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Environmental and economic profile of six typologies of wastewater treatment plants

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ABSTRACT

The objective of wastewater treatment plants (WWTPs) is to prevent pollution. However, it is necessary to assess their sustainability in order to ensure that pollution is being removed, not displaced. In this research, the performance of 24 WWTPs has been evaluated using a streamlined Life Cycle Assessment (LCA) with Eutrophication Potential (EP) and Global Warming Potential (GWP) as environmental indicators, and operational costs as economic indicators. WWTPs were further classified in six typologies by their quality requirements according to their final discharge point or water reuse. Moreover, two different functional units (FU), one based on volume (m^3) and the other on eutrophication reduction (kg PO_4^{3-} removed) were used to further determine sustainability. A correlation between legal requirements and technologies used to achieve them was found: Organic matter removal plants were found to be less costly both in environmental and economic terms if volume was used as the functional unit, while more demanding typologies such as reuse plants showed a trade-off between lower EP and higher cost and GWP; however, this is overcome if the second FU is used instead, proving the sustainability of these options and that this FU better reflects the objectives of a WWTP.

1. Introduction

Over the past fifty years, public attitude toward the environment has changed. Adapting itself to the demands of an evolving society, engineering has added sustainability to its general objectives (Davidson et al., 2007). As presented in the report of the United Nations 2005 World Summit, the pillars for sustainability are environmental protection as well as economic and social development (United Nations General Assembly, 2005). This has produced a substantial change in how technology is designed and operated. In this sense, the application of sustainability criteria for the provision of goods and services is now the main focus, rather than environmental protection based on an end-of-pipe approach (Davidson et al., 2007).

Wastewater treatment, an end-of-pipe technology, must comply with environmental, social and economic requirements in order to be considered sustainable (Balkema et al., 2002). The aim of this research paper is to environmentally and economically assess the operation of 24 wastewater treatment plants (WWTPs), classified according to six different typologies. The criteria for comparison among the WWTPs include the selection of the most appropriate functional unit of the system, which assures that the conclusions

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derived from the analysis are consistent. In this sense, two functional units were considered and a sensitivity analysis was carried out.

1.1. *Environmental sustainability and WWTPs*

In the last two decades a number of methodologies have been developed for evaluating the environmental sustainability of a product or process. Among them, Life Cycle Assessment (LCA) is a well-established procedure quantifying inputs and outputs as well as the potential environmental impacts associated with a product throughout its whole life cycle (Bauman and Tillman, 2004; ISO, 2006; Finnveden et al., 2009).

LCA has been applied to water treatment systems (water treatment plants, sewer systems, and WWTPs) from the earliest stages of the development of the methodology (a review of a majority of published papers on LCA of WWTPs can be found in Larsen et al. (2007)). More recently, literature has been focused on pharmaceutical and personal care products (PPCPs; Wenzel et al., 2008; Muñoz et al., 2008a), nutrient removal (Foley, 2009), tertiary treatments (Muñoz et al., 2009; Høibye et al., 2008; Larsen et al., 2010), sludge treatment and disposal (Lundin et al., 2004; Murray et al., 2008; Hospido et al., 2010), or global warming impact associated with wastewater treatment (Stokes and Horvath, 2010).

Even when the removal of organic matter (OM) and nutrients is a key objective in the operation of a WWTP, the eutrophication produced by the treated effluent is the main environmental impact made by most plants (Roeleveld et al., 1997; Hospido et al., 2004). The magnitude of the other impact categories varies. While WWTPs with tertiary or advanced treatments seem to significantly impact on global warming and acidification (Beavis and Lundie, 2003; Clauson Kaas et al., 2006), the toxicity-related impacts, caused by the presence of heavy metals and PPCPs, both in water (Roeleveld et al., 1997; Larsen et al., 2010) and in the sludge applied to land (Hospido et al., 2005, 2010), are present in all plants. The significance of other impact categories, such as ozone layer depletion and photochemical oxidants formation, has been found negligible in most cases.

1.2. *Economical sustainability and WWTP*

The established regulation mechanisms for environmental protection may not be enough to assure the objectives for environmental quality and efficient natural resource use (Zhang and Wen, 2008). A number of authors argue that economic instruments are also very important for the implementation of policies and selection of measures to assist in environmental protection; the economy provides tools, information and instruments for streamlining the decision-making process (Ashley, 2009; Wissel and Wätzold, 2010; Hepburn, 2010).

An example of this growing interest is the new role of economic analysis in the Water Framework Directive (WFD, EU, 2000). This directive represents a new advance in water resource planning by integrating a number of economic principles into the management of water in EU member states (Hernández-Sancho et al., 2010). These principles include polluter pays, as well as additional approaches such as the analysis of cost-effectiveness of pollution mitigation measures and the consideration of economic instruments such as water pricing (Moran and Dann, 2008).

Despite the significance of economic analysis in the field of wastewater treatment processes, it has received less attention than environmentally or technologically focused assessments. Available, however, in the field of water reuse are studies with detailed cost analysis, useful in the assessment of different treatment schemes (Hernández et al., 2006; Asano et al., 2007). Other researchers use cost modeling for a better understanding of the cost structure as well as for planning new investments. Several studies (Gonzalez-Serrano et al., 2005; Hernandez-Sancho et al., 2011) have validated and defined cost functions for different wastewater treatment technologies. These studies have considered the correlation of investment, operation, and maintenance costs of the WWTPs with some representative variables. Taking into account the WFD requirements, especially those related to the cost recovery for water services, several cost benefit analyses (CBA) (Godfrey et al., 2009; Chen and Wang, 2009; Molinos-Senante et al., 2010) have been carried out with the aim of identifying cases in which the adoption of measures to achieve a good ecological status for water bodies was required. All the benefits and costs including those which qualify as “non-market” must be integrated into the CBA.

In recent years, LCA of WWTPs has been combined with different economic indicators. Muñoz et al., (2008b) developed an Environmental Economic Score (EES) and applied it to different advanced oxidation technologies. In Larsen et al. (2010) the cost-efficiency of ozonation and pulverized carbon addition is calculated both as stand-alone processes or combined with sand filtration. Another group (Nogueira et al., 2007) compared the technology of activated sludge (AS) with constructed wetlands and slow rate infiltration for small communities. Lin (2009) combined one LCA study with an input–output model for the wastewater system of the metropolis of Tokyo, highlighting that the implementation of the secondary treatment turned into larger GHG emissions. The present study aims to combine LCA and economic assessment based on real process data.

2. Materials and methods

2.1. *Objectives*

The main objective of this paper is to compare the environmental and economic performance of 24 Spanish WWTPs. After a preliminary analysis, the criteria for the classification of the WWTPs in different typologies was based on the quality requirements set in the European urban wastewater directive (EEC, 1991) and Spanish legislation concerning water reuse (MP, 2007) according to the final destination of the treated wastewater (Table S1, Supplementary information).

