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Assessment of carbon efficiency in wastewater treatment plants through Stochastic non-parametric data envelopment analysis (StoNED): Insights from Spanish facilities

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ABSTRACT

Evaluating the carbon efficiency (CE) of wastewater treatment plants (WWTPs) is crucial for guiding these facilities towards carbon neutrality. Nevertheless, enhancing carbon performance ought not to be pursued to the detriment of pollutant removal efficiency. In this study, the CE of WWTPs is calculated as a composite index that integrates carbon emissions with the volume of pollutants removed from wastewater, including organic matter, suspended solids, nitrogen, and phosphorus. To achieve this, the Stochastic Non-parametric Envelopment of Data (StoNED) method is employed. This approach, distinct from the commonly used Data Envelopment Analysis (DEA), accounts for both empirical data and random variations in the estimation of CE, thereby enhancing the reliability of the CE evaluation. The study assesses the CE of 109 Spanish WWTPs, finding that none of them are fully carbon efficient. This involves that all plants have potential to reduce greenhouse gas emissions without sacrificing pollutant removal efficiency. The average CE of the WWTPs is 0.529, indicating a possible reduction in carbon emissions by approximately 0.076 kg of CO_2 equivalent per cubic meter of wastewater treated. The analysis also reveals that neither the volume of wastewater treated nor the type of reactor used for secondary treatment has a significant impact on the CE of the facilities. The CE metric proposed in this study serves as an important decision-support tool for advancing towards the carbon neutrality of wastewater treatment processes. By providing a more comprehensive understanding of the environmental performance of WWTPs, it helps identifying areas for improvement and guiding policy and operational decisions.

1. Introduction

High-standard wastewater treatment is essential to remove pollutants prior to safe environmental discharge. Untreated sewage released into water ecosystems such as rivers and seas can significantly damage them (Feng et al., 2022). Such practices contravene the Sustainable Development Goals, specifically Goal 6, which emphasizes the critical role of wastewater treatment in fostering a sustainable and healthy environment (United Nations, 2015). However, the energy-intensive nature of wastewater treatment is well-documented (Huang et al., 2021), with wastewater treatment plants (WWTPs) accounting for over 20% of electrical consumption in local authorities (Longo et al., 2016). This energy use has substantial implications for greenhouse gas (GHG) emissions, especially in areas predominantly reliant on non-renewable energy sources (Cardoso et al., 2021).

The necessity to curtail GHG emissions is formally acknowledged in the Proposal for a Directive of the European Parliament and of the Council concerning Urban Wastewater Treatment (UE, 2023). This proposal aims to align the reduction of GHG emissions from wastewater with the objectives of the European Green Deal and the RePower EU Plan, underlining the urgency to address the environmental impacts of wastewater management. Understanding the current carbon efficiency (CE) of WWTPs is instrumental in quantifying the potential for reducing GHG emissions in these facilities (Xi et al., 2023). This approach aims to achieve GHG reductions without sacrificing the quality of the treated effluent. In essence, it involves diminishing GHG emissions while

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ensuring that the level of pollutants removed from the wastewater remains consistent, thereby minimizing the environmental impact of the treatment processes (Sala-Garrido et al., 2023). This strategy is in line with the overarching objectives of sustainable wastewater management, which focuses not only on adhering to treatment standards but also on reducing the carbon footprint associated with the treatment process. Such a dual focus is increasingly recognized as a critical component of environmental sustainability in wastewater management (Gémar et al., 2018; Chen et al., 2023).

Because of the relevance of this topic, some previous studies have assessed the eco-efficiency of WWTPs from a multi-dimensional perspective, i.e., integrating carbon emissions, quantity of pollutants removed and operational costs into a synthetic index. Although these assessments uniformly employ the Data Envelopment Analysis (DEA) technique, they vary in the complexity of the models applied. Some earlier studies (Molinos-Senante et al., 2014; Xi et al., 2023) utilized the most fundamental DEA model. In contrast, others like Molinos-Senante et al. (2016) and Gémar et al. (2018) adopted a non-radial DEA approach. Further research (Dong et al., 2017; Gómez et al., 2018; Ramírez-Melgarejo et al., 2021; Ferreira et al., 2023; Afonso et al., 2024) introduced elements of uncertainty in the eco-efficiency assessment. Cross-efficiency techniques were also employed in the eco-efficiency assessment of WWTPs (Mocholi-Arce et al., 2020; Sala-Garrido et al., 2023). Additionally, the temporal dimension has been considered in recent research, as evidenced by Fallahiarezoudar et al. (2022) and Chen et al. (2023).

