Análisis comparativo a través de metafrontera de la eficiencia técnico-económica de las EDARs

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RESUMEN

La evaluación de la eficiencia económica y técnica constituye una herramienta de gran utilidad para seleccionar la tecnología de tratamiento de aguas residuales más adecuada. Sin embargo, los modelos tradicionales usados para este fin, requieren que las unidades evaluadas operen bajo la misma tecnología. Para superar esta limitación, proponemos el uso de un modelo Data Envelopment Analysis (DEA) basado en el concepto de metafrontera no cóncava. De esta forma, es posible calcular tanto la eficiencia como el ratio de desfase tecnológico (RDT) de estaciones depuradoras de aguas residuales (EDARs) que utilizan tecnologías no homogéneas. Los resultados indican que la eficiencia media de las EDARs es alta y uniforme para las distintas tecnologías evaluadas. Además, los valores de RDT muestran que las EDARs que operan bajo la tecnología de fangos activados se encuentran en el óptimo en comparación con el resto de tecnologías evaluadas. En definitiva, este trabajo demuestra la utilidad que tiene la evaluación de la eficiencia de las EDARs a la hora de seleccionar la tecnología más adecuada para el tratamiento de aguas residuales.

***Palabras claves*:** benchmarking; tecnología no homogénea; eficiencia técnica; ratio de desfase tecnológico; tratamiento de aguas residuales.

***Área temática*:** Programación Matemática

ABSTRACT

The assessment of economic and technical efficiency provides a useful tool to select the most appropriate technology for wastewater treatment. However, traditional models require that the units being assessed operate with the same technology. To overcome this limitation, we investigate the viability of using a non-concave metafrontier approach, which is based on Data Envelopment Analysis (DEA) to calculate techno-economical efficiency and Technological Gap Ratios (TGRs) of wastewater treatment plants (WWTPs) operating with non-homogeneous technology. The results indicate that mean efficiencies are relatively high and uniform across the different technologies. Furthermore, analysis of TGR values shows that the efficiency performance is optimal for WWTPs operating with activated sludge in comparison to the other evaluated technologies. Our study shows the importance of quantitatively comparing the efficiency of WWTPs that use different technologies, for managers to make informed decisions when selecting the most appropriate technology for wastewater treatment.

***Keywords*:** benchmarking; non-homogeneous technology; technical efficiency; technological gap ratio (TGR); wastewater treatment.

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1. INTRODUCTION

The implementation of Directive 91/271/EEC, concerning urban wastewater treatment, has resulted in a significant increase in the volume of treated wastewater by the Member States of the European Union. Thus, the percentage of the population connected to wastewater treatment plants (WWTPs) has increased from 67% in 1990 to 87% in 2005 (WISE, 2010). While this Directive delineates the minimum quality requirements of treated water, the type of processes that should be used to achieve this purpose has not been clarified. In fact, following the establishment of the first wastewater treatment plants in the UK almost a century ago (by E. Ardern and T. Lockett in the UK in 1914), many technologies have been developed to obtain treated water that causes the lowest possible impact when discharged into the environment to meet legislation requirement. Examples include, activated sludge, aerated lagoon, trickling filter, rotating biological contactor (Cheremisinoff, 2001).

Feasibility studies provide a useful tool for selecting the type of water treatment process that best meets the needs defined by environmental legislation (Hernández-Sancho et al., 2010; Molinos-Senante et al., 2010). A WWTP may be considered as a firm that carries out a productive process, in which the outputs are the pollutants removed from wastewater and the input is the operational and maintenance cost of the facility. Logically, both technical and economic criteria should be evaluated when assessing the viability of a given technology (Urkiaga et al., 2006). However, most studies focus on evaluating the efficiency of pollutant removal from different wastewater treatment technologies (for example, Chen et al., 2004; Baeza et al., 2004; Maine et al., 2007; Zhou et al., 2009; Xue et al., 2010), while studies on economic efficiency-related aspects are scarce (see, Mufioz et al., 2008; Oa et al., 2009; Galleti and Landon, 2009; Molinos-Senante et al., In press). In contrast, recent studies have used Data Envelopment Analysis as an alternative approach to assess simultaneously both the technical and economic efficiency of wastewater treatment facilities (pig farming in Taiwan (Hsiao and Yang, 2007) and urban WWPTs in Spain (Hernández-Sancho and Sala-Garrido, 2009).