Plants that discharge the treated wastewater to non-sensitive and sensitive areas (as defined by the European Directive)

Type 1: Plants designed and operated for the removal of organic matter discharging the treated wastewater to non-sensitive areas.

Type 2: Plants designed and operated for the removal of organic matter and nutrients discharging the treated wastewater to non-sensitive areas.

Type 3: Plants designed and operated for the removal of organic matter and nutrients discharging the treated wastewater to sensitive areas.

Plants that reuse the treated wastewater

Type 4: Plants reusing the treated wastewater for irrigation in agricultural land.

Type 5: Plants reusing the treated wastewater for industrial purposes.

Type 6: Plants reusing the treated wastewater for aquifer recharge.

A streamlined methodology based on environmental and economic indicators is presented. Special attention has been given to the technological differences among the six typologies. To a lesser extent, the effect of influent quality, very different due to climatic conditions, such as rainfall, and water use management, has been assessed.

2.2. *Case study*

A brief description of the different WWTPs studied can be found in Table 1. The plants under study were selected according to the completeness of the data offered. A representative sample of 24 plants designed for populations larger than 50,000 inhabitants was selected from two different areas: WWTP 1–5 from an Atlantic region, Galicia (NW Spain), with an average rainfall of 1289 mm/year and WWTP 6–24 from a Mediterranean region, Valencia (E Spain), with an average rainfall of 405 mm/year, as described by Rodriguez-Garcia et al. (2011). This group represents around two-thirds of the total number of large plants in the regions of interest.

2.3. *Functional unit*

The definition of the functional unit (FU) comprises a physical measurement of the function provided by the system, usually expressed as a certain amount of product (i.e. 1 kg of detergent) or as the service provided by it (i.e. washing of 100 shirts). The potential impacts that can be associated with the product or service will then be totalized and further referred to the FU. When defining the FU of a WWTP, different choices are possible. On one hand, there are studies that considered the volume (m^3) of treated water for a certain period of time as the FU (Suh and Rousseaux, 2001; Hospido et al., 2004). Conversely, there are those based on the environmental load associated with a one person equivalent (PE) (Tillman et al., 1998; Hospido et al., 2007). The former has the advantage of being based on physical data while the latter tends to be used for comparative purposes, since it minimizes the differences associated with the influent composition and flow.

Here, a functional unit based on the volume of treated wastewater (m^3) was used as the first choice for the comparison of the WWTPs (from now, FU1). This approach may give insight into the effect of differences between facilities, both in regard to the influent flow and quality, as well as the removal yields. However, speaking in a stricter sense, the function of a WWTP is to meet the restrictions imposed by the existing regulations in terms of pollutant concentrations in the discharge of the treated effluent. The existing framework legislation developed in EEC (1991) and EC (1998) directives only requires the reduction of nitrogen and phosphorous for the treated effluents returned to a sensitive area (Table S1). In fact, three of the plants addressed in this study return the treated water to a sensitive body (Type 3) and a fourth one, WWTP 24 must fulfill similar nitrogen requirements for discharging to an aquifer (Type 6, Table S1). Therefore, another choice for the definition of the FU should comprise the removal of both nutrients and organic matter, expressed in terms of kg PO_4^{3-} eq. removed (from now FU2).[1] For that reason, the use of this second FU will highlight the differences between the environmental and economic costs of reducing the potential eutrophication associated with the effluent for all the WWTPs.

2.4. *System boundaries*

The selection of the system boundaries in LCA studies on wastewater treatments was studied by Lundin et al. (2000). Although the sewer systems have proved to be environmentally relevant (Doka, 2009; Lassaux et al., 2006), the treatment plant remains the main impact contributor. All the plants under study are preceded by combined sewers systems, i.e. a system that jointly collects wastewater and rainwater resulting in the dilution of the influent in all WWTPs. For this reason and for the lack of data concerning the sewer systems, they were not included in this study. However, the effect of dilution will be more relevant in the Atlantic WWTPs due to climatic reasons (Rodriguez-Garcia et al., 2011).

Regarding the treatment plant, although the construction stage has been found to be responsible for 25–35% of the GWP associated with a WWTP (Tangsubkul et al., 2005; Doka, 2009), the operation of the facility is considered far more relevant for the rest of the categories (Lundie et al., 2004; Lassaux et al., 2006). On the other hand, the impact demolishing/disposal stage has been found to be negligible (Corominas et al., 2011). Therefore, this assessment considered the environmental impact associated with the operation of primary, secondary, and tertiary treatments (when present); final discharge of the treated effluent; as well as the sludge treatment and its final disposal. The latter is mainly as fertilizer in agricultural soil in the case of most plants, except WWTP 3 where an important fraction of the sludge produced is landfilled.

Some plants reuse a fraction of the treated effluent for agriculture irrigation (Type 4: WWTP 17 to 22). Despite the unavailability of specific data for the fraction of reused water for each plant, most WWTPs are located in the Jucar watershed, and since this watershed displays the highest rate of reused wastewater in Spain (MARM, 2008) it was assumed that

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[1] According to the CML environmental impact assessment method (Guinée et al., 2002), all substances that could potentially cause eutrophication are related to the reference or equivalence substance (PO_4^{3-} eq) in order to establish the potential impact of a product/process referred to this impact category.

Table 1 – Wastewater treatment plants under study.

