Life cycle assessment of introducing an anaerobic digester in a municipal wastewater treatment plant in Spain

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ABSTRACT

Anaerobic digestion (AD) is being established as a standard technology to recover some of the energy contained in the sludge in wastewater treatment plants (WWTPs) as biogas, allowing an economy in electricity and heating and a decrease in climate gas emission. The purpose of this study was to quantify the contributions to the total environmental impact of the plant using life cycle assessment methodology. In this work, data from real operation during 2012 of a municipal WWTP were utilized as the basis to determine the impact of including AD in the process. The climate change human health was the most important impact category when AD was included in the treatment (Scenario 1), especially due to fossil carbon dioxide emissions. Without AD (Scenario 2), increased emissions of greenhouse gases, mostly derived from the use of electricity, provoked a rise in the climate change categories. Biogas utilization was able to provide 47% of the energy required in the WWTP in Scenario 1. Results obtained make Scenario 1 the better environmental choice by far, mainly due to the use of the digested sludge as fertilizer.

Key words | anaerobic digestion, biogas, life cycle assessment, sludge, Spain, wastewater treatment plant

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INTRODUCTION

Wastewater treatment plants (WWTPs) play an important environmental role minimizing the impact of discharges in river ecosystems. Simultaneously, their operation involves a series of activities that provoke an impact on the environment (use of energy, emissions, waste generation, etc.). A correct evaluation of design and operation of the plant, as well as improvements in the process, is critical in reducing these impacts. Owing to this, some studies have been developed in order to achieve energy self-sufficiency in WWTPs (Nowak *et al.* 2011; Svardal & Kroiss 2011; Balmer & Hellström 2012; Jenicek *et al.* 2012, 2013).

Another key factor is the management of the sewage sludge, not only from the economic point of view, but also from the environmental one (Iranpour *et al.* 2004). Nutrient contained in the sewage sludge make its use interesting as a fertilizer (Singh & Agrawal 2008). Nevertheless, the possibilities for disposal of sewage from municipal wastewater treatment are being increasingly restricted and its application as a fertilizer remains controversial (Busetti *et al.* 2005). Stabilization processes aim to destroy pathogens, eliminate offensive odors and improve esthetics and transportability (Yoshida *et al.* 2013). The current importance of anaerobic digestion (AD) in wastewater treatment is based on in its efficiency for sludge transformation into biogas which can be used as an alternative energy source (Carlos-Hernandez *et al.* 2009). The price and demand of electricity has increased in recent years, encouraging the use of energy sources less dependent on fossil fuels (Manzoor & Haqiqi 2012). Unfortunately, implementation of AD has some potential negative impacts that need to be minimized.

Aiming to study the environmental behavior of WWTPs, life cycle assessment (LCA) has been widely used (Corominas *et al.* 2013a). Recently, this methodology has exhibited significant performance as a tool to support investment decisions taken on the basis of environmental information (Rodriguez-Garcia *et al.* 2011; Antonopoulos *et al.* 2013; Remy *et al.* 2013). During the last decades, many studies have been developed in several countries focusing on different key aspects of WWTPs, such as greenhouse gas emissions (Bani Shahabadi *et al.* 2009; Flores-Alsina *et al.* 2011), nutrient removal or

doi: 10.2166/wst.2015.545

recovery (Nakakubo *et al.* 2012; Corominas *et al.* 2013b), and sewage sludge treatments (Lundin *et al.* 2004; Johansson *et al.* 2008; Murray *et al.* 2008; Manfredi & Christensen 2009; Remy *et al.* 2013; Bertanza *et al.* 2015). Ecotoxicity impacts caused mostly by sewage sludge disposal were present in all plants (Lassaux *et al.* 2007; Gallego *et al.* 2008), whereas global warming impact was especially important in WWTPs with advanced treatments (Muñoz *et al.* 2009; Rodriguez-Garcia *et al.* 2011; Amores *et al.* 2013).

To our knowledge, although many studies have been developed treating different aspects of AD on a WWTP, no studies have focused on checking the environmental effect of introducing this treatment in a real plant. Therefore, the main goal pursued in this work was to conduct an LCA in order to compare the environmental behavior of a WWTP with and without AD, creating a good reference for researchers and LCA practitioners in the field of wastewater.

