs in the sample reached full eco-efficiency. The best-performing plant achieved an EcoEI of 0.867, suggesting that even the most efficient facilities have room for improvement—up to 13.3%.

These findings are in line with previous research on the eco-efficiency of Spanish WWTPs. Thus, studies by Molinos-Senante et al. (2016), Gómez et al. (2018), and Mocholi-Arce et al. (2020) found average eco-efficiency scores of 0.598, 0.454, and 0.480, respectively for a group of Spanish WWTPs. On the other hand, Ramírez-Melgarejo et al. (2021) reported a significantly higher average eco-efficiency score of 0.929 for a small sample of Spanish WWTPs. The differences in eco-efficiency scores between previous studies and the present one can largely be attributed to methodological variations. While earlier studies employed nonparametric approaches to estimate EcoEI, our study used econometric methods, specifically SFA, which capture different aspects of performance.

The estimated EcoEI for each WWTP under evaluation is presented in Figure 3. The results show that the majority of facilities—67 out of 108 (62%)—exhibited an EcoEI ranging from 0.61 to 0.80. This indicates that these facilities have the potential to improve their eco-efficiency by approximately 20% to

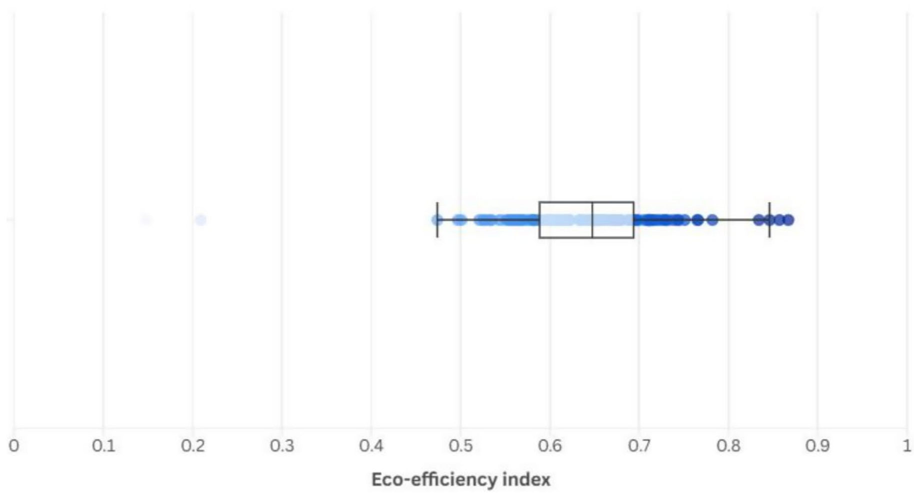

FIGURE 2 | Box plot of the estimated eco-efficiency index for wastewater treatment plants. *Source:* Own elaboration.