			Size			Secondary treatment							Tertiary treatment	Removal efficiency			
			m^3/day treated (d)	m^3/day treated (r)	pe (r)	Activated sludge (AS)	AS + N removal	AS + P removal	AS + N and P removal	Extended aireation (EA)	EA + N and P removal	Oxidation ditch		COD	N_T	P_T	Average
Discharge	T1. non-sensitive OM removal	WWTP 1	26,480	53,935	125,452	✓	–	–	–	–	–	–	–	83%	15%	39%	46%
		WWTP 2	54,560	51,111	130,929	✓	–	–	–	–	–	–	–	89%	27%	44%	53%
		WWTP 3	24,640	45,227	191,762	–	–	–	–	–	–	✓	–	93%	50%	37%	60%
		WWTP 4	8080	6300	40,770	–	–	–	–	✓	–	–	✓	96%	85%	63%	82%
		WWTP 5	12,000	14,722	49,393	✓	–	–	–	–	–	–	–	93%	92%	60%	81%
		WWTP 6	40,000	38,634	193,046	✓	–	–	–	–	–	–	✓	96%	70%	85%	83%
		WWTP 7	20,664	13,681	66,787	✓	–	–	–	–	–	–	–	94%	39%	95%	76%
	T2. non sen. OM + nut Rem.	WWTP 8	24,000	20,825	127,271	–	–	✓	–	–	–	–	–	92%	52%	87%	77%
		WWTP 9	60,000	37,735	243,144	–	–	✓	–	–	–	–	✓	93%	68%	83%	82%
		WWTP 10	45,000	42,029	264,744	–	–	–	✓	–	–	–	–	94%	47%	90%	77%
		WWTP 11	32,000	12,707	62,340	–	–	–	✓	–	–	–	✓	96%	73%	74%	81%
		WWTP 12	8400	10,699	83,890	–	✓	–	–	–	–	–	–	97%	89%	84%	90%
		WWTP 13	18,000	7359	58,693	–	✓	–	–	–	–	–	–	96%	88%	83%	89%
	T3. sen. area	WWTP 14	25,000	21,290	54,162	–	–	–	✓	–	–	–	✓	96%	84%	96%	92%
		WWTP 15	22,486	10,735	60,752	–	–	–	✓	–	–	–	✓	95%	63%	82%	80%
		WWTP 16	8000	7945	65,422	–	–	–	✓	–	–	–	✓	97%	92%	92%	94%
Reuse	T4. agricultural	WWTP 17	30,000	28,870	117,816	–	✓	–	–	–	–	–	✓	92%	16%	65%	58%
		WWTP 18	60,000	35,613	229,154	–	–	–	✓	–	–	–	✓	94%	66%	65%	75%
		WWTP 19	24,000	14,048	149,575	✓	–	–	–	–	–	–	✓	94%	29%	76%	66%
		WWTP 20	60,000	30,584	200,908	–	–	✓	–	–	–	–	✓	95%	47%	71%	71%
		WWTP 21	60,000	17,676	141,609	–	–	–	✓	–	–	–	✓	96%	70%	74%	80%
		WWTP 22	38,000	23,695	213,676	–	✓	–	–	–	–	–	✓	93%	54%	77%	75%
	T5. Ind.	WWTP 23	15,000	12,517	60,701	–	–	–		–	✓	–	✓	93%	70%	89%	84%
	T6. Aq.	WWTP 24	42,000	8474	66,025	–	–	–	–	–	✓	–	✓	97%	95%	93%	95%

(d) design (r) real.

all the treated effluent is reused. The presence of nutrients in reused wastewater also prevents the production of fertilizers in the same way as sludge does (see below). Since in this case wastewater reuse does not displace any marginal technology due to the high cost of desalination, no other avoided products have been included.

2.5. *Life cycle inventory*

Inventory data presented in Table 2 is the annual averages for year 2008 except for WWTP 1 (average data corresponds to the period 1998–2003) and WWTP 4 (average date corresponds to 2009). Regarding the sources, data for WWTP 1 was obtained from a previous study (Hospido et al., 2007); data for WWTPs 2–5 was provided by the company in charge of their management and operation; and data for WWTPs 6–24 is from the regional wastewater treatment authority.

In addition, background data was obtained from SimaPro databases as follows:

- Medium voltage electricity (Dones et al., 2007): The process selected includes electricity production and import/export (data from 2004), transformation from high voltage, direct SF_6 emissions to air and electricity losses from medium voltage transmission system. Electricity production and import/export data were updated for 2008 based in MITYC (2009), ONE (2008) and REE (2009).
- Chemical products (Althaus et al., 2007): Acrylonitrile manufacture was used for the production of polyelectrolyte (polyacrilamide). The remaining chemicals were directly selected from the Ecoinvent database (Iron III 40%, sodium hypochlorite 15%, sodium hydroxide 50%, liquid sulfuric acid and quicklime, milled, loose and phosphoric acid 85%).
- Transport (Spielmann et al., 2007): Trucks 7.5–16 t EURO 3 (2000) were selected as standard transport for chemicals, waste and sludge. The vehicles under this regulation represented 34% of total Spanish trucks in 2008 (DGT, 2009).
- Waste (Doka, 2009). Waste from the primary treatment was regarded as municipal waste and treated in an incineration plant with energy recovery. Typically, grit is disposed at an inert landfill and fats are stabilized with lime and cement before disposal in a secure deposit. For those plants where sludge is landfilled (3, 9 and 11), this output was modeled as municipal waste.
- Fertilizers avoided (Nemecek and Kägi, 2007): After a sensitivity analysis of 10 N-based and 6 P-based fertilizers from the Ecoinvent database, ammonium sulphate and diammonium phosphate were selected as generic N and P_2O_5 sources, and a substitutability of 50% and 70% was assumed for the N and P present either in the sludge or in the effluent (in Type 4 plants), respectively (Bengtsson et al., 1997).
- Direct emissions from sludge disposal. N_2O emissions from sludge application were calculated according to Hobson (2003) and NH_3 emissions as defined by Lundin et al. (2000). PO_4^{3-} leakage was considered according to Doka (2009).
- CO_2 emissions from the water line as well as those derived from the biogas combustion from the anaerobic digestion of sludge were not taken into account since it was considered to be biogenic according to IPCC guidelines (Doorn et al., 2006).

2.6. *Environmental sustainability indicators*

As previously stated in section 1.1., the eutrophication potential (EP) has been considered the most relevant impact category in the majority of published LCAs on WWTPs (Larsen et al., 2007). For this reason, eutrophication was selected as the main environmental sustainability indicator and quantified by means of the CML method, which converts all eutrophying substances (Table S1 Supplementary information) to phosphate equivalent (Guinée et al., 2002).

According to Larsen et al. (2007), the global warming potential (GWP) is not among the most relevant impact categories for WWTPs. However, it is usually regarded as a significant environmental problem, at least from a political and social point of view, and it can also be indicative of other energy dependent impacts such as acidification. As a consequence, it was chosen as the second environmental indicator and quantified in accordance with the IPCC guidelines (Table S2, Supplementary information).

2.7. *Economic sustainability indicators*

Operational costs, subdivided by categories (energy, staff and others), were chosen as economic indicators, due to their relationship with overall plant management, and presented for both FU1 and FU2. The data shown is the annual average value for 2008, except for WWTP 1 (for which no economic data was available) and WWTP 4 (whose data was from 2009).

3. Results and discussion

Due to the large amount of data generated, results are presented in figures and tables grouped according to the 6 different typologies. However, similar information for all the individual plants can be found in the supplementary information.