MATERIAL AND METHODS

Goal and scope definition

The present study closely follows the guidelines of ISO 14040 to ISO 14044, describing the principles and framework for LCA. The goal of the study was to compare the environmental behavior of a real WWTP and the same one without the anaerobic step. The two scenarios considered are defined below.

Scenario 1 is a municipal WWTP located in central Spain. It has a wastewater treatment capacity of 76,000 m^3/day, and produces 37 tons/day of dewatered sludge with a yearly average of 441,141 person equivalents (PE). The system consists of the following treatment stages: pretreatment (screening, grit, and grease removal), primary treatment (pre-aeration and sedimentation), secondary treatment (biological process and sedimentation), and sludge treatment. The biological treatment consists of a conventional activated sludge plug flow reactor with nitrification–denitrification and a system configuration for biological phosphorus removal (UCT (University of Cape Town) or Bardenpho, as needed). The primary and secondary sludges are mixed and treated by thickening, AD, and centrifugation. The stabilized sludge is deposited on agricultural land (despite the controversy existing in Europe about using WWTP sludge in agriculture). The only chemicals employed are $FeCl_3$ and polyelectrolyte, added in the sludge line. The biogas produced is used in a cogeneration system. The average composition of this biogas is: CH_4 70%, CO_2 29.65%, SH_2 0.001%.

Scenario 2 is the same WWTP without AD. Basically, the consequences of removing the AD were incorporated, i.e., an increase of the volume of sludge generated (with the resulting changes in transport), the change in the electricity needs of the plant (as a result of the absence of cogeneration, requirements of AD unit and more sludge to dewater), and the elimination of the emissions from the biogas burning. The disposal of the sludge on agricultural land was not considered in this scenario. According to Spanish regulations, sludge not going through an appropriate treatment to reduce its fermentability and health risks cannot be used in agriculture (RD 1310/1990). Landfill disposal was considered in this case. Figure 1 shows a block diagram for both scenarios.

Different LCA studies have considered different functions for a WWTP, leading to variability among the works developed in this field in the definition of the functional unit (FU) and the system boundaries, the selection of the methodology, and the procedure followed for interpreting results (Finnveden *et al.* 2009; Corominas *et al.* 2013a; Yoshida *et al.* 2013). According to regulations, the main function of the studied system considered is the treatment of an influent in order to discharge a suitable effluent to the environment. The FU selected was a PE, defined as the biodegradable organic load with 60 g of 5-day biochemical oxygen demand per day. This FU allowed taking into account both the volume of the influent and its associated load, unlike other FUs based only on volume (m^3). This is consistent with other published works in this field (Lundin *et al.* 2000; Gallego *et al.* 2008).

Inventory analysis

After goal and scope have been determined, SimaPro v.7.3 was used in order to make an inventory analysis (Spriesma 2004). Most of the data used to perform this stage were supplied by Acciona Agua from the operation of a real WWTP during 2012. The subsystems considered to carry out the LCA are shown and described in Table 1. In addition, there have been some approaches and simplifications based on bibliographic references on similar processes considered for this stage:

- Direct emissions of CO_2, N_2O, CH_4, SO_2, NH_3 (operation and disposal) have been calculated following the recommendations of the Intergovernmental Panel on Climate Change (Houghton *et al.* 2001; Doorn *et al.* 2006). Emissions from biogas combustion were calculated from actual data of the biogas collected, mainly CO_2 and SO_2 due to the presence of H_2S. The emissions from the