Despite this diversity in models, all these studies share the general limitations inherent in the DEA methodology. As a non-parametric method, DEA is deterministic and does not account for noise in the estimation, implying that any deviation from the efficiency frontier is attributed solely to inefficiency. Moreover, DEA does not allow for the statistical significance evaluation of estimated parameters (Molinos-Senante and Maziotis, 2022). The identified limitations of the DEA underscore the necessity for alternative methodological approaches to assess the CE of WWTPs. In contrast to DEA, parametric methods such as Stochastic Frontier Analysis (SFA) account for both inefficiency and statistical noise. However, a major limitation of SFA is the need to specify a functional form, such as Cobb-Douglas or Translog, for the production technology. Moreover, the results are highly sensitive to the assumed distribution of inefficiency, such as half-normal, exponential, or gamma distributions (Murwirapachena et al., 2024). Equally, the Stochastic Non-parametric Envelopment of Data (StoNED) method, pioneered by Johnson and Kuosmanen (2011), stands out as a significant advancement. The StoNED method effectively addresses some of the shortcomings of DEA by incorporating a stochastic element into the non-parametric efficiency analysis.

The StoNED methodology merges econometric techniques with linear programming. This approach employs non-linear programming to delineate the frontier's form, specifically to determine the coefficients of variables. It then postulates about the distribution of inefficiency and noise to ascertain efficiency scores for each unit (Kuosmanen et al., 2013; Cheng et al., 2015). This method incorporates both inefficiency and noise elements. Analogous to DEA, StoNED does not necessitate a predefined functional form for the production technology. Additionally, it maintains the principles of convexity, monotonicity, and returns to scale (Kuosmanen and Kortelainen, 2012).

In the context of assessing the performance of water utilities, Murwirapachena et al. (2024) evaluated the efficiency of a sample of water utilities in South Africa using DEA, SFA, and StoNED. They concluded that the StoNED approach is most suitable for samples with high heterogeneity. This aligns with our case study, which includes over 100 WWTPs varying significantly in reactor type for secondary treatment and in size. Conversely, Lin and Lu (2024) explored the performance assessment of cities' cultural regeneration using chance-constrained data envelopment analysis (CCDEA), StoNED, and bootstrap methods, finding that both CCDEA and bootstrap methods are appropriate in contexts with data or industry uncertainty. However, this does not apply to the wastewater treatment sector, where data tends to be robust. Instead, the StoNED method proves valuable in industries or processes where external factors, such as water demand, significantly impact performance (Lin and Lu, 2024).

Originally devised for efficiency evaluation in the Finnish electricity sector (Kuosmanen, 2012; Saastamoinen and Kuosmanen, 2016), the StoNED method has been adopted in various other industries due to its advantageous attributes. This includes applications in the port sector (Rødseth et al., 2024), solar power energy (Delnava et al., 2023), and domestic water supply (Maziotis et al., 2023). Within the context of wastewater treatment, there is a solitary study employing the StoNED method, which concentrated on the influence of age and technology on the energy efficiency of WWTPs (Molinos-Senante and Maziotis, 2022). However, the efficiency assessments carried out using this method have not incorporated variables pertaining to carbon emissions.

The primary aim of this study is to evaluate the CE of a sample of WWTPs using the StoNED method. Unlike past research based on the DEA method, the StoNED approach provides a more robust and reliable framework for analyzing CE in WWTPs. It yields insights that are not solely reliant on empirical data but are also adjusted for random fluctuations, thereby augmenting the precision and trustworthiness of the efficiency evaluation. This methodological advancement represents a notable progression in appraising WWTPs, facilitating a more thorough and realistic examination of their carbon performance. Additionally, this study quantifies the potential carbon emission reductions for each evaluated facility. The empirical analysis is centered on a dataset comprising 109 Spanish WWTPs for the year 2021.

2. Methodology

This section outlines the procedural steps undertaken to estimate the CE of the assessed WWTPs utilizing the StoNED methodology. The initial phase in the StoNED technique involves establishing the objective function, which, for this investigation, is identified as the carbon frontier function:

$$lnC_i = ln(a_i + \beta_i y_i) + \varepsilon_i \tag{1}$$

where ln stands for logarithm, C denotes carbon emissions, i is the WWTP evaluated, a presents the constant term (intercept), y is a vector of outputs generated in WWTPs. As we discuss in the next section, outputs include the quantity of different pollutants removed during the wastewater treatment process. We note that in Eq. (1), β_i is a parameter to be estimated. ε_i is the composite error term of the frontier model. The error term includes two parts, inefficiency, u_i and noise, v_i which follow the normal distribution and the standard normal distribution, respectively (Kuosmanen and Kortelainen, 2012). In other words, $\nu_i \sim N(0, \sigma_\nu^2)$ and $u_i \sim N^+(0, \sigma_u^2)$, where σ_ν^2 and σ_u^2 denote the variance of noise and inefficiency, respectively. Inefficiency has an expected value which is presented by $E(u) = \mu$. It is directionally proportional to the parameter $\sigma_u : \mu = \sigma_u \sqrt{\frac{2}{\pi}}$ (Aigner et al., 1977), where σ_u shows the standard deviation of inefficiency.