3.1. *Typologies and inventory*

Taking into account their legal objectives, both Type 1 and 2 plants constitute a homogenous group since they are only required to remove OM. The difference is, despite not legally being required to do so, Type 2 plants also remove nutrients (N or/and P). A reason for that might be that, on average, the Type 2 influents are noticeably more loaded than the Type 1 influents (Fig. 1, Table 2). The extent of nutrient removal is generally associated with their presence in relatively high concentrations, as occurs in WWTPs 8 and 9 in order to attain high levels of P removal (Tables 1 and 2). Another possible explanation might be that since the areas considered sensitive might vary through time, the managers of Type 2 plants built or upgraded during the last decade, and may have taken into account that their receiving body could be considered sensitive in the future; thus nutrient removal could become a legal requirement. This would also explain why some Type 2 plants have lower removal efficiency than the Type 3 plants, which discharge in sensitive areas and therefore nutrient removal must be accomplished (Table 1).

Table 2 – Life cycle inventory of WWTP, all data is presented for FU1 (m^3).

	Influent			Effluent			Electricity		Chemicals consumption						
	COD (g)	N_T (g)	P_T (g)	COD (g)	N_T (g)	P_T (g)	From the grid (kWh)	To the grid (kWh)[a]	Polyelectrolyte (g)	$FeCl_3$ (g)	CaO (g)	NaClO (g)	NaOH (g)	H_2SO_4 (g)	Transport (kg km)
WWTP 1	327	19.45	0.70	55	16.45	0.43	0.13	–	0.27	–	–	–	–	–	0.01
WWTP 2	340	19.84	1.22	38	14.53	0.68	0.14	–	–	22.33	51.38	–	–	–	1.47
WWTP 3	422	22.37	4.12	29	11.20	2.60	0.20	–	0.41	–	–	–	–	–	0.01
WWTP 4	220	47.28	6.70	8	7.08	2.46	0.54	–	3.91	–	–	–	–	–	0.08
WWTP 5	685	53.36	5.06	51	4.23	2.04	0.29	–	0.54	–	–	0.00	–	–	0.01
WWTP 6	648	58.94	8.76	27	17.95	1.34	0.27	0.10	1.79	65.25	–	5.19	0.97	0.17	1.47
WWTP 7	585	54.98	10.65	37	33.48	0.54	0.33	0.24	2.09	–	–	–	–	–	0.04
WWTP 8	623	47.61	6.98	50	22.94	0.91	0.13	–	2.23	–	–	–	–	–	0.04
WWTP 9	763	54.98	8.62	53	17.53	1.43	0.48	0.04	1.67	54.48	–	2.92	0.13	0.03	1.18
WWTP 10	673	59.42	9.55	43	31.37	1.00	0.36	–	2.86	21.75	–	5.53	0.89	–	0.62
WWTP 11	609	64.15	10.53	26	17.22	2.69	0.63	0.06	2.41	0.74	–	–	–	–	0.06
WWTP 12	918	65.68	8.77	31	7.02	1.44	0.52	–	2.16	22.54	–	2.58	1.00	0.00	0.57
WWTP 13	787	73.86	10.21	31	8.59	1.70	0.85	–	2.70	–	–	1.16	1.20	1.08	0.12
WWTP 14	419	30.91	4.49	17	5.03	0.20	0.31	–	0.88	–	–	2.86	3.61	–	0.15
WWTP 15	599	57.15	7.14	32	20.90	1.28	0.51	–	3.26	20.54	80.63	2.93	0.81	0.56	2.17
WWTP 16	846	59.41	8.83	23	5.01	0.73	0.59	–	6.67	21.10	–	–	–	–	0.56
WWTP 17	617	41.59	6.37	49	34.98	2.24	0.13	0.13	2.67	53.30	–	2.24	1.50	1.25	1.22
WWTP 18	623	55.30	7.52	39	18.81	2.63	0.69	0.07	1.59	44.37	–	23.19	0.12	–	1.39
WWTP 19	1107	70.65	6.78	67	50.19	1.66	0.56	–	3.65	119.95	–	6.77	0.15	0.29	2.62
WWTP 20	763	71.98	9.86	39	38.00	2.90	0.56	–	5.39	81.90	–	21.92	6.74	–	2.32
WWTP 21	752	75.62	9.57	28	22.32	2.49	1.37	–	3.03	–	–	3.57	7.44	0.08[b]	0.28
WWTP 22	886	76.10	12.84	65	34.74	2.99	0.66	0.27	3.84	20.23	–	4.29	1.34	0.26	0.60
WWTP 23	750	30.20	5.78	49	9.16	0.65	0.50		0.00	89.93	–	–	–	–	1.80
WWTP 24	954	65.94	15.73	24	3.43	1.06	0.80	–	11.37	47.81	–	17.93	3.40	0.70	1.62

	Sludge									Waste				Operational costs (€)		
	To agriculture (kg WW)[c]	To landfill (kg WW)[c]	Transport (kg km)	Application as slurry (l)	N (g)[d]	P_2O_5 (g)[d]	N_2O (g) to air	NH_3 (g) to air	PO_4 (g) to water	Grit (g)	MSW (g)	Fats (g)	Transport (kg km)	Energy	Staff	Others
WWTP 1	0.25	–	5.13	0.24	2.19	2.87	0.03	0.66	0.10	–	54.70	–	6.02	–	–	–
WWTP 2	0.34	–	6.82	0.27	4.63	4.88	0.07	1.41	0.17	10.13	12.17	1.45	1.94	0.013	0.024	0.032
WWTP 3	0.17	0.22	7.88	0.17	0.23	0.13	0.00	0.07	0.00	19.28	13.18	4.24	4.80	0.027	0.033	0.018
WWTP 4	0.87	–	43.49	0.86	12.48	0.02	0.23	3.79	0.00	32.62	31.31	15.66	15.04	0.039	0.053	0.025
WWTP 5	0.70	–	13.95	0.67	4.99	1.00	0.08	1.52	0.03	3.70	3.63	1.67	1.69	0.028	0.015	0.048
WWTP 6	0.54	–	10.99	0.53	1.73	5.46	0.03	0.53	0.19	10.12	16.67	0.85	0.55	0.041	0.060	0.077
WWTP 7	0.72	–	14.70	0.71	8.57	12.03	0.13	2.60	0.41	3.70	56.31	0.70	1.23	0.084	0.108	0.031
WWTP 8	0.78	–	16.00	0.77	9.70	7.40	0.15	2.94	0.25	4.78	17.83	1.05	0.46	0.069	0.074	0.068
WWTP 9	1.06	0.05	21.76	1.05	10.18	12.35	0.16	3.09	0.43	17.34	22.00	6.55	0.81	0.032	0.032	0.100
WWTP 10	0.76	–	9.18	0.76	3.13	8.87	0.05	0.95	0.31	25.69	115.45	9.95	1.69	0.054	0.082	0.100
WWTP 11	0.90	0.01	18.41	0.89	–	–	–	–	–	25.43	20.40	0.97	0.94	0.078	0.063	0.068
WWTP 12	1.44	–	29.58	1.43	16.73	15.89	0.26	5.08	0.55	0.00	25.53	–	0.52	0.072	0.065	0.075
WWTP 13	1.75	–	35.80	1.73	3.25	0.78	0.05	0.99	0.03	55.78	27.48	1.23	1.71	0.061	0.153	0.090
WWTP 14	0.53	–	6.56	0.52	5.41	5.33	0.09	1.64	0.18	10.14	5.76	–	0.20	0.042	0.103	0.060