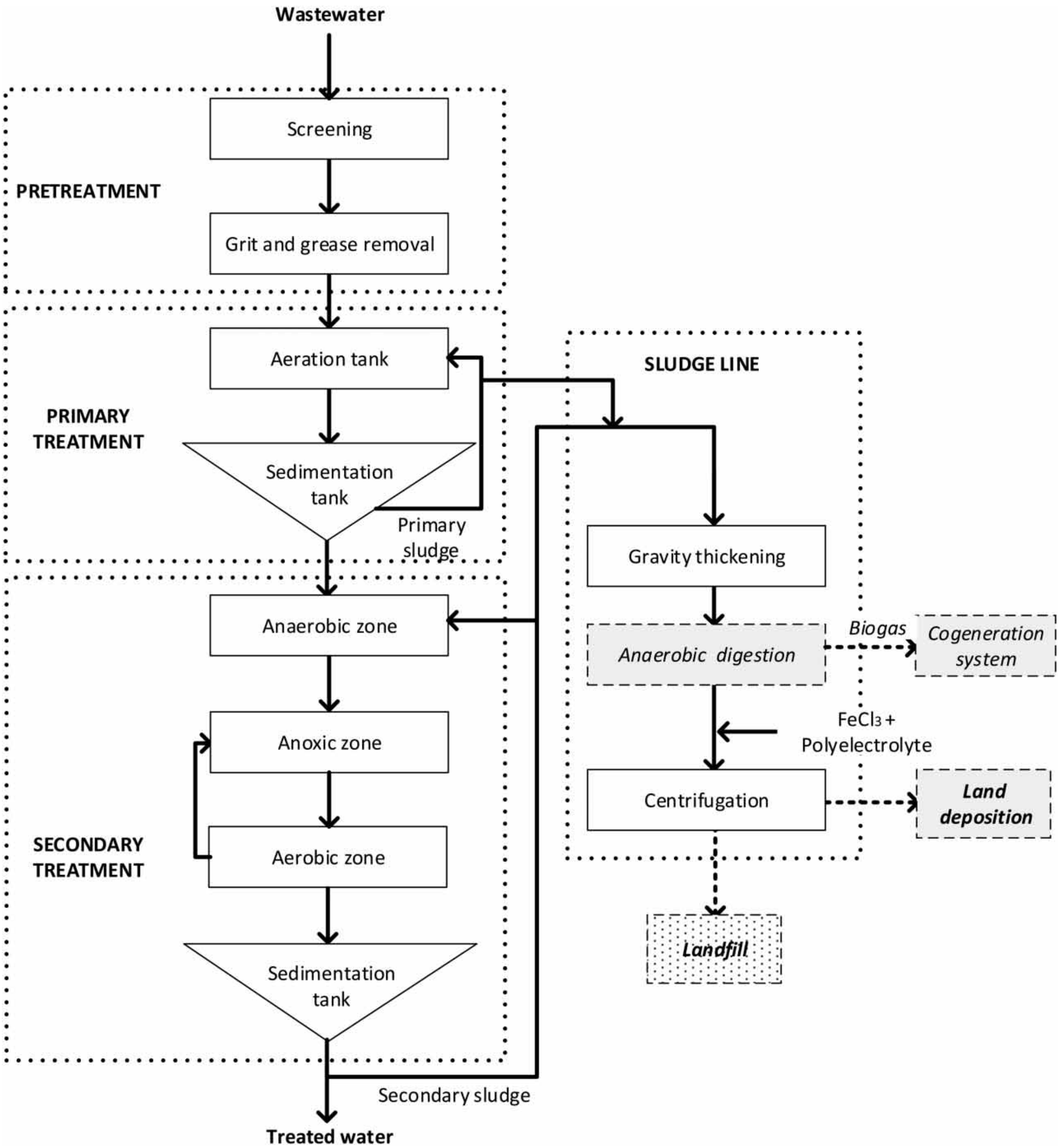

Figure 1 | Block diagram for Scenarios 1 and 2 (gray blocks are removed in Scenario 2 whereas the spotted one is removed in Scenario 1).

sludge during storage transport and degradation in the soil were not taken into account.

- The database used for electricity production was Ecoinvent Unit Processes V.2.2, using the units *Electricity, medium voltage, at grid [ES]* (Hischier *et al.* 2010).
- For the bioavailability of metals contained in the sludge, data regarding the percentage of metal extracted with EDTA (ethylenediaminetetraacetic acid) were considered. The corresponding values are 58.5% for Cu, 7.8% for Pb, 4.1% for Cr, 7.5% for Ni, and 18.0% for Zn. Due to the absence of data for other metals (Hg, Cd), the worst-case scenario was considered, with 100% bioavailability (Gallego *et al.* 2008).
- In Scenario 1, the application of digested sewage sludge (N and P content) in agricultural soils provides an environmental benefit by avoiding the production of synthetic fertilizers. To calculate the amount of avoided fertilizer, it has been assumed that 1 kg of dry sludge is equivalent to 0.3 kg of a chemical fertilizer, based on the composition of the sludge (Bengtsson *et al.* 1997).
- The only chemicals considered were ferric chloride and polyelectrolyte, added to the sludge after AD. The