However, DEA tecnique assumes that when the efficiency across WWTPs is assessed, the facilities have similar characteristics (Yang and Chen, 2009). This assumption is based on the argument that traditional production frontier models should not be used to compare the efficiency of firms from different or technologies (Lozano-Vivas and Pastor, 2002). One possible solution is to estimate a production frontier for each studied technology, and only make efficiency comparisons within each technology (Sala-Garrido et al., 2011). This study calculated separate production frontiers for two wastewater treatment technologies (activated sludge and extended aeration) to assess which was most affected by seasonality. However, this approach does not resolve the problem of the comparability of efficiency scores, because the efficiency levels that were measured relative to one frontier (e.g., activated sludge frontier) could not be compared with efficiency levels measured relative to another frontier (e.g., extended aeration frontier) (O´Donell et al., 2008).

Metafrontier analysis is an approach that allows comparison between different technologies (Hayami, 1969; Battese and Rao, 2002; Battese et al., 2004). The attractive feature of metafrontier model is that takes into account any heterogeneity between firms (in this study, WWTPs) in the comparison of efficiency (Assaf and Matawie, 2010). A metafrontier may be considered as an umbrella (upper or lower) of all possible frontiers that might arise as a result of heterogeneity between firms (Rao et al., 2003). This model therefore produces the maximum output from a given input using the best technology. Since its introduction, the metafrontier function has been used in a wide range of studies cover diverse topics, including agriculture (Boshrabadi et al., 2008; O´Donell et al., 2008; Chen and Song, 2008; Wang and Rungsuriyawiboon, 2010), hotels (Assaf et al., 2010), football players (Tiedemann et al., 2010), airports (Assaf, 2009), banking markets (Lozano-Vivas and Pastor, 2002; Bos and Schmiedel, 2007; Kontolaimou and Tsekouras, 2010), hospitals (Assaf and Matawie, 2010) and dairy farms (Zibaei et al., 2008; Moreira and Bravo-Urieta, 2010). The reviewed literature demonstrates that the metafrontier approach is a well-established tool for evaluating efficiency analysis of non-homogeneous firms. Therefore, this approach may provide a solution to the problem of comparing techno-economical efficiency of WWTPs operating under different technologies.

In this study, we apply the metafrontier model to compare the techno-economical efficiency of four technologies that are used for wastewater treatment; namely activated sludge (AS), aerated lagoon (AL), trickling filter (TF), and rotating biological contactor or biodisk (BD). In addition, we use the concept of the technological gap ratio (TGR) to predict the maximum output that is feasible to produce by each WWTP given the input vector. We apply our results to consider the importance of quantitatively comparing the efficiency of WWTPs that use different technologies, for managers to make informed decisions when selecting the most appropriate technology for wastewater treatment.

2. METHODOLOGY

Several technologies exist for wastewater treatment, each characterized by a different functional relationship between inputs and outputs. Therefore, it is not possible to compare the techno-economical efficiency of a sample of WWTPs directly, if different technologies are being used.

Production frontiers may be estimated by using two types of approaches: (i) stochastic methods (for example Battese and Rao, 2002; Battese et al., 2004; Boshrabadi et al., 2008; Chen and Song, 2008; Assaf, 2009; Wang and Rungsuriyawiboon, 2010) and (ii) the non-parametric and non-stochastic approach (as do O´Donnell et al., 2008; Zibaei et al., 2008; Kontolaimou and Tsekouras, 2010; Assaf et al., 2010. The non-parametric method offers a large degree of flexibility and eliminates specification errors, as it is not necessary to select a specific functional form (Boscá et al., 2009). Because of these advantages, we have adopted this approach in our empirical evaluation.

When using both parametric and non-parametric methods for metafrontier calculation, all published studies have pooled the data across all production technologies. In this way, a concave metafrontier is obtained as shown in Fig. 1.