To estimate the parameters of Eq. (1), the convex nonparametric least squares (CNLS) techniques, i.e., a non-linear programming method was employed (Eq. (2)). CNLS identifies the function that best fits the data from the family of continuous, monotonic increasing, concave functions that can be non-differentiable (Kuosmanen and Kortelainen, 2012):

$$\min_{\alpha,\beta} \sum_{i=1}^{I} \varepsilon_i^2 \tag{2}$$

subject to:

$$lnC_i = ln(a_i + \beta_i y_i) + \varepsilon_i \quad i = 1, \ldots, I;$$

$\delta_i = a_i + \beta_i y_i \geq a_j + \beta_j y_i \quad i,j = 1, \ldots, I;$

$\beta_i \geq 0 \quad i = 1, \ldots, I$

The first constraint in Model (2) is the carbon emissions regression equation. We note that the β coefficients can be viewed as marginal products, analogous to the multiplier weights in a linear programming framework within DEA (Eskelinen and Kuosmanen, 2013). The difference is that the coefficients β_i are specific to each treatment plant while coefficients in DEA method are only explicit to each input. The constant term a presents the scale of operations of wastewater treatment process. It is set $a_i = 0$, under the assumption that WWTPs are functioning at their optimal scale size. The second constraint in Model (2) ensures convexity of the carbon function with outputs which means that when carbon emissions reach its optimal levels then outputs will incur small increases.

Finally, the last constraint guarantees monotonicity in outputs (Johnson and Kuosmanen, 2011, 2012), aligning these constraints with the foundational assumptions of DEA (Saastamoinen and Kuosmanen, 2016).

The subsequent phase entails calculating the CE scores, achieved by adopting specific distributional assumptions for the inefficiency and noise terms, which are assumed to follow half-normal and standard normal distributions, respectively. According to Kuosmanen (2012), Kuosmanen et a. (2013), and Kuosmanen et al. (2015), the method of moments is then applied to estimate the expected value of inefficiency along with the variances of both inefficiency and noise terms. Analogous to SFA, the StoNED methodology incorporates Jondrow et al.'s (1982) technique for determining the expected inefficiency value, described as follows:

$$E(u_i|\varepsilon_i) = \mu_* + \sigma_* \left[\frac{\phi\left(-\frac{\mu_*}{\sigma_*}\right)}{1 - \Phi\left(-\frac{\mu_*}{\sigma_*}\right)} \right] \tag{3}$$

where ϕ is the standard normal density function and Φ is the standard normal cumulative distribution function, $\mu_* = -\varepsilon_i \sigma_u^2 / (\sigma_u^2 + \sigma_v^2)$ and $\sigma_*^2 = \sigma_u^2 \sigma_v^2 / (\sigma_u^2 + \sigma_v^2)$ (Kuosmanen and Kortelainen, 2012). The estimated inefficiency value $\widehat{u}_i$ is subsequently used to calculate the CE score for any WWTP i as follows:

$$CE_i = \exp(-\widehat{u}_i) = \exp\left(E(u_i|\varepsilon_i)\right) \tag{4}$$

CE_i vary between zero and one. A score of one signifies complete efficiency in terms of carbon emissions for the WWTP, indicating optimal performance in comparison to its peers. Scores below one highlight carbon inefficiency, suggesting the possibility for reduction in carbon emissions while maintaining the level of pollutants removed from the wastewater unchanged.

Since GHG emissions are incorporated as inputs in the assessment, utilizing the CE scores derived from Equation (4), the potential carbon emission reductions achievable by a plant, should it operate at full carbon efficiency, are calculated in the following manner:

$$PCS_i = AC_i \times (1 - CE_i) \tag{5}$$

where PCS_i denote the potential savings in carbon emissions (kg/m^3 wastewater), AC_i are the actual (observed) levels of carbon emissions for each WWTP i (kg/m^3 wastewater) and CE_i is the CE efficiency score obtained from the StoNED approach.

3. Case study and data sample

The identification of outliers and atypical observations is crucial for assessing the relative performance of units, such as WWTPs (De Witte and Marques, 2010a). A peer index approach (De Witte and Marques, 2010b) was applied to the original database comprising 147 WWTPs to identify atypical observations. As a result, 38 WWTPs identified as outliers and therefore, were removed from the database leading to a total of 109 WWTPs whose carbon efficiency was evaluated.

Data from 109 Spanish WWTPs were collected through a regional water authority, i.e., Catalan Water Agency. All evaluated facilities are located in the Catalonia region, situated in the northeast of Spain. They are operated by both private companies and public entities. Regardless of the operator, all facilities are regulated by the Catalan Water Agency in accordance with the European Urban Wastewater Directive (91/271/ECC). All evaluated facilities incorporate a standard treatment sequence comprising pretreatment, primary treatment, and secondary treatment stages. The distinctions among them primarily lie in the specific technology utilized for secondary treatment. Thirty-three facilities, constituting 30.3% of the total, employ piston flow technology for secondary treatment. An identical number of WWTPs utilize a concentric reactor design for this stage, while 22 facilities, representing 20.2% of the sample, adopt the carousel modality. Additionally, 16 WWTPs, or 14.7% of the total, operate based on the complete mix approach, and 2 facilities, accounting for 1.8% of the sample, utilize biofilters for secondary treatment. All WWTPs remove 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 assessed WWTPs vary significantly in size, with capacities ranging from 7844 m^3 per year to 121,095,795 m^3 per year. The average capacity of these facilities is approximately 4,104,880 m^3 per year.