Table 1 | Description of subsystems

Subsystems		**Description**
Influent		Wastewater treated (BOD_5, COD, N_T, P, SS), considered as avoided emissions
Effluent		Wastewater discharged (BOD_5, COD, N_T, P, SS)
Air emissions		Gas emissions due to plant operation: (CO_2, N_2O, CH_4, NH_3) and burning biogas (CO_2, SO_2)[a]
Soil emissions		Heavy metals contained in the sludge (Cu, Cd, Cr, Hg, Ni, Zn, Pb) deposited on land
Chemicals production		Production of chemicals required in the sewage sludge treatment (polyelectrolyte and ferric chloride)
Electricity		Power consumed by plant operation
Transport	Sludge	From the plant to the agricultural land[a] or to the landfill
	Chemicals	From the site of manufacture to the plant
	Solid wastes	From the plant to the landfill
Biogas*		Impacts derived from managing the biogas produced during sludge digestion
Chemical fertilizer avoided		Result of the use of sludge as farm fertilizer, avoiding the production and use of chemical fertilizers (N, P)

[a]Only for Scenario 1. BOD_5: biochemical oxygen demand; COD: chemical oxygen demand; N_T: total nitrogen; SS: suspended solids.

amount of chemicals needed was considered proportional to the amount of sludge centrifugated. *Acrylonitrile* and *iron(III) chloride 40%* units available at Ecoinvent V.2.2 were used to approach these chemicals (Hischier *et al.* 2010).

- The odor issue was not considered in this work due to the impossibility of having accurate data to estimate its impact.
- The impact of plant construction was not taken into account (Lassaux *et al.* 2007). It was considered negligible in other similar cases and even studies that have included this phase showed that sewer net and plant construction contribute less than 10% to the total environmental impact (Del Borghi *et al.* 2008).
- The real distances between the WWTP and the areas of chemical production (polyelectrolyte 1,800 km, ferric chloride 400 km), waste management (32 km), and application of sludge (40 km) were considered for the transport of chemicals, solid waste, and sludge. The Ecoinvent Unit Processes v.2.2 (Hischier *et al.* 2010) data were used to evaluate the transport impact since it was the best suited to the characteristics of the trucks used (*transport, lorry >32t*).

The yearly average of the inventory data for the two scenarios during 2012 is shown in Table 2, adding the standard deviation calculated considering monthly data.

Impact assessment

Inventory results are usually a very long list of emissions, consumed resources, and sometimes other items with difficult interpretation. A life cycle impact assessment procedure, such as the ReCiPe v.1.08 method included in SimaPro software, is designed to manage this issue, helping in the development of this work.

The primary objective of this method is to transform the list of life cycle inventory results into a limited number of indicator scores, showing the relative severity on an environmental impact category. Impact characterization allows comparison of the inventory results within each impact category. Normalization applies a selected reference value, obtaining dimensionless data and allowing the comparison between categories. The unit 'Pt' (point) is just a reference unit and must only be used for comparison between data obtained with the same calculation method. The absolute value of the points is not very relevant as the main purpose is to compare (Goedkoop *et al.* 2009). Average data of year 2012 sorted by month were supplied for characterization and normalization steps, in order to obtain the mean behavior of the year.

RESULTS AND DISCUSSION

Comparison between scenarios with and without AD

In order to know the relative importance of the impact categories on the overall system, Figure 2 (gray bars) presents normalization results of Scenario 1 using Pt as a measure of impact. At first glance, it is clearly noticeable that the main impacts were due to climate change categories, with a contribution slightly greater for human health than for ecosystems. The air emissions subsystem was mostly

Table 2 | Inventory data in 2012 given per month (inputs and outputs)