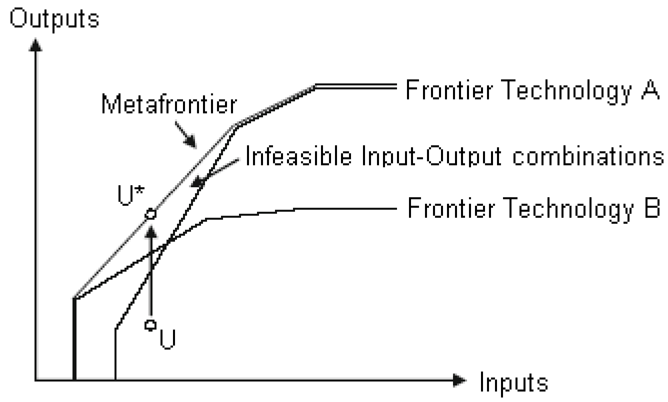

Figure 1: Concave metafrontier.
Source: Adapted from Tiedemann et al. (2011)

By performing two separate DEA efficiency analyses, the curves in Fig. 1 (labeled Technology A and Technology B) are obtained and represent technology-specific best practice frontiers. The all-encompassing metafrontier is obtained by pooling the data from the two technologies and repeating a standard DEA. However, as indicated in the works of O´Donell et al., (2008) and Tiedemann et al., (2011), the metafrontier may also encompass input/output combinations, which are not feasible in either of the two technologies. These points are located in the triangle labeled by Tiedemann et al., (2010) as “infeasible input-output combinations” (Fig. 1). For example, consider that the Unit U operates under technology B. His projected metafrontier output is represented by point U* but, an input/output combination with Unit U cannot be achieved as Technology A or as Technology B. The fact that U^* is within the triangle termed “infeasible input-output combinations” indicates that, although this combination is encompassed by the metafrontier, it falls outside the feasible production set.

To solve this problem, Tiedemann et al., (2011) proposed an alternative method, which was based on the concept of the non-concave metafrontier. This metafrontier only envelopes the input-output combinations that are part of the delineated technology set of at least one of the technologies. As a result, the area identified as “infeasible input-output combinations” is no longer present, as shown in Fig. 2.

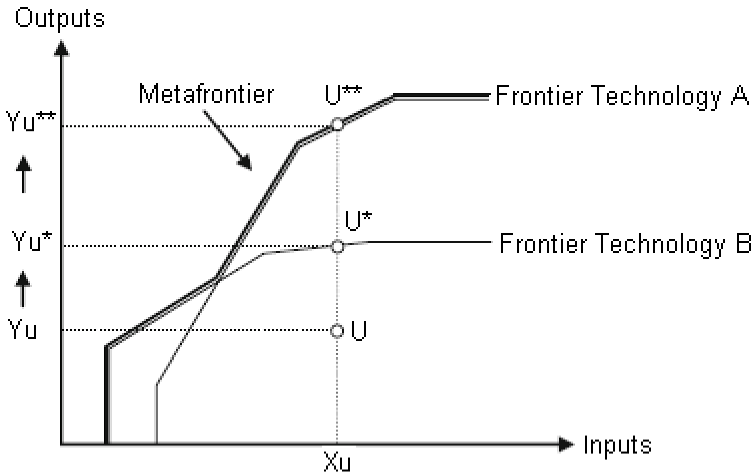

Figure 1: Non-concave metafrontier.
Source: Adapted from Tiedemann et al. (2011)

For the example shown in Fig 2, the estimation of the non-concave metafrontier involves two stages. In the first one, the technical efficiency scores are estimated, for each of the units being studied, in relation to the efficient production frontier technology to which they belong. Thus, if unit U belongs to Technology B, the ratio of distance $\overline{XuU}$ to distance $\overline{XuU*}$ reflects the output-oriented efficiency score in his own technology. In the second stage, we estimate the efficiency score of unit U in relation to the frontier of alternative technology (Technology A). This efficiency index is determined by the ratio of distance $\overline{XuU}$ to distance $\overline{XuU**}$. If the efficiency score using of the alternative technology (Technology A) is lower than that obtained for the technology to which the unit belong (Technology B), this result indicates that, when the level of inputs are kept constant, the unit evaluated may get greater amount of outputs if operates under the alternative technology. This form of comparative analysis allows us to identify the technology that represents the metafrontier at input levels around Xu.