The choice of variables in this research was guided by the primary aim of the study, namely, the assessment of CE of WWTPs, along with insights from previous studies (Ramírez-Melgarejo et al., 2021; Chen et al., 2023) and the availability of data. Given that the principal function of WWTPs is to remove pollutants from wastewater, a collection of quality-adjusted outputs (Equation (6)) was incorporated into the estimation of CE:

$$PR_{ij} = WV_j * \left(Pollutant_{iij} - Pollutant_{eij}\right) \tag{6}$$

where PR_{ij} denotes the per annum quantity of pollutants removed when treating wastewater for each pollutant j and WWTP i measured in kg/year; WV_i presents the volume of treated wastewater by the WWTP i measured in m^3/year; $Pollutant_{iij}$ captures the concentration of each pollutant j in the influent (i) of the WWTP i measured in kg/m^3 and $Pollutant_{eij}$ captures the concentration of each pollutant j in the effluent (e) of the WWTP i measured in kg/m^3. Reflecting the primary pollutants extracted from wastewater in the evaluated facilities, our study encompasses four quality-adjusted outputs, specifically: i) organic matter (expressed as chemical oxygen demand, COD), SS, N and P.

Regarding the input, our evaluation concentrated on indirect GHG emissions linked to the electricity usage in WWTPs, quantified in kilograms of CO_2 equivalent per year (kg CO_{2eq}/year). Statistical data on indirect GHG emissions for each assessed WWTP were provided by the Catalan Water Agency, the regulatory body for all facilities analyzed in this study. These emissions were calculated based on the carbon emission factor for electricity production in 2022, which stood at 273 gCO_{2eq}/kWh (Gencat, 2024). It is important to note that all WWTPs evaluated exclusively utilize electricity sourced from the external grid. There was an absence of statistical information on direct GHG emissions for the WWTPs under consideration. This represents a limitation of the current study, which could potentially be addressed in future research if WWTPs commence monitoring and gathering data on direct GHG emissions.

The descriptive statistics of the variables employed in the study are reported in Table 1.

Table 1
Descriptive statistics of the WWTPs evaluated.

Variable	Unit of measurement	Average	Std. Dev.	Minimum	Maximum
Indirect carbon emissions	$kgCO_{2eq}$/year	411,307	1,275,428	2338	10,039,318
COD removed	kg/year	2,791,539	11,680,492	2567	106,021,387
SS removed	kg/year	1,504,366	6,932,355	893	67,171,650
N removed	kg/year	149,680	536,491	163	4,152,857
P removed	kg/year	35,558	164,284	16	1,506,131

4. Results and discussion

4.1. Carbon frontier function estimation

As we discussed in the methodology section, the first step to estimate CE of WWTPs is estimating the carbon frontier function (Eq. (1)). The estimated coefficients (β) for the quality-adjusted outputs (y)) are detailed in Table 2. These coefficients are all statistically significant from zero, indicating that for the WWTPs evaluated, an increase in the quantity of pollutants removed from wastewater correlates with higher carbon emissions. According to the estimated parameters' magnitudes, the removal of organic matter from wastewater has a notably high impact on carbon emission levels. The findings suggest that a 1% increase in the removal of organic matter (COD) and SS from wastewater is associated with a rise in GHG emissions by 0.312% and 0.283%, respectively. Additionally, the removal of N and P from wastewater is also found to affect carbon emissions, with a 1% increase in the removal of P and N leading to a 0.244% and 0.125% increase in carbon emissions, respectively.

Results shown in Table 2 are aligned with the findings of Longo et al. (2016), who, based on an analysis of 601 WWTPs, evidenced that the removal of organic matter and nutrients predominantly drives the energy consumption in WWTPs. It is important to recognize that the production of electricity through conventional (non-renewable) energy sources entails GHGs emissions and therefore, the operation of WWTPs embraces carbon emissions as they are energy intensity facilities (Ramírez-Melgarejo et al., 2021). The results presented in Table 2 corroborate that an increased removal of pollutants from wastewater leads to higher carbon emissions levels. This finding underscores the importance of evaluating the environmental impact of wastewater treatment from a life cycle perspective, incorporating various environmental impact categories (Li et al., 2021). Within this framework, it is crucial for wastewater managers and regulators to adopt a range of policies and strategies aimed at achieving carbon neutral WWTPs, including reducing energy consumption, recovering energy from organic matter, and utilizing electricity generated from renewable sources (Li et al., 2022).

4.2. Carbon efficiency estimations

The CE scores for each WWTP assessed are depicted in Fig. 1. A significant observation from the analysis is that no facility is carbon efficient, with the highest CE score being 0.670 for WWTP16. This indicates a universal potential for enhancement in CE across all evaluated

Table 2
Estimates of the coefficients of the carbon production function (Eq. (1)).

Variable	Coef (β)	St.Error	T-stat	P-value
Volume of COD removed	0.312	0.083	**3.759**	0.000
Volume of SS removed	0.283	0.094	**3.011**	0.003
Volume of P removed	0.244	0.041	**5.951**	0.000
Volume of N removed	0.125	0.031	**4.032**	0.000
R^2	0.860			

The dependent variable is the GHG emissions.
Bold indicates that coefficients are statistically significant at 5% significance level.