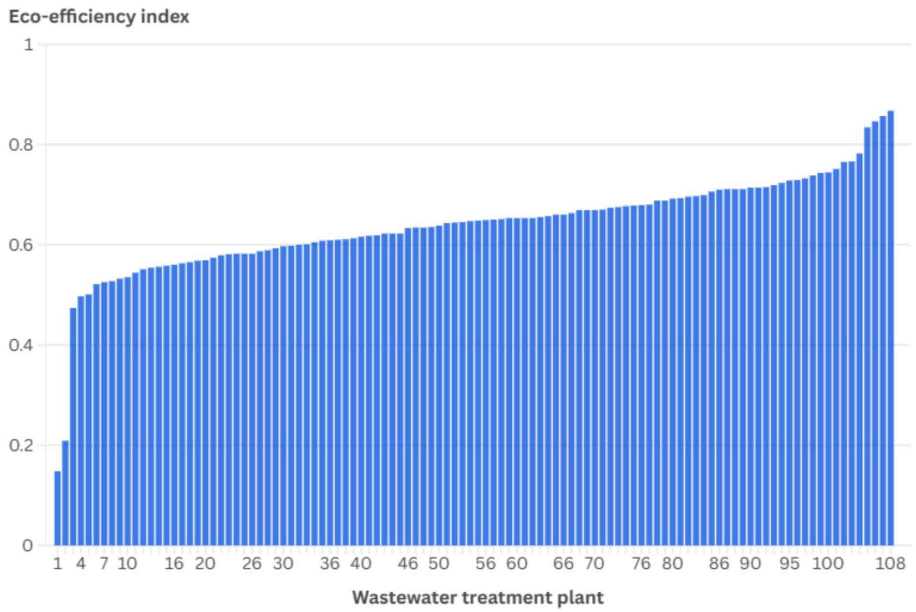

FIGURE 3 | Eco-efficiency index for each wastewater treatment plant. *Source:* Own elaboration.

39%. Additionally, 35 WWTPs (32.4%) exhibited lower EcoEI scores, between 0.41 and 0.60, suggesting a greater need for improvements in operational cost efficiency and GHG emission reductions to converge with the sector's leading performers. Two WWTPs performed particularly poorly, with EcoEI scores below 0.20, highlighting significant inefficiencies. In contrast, only four WWTPs reported EcoEI values above 0.81, positioning them as the top performers within the sample. Overall, the findings reveal considerable potential for eco-efficiency improvements across the sector, both among underperforming and relatively efficient facilities.

From the perspective of the conceptual framework presented in the methodology section, the observed heterogeneity in EcoEI values is particularly relevant for regulatory benchmarking, as it highlights the potential for performance improvements through managerial optimization and technological adjustments. By identifying WWTPs operating far from the efficiency frontier, the EcoEI provides actionable information for regulators and utilities seeking to enhance sustainability performance while maintaining cost efficiency.

To better understand the factors underlying both low and high EcoEI values, Table 3 presents the main characteristics of the 10 most and 10 least eco-efficient WWTPs. Each group (top and bottom performers) includes facilities with varying treatment capacities, indicating that eco-efficiency is not directly correlated with facility size. For example, WWTP No. 77, which treats over 17 million cubic meters per year, has a low EcoEI. In contrast, WWTPs No. 45 and No. 10 rank among the top ten performers despite processing relatively low volumes of wastewater annually. Significant variability is also observed within each group in terms of operational costs and GHG emissions, ranging from €0.115/m^3 to €1.678/m^3 and from 49.4 to 468.47 g CO_2eq/m^3. As expected, given that the EcoEI is a composite index, its value for each WWTP depends on the performance across the six indicators embracing the index (Table 1).

3.3 | Marginal Costs or Reducing Greenhouse Gas Emissions

The estimated marginal cost of reducing GHG emissions from WWTPs ranges from 0.010 to 1.240 €/kgCO_2eq. The average, median, and mode are 0.309, 0.251, and 0.313 €/kg CO_2eq, respectively (see Figure 4). This implies that, on average, WWTPs must spend an additional 0.309 € in operating expenditure to prevent the emission of 1 kg of CO_2eq into the atmosphere. Thus, the release of 1 kg of CO_2eq represents an environmental cost of 0.309 €. Figure 5 presents the estimated marginal abatement cost of GHG emissions for each WWTP under evaluation. The results show that nearly half of the plants (48 out of 108, or 44.4%) would need to increase operating expenditure by 0.21–0.40 € to avoid emitting 1 kg of CO_2eq. Additionally, 38 WWTPs could incur an environmental cost of less than 0.20 € per extra kg of GHG released. However, for some facilities, reducing emissions is relatively expensive. For example, 13 plants would require an increase in annual operating costs of 0.41–0.60 € per kg of avoided CO_2eq emissions.

To the best of our knowledge, the cost of reducing GHG emissions from treated wastewater has received limited attention in the literature. Molinos-Senante et al. (2015) estimated the average implicit cost of carbon emission reductions for several Spanish WWTPs at €0.088 per kilogram. However, their analysis was based on 2010 data and relied on nonparametric methods to estimate these costs. In contrast, Sala-Garrido et al. (2021) and Maziotis et al. (2022) found that the cost of reducing carbon emissions in the water and sewerage services of England and Wales was £0.181 and £0.144 per kg CO_2eq, respectively. These studies, however, considered both water and sewerage services, employed panel data, and accounted for operational characteristics in their evaluation.