This same procedure may be applied to cases where more than two technologies exist that serve a similar purpose. If there are k different technologies $(k = 1,...,K)$, efficiency scores are computed for each unit against the specific frontiers for all k technologies. To estimate the efficiency scores with respect to the metafrontier (TE) and respect to technology of the group k (TE^k), assuming variable returns to scale (VRS), the following linear programming problem must be solved for each WWTP that is evaluated:

$$
\begin{aligned}
& \underset{\phi,\lambda}{Max} \quad \phi \\
& s.t. \\
& \sum_{j=1}^{n} \lambda_j x_{ij} \le x_{io} \qquad i = 1,\dots,m \\
& \sum_{j=1}^{n} \lambda_j y_{rj} \ge \phi\, y_{ro} \qquad r = 1,\dots,s \\
& \sum_{j=1}^{n} \lambda_j = 1 \\
& \lambda_j \ge 0 \qquad\qquad j = 1,\dots,n
\end{aligned}
\tag{1}
$$

where variables x_{ij} and y_{rj} represent the quantity of inputs ($i = 1,\dots,m$) and outputs ($r = 1,\dots,s$) for each WWTP ($j = 1,\dots,n$). The objective function of this optimization problem requires maximization of the output enhancement potential ϕ across all outputs. The reciprocal $1/\phi$ is bounded by an interval of 0 to 1, and may be interpreted as an efficiency score. For example, TE = 0.5 indicates that the output vector, y_r, is 50% of the maximum output that could be produced by a WWTP using the vector, x_i. If TE^k is 0.8, this represents 80% of the maximum output that could be produced by a WWTP using the input vector, x_i, and group-*k* technology.

The technical efficiency for each group (TE^k) cannot process a value that is below the technical efficiency with respect to the metatechnology (TE), since the restrictions of the problems of the different groups are subsets of the constraints of the metafrontier problem. In other words, the metafrontier envelops the group-*k* frontier. Whenever strict inequality is observed between the group-*k* distance function and the distance to the metafrontier function, we obtain a measure of the proximity of the group-*k* frontier to the metafrontier (Hong et al., 2008). Specifically, the TGR for group-*k* firms (or WWTPs in our study) was defined by Battese et al., (2004) as:

$$TGR^k = \frac{TE}{TE^k} \tag{2}$$

Assuming that TE is 0.5 and TE^k is 0.8, the TGR would be 0.625. This means that, given the input vector (cost), the maximum output (efficiency at removing pollutants) that could be produced by a WWTP from group-*k* is 62.5% of the output that is feasible if using the metafrontier as a benchmark. Thus, an increase in the TGR implies a decrease in the gap between the group frontier and the metafrontier.

Hence, in this study we use the non-concave metafrontier model developed by Tiedemann et al., (2011) to compare the techno-economical efficiency of a sample of WWTPs that operate under four different technologies. In addition, the technological gap between each group –*k* technology and its metafrontier is calculated.

3. CASE STUDY

3.1. Description of wastewater treatment technologies

Pollutants in wastewater are removed by physical, chemical and/or biological processes. These processes are grouped together to provide various levels of treatment known as preliminary, primary, secondary (with or without nutrient removal), and tertiary treatment.

The preliminary treatment removes gross solids and grit, the presence of which may damage equipment. In primary treatment, a physical operation, usually sedimentation is used to remove the floating and settleable materials found in wastewater. In the secondary treatment, biological processes are carried out to remove organic matter and nutrients. In conventional secondary treatments, only nutrients associated with the growth of micro-organisms responsible for the degradation of organic matter are removed. In comparison, in secondary treatment that involves nutrient removal, the operating conditions of reactors are modified to include the removal of nitrogen and/or phosphorus. In the tertiary treatment, high quality effluent is obtained by removing pathogens and substances that were not previously eliminated.

In general, all WWTPs have a common preliminary and primary treatment while it is in secondary treatment in which they differ. Hence, different technologies for wastewater treatment are based on differences in secondary treatment types. Each of the technologies that are discussed in this paper is briefly described below; including activated sludge (AS), aerated lagoon (AL), trickling filter (TF) and rotating biological contactor or biodisk (BD).