	Scenario 1		Scenario 2	
	Average	SD	Average	SD
PE	441,141	185,120	441,141	185,120
Inputs				
COD (kg/PE)	3.42	0.37	3.42	0.37
BOD_5 (kg/PE)	1.82	0.05	1.82	0.05
N_T (kg/PE)	0.34	0.04	0.34	0.04
P (kg/PE)	0.05	0.005	0.05	0.005
SS (kg/PE)	1.63	0.27	1.63	0.27
Electricity (kWh/PE)[a]	**1.29**	**0.46**	**2.01**	**0.23**
Chemicals transport ((t·km)/PE)	**0.15**	**0.06**	**0.26**	**0.10**
Sludge transport ((t·km)/PE)	**0.12**	**0.05**	**0.16**	**0.07**
Waste transport ((t·km)/PE)	0.002	0.003	0.002	0.003
Chemicals (kg/PE)	**0.35**	**0.14**	**0.59**	**0.23**
Outputs				
COD (kg/PE)	0.16	0.03	0.16	0.03
BOD_5 (kg/PE)	0.04	0.009	0.04	0.009
N_T (kg/PE)	0.08	0.009	0.08	0.009
P (kg/PE)	0.003	0.0006	0.003	0.0006
SS (kg/PE)	0.03	0.02	0.03	0.02
N_2O (kg/PE)	0.0006	7×10^{-5}	0.0006	7×10^{-5}
CH_4 (kg/PE)	**0.0007**	**0.0003**	**0.001**	**0.0005**
Biogas (m^3/PE)	**0.487**	**0.182**	**–**	**–**
CO_2 fossil (kg/PE)	**0.59**	**0.20**	**0.76**	**0.20**
CO_2 bio (kg/PE)	**2.06**	**0.75**	**1.11**	**0.56**
NH_3 (kg/PE)	**0.00006**	**2×10^{-5}**	**0.00008**	**3×10^{-5}**
SO_2 (kg/PE)	**0.00001**	**5×10^{-6}**	**–**	**–**
Dried sewage sludge (kg/PE)	**0.75**	**0.32**	**1.25**	**0.53**
Cd (kg/PE)	4.93×10^{-6}	1.88×10^{-6}	4.93×10^{-6}	1.88×10^{-6}
Cu (kg/PE)	6.56×10^{-4}	2.5×10^{-4}	6.56×10^{-4}	2.5×10^{-4}
Cr (kg/PE)	1.61×10^{-4}	6.15×10^{-5}	1.61×10^{-4}	6.15×10^{-5}
Hg (kg/PE)	2.38×10^{-6}	0.91×10^{-6}	2.38×10^{-6}	0.91×10^{-6}
Ni (kg/PE)	5.77×10^{-5}	2.20×10^{-5}	5.77×10^{-5}	2.20×10^{-5}
Pb (kg/PE)	1.16×10^{-4}	4.43×10^{-5}	1.16×10^{-4}	4.43×10^{-5}
Zn (kg/PE)	1.58×10^{-3}	6×10^{-4}	1.58×10^{-3}	6×10^{-4}

[a]Bold type: inputs and outputs significantly changing between scenarios.

responsible for this impact followed closely by electricity, mainly due to the fossil carbon dioxide emissions in both cases. Beneficial contributions derived from the use of sludge as agricultural fertilizer appeared especially in three impact categories: climate change human health, climate change ecosystems, and fossil depletion. The positive impact to prevent spillage of raw water entering the treatment plant affected the freshwater eutrophication category.

The environmental analysis of Scenario 2 (black bars) was qualitatively similar to Scenario 1, with the contributions to impact categories climate change human health, climate change ecosystems, and particulate matter