The estimated cost of reducing GHG emissions highlights the significant variability among WWTPs in their capacity to lower carbon emissions on the path to carbon neutrality. This variability suggests a diverse potential for their participation in

TABLE 3 | Summary of characteristics of most and least eco-efficient WWTPs.

	WWTPs	Eco-efficiency	Flow (m^3/year)	COD removed (mg/L)	SS removed (mg/L)	N removed (mg/L)	P removed (mg/L)	Operating costs (€/m^3)	GHG emission (g/m^3)	Secondary treatment type
Most eco-efficient WWTPs	108	0.867	5,900,482	1119	409	41.6	5.94	0.219	103.194	PF
	102	0.857	2,625,516	108	57	4.6	0.83	0.115	49.413	C
	103	0.846	4,174,891	757	330	56.4	7.82	0.264	155.883	PF
	101	0.834	6,763,926	759	350	46.8	12.89	0.331	150.969	CS
	100	0.782	87,553	130	73	7.09	2.5	0.326	162.162	C
	69	0.766	287,111	673	260	43	5.21	0.516	304.668	CS
	13	0.765	161,996	891	377	119.7	10.24	0.581	264.537	C
	11	0.751	170,214	454	112	8.5	2.3	0.654	182.637	C
	45	0.744	54,443	463	245	76.6	7.42	0.688	273.546	C
	10	0.743	10,090	395	106	72.4	2.93	0.619	240.513	C
Least eco-efficient WWTPs	77	0.535	17,042,783	548	283	49.2	5.64	0.304	98.28	PF
	36	0.532	1,206,014	432	147	50	5.95	0.636	145.782	CM
	104	0.527	21,301	470	120	51.2	4.56	1.678	468.468	C
	2	0.525	1,193,937	310	86	12.8	2.08	0.170	111.657	C
	86	0.521	659,281	381	149	40.6	3.9	0.836	161.07	CS
	75	0.501	1,652,862	364	141	48	4.82	0.553	133.224	C
	60	0.497	55,229	217	49	11	1.34	1.325	94.458	C
	106	0.474	87,553	130	73	25.5	2.5	0.881	244.062	C
	105	0.209	169,799	274	171	49.2	7.22	0.837	216.489	CS
	99	0.148	93,573	578	281	69.1	13.07	1.290	199.563	C

Abbreviations: C, concentric; CM, complete mix; CS, carousel; PF, piston flow.
Source: Own elaboration.

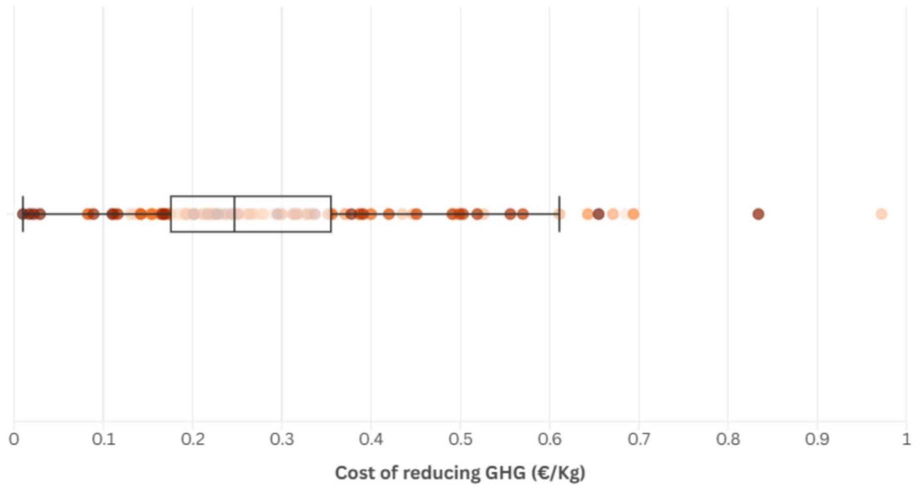

FIGURE 4 | Box plot of the estimated marginal cost of reducing greenhouse gas emissions in wastewater treatment plants. *Source:* Own elaboration.