AS and AL treatments are suspended growth processes, in which the microorganisms used for the treatment process are maintained in liquid suspension. In comparison, TF and BD treatments are attached growth processes, in which microorganisms are attached to an inserted packing material.

The basic AS treatment process comprises three basic components: (i) a reactor, in which the microorganisms used for treatment are kept in suspension and aerated; (ii) the separation of liquid-solids, usually in a sedimentation tank; and (iii) a recycling system for returning solids that were removed from the liquid-solids separation unit to the reactor.

An AL treatment process is a pond that is 1 to 4 meters in depth, in which there is a continuous flow of wastewater. The concentration of solids in the lagoon is much lower than that used in AS treatment processes, and the fundamental difference between the two processes is that sludge recirculation is not present in the AL process.

TF treatment processes are non-submerged fixed-film biological reactors, using rock or plastic packing over which wastewater is distributed continuously. Treatment occurs as the liquid flows over the attached biofilm, and wastewater is distributed above the bed by a rotary distributor. The collected liquid is transferred to a sedimentation tank, where the solids are separated from the treated wastewater.

A BD treatment process consists of plastic disc mounted on a long, horizontal, rotating shaft. Biological slime, similar to that of the trickling filter, is attached to the filter media. However, rather than being stationary, the filter media rotates into the settled wastewater, and then emerges into the atmosphere where the microorganisms receive oxygen that facilitates the consumption of organic materials in the wastewater.

3.2. Description of study WWTPs

In this study, the four technologies to compare mainly differ in the type of biological reactor used by WWTPs to remove organic matter and nutrients. This is because all technologies studied require a secondary settling process for the sedimentation of suspended solids, such as separating the solids from the liquid fraction. Hence, it is considered that three pollutants are removed as a result of wastewater treatment; including (i) organic matter, which is measured as chemical oxygen demand (COD), (ii) nitrogen (N), and (iii) phosphorus (P). These three contaminants constitute the outputs obtained from the treatment process, while the input to this process is the operation and maintenance costs of facilities. Details of these variables for each of the four technologies are provided in Table 1.

Table 1: Sample description of wastewater treatment technologies.
Source: Agència Catalana de l´Aigua-ACA.

			AS	**AL**	**TF**	**BD**
	Number of WWTPs		68	12	10	9
	Volume (m^3/year)	Mean	142,957	115,887	102,006	48,678
		Std. Dev.	95,369	77,829	94,243	39,096
OUTPUTS (Kg/year)	**COD**	Mean	66,885	62,511	60,005	28,161
		Std. Dev.	62,203	50,439	44,642	17,329
	N	Mean	4,581	3,555	2,508	1,028
		Std. Dev.	4,203	2,671	2,162	816
	P	Media	716	446	511	138
		Std. Dev.	888	303	395	96
INPUTS (€/year)	**COST**	Mean	82,645	45,376	65,774	54,668
		Std. Dev.	40,002	43,116	50,653	50,527

In total, 99 WWTPs were evaluated, which are located in the region of Catalonia (Northeastern Spain). All selected units had secondary treatment processes with nutrient removal. The wastewater that was treated at these facilities primarily originated from domestic discharges. The volume of uncontrolled discharges toxic for biological process is very limited, causing minimal impact to the efficiency of facilities. Statistical information for 2009 was supplied by the regional wastewater treatment authority (Agència Catalana de l´Aigua-ACA).

4. RESULTS AND DISCUSSION

Before estimating the metafrontier, it was first necessary to validate whether the observed differences between the four technologies was statistically significant. To do this, we used the Kruskal-Wallis non-parametric test, in which the results were consider significant if the *p* value was equal or smaller than 0.05 (Kruskal and Wallis, 1952). As expected, the test indicated that all differences in the variables among the four groups were statistically significant (Table 2). This finding also supports the theory that a single production frontier cannot be used to compare the efficiency of WWTPs that use different processes to treat wastewater.

Table 2: Kruskal-Wallis test statistics for differences in the four wastewater treatment technologies.