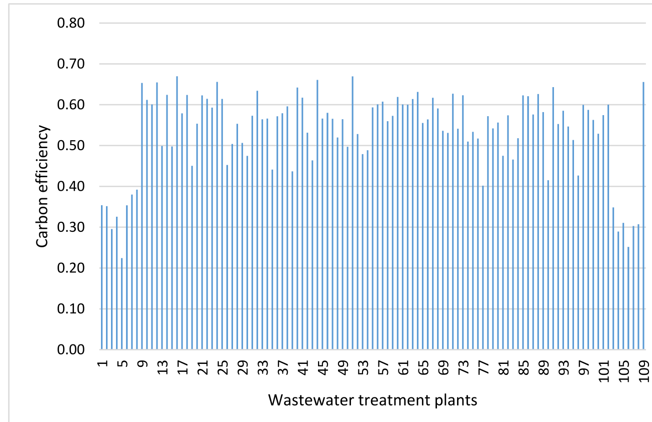

Fig. 1. Carbon efficiency of the 109 wastewater treatment plants evaluated.

WWTPs. WWTP16, characterized as a medium-sized facility, treats approximately 1 million cubic meters of wastewater annually and is situated in a nitrate vulnerable zone, hence exhibiting a high N removal efficiency. Conversely, WWTP5, which records the lowest CE score of 0.224, is another medium-sized facility with an annual treatment capacity of about 1.4 million m^3. Its location is in a touristic region leads to significant variations in monthly wastewater flows, likely contributing to its reduced CE. The mean CE score across the WWTPs stands at 0.529, suggesting an average potential to reduce GHG emissions by 47% while maintaining the current pollutant removal levels.

To gain deeper insights into the distribution of CE scores among the evaluated WWTPs, an examination of Fig. 2 is essential. The findings reveal that a majority of the WWTPs, 68 out of 109 (equating to 62%), registered CE scores within the range of 0.41–0.60. This indicates that these facilities need to reduce their GHG emissions by 40%–59% to be carbon efficient. Additionally, 26 plants, representing 24% of the total, exhibited moderate carbon performance, with CE scores spanning from 0.61 to 0.80. Notably, this segment constitutes the facilities with the highest CE scores among all the WWTPs assessed. On the lower end of

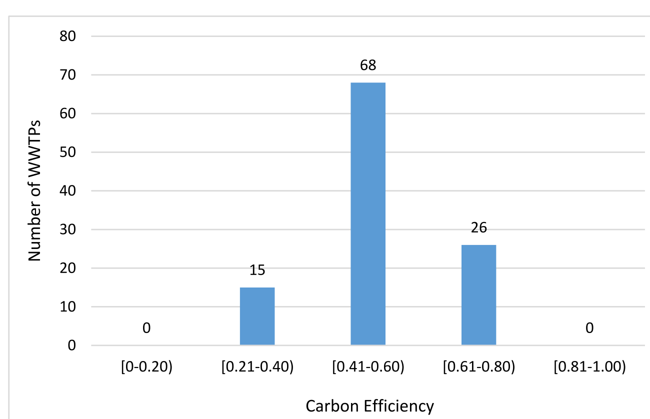

Fig. 2. Distribution of carbon efficiency scores across WWTPs.

the spectrum, 15 plants (or 14%) displayed poor carbon performance, with CE scores between 0.21 and 0.40. Overall, these results underscore the suboptimal carbon performance of the wastewater treatment processes across the assessed WWTPs, highlighting that even the best performers have significant potential for GHG emission reductions.

In the pursuit of a circular economy and carbon neutrality, WWTPs are incorporating innovative combined technologies. For instance, the WWTP in Brunswick, Germany, exemplifies advanced resource recovery. This facility employs a thermal hydrolysis process that not only removes phosphorus and nitrogen from the return load of the sludge liquor but also facilitates the recovery of phosphorus to produce struvite and the recovery of nitrogen to produce ammonium sulfate solution. This process not only reduces waste but also generates renewable fertilizers and biogas, illustrating a shift towards producing valuable byproducts (Kleyböcker et al., 2024). Additionally, the integration of cutting-edge digital tools is transforming traditional wastewater management approaches. Technologies such as the Internet of Things, cloud computing, big data analytics, artificial intelligence, blockchain, robotics, and digital twins are being deployed to enhance the automation and control of treatment processes. These technologies support more efficient operations and foster a transition from conventional wastewater treatment to resource recovery facilities, which are foundational to a sustainable and circular economy-based approach (Cairone et al., 2024).