WWTP 15	1.27	–	26.09	1.02	13.22	12.45	0.21	4.01	0.43	19.81	22.83	0.35	0.87	0.055	0.058	0.190
WWTP 16	1.72	–	35.30	1.65	3.46	0.07	0.05	1.05	0.00	22.92	28.90	1.82	1.06	0.107	0.061	0.115
WWTP 17	0.61	–	19.00	0.61	6.93	8.00	0.11	2.10	0.28	14.70	10.31	0.36	0.78	0.052	0.078	0.107
WWTP 18	0.93	–	18.98	0.91	9.28	11.67	0.15	2.82	0.40	5.26	23.70	2.04	0.59	0.045	0.081	0.050
WWTP 19	2.10	–	42.99	1.69	4.61	0.09	0.07	1.40	0.00	13.91	20.27	–	0.70	0.038	0.105	0.122
WWTP 20	1.07	–	21.84	1.05	11.70	19.08	0.18	3.55	0.66	4.92	56.77	0.80	1.26	0.059	0.082	0.135
WWTP 21	1.89	–		1.87	3.84	0.85	0.06	1.17	0.03	100.44	67.98	8.58	4.04	0.101	0.137	0.185
WWTP 22	1.73	–	35.44	1.71	–	–	–	–	–	20.35	146.84	0.90	3.43	0.064	0.094	0.131
WWTP 23	1.18	–	24.11	1.16	10.10	9.66	0.16	3.06	0.33	13.75	0.88	1.29	0.30	0.058	0.133	0.069
WWTP 24	1.30	–	29.95	1.25	2.84	0.11	0.04	0.86	0.00	16.38	35.08	3.84	1.18	0.125	0.103	0.083

a Some plants produce a certain amount of electricity by combustion of the CH_4 produced by the anaerobic digestion of their sludge that is sold to the net rather than used inside the WWTP.
b WWTP 21 consumes H_3PO_4 rather than H_2SO_4.
c WW: Wet weight.
d Nutrients values presented reflect their total amount present in the sludge, not the amount that is used by plants according to Bengtsson et al. (1997).

Tertiary treatment, although not required, is present in some facilities included in Type 1 and Type 2. In the Type 1 group, UV disinfection is partially responsible for the higher electricity use of WWTP 4, much in the same way as coagulation/flocculation for the consumption of $FeCl_3$ in WWTP 6 (Table 2). In the Type 2 group, the effect of tertiary treatment is not so obvious: both WWTP 9 and WWTP 11 present coagulation/flocculation stages as primary and tertiary treatment, but the consumption of $FeCl_3$ for the latter is almost irrelevant (Table 2). Even more, WWTP 11 also has UV disinfection, but the effect on the energy use is not as evident for WWTP 11 compared to other Type 2 plants as it is for WWTP 4 compared to the rest of Type 1 plants (Table 2).

The Type 3 plants do not present such a high influent load as the Type 2 ones; nevertheless they are probably large enough to require nutrient removal in order to fulfill their correspondent legal requirements found in EC (1998) (Table 1, Fig. 1 and Table S1). Although tertiary treatment, and specifically disinfection, is not required to discharge in a sensitive area, this stage is present in all plants. In any case, its effect is not noticeable since all have a chlorination process, although no consumption of chlorinating agents was reported for 2008. This is because the tertiary treatment is not in use at present, and was built in case that reuse of the treated water was required instead of being discharged.

All Type 4 plants present tertiary treatments since they require some kind of disinfection process in order to fulfill sanitary requirements. UV disinfection, present in all except WWTP 18 and 19, might be a reason for higher electricity use compared with Type 1. WWTP 18 presents ultrafiltration and reverse osmosis, which might be less energy efficient than UV (Beavis and Lundie, 2003; Clauson Kaas et al., 2006). On the other hand, WWTP 19, with an average consumption (0.56 kWh/m^3) uses a filtration process, using electricity at a similar rate to the UV process (Clauson Kaas et al., 2006).

WWTP 21 uses by far the most electricity, most likely because of the use of aerobic sludge digestion rather than anaerobic or lime stabilization like the other WWTPs. All Type 4 plants except one utilize some nutrient removal technology, which might seem contradictory since, as indicated in Section 2.4, nutrients present in the reused water partially avoid the use of N and P_2O_5 -based fertilizers. However, all plants were built and upgraded years before the legislation for water reuse was published, suggesting, as in the case of Type 2 plants, that they can target a specific nutrient or remove both in case the effluent has to be discharged to a sensitive area. Since the data is from 2008, the first year with water reuse regulations, it is likely the high nutrient removal efficiencies correspond to a transition process between water discharge and water reuse (Table 1).

Required to supply part of the treated water for industrial purposes, WWTP 23 (Type 5) must fulfill similar requirements to Type 4 plants and thus uses similar technology. Still, their electricity use is not particularly high (Table 2), especially considering this plant makes use of filtration, ultrafiltration, and UV stages, indicating the fraction of water reused in industry might be small.

WWTP 24 (Type 6) shows two important characteristics which will notably affect their environmental profile: on the one hand, this plant deals with the highest average load (Fig. 1,

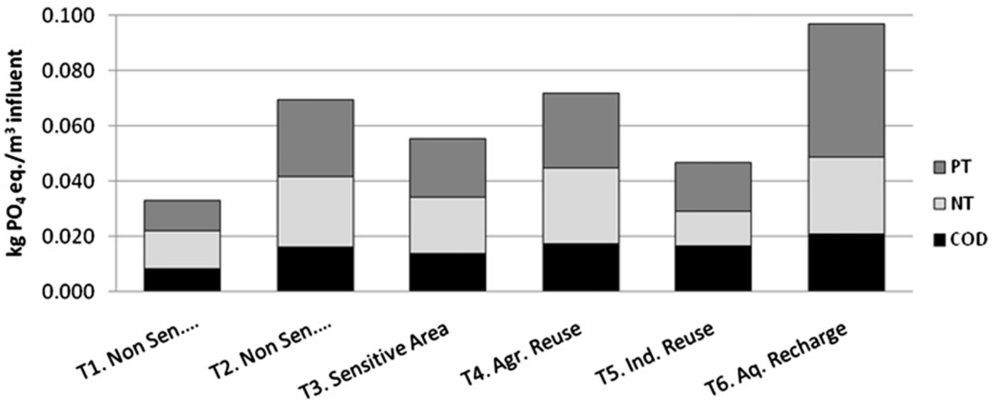

Fig. 1 – Eutrophication Potential associated to the influent (per m^3 of influent, FU1).