	Chi-squared	***p* value**
COD	8.511	0.037
N	12.897	0.005
P	23.060	0.000
Cost	14.757	0.002

After validating that the four groups of WWTPs operate under different technological frontiers, the technical efficiency was estimated with respect to the group frontiers and to the metafrontier for each of the 99 WWTPs, which were grouped in the four technologies. All results were obtained by using Eq. (1). Table 3 provides the descriptive statistics for these estimates.

Table 3: DEA estimates of technical efficiencies (TE^k and TE) and technological gap ratios (TGR) of four WWTPs technologies: activated sludge (AS), aerated lagoon (AL), trickling filter (TF) and biodisk (BD).

WWTP technology	**Mean**	**Std. Dev.**	**Minimum**	**Maximum**	**WWTPs efficient (%)**
AS					
TE^k	0.878	0.116	0.556	1.000	11.8
TE	0.877	0.116	0.548	1.000	11.8
TGR	0.999	0.002	0.987	1.000	
AL					
TE^k	0.954	0.061	0.843	1.000	41.7
TE	0.879	0.069	0.763	1.000	8.33
TGR	0.921	0.030	0.887	1.000	
TF					
TE^k	0.912	0.093	0.729	1.000	40.0
TE	0.812	0.064	0.651	1.000	10.0
TGR	0.882	0.108	0.618	1.000	
BD					
TE^k	0.957	0.072	0.777	1.000	56.0
TE	0.905	0.073	0.756	1.000	10.0
TGR	0.947	0.034	0.914	1.000	

We first explain and discuss the obtained efficiency scores with respect the group frontiers. If we focus on the percentage of efficient plants, i.e. those which constitute best practice within technology, our results indicate that there are important differences for the four types of technologies that were analyzed. BD process is the one with a higher percentage of efficient plants since over half of the studied plants (56%) had an efficiency score equal to one. In contrast, just 12% of WWTPs using the AS process were efficient. In other words, 88% of plants that used AS as secondary treatment process, with the same level of inputs could remove more quantity of pollutants. In comparison, plants with AL and TF processes exhibit an intermediate performance since the percentage of facilities operating on the frontier is 41.7% and 40.0%, respectively. Table 3 shows that the average technical efficiency scores for the studied technologies range between a minimum of 0.878 (AS technology) and a maximum of 0.957 (BD technology). These results indicate that the mean technical efficiencies are relatively uniform for the different technologies in the estimated group frontier models, and that the WWTPs examined in this study have a high efficiency within their respective technology. For example, the mean technical efficiency score for AL technology is 0.954, indicating output is increasing by about 95% of potential given its group frontier. In other words, the technical efficiency score shows that the mean gap between the best producer and other producers in AL technology is only about 5%. Table 3 also shows that AL, TF and BD technologies display low variation in the obtained efficiency scores, indicating a high degree of homogeneity within each group. In contrast, WWTPs using AS technology are characterized by the highest degree of performance variability, implying a high degree of heterogeneity. This outcome was expected because the AS technology group has a larger number of plants than the other studied technologies, resulting in the variability of both the outputs and input being higher for this technology, as shown in Table 1.

The efficiency of the four wastewater treatment technologies was compared by analyzing the efficiency scores concerning to metafrontier, which are presented in Table 3. As expected, we found that the efficiency scores are smaller and more dispersed for all technologies, than those calculated based on the individual frontiers. This result is shown in Fig. 3, which presents a graphical illustration of the group-*k* and metafrontier efficiency of all WWTPs evaluated in our study[1]. In addition, we found that when the techno- economical efficiency is calculated using the metafrontier as a reference point, the number of efficient WWTPs also decreases. However, this reduction in efficiency does not affect all technologies equally. For instance, the number of efficient plants using the AS process remains constant, while the number of efficient facilities is reduced by 80%, 75% and 82% for plants that use AL, TF and BD processes, respectively. Our results show that BD technology continues to obtain the highest mean technical efficiency (0.905) of all four processes. However, the lowest mean score was no longer associated with the AS process, being replaced by the TF process (0.812). This result highlights the importance of model specifications for WWTPs operating under different technology frontiers. The mean techno-economical efficiency across all technologies was 0.873, which indicated that the output vector was 87.3% of the maximum output that could be produced on average by WWTPs using the current inputs. In other words, the relative measure of efficiency indicates that, when using the same input level, the WWTPs evaluated in the current study would be able to produce about 12.7% more outputs on average if operating in the metafrontier.