While the WWTPs analyzed in this study exhibit suboptimal performance in terms of carbon emissions, these findings are in alignment with existing literature. Employing machine learning and non-parametric techniques for a sample of Spanish WWTPs, Maziotis and Molinos-Senante (2023) concluded that operating costs and GHG emissions could be reduced by 62.7% to maintain the same level of wastewater services. Similarly, other studies assessing the eco-efficiency of Spanish WWTPs through non-parametric methods have reported modest eco-efficiency scores. For example, Molinos-Senante et al. (2014), Gómez et al. (2018), and Mocholi-Arce et al. (2020) recorded average eco-efficiency scores of 0.598, 0.454, and 0.480, respectively. In the context of Chinese facilities, Dong et al. (2017) noted an average eco-efficiency score of 0.619 across 736 WWTPs, while Chen et al. (2023) calculated an average eco-efficiency of 0.59 for a sample of 225 WWTPs. A further decline in CE was highlighted by Xi et al. (2023), who reported an average score of 0.24 for over 1000 Chinese WWTPs. Consequently, our findings resonate with those from previous studies, indicating a consistent pattern of CE across different regions. The variation in CE scores can be attributed to the analytical methods employed. Previous studies predominantly utilized non-parametric techniques for evaluating the performance of wastewater treatment processes, whereas our study innovatively combines non-parametric with parametric methods, marking a novel approach in this field of research.

Previous studies (Dong et al., 2017; Chen et al., 2023), have demonstrated the influence of technology and the volume of wastewater treated on the eco-efficiency of WWTPs. Consequently, the 109 facilities examined in this research were classified based on the type of secondary treatment technology employed, given that all WWTPs share similar pretreatment and primary treatment processes. Fig. 3 illustrates the average CE scores for each group of WWTPs, categorized by their respective technology. The findings reveal minor variations in CE across the different wastewater treatment technologies, with average values fluctuating between 0.517 and 0.545. To validate these observations statistically, a Kruskal-Wallis H test for independent samples was conducted to assess if there were significant differences in mean CE scores across the five technology groups. The derived $p-$ value exceeded 0.05, indicating that the differences in average CE scores among the five groups are not statistically significant, thus supporting the initial observation of negligible differences in CE across the technologies.

Focusing on the size of the WWTPs, the volume of wastewater treated by the evaluated facilities ranges between 7844 m^3/year and 121,095,795 m^3/year with an average value of 4,104,880 m^3/year.

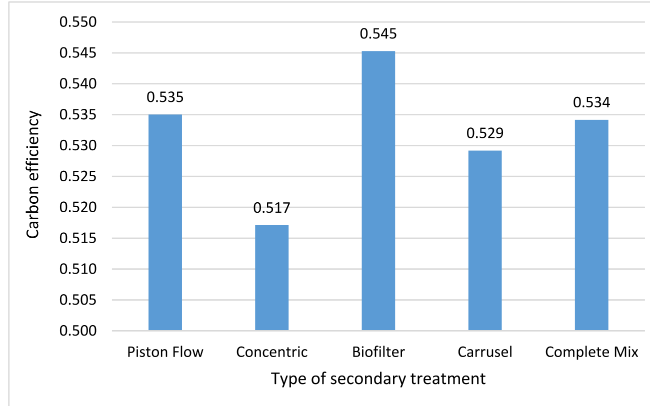

Fig. 3. Average carbon efficiency scores of wastewater treatment plants based on the type of secondary treatment.

Based on the distribution of WWTPs' capacity, the following categories were established: i) facilities treating less than 100,000 m^3/year (n = 18); ii) those treating between 100,000 and 500,000 m^3/year (n = 29); iii) those treating between 500,000 and 2,000,000 m^3/year (n = 29); iv) those treating between 2,000,000 and 8,000,000 m^3/year (n = 23); and v) those treating more than 8,000,000 m^3/year (n = 10).

Fig. 4 presents the average CE for each category based on the volume of wastewater treated. The range of these average CE scores is from 0.417 to 0.569. However, similar to the findings regarding reactor type, the Kruskal-Wallis H test's value exceeded 0.05. This outcome implies that the null hypothesis cannot be rejected, involving that the differences in CE among the different size categories of WWTPs are not statistically significant. Therefore, the study concludes that, irrespective of the plant size, the variance in CE is not considerable enough to be deemed statistically meaningful. This finding indicates that, unlike variables such as energy use or operational costs, the assessed WWTPs did not demonstrate economies of scale with respect to carbon efficiency. A plausible explanation for this discrepancy lies in the composition of the synthetic indicator used in our analysis. Unlike traditional measures that focus solely on energy use or carbon emissions, our indicator also includes pollutants' removal efficiency. This aspect introduces additional variability that may be influenced by factors not directly related to scale, thereby affecting the expected economies of scale in carbon efficiency.

4.3. *Potential carbon emission savings*

Using the current carbon emissions data and the estimated CE scores for each WWTP as defined in Eq. (5), the potential carbon emissions per

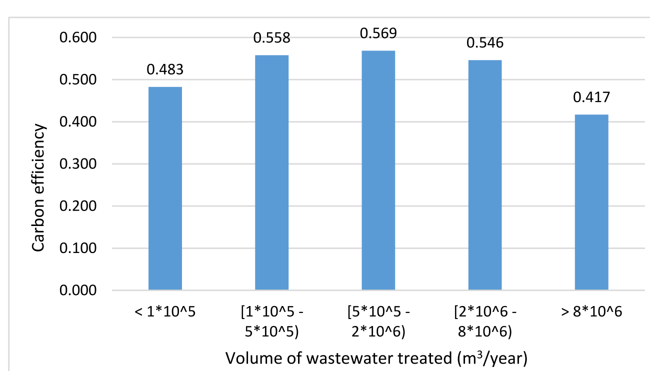

Fig. 4. Average carbon efficiency scores of wastewater treatment plants based on the volume of wastewater treated.