Table 2); but on the other, it is the facility with the highest requirements, since it not only must achieve a substantial nutrient removal (Tables 1 and 2) but also disinfect the treated water—water recharging an aquifer. This explains its high energy use (Table 2), associated not only with the extended aeration process, but also with the UV disinfection and the filtration of the tertiary treatment.

3.2. *Environmental profile according to the volume-related functional unit (FU1)*

3.2.1. *Eutrophication potential calculated for FU1*

Average results of the EP based on the FU1 (m^3), grouped by typology, are presented in Fig. 2, while individual data for all the plants is detailed in Figs. S1 and S2 in the supplementary information. In addition to the impact associated with the effluent of the plants, the eutrophication associated with the treatment process, as well as the beneficial consequences of the different avoided products, are also included here. This indirect eutrophication is never higher than 10% of the effluent EP and is approximately 4% for most plants. Avoided products show a small contribution to the whole picture, although they are not insignificant for Type 4.

Despite the obvious differences in the influent composition (Fig. 1) of types 1 and 2, the effluents of both groups present a relatively similar effluent quality (Fig. 2) since the WWTPs operate to accomplish identical legal requirements (maximum concentration of 125 mg COD/m^3 in the discharged effluent). As seen in Table 1 and already discussed in Section 3.1, Type 2 plants have implemented technologies for nutrient removal for their highly loaded wastewater, which probably justifies the large difference between both Figs. 1 and 2 regarding Type 1 and Type 2. For Type 3, they are legally required to remove both N and P, which explains their high efficiencies (Table 1). However, their lower EP is not only due to their efficiency, but also because of their lower influent loads (Fig. 1).

The Type 4 WWTPs present a noticeably high impact (Fig. 2). Despite most of them using some kind of nutrient removal process, their removal efficiency is relatively low compared to that of Type 3, the reason being nutrients present in the water are a valuable resource for agriculture and there would be no point in totally eliminating them. It is worthwhile to note the impact of the effluent is still high, even considering more than half of the nutrients are expected to be absorbed by plants (Bengtsson et al., 1997).

Type 5 presents a behavior much like the Type 3 plants as both of them remove nutrients with distinctive efficiency (Table 1) and the influent loads are not particularly different (Fig. 1. and Table 2.). Finally, although Type 6 presents the

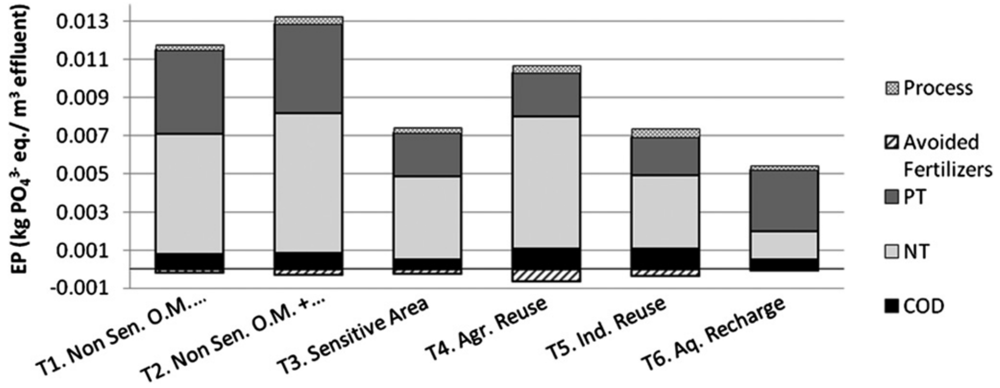

Fig. 2 – Eutrophication Potential of the WWTP typologies considered based on FU1 (kg PO$_4$ eq./m^3).

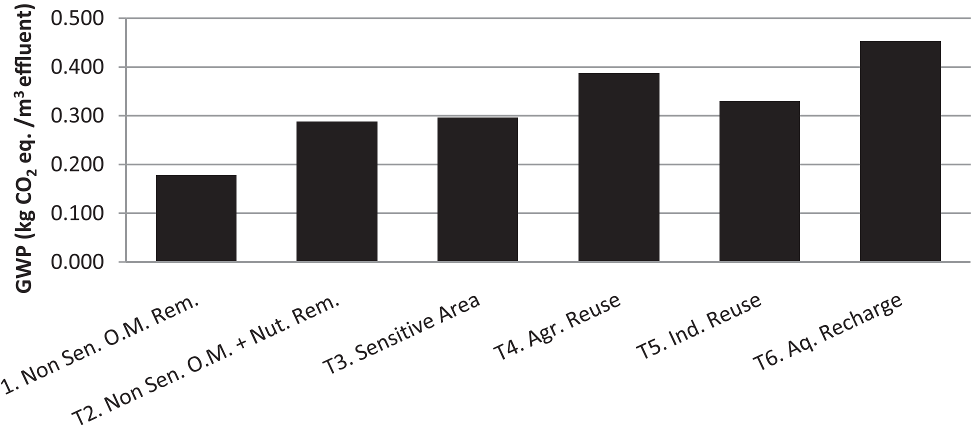

Fig. 3 – Global Warming Potential of the WWTP typologies considered based on FU1 (kg CO_2 eq./m^3).

highest influent load of all WWTPs, its extraordinary high removal yields (Table 1) make this plant one of the facilities with the lowest effluent loads.

3.2.2. *Global warming potential calculated for FU1*

Average values of GWP impacts for the different typologies are presented in Fig. 3, while individual results are included in the Supplementary Information (Fig. S3). Not surprisingly, the increasing impacts in GWP are due to the increasing complexity of technology applied, and it is mainly associated with larger consumptions of electricity and chemicals (Table 2).

Type 1 plants can be considered as a baseline scenario since they only fulfill the basic function of a WWTP: OM removal. The higher impact of the WWTPs belonging to Types 2, 3 and 4 can be partially attributed to their higher average COD concentration in the influent (Table 2), which requires larger aeration periods. Another factor would be the nitrification process (Table 1), which also demands more oxygen and thus, more electricity (Table 2). In some cases, it is also associated with tertiary treatments (Beavis and Lundie, 2003; Clauson Kaas et al., 2006), which are necessary to fulfill the requirements of the reuse water legislation but which are also employed by WWTPs discharging in sensitive areas. Types 4 and 5 present a similar emission rate to previous groups, although greater emissions for Type 4 plants are caused by WWTP 21, which displays by far the peak emission rate (Fig. S3) due to its high electricity use.