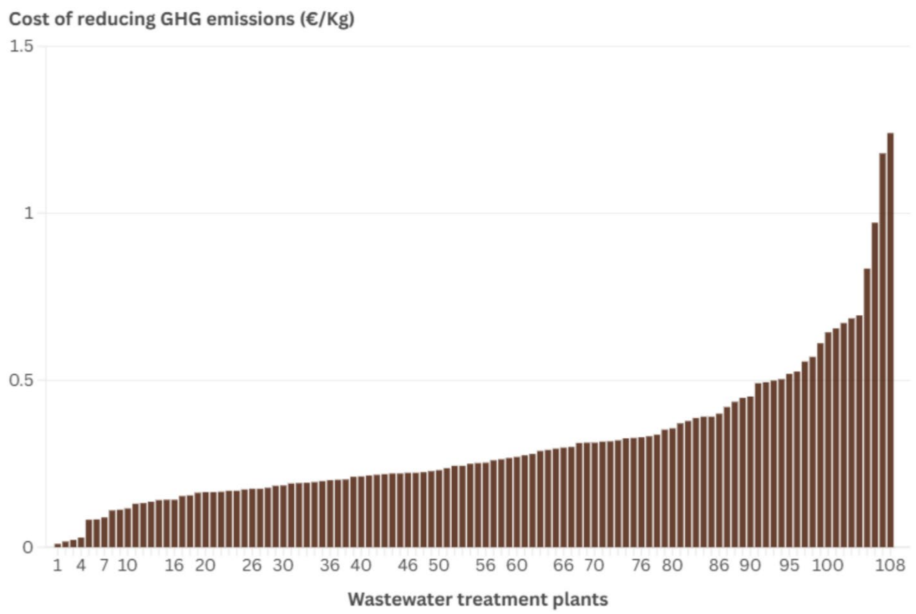

FIGURE 5 | Estimated marginal cost of reducing greenhouse gas emissions for each wastewater treatment plant. *Source:* Own elaboration.

voluntary carbon markets. Moreover, it reinforces the importance of differentiated policy instruments and performance-based incentives, as uniform regulatory approaches may fail to capture the heterogeneous mitigation potential across WWTPs. Carbon prices vary considerably across the globe, depending on the type of pricing instrument—such as a carbon tax or an emissions trading system (ETS). According to the World Bank (2025), carbon prices in 2025 range from as low as 0.72 USD/ton CO_2eq under Indonesia's ETS to 158.7 USD/ton CO_2eq under Uruguay's carbon tax. In the case of the EU, the carbon price within its ETS stands at 65 €/ton CO_2eq. The estimated marginal abatement cost of carbon emissions for the analyzed WWTPs (Figure 5) shows that only 4 out of 108 plants (3.7%) have a cost below 65 €/ton CO_2eq. These facilities, therefore, would be eligible to participate in a voluntary carbon market using the EU ETS price as a benchmark. However, according to projections by Ernst and Young (2024), carbon prices are expected to rise between 80 and 150 USD/ton CO_2eq by 2035. Based on these forecasts, between 5 and 16 of the evaluated WWTPs could potentially participate in voluntary carbon markets. A global review by Ecklu et al. (2024) estimated that the wastewater treatment sector (both domestic and industrial) has the potential to generate approximately 823 million tonnes of CO_2eq annually in carbon credits. Despite this potential, fewer than 10 million tonnes of CO_2eq were registered as carbon credits in 2023. Thus, it is illustrated the difficulties of WWTPs in participating in carbon markets despite its large potential.

A moderate negative correlation (−0.490) is observed between EcoEI and the marginal cost of reducing GHG emissions, suggesting that more eco-efficient WWTPs tend to face lower carbon abatement costs. However, this relationship should be interpreted as descriptive rather than causal because both the EcoEI and the marginal abatement cost are derived from the same stochastic frontier framework, implying a degree of mechanical interdependence between the two indicators. Moreover, the analysis is based on cross-sectional data, which limits the ability to infer causality.