cubic meter of treated wastewater were calculated for each individual facility (Fig. 5). The average potential emission reduction across the 109 evaluated facilities is estimated at 0.076 kg CO_{2eq}/m^3 wastewater. This implies that, on average WWTPs could potentially reduce GHG emissions by 0.076 kg for every cubic meter of wastewater treated. There is a notable variance in the potential emission reductions among the evaluated WWTPs, with the lowest being 0.001 Kg CO_{2eq}/m^3 and the highest reaching 0.419 Kg CO_{2eq}/m^3. According to Eq. (5), these differences are primarily attributable to the varying quantities of pollutants removed from the wastewater in each facility. Considering the total volume of wastewater treated by all the evaluated facilities, the total potential reduction in carbon emissions is estimated to be approximately 19,284 tons per year. Reducing these carbon emissions could represent a significant step towards diminishing GHG emissions from urban wastewater collection and treatment processes, as encouraged by the Proposal for a Directive of the European Parliament and of the Council concerning urban wastewater treatment (UE, 2023). Furthermore, achieving these reductions in GHG emissions from wastewater treatment processes could contribute significantly towards meeting Spain's 2030 GHG reduction targets, which are set at a 27% reduction compared to 1990 levels (UE, 2023). This approach not only aligns with environmental regulatory goals but also advances broader efforts to mitigate climate change impacts.

This study assesses the carbon efficiency of WWTPs focusing on indirect GHG emissions associated with electricity use in WWTPs. However, these facilities also present direct GHG emissions. On the one hand, direct CO_2 emissions are considered carbon neutral due to their biogenic nature (Zhou et al., 2022). On the other hand, non- CO_2 direct emissions such as CH_4 and N_2O are relevant due to their high global warming potential (Campos et al., 2016). According to a literature review by Maktabifard et al. (2023), approximately 30% of total GHG emissions from WWTPs are indirect, with the remainder being direct emissions. These proportions, however, may vary based on site-specific factors such as treatment technologies, plant size, and wastewater management strategies. Implementing mitigation strategies for reducing carbon emissions in WWTPs comes with recognized limitations and trade-offs. Effluent quality, operational cost and GHG emissions are potentially conflicting objectives (Barbu et al., 2017; Arnell et al., 2017). Hence, this study focuses on evaluating carbon efficiency rather than the overall carbon footprint of WWTPs. Carbon efficiency metric used is a synthetic index that, besides accounting for indirect GHG emissions, also integrates pollutants removal efficiency, providing a more comprehensive measure of carbon efficiency.

WWTPs have a range of options to enhance carbon footprint, contingent upon their specific operational characteristics, primary sources of GHG emissions, and targeted outcomes. Some well-established measures for reducing carbon emissions in wastewater treatment processes include: i) use of renewable energy sources: utilizing renewable energy can significantly cut indirect GHG emissions. Wastewater and sewage sludge are valuable sources for methane production, while WWTP areas can effectively accommodate solar panels (Płuciennik-Koropczuk et al., 2022). Transitioning to energy generated from renewable sources like these can significantly improve carbon efficiency; ii) energy reduction: Operational modifications and the adoption of energy-efficient treatment technologies can reduce energy usage. Key strategies include adjusting solids retention time, optimizing mixed liquor recirculation, and regulating dissolved oxygen levels (Maktabifard et al., 2022); iii) enhancing energy production: Co-digestion enhances macronutrient balance, positively impacting energy production and carbon efficiency within WWTPs (Chrispim et al., 2021); iv) innovative technologies for N_2O removal: Implementing systems based on anaerobic ammonia oxidation (anammox) is an emerging strategy for achieving energy neutrality and enhancing carbon efficiency in WWTPs (Wang et al., 2018) and; v) source separation systems: Separating black water from grey water at the source can lead to more efficient treatment, higher nutrient recovery, and increased biogas yield, all contributing to improved carbon efficiency (Maktabifard et al., 2023; Garrido-Baserba et al., 2022).The new Proposal for a Directive of the European Parliament and of the Council concerning urban wastewater treatment, approved in April 2024, highlights the necessity for 'progressively reducing greenhouse gas emissions to sustainable levels' (Article 1). However, findings from our study, aligning with previous research, indicate that the majority of WWTPs currently exhibit poor carbon performance. In response, it is imperative that WWTPs adopt comprehensive technical actions, such as those described previously, to enhance their carbon efficiency and reduce their carbon footprint. Simultaneously, these technical actions must be supported by robust policy measures. This could involve establishing stricter regulatory standards for carbon emissions, offering financial incentives for early adopters of green technologies, and providing funding for research into innovative wastewater treatment solutions. Policymakers should also consider developing a framework for regular monitoring and reporting of carbon emissions from WWTPs, ensuring transparency and accountability. Together, these combined efforts will help align the operations of WWTPs with the objectives set forth in the new directive, fostering a more sustainable approach to urban wastewater management that not only addresses immediate environmental impacts but also contributes to broader climate change mitigation goals.