3.3. *Operational efficiency: environmental profile according to the eutrophication-related functional unit (FU2)*

3.3.1. *Eutrophication potential calculated for FU2*

Based on the FU2 (kg of PO_4^{3-} eq. removed), average results are presented in Fig. 4, while detailed information for individual facilities is found in the supplementary information (Fig. S4). On average, this approach establishes clear differences between simple and increasingly complex technologies, penalizing the scheme used for the removal of the organic matter only (Type 1). This might suggest there is a margin for improvement for Type 1 plants, particularly WWTP 1, 2 and 3, either by optimizing the OM removal or by including the removal of nutrients. However, it is also necessary to indicate that the treatment of low load water (a feature of Type 1) has particular difficulties such as low sludge decantability (Seijas et al., 2003), and high OM removal rates could not always be guaranteed.

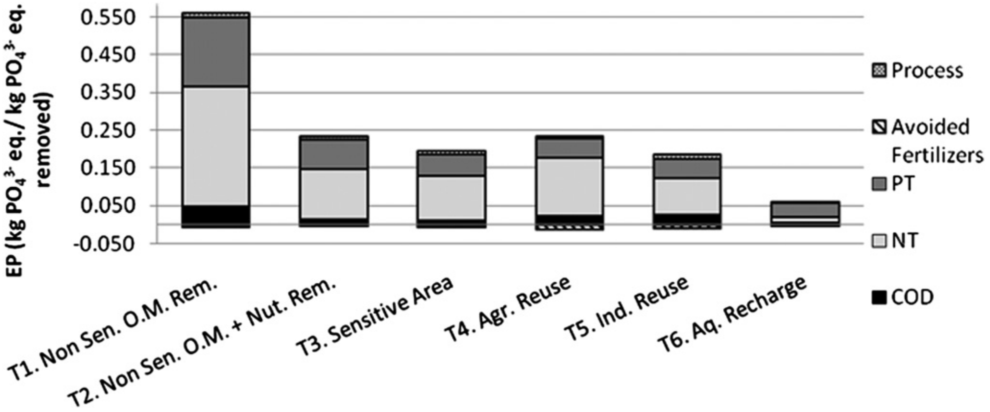

Fig. 4 – Eutrophication Potential of the WWTP typologies considered based on FU2 (kg PO_4 eq./kg PO_4 eq. removed).

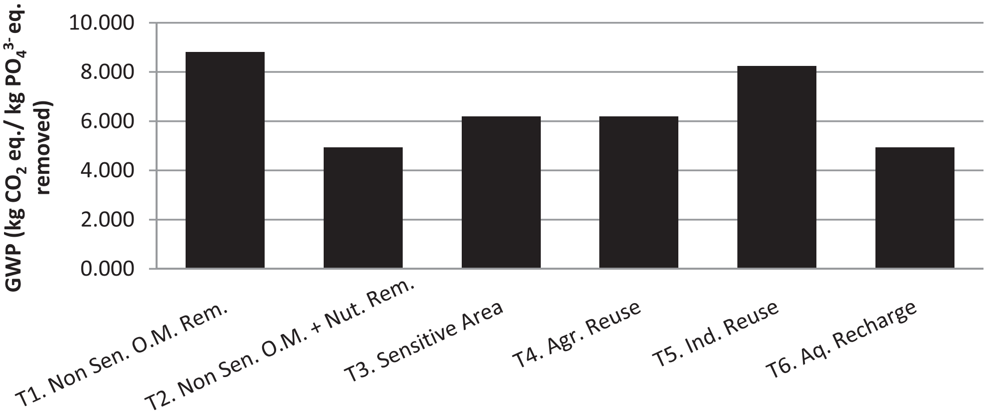

Fig. 5 – Global Warming Potential of the WWTP typologies considered based on FU2 (kg CO_2 eq./kg PO_4 eq. removed).

According to the results based on FU2, the implementation of combined treatment for organic matter and nutrient removal clearly benefits the environmental performance of non-Type 1 plants, especially in the case of Type 6, which has the highest removal efficiency (Table 1). FU2 also shows, despite being less efficient in absolute terms (Table 1, Fig. 2), Type 2 presents a profile relatively similar to Type 3, reinforcing the idea that even when Type 2 plants do not need to remove nutrients, they put the same effort into doing so as plants legally required to do it (Type 3). It also balances the higher values presented in Fig. 1 for Type 4 due to its high removal in absolute terms.

3.3.2. *Global warming potential calculated for FU2*

The contributions of the different wastewater treatment typologies to global warming expressed by the avoided eutrophication (FU2) are presented in Fig. 5 (individual results in Fig. S5). The differences between Types 1 and 2 are also evident here, further emphasizing that the former are on average less efficient, requiring more electricity for the same level of eutrophication reduction. To a lesser extent, this is also the case for Type 5, which presents a relatively higher profile than in Fig. 3 Type 3 and 4 share a similar profile despite the higher electricity use of the latter (Table 2, Fig. 3) due to the higher absolute removal by Type 3 plants. Aquifer recharge (Type 6) is also revealed as a fairly good environmental option (Fig. 5), even in spite of extensive use of electricity (Table 2) and GWP emissions (Fig. 3).

3.4. *Economic profile*

3.4.1. *Economic profile according to the volume-related functional unit (FU1)*

Operational costs (OC) per FU1 (m^3) are presented in Fig. 6 (as well as Fig. S6).

As shown in Fig. 6, the operational costs of the six WWTP typologies are highly variable, since the minimum value is 0.127 €/m^3 for Type 1 WWTPs, while the maximum is 0.311 €/m^3 for Type 6. For plants that discharge the treated wastewater to non-sensitive areas, Type 2 increase in cost of 75.6% compared Type 1 due to their nutrient removal. In regards to the two typologies of WWTPs that remove organic matter and nutrients (Types 2 and 3), the cost difference is quantified by 18%. This is because plants discharging regenerated water to sensitive areas display higher removal efficiencies for both N and P (Table 1). In relation to the three types of WWTPs that reuse the treated water, cost differences between them are very small, although the Type 6 plant presents slightly higher costs due to two factors: first, as shown in Table 1, the pollutants removal efficiency is higher than for the other

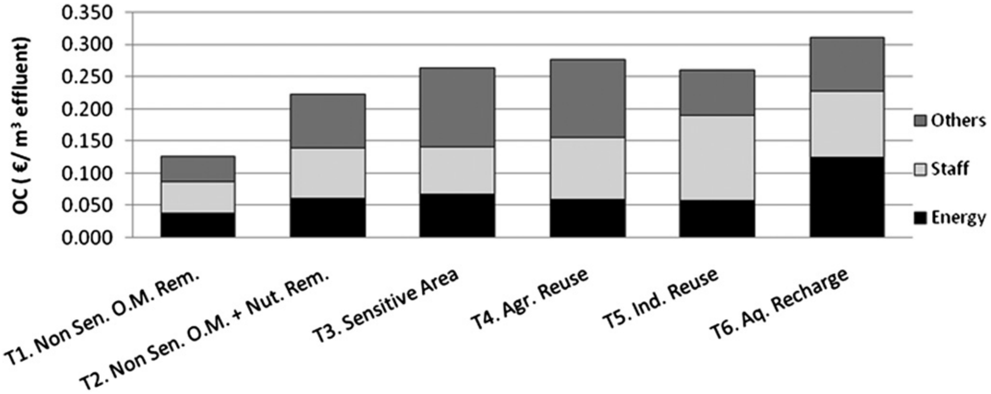

Fig. 6 – Operational costs of the WWTP typologies considered based on FU1 (€/m^3).