3.4 | The Influence of Technology on Eco-Efficiency and Marginal Cost of Carbon Emissions

All 108 WWTPs assessed include secondary treatment processes aimed at removing N and P, in addition to SS and COD. However, the specific technologies used for secondary treatment vary, including piston flow, concentric, biofilter, carousel, and complete mix systems. Figure 6 shows the EcoEI for each WWTP categorized by its secondary treatment technology. The average EcoEI values for biofilter, concentric, piston flow, carousel, and complete mix technologies are 0.633, 0.641, 0.647, 0.633, and 0.650, respectively. The *p* value from the Kruskal–Wallis test is 0.559, indicating that the differences in EcoEI across technologies are not statistically significant. This finding aligns with previous research by Dong et al. (2017), based on a sample of 736 Chinese WWTPs.

Analyzing the marginal cost of reducing carbon emissions from WWTPs (Figure 7), the average values observed were 0.230 €/kg CO_2eq for biofilter, 0.444 €/kg CO_2eq for concentric, 0.222 €/kg CO_2eq for piston flow, 0.295 €/kg CO_2eq for carrousel, and 0.239 €/kg CO_2eq for complete mix systems. These results indicate that facilities using concentric technology as secondary treatment exhibit the highest average cost for GHG emissions reduction. Unlike the EcoEI indicator, the *p* value obtained from the Kruskal–Wallis test was 0.0017 ($p < 0.005$), confirming that the differences among technologies are statistically significant.

Although statistically significant differences in marginal abatement costs are observed across secondary treatment technologies, their practical relevance should be interpreted carefully. The differences in average costs are relatively modest in absolute terms and are therefore unlikely, on their own, to justify changes in technology choice or major retrofit investments. Such decisions are generally driven by long-term capital costs, regulatory obligations, plant size, and site-specific constraints rather than marginal carbon abatement costs alone.

From a policy and regulatory perspective, however, these cost differences are informative. They can support the development of technology-specific benchmarks and performance-based regulatory instruments aimed at promoting cost-effective emission reductions within existing facilities. In particular, regulators may use marginal abatement cost estimates to prioritize mitigation measures, differentiate incentives across technologies, and guide the allocation of public funds toward interventions that deliver the greatest emissions reductions per euro spent. This information is especially relevant in the context of climate-oriented wastewater regulation, where incremental efficiency improvements across a large number of plants can collectively yield substantial emission reductions.

3.5 | Policy Recommendations

The findings of this study have important implications for sustainability governance in the wastewater sector, particularly in light of the EU's transition toward climate-neutral and resource-efficient urban water services. By jointly estimating eco-efficiency and the marginal cost of reducing GHG emissions, the analysis provides an integrated evidence base to inform regulatory design, economic incentives, and sustainability monitoring frameworks. The results suggest that substantial heterogeneity exists across WWTPs in both operational performance and carbon mitigation costs, reinforcing the need for differentiated and performance-oriented policy approaches.