The frontier and metafrontier production estimates for each technology may also be used to calculate the technological gaps ratios (TGR) by using Eq. (2). TGR measures the proximity of the group-*k* frontier to the metafrontier, which represents the current state of knowledge. According to Eq. (2), an increase in the TGR implies a decrease in the gap between the group frontier and the metafrontier.

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[1] The difference between Fig. 1 and Fig. 3 should be noted. In Fig. 1, the metafrontier is the upper bound, because the score ϕ of Eq (1) has been used. In Fig. 3, the metafrontier is the lower bound, because the scores belong to the form $1/\phi$, to ensure that the values are delimited between 0 and 1.

Figure 3. Group-*k* and metafrontier technical efficiency of the 99 WWTPs grouped in four technologies: activated sludge (AS), aerated lagoon (AL), trickling filter (TF) and biodisk (BD).

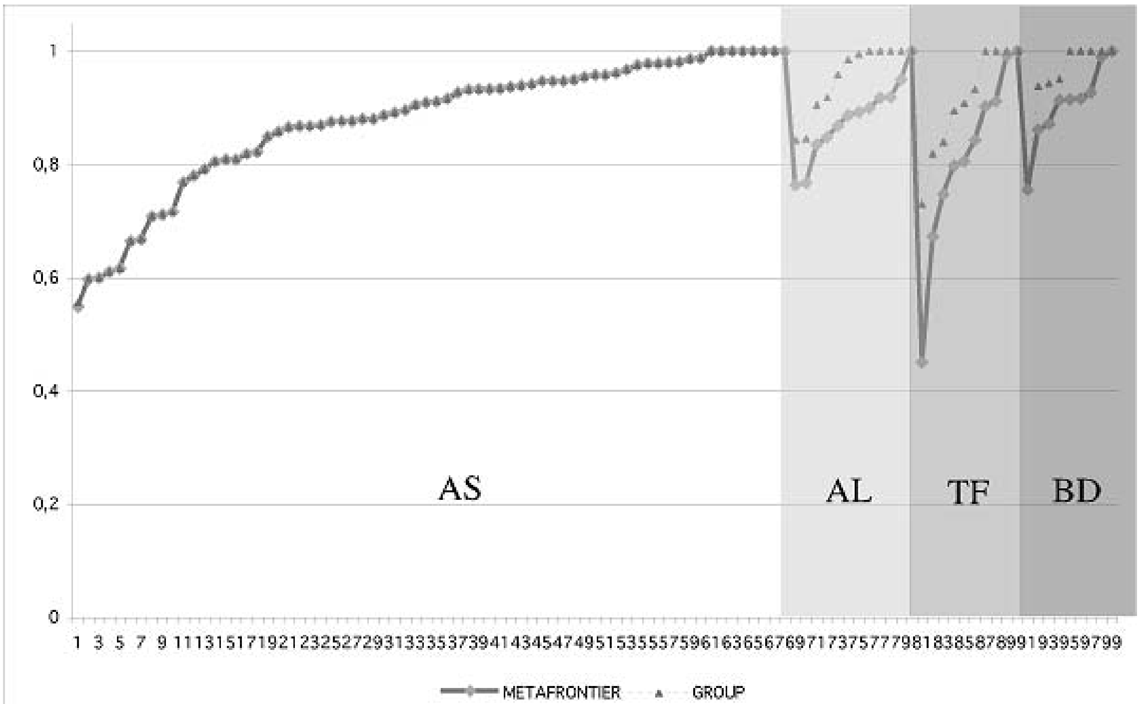

Table 3 shows that the mean TGR values vary from 0.882 to 0.999. Specifically, AS technology has the highest TGR, in which the mean value was very close to unity (i.e. the maximum value). In fact, only one of the 68 WWTPs studied with this technology presents a TGR different to one, as shown in Fig. 3. This means that, given the input vector, these plants are producing the maximum output that is feasible. Conversely, TF technology had a lower TGR value (0.882), indicating that WWTPs with this technology are on average producing 88.2% of their potential outputs. For all technologies, the mean TGR value is 0.971, which indicates that the potential for improvement is estimated at 3% on average. The results indicate that WWTPs using AS technology have the best technical efficiency performance compared with the other technologies under study, followed by the plants using BD and AL technology. In addition, our empirical analysis shows that TF technology is the least appropriate with respect to techno-economical efficiency.