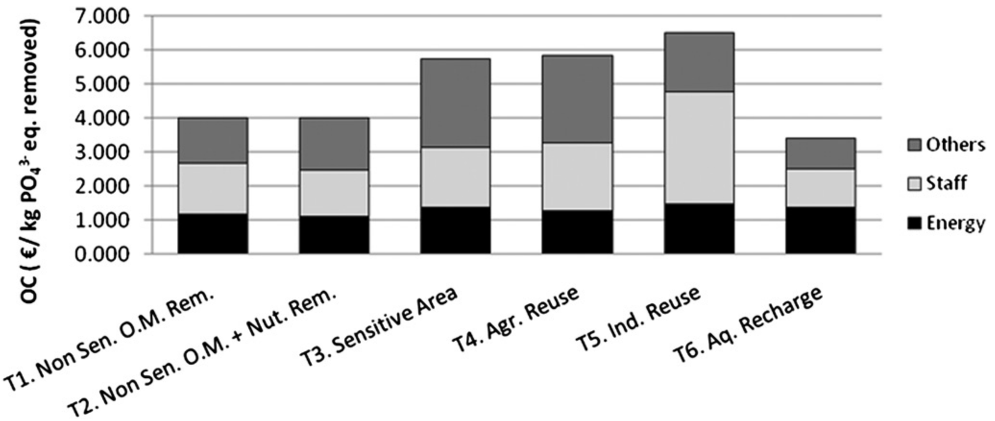

Fig. 7 – Operational costs of the WWTP typologies considered based on FU2 (€/kg PO_4 eq. removed).

WWTPs; second, the real wastewater flow treated by this plant (Table 1) is the lowest and therefore, is less affected by scale economies.

Regarding the cost distribution: on average 26% of the total cost is associated with energy consumption, 35% with the staff, and the remaining 39% with others. That about a quarter of the total cost is linked to electricity highlights the importance of efficiency in the use of energy, both from an environmental and economic point of view. Fig. 6 shows that Types 4 and 5 are those spending the smallest percentage of total cost on the item energy. In contrast, WWTP 24 (Type 6) is the one with the highest dependence on electricity. In looking at electricity use data, expressed in kWh/m^3 (Table 2), it is verified there is no direct relationship between electricity use and costs. This is because currently WWTP operators can negotiate their fee with the electric companies. Therefore, to reduce energy costs in WWTPs, a double strategy may be adopted: operators may negotiate lower electricity fees, while they may also reduce the use of electricity by increasing their efficiency. The second strategy is more beneficial since it would effect not only a reduction in costs but also reduce the carbon footprint of these facilities, but both may be implemented. In relation to staff costs, they are similar to those presented by Molinos-Senante et al. (2010), who quantified them at 32% of the total operation costs. It is worth noting the percentage of the Type 5 WWTP in which staff costs represent a significantly higher percentage than the average (51% vs. 35%). That regenerated water is used for industrial purposes supposes a high monitoring of effluent parameters and ergo, high staff costs. Finally, the item “Others” is the least value-consistent parameter among WWTP types. This item consists of multiple elements (i.e. reagents, waste management and maintenance) and thus large variations would be expected.

3.4.2. *Economic profile according to the eutrophication-related functional unit (FU2)*

Economic efficiency results based on FU2 are presented in Fig. 7, while individual results are displayed in Fig. S7. It is noted that the differences among the WWTP’s types are even more significant when using the FU2 than FU1. Type 1 and 2 experienced slightly lower costs than those discharged to sensitive areas. In the case of the non-sensitive areas, unlike FU1 results, Type 2 plants show lower costs than Type 1. Thus, when using FU2 as a basis for comparison, it is revealed that nutrient removal is not necessarily more expensive than OM removal. Also, it is noted that plants discharging treated water to sensitive areas and those reusing the regenerated water for agricultural purposes have very similar operating costs.

In regards to other plants, Type 5 and 6 are those experiencing the maximum and minimum costs, respectively. Nevertheless, it is necessary to state that these are typologies represented only by one plant and they may not be an accurate reflection of Industrial Reuse and Aquifer Recharge WWTPs.

4. Conclusions

According to the results of this study, grouping WWTPs based on their legal requirements has exposed the link between these legalities and the technology used to achieve them. Non-Sensitive Discharge WWTPs tend to be associated with OM removal technology or with nutrient removal for specific problems and with relatively low efficiency. Sensitive Discharge and Environmental Reuse (aquifer refill) plants always present combined N and P removal as well as tertiary treatment. Agricultural and Industrial Reuse plants demand tertiary treatment due to microbiological requirements and although nutrients can be considered a valuable resource, several plants implement N and P removal, although with lower efficiency.

The selection of the functional unit has proved to be a key aspect in defining both economic and environmental profiles. The first FU defined here (m^3 of treated water) showed that Type 1 (non-sensitive discharge, OM removal only WWTPs), resulted in lower impacts for EP and GWP as well as lower costs, suggesting that the other typologies were less efficient. Conversely, the definition of a second FU based on EP reduction acknowledged the higher efficiency of Types 2 and 6 (non-sensitive areas discharge with OM and nutrient removal and aquifer recharge plants), resulting, on average, in a better environmental and economic performance. Although FU1 (m^3) presents more intuitive results, FU2 (kg PO_4^{3-} removed) has proved to better reflect the function of a WWTP when focus is on eutrophication and thus is considered a more useful FU for comparative studies. All in all, results show obtaining an effluent of higher quality, meaning disinfected and with lower eutrophication potential, increases both with GWP and overall expense. It also revealed this higher cost is well-balanced, and is even beneficial for advanced typologies. Finally, for a wastewater treatment technology to be judged sustainable, it must comply with environmental, socio-cultural and economic needs. Therefore, the on-going research is focused on incorporating social variables with the already-established approach in order to obtain a complete set of indicators of sustainability for each WWTP under consideration.

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Appendix. Supplementary material

Supplementary data related to this article can be found online at doi:10.1016/j.watres.2011.08.053.

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