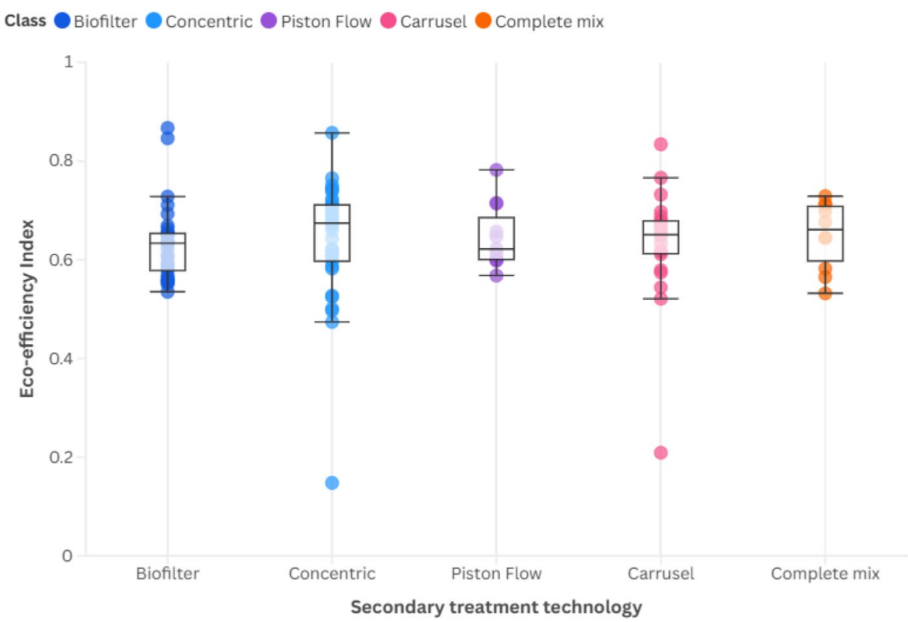

FIGURE 6 | Box plot of the estimated eco-efficiency index for wastewater treatment plants grouped by secondary treatment technology. *Source:* Own elaboration.

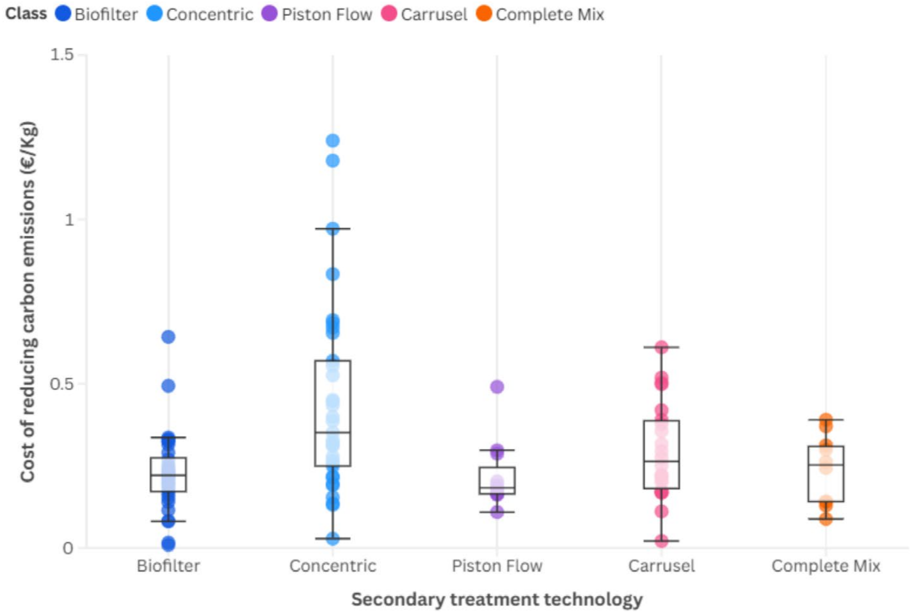

FIGURE 7 | Box plot of the estimated marginal cost of reducing carbon emissions for wastewater treatment plants grouped by secondary treatment technology. *Source:* Own elaboration.

The EcoEI developed in this study can serve as a regulatory benchmarking instrument to complement traditional compliance-based oversight focused primarily on effluent quality standards. While environmental regulation in the wastewater sector has historically emphasized discharge limits, achieving long-term sustainability requires integrating economic efficiency and climate performance into regulatory evaluation frameworks. Environmental improvements can be achieved through institutional innovation and performance-based governance mechanisms that incentivize efficiency and technological upgrading rather than relying solely on command-and-control instruments. In this context, the EcoEI offers regulators a composite, data-driven metric that captures the joint performance of WWTPs in terms of cost efficiency, pollutant removal, and carbon emissions. Because the index is derived from a stochastic frontier approach that accounts for statistical noise, it provides a robust basis for benchmarking utilities operating under heterogeneous conditions.

Incorporating the EcoEI into regulatory practice could support the design of incentive-compatible tariff frameworks, where utilities demonstrating sustained improvements in eco-efficiency are rewarded through regulatory recognition, financial incentives, or accelerated approval of investment plans. Such performance-based regulation would align economic and environmental objectives, encouraging utilities to optimize operational processes while reducing emissions. This approach is particularly relevant under Directive 2024/3019, which calls for enhanced cost-effectiveness and climate performance in urban wastewater treatment.