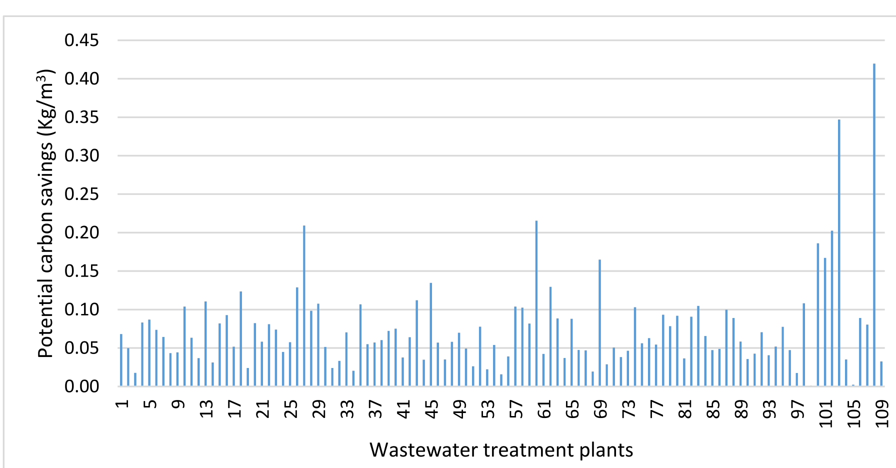

Fig. 5. Potential carbon emission savings if wastewater treatment plants were carbon efficient.

5. Conclusions

A comprehensive assessment of the CE of WWTPs is essential for reducing GHG emissions associated with wastewater treatment processes, aligning with the environmental goals set by the European Union (and other countries). Despite the significance of this issue, previous research has been somewhat limited and predominantly utilized DEA, a non-parametric and deterministic method. To address the constraints of DEA, this study is at the forefront of estimating the CE of WWTPs utilizing the StoNED method. This methodological shift marks a significant advance in the evaluation of WWTPs, enabling a more detailed and realistic analysis of their carbon performance.

The empirical study conducted focuses on a sample of 109 WWTPs located in Spain. The findings indicate that none of the evaluated WWTPs achieved carbon efficiency, implying that all possess the potential to diminish GHG emissions while maintaining their current levels of pollutant removal from wastewater. Specifically, it was estimated that, on average WWTPs could reduce GHG emissions by 0.759 kg of CO_{2eq} per cubic meter of wastewater treated. The study also found that neither the type of reactor employed for secondary treatment, nor the annual volume of wastewater treated had a significant impact on the CE of WWTPs. The consistency of the CE results obtained through the StoNED method with previous research underscores the method's utility and relevance in the context of the wastewater treatment process.

To align with the new carbon emissions standards set by the Proposal for a Directive of the European Parliament and of the Council on urban wastewater treatment, WWTP managers and policymakers should promptly initiate both technical and regulatory measures. These actions are essential for reducing the carbon footprint associated with wastewater treatment processes, thereby facilitating a transition toward more sustainable GHG emission levels. In the short to medium term, this will involve integrating advanced treatment technologies that are more energy-efficient, adopting renewable energy sources, and enforcing stricter emission regulations. Additionally, incentivizing innovations in carbon reduction techniques and enhancing operational efficiencies will be crucial for meeting these new standards and promoting sustainable environmental practices. The application of the StoNED approach in this study provides valuable insights into the CE of WWTPs. This aligns with broader environmental objectives and sustainability goals, emphasizing the importance of integrating advanced and nuanced methodological approaches in environmental performance assessments. Furthermore, the StoNED approach enables policymakers to distinctly identify the impact of the removal of each specific pollutant during the wastewater treatment process on GHG emissions. This capability facilitates a more targeted approach in the decision-making process, allowing for more precise interventions and strategies to reduce emissions in wastewater treatment. Such an approach is particularly beneficial for tailoring policies and operational adjustments to the specific emission profiles and treatment efficiencies of individual pollutants, thereby enhancing the overall effectiveness of environmental management in the wastewater sector.

Our study is subject to certain limitations. Firstly, it only incorporates indirect GHG emissions due to the unavailability of data on direct GHG emissions. Therefore, future research endeavors should aim to encompass the assessment of direct GHG emissions in WWTPs. Such an inclusion would permit a more nuanced analysis of the environmental performance of wastewater treatment processes. Additionally, the present analysis is confined to data pertaining to GHG emissions and wastewater volume for the year 2021. Future studies should extend their focus to a longitudinal examination of carbon performance. This would involve measuring productivity changes and their components over time, providing a more comprehensive understanding of how the most and least efficient plants have evolved and improved their performance over time.

CRediT authorship contribution statement

Ramon Sala-Garrido: Writing – review & editing, Supervision, Methodology, Conceptualization. **Manuel Mocholi-Arce:** Writing – review & editing, Methodology, Conceptualization. **Alexandros Maziotis:** Writing – original draft, Software, Methodology, Data curation, Conceptualization. **Maria Molinos-Senante:** Writing – original draft, Validation, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.143928.

Data availability

Data will be made available on request.

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