Our results are consistent with that expected providing quantitative support that AS technology (which is a biomass system with sludge recirculation) has high operational flexibility with respect to organic load and hydraulic variations. This flexibility arises because it is possible to modify the microbial population through the purge control of the wastewater process. Furthermore, in this technology, internal recirculation from the aerobic to anoxic reactor increases the efficiency of nitrogen removal, which in turn reduces the need for aeration and promotes the elimination of phosphorus (Hanhan et al., 2011). Moreover, AS technology has been in operation for almost a century, hence the know-how acquired by operators of facilities over this long time frame also contributes to this technology being defined as best practice. This status is evidenced by both the Environmental Spanish Administration and the wastewater treatment companies transferring back to this technology, after opting for attached growth processes in recent decades. Specifically, the regional Programme of Urban Wastewater Treatment for Catalonia (PSARU, 2005) for the 2006 to 2014 delineates the construction of most new facilities based on this technology. However, alternative innovative technologies with higher operating costs are also being introduced, in cases with severe restrictions regarding effluent quality or space.

5. CONCLUSIONS

Today, a wide range of wastewater treatment technologies are available to obtain the level of effluent quality stipulated by environmental legislation. Hence, comparative evaluation of the efficiency of all available technologies provides a useful tool to select the most appropriate process. While the traditional DEA technique to facilitate the simultaneous assessment of both the technical and economic efficiency of WWTPs, the technology used must be as similar as possible.

In the current study, we provided an application of a metafrontier model, using DEA and performance data, to obtain comparable efficiency scores for Spanish WWTPs operating under four different technologies (activated sludge, aeration lagoon, trickling filter and rotating biological contactor). The results of our study indicated that the mean techno-economical efficiencies are relatively uniform across all four technologies, whether the frontier of each group or the metafrontier is used as the reference (benchmark). Moreover, the average efficiency scores of all technologies were high, which means that for sampled WWTPs the margin for improvement was reduced. At the individual level, the low variation in the recorded efficiency scores of WWTPs using AL, TF and BD technologies show they as homogeneous groups, while WWTPs using AS technology were characterized by a higher degree of heterogeneity. For TGR, the mean value of AS technology occurred very close to the unit, which implied that plants operating with this technology are producing the maximum potential outputs, with respect to the current level of inputs. Therefore, WWTPs operating with AS technology have the best performance with respect to efficiency compared to the other technologies evaluated in this study.

To the best of our knowledge, this is the first application of this approach towards evaluating the performance of different WWTPs technologies, providing a novel framework for identifying optimal facilities for specific regions within a country, hence we could not provide a direct comparison between the efficiency results of this study against existing published literature. While we suggest caution in the interpretation of the efficiency scores and TGRs, these values provide an opportunity to identify the technologies that are relatively efficient. Hence, this study quantitatively supports the importance of do not use the same frontier production when comparing the efficiency of WWTPs that use different types of technologies.

We recommend that wastewater companies and agencies should focus on the different efficiencies of techno-economical instruments, when selecting the most appropriate technology for wastewater treatment. Our study clearly demonstrates that efficiency performance is a useful quantitative tool to support decision-making by managers. In addition, we show the importance of using the TGR values to explain how the WWTPs of one group may compete with the WWTPs from other groups. However, our interpretation of the technical efficiency scores and TGRs in the current study should be viewed as a preliminary analysis. This methodology could potentially be used as a baseline to develop an assessment of a wider range of wastewater treatment technologies. Such information would contribute towards improving our understanding of factors that affect technical efficiency and technological gaps in wastewater treatment processes, and to analyze how technical inefficiency changes over time.

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