The estimation of plant-level marginal abatement costs of GHG emissions provides critical information for the design of climate-aligned economic instruments. Carbon pricing theory suggests that emission reductions should occur where marginal abatement costs are lowest, thereby ensuring cost-effective climate mitigation. The substantial variation observed in marginal costs across WWTPs indicates differentiated mitigation potential within the sector. Although only a limited share of plants currently exhibit abatement costs below prevailing EU ETS prices, the results highlight the strategic importance of reducing operational inefficiencies to lower marginal costs and enhance future participation in carbon markets. From a transition economics perspective, early investments in efficiency improvements can reduce long-term adjustment costs and accelerate alignment with tightening climate policies and rising carbon prices.

Regulators and policymakers may therefore consider integrating carbon pricing signals into wastewater governance frameworks, either directly through inclusion in trading schemes or indirectly through shadow carbon pricing in investment appraisal. Public funding mechanisms could prioritize projects that demonstrate both low marginal abatement costs and high eco-efficiency gains, thereby maximizing emissions reductions per euro invested. Such alignment between infrastructure planning and carbon pricing mechanisms supports a smoother transition toward climate-neutral public services.

The integration of eco-efficiency and carbon abatement indicators into regulatory frameworks also contributes to broader sustainable development objectives, particularly SDG 6 (Clean Water and Sanitation) and SDG 13 (Climate Action). While SDG 6 traditionally focuses on access and water quality, achieving sustainable sanitation services increasingly requires consideration of energy use and climate impacts. Similarly, SDG 13 calls for integrating climate measures into national policies and planning, which includes emissions from essential public infrastructure.

To support these objectives, standardized and transparent GHG reporting in the wastewater sector is essential. The present analysis relies on indirect emissions due to data limitations, underscoring the need for comprehensive monitoring systems covering both Scope 1 (process-related) and Scope 2 (energy-related) emissions. Regulators could mandate harmonized reporting protocols and develop centralized emissions databases to facilitate benchmarking, public transparency, and integration into national GHG inventories.

Enhanced data governance would not only improve accountability but also enable evidence-based policymaking and cross-sectoral learning. Transparent performance metrics can strengthen stakeholder trust, support informed tariff-setting decisions, and encourage continuous improvement within utilities. In this sense, eco-efficiency measurement becomes part of a broader sustainability monitoring architecture linking operational management to national and European climate commitments.

The results of this study generate implications at different temporal scales, which should be analytically distinguished. In the short term, improvements in eco-efficiency translate into operational cost savings and incremental reductions in indirect GHG emissions. Plants operating below the efficiency frontier can achieve measurable gains through process optimization, energy efficiency measures, and improved operational management. Similarly, marginal abatement cost estimates provide immediate signals regarding the cost-effectiveness of emission reduction strategies within existing technological configurations. However, long-term systemic sustainability implications extend beyond incremental efficiency gains. Over time, sustained performance benchmarking and carbon pricing signals may influence infrastructure investment decisions, technology adoption pathways, and regulatory evolution. As carbon constraints tighten and energy systems decarbonize, the relative economics of wastewater treatment technologies are likely to shift. In this context, eco-efficiency measurement becomes part of a broader transition dynamic, supporting structural adjustments toward climate-neutral and resource-efficient urban water systems.

4 | Conclusions

Assessing the eco-efficiency of WWTPs is essential for enhancing their economic and environmental performance, while also contributing to the reduction of carbon emissions. This study evaluated the eco-efficiency and the marginal cost of reducing GHG emissions for 108 WWTPs in Spain using a parametric approach based on SFA. The first key contribution of the study was the development of an EcoEI that integrates operational expenditure, pollutant removal, and GHG emissions into a single composite measure. The estimated average EcoEI was 0.638 on average. None of the facilities in the sample achieved full eco-efficiency, and even the best-performing facilities exhibited performance gaps of up to 13%. These results are consistent with previous studies but highlight that substantial efficiency gains remain untapped.

The second major contribution was the estimation of the marginal cost of reducing GHG emissions at the plant level. On average, WWTPs would need to incur an additional €0.309 in operating costs to avoid emitting 1 kg of CO_2eq. However, the results show considerable variability across facilities, with marginal abatement costs ranging from €0.010 to €1.240 per kg CO_2eq. This variation is critical for understanding the feasibility of carbon reduction strategies and for assessing the economic viability of WWTP participation in voluntary carbon markets.

Another important finding relates to the influence of secondary treatment technologies on both eco-efficiency and GHG reduction costs. Although no statistically significant differences were found across technologies in terms of EcoEI, the Kruskal–Wallis test showed significant differences in marginal abatement costs. In particular, WWTPs using concentric systems reported the highest average GHG reduction costs. These findings underscore the need to consider technology-specific factors in both operational planning and regulatory design.

Despite the robustness of the methodology and relevance of the findings, several limitations should be acknowledged. First, the analysis is based on a cross-sectional sample of WWTPs from a single Spanish region. Although this choice ensures regulatory and institutional consistency, it may limit the external validity of the results for contexts characterized by different energy systems, regulatory frameworks, or climate policies. It should be noted that carbon abatement costs and eco-efficiency depend on local factors such as electricity prices, energy mix, regulation, and technology. While the specific numerical results may not be directly transferable to other regions, the methodological framework can be replicated elsewhere. Second, the analysis relies on data for a single year (2022). Eco-efficiency and carbon abatement costs are likely to evolve over time due to technological learning, investment decisions, and energy price volatility. Future research should therefore extend the analysis to panel data settings and multi-regional or cross-country samples to capture dynamic effects and enhance the generalizability of the findings. Another relevant limitation of this study relates to the accounting of GHG emissions. Due to data availability constraints, the analysis only incorporates indirect emissions associated with electricity consumption during wastewater treatment (Scope 2 emissions). Direct process emissions, particularly methane (CH_4) and nitrous oxide (N_2O) generated during biological treatment processes, were not included. These emissions can represent a significant share of the overall carbon footprint of WWTPs and may vary considerably depending on operational conditions, treatment technology, and plant design. As a result, the marginal abatement cost estimates presented in this study should be interpreted as reflecting the cost of reducing indirect energy-related emissions rather than the full carbon footprint of wastewater treatment operations. In addition, the estimation relies on a single emission factor for electricity generation, which may not fully capture temporal variability in the energy mix. Future research should aim to incorporate comprehensive carbon accounting frameworks including both Scope 1 and Scope 2 emissions, as well as plant-specific emission measurements, to provide more precise estimates of carbon abatement costs in wastewater treatment systems. Moreover, although this study focuses on the influence of secondary treatment technology, eco-efficiency in WWTPs may also be affected by other factors such as plant size and economies of scale, influent characteristics, and capacity utilization rates. Thus, future research should aim to incorporate these factors using richer and preferably panel datasets to better capture their influence on eco-efficiency dynamics.

Beyond the wastewater sector, the analytical framework developed in this study contributes to broader debates on how infrastructure-intensive public services can align operational efficiency with climate neutrality objectives. As cities and utilities transition toward low-carbon systems, integrated performance metrics that jointly evaluate economic and environmental outcomes will become increasingly central to sustainable development policy and governance.

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Endnotes

[1] A carbon credit represents the reduction, avoidance or removal of one metric tonne of CO_2eq (Show and Lee 2008).

[2] Piston flow: A treatment configuration in which wastewater flows sequentially through the reactor with limited mixing, creating concentration gradients that can enhance biological treatment efficiency; concentric: a fully mixed activated sludge system where wastewater and biomass are uniformly mixed, providing stable treatment conditions but potentially higher energy consumption; biofilter: a fixed-film biological treatment process in which microorganisms grow on a solid medium, allowing pollutant removal as wastewater passes through the filter; Carousel: an extended aeration activated sludge system characterized by a circular channel, designed for stable operation and effective nutrient removal and; Complete mix: an activated sludge system with intensive mixing, ensuring uniform conditions throughout the reactor and consistent treatment performance.

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