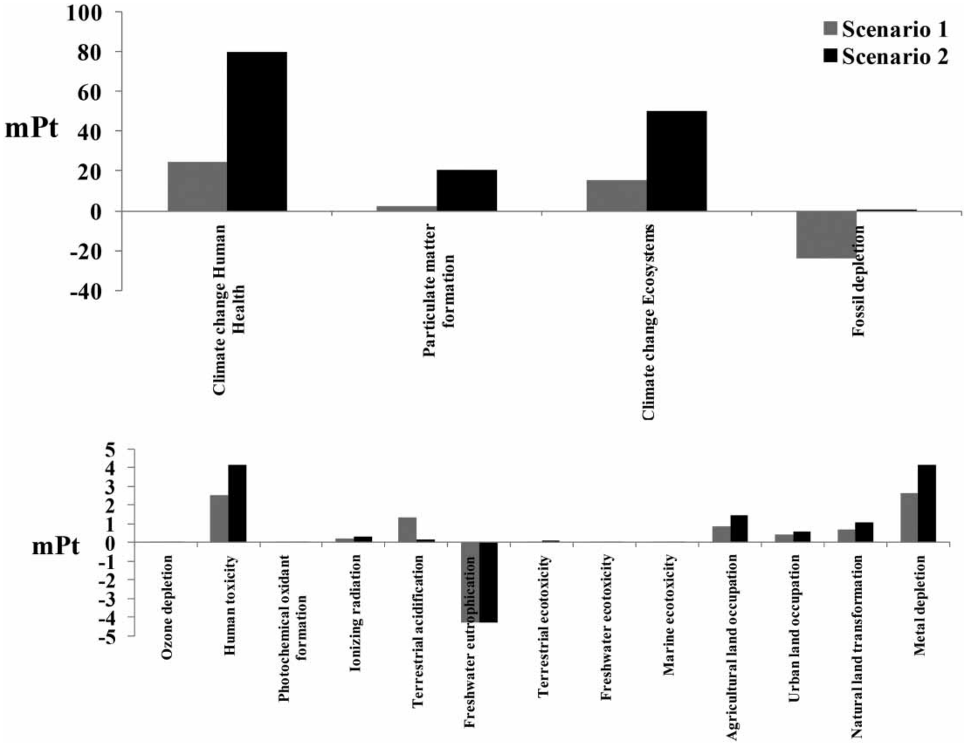

Figure 2 | Comparison between normalization impacts of both scenarios in 2012 (ReCiPe method).

formation being substantially greater in this case. As well, the absence of AD affected especially the fossil depletion category, with no beneficial impact in this scenario due to the consideration of not using the undigested sludge for agricultural purposes. On the other hand, AD causes harmful emissions caused by the generation of SOx from biogas

Table 3 | Most relevant categories of impact and subsystems (>5 mPt) in both scenarios for 2012

ReCiPe Endpoint (H) V1.08

	Air emissions (mPt)	Chemicals production (mPt)	Electricity (mPt)	Biogas (mPt)	Avoided fertilizer (mPt)	Total[a] (mPt)
Scenario 1						
Fossil depletion	–	0.1	0.2	–	−24.1	−23.8
Climate change human health	29.6	9.3	18.7	5.2	−39.7	24.6
Particulate matter formation	0.2	3.0	8.5	0.3	−10.2	2.3
Climate change ecosystem	18.7	5.9	11.8	3.3	−25.1	15.6
Total[a] (mPt)	49.8	23.5	41.1	9.1	−99.2	23.2
Scenario 2						
Fossil depletion	–	0.1	0.3	–	–	0.4
Climate change human health	29.9	15.5	31.9	–	–	79.6
Particulate matter formation	0.1	5.0	14.5	–	–	20.4
Climate change ecosystem	18.9	9.8	20.1	–	–	50.2
Total[a] (mPt)	49.0	39.2	69.8	–	–	158.4

[a]Total values considering all the impact categories and subsystems.

burning, practically negligible due to the low amount of H_2S in the biogas composition.

The main results of both scenarios (with and without AD) are summarized in Table 3, taking into account only the most important categories of impact (fossil depletion, climate change human health, particulate matter formation, and climate change ecosystems) and the main subsystems.

Analyzing the results obtained from the subsystems point of view, most of the impact comes from air emissions in Scenario 1 (49.8 mPt) and from electricity in Scenario 2 (69.8 mPt). Air emissions contribution was almost the same for both scenarios. On the other hand, electricity grew without the AD (41.1 to 69.8 mPt) and chemicals production almost doubled its impact in the absence of AD. This is due to the increase in the volume of sludge to manage and the absence of cogeneration, slightly affecting all impact categories. Additionally, the beneficial impact of agricultural use of sludge made a difference between scenarios due to the avoided fertilizer. Transport contributions were very low for both scenarios (not shown in Table 3). Finally, the overall impact analysis (Pt) revealed huge environmental damage if the AD was removed from the system, mainly due to the inability to use the sludge for agricultural purposes.

CONCLUSIONS

The most important impact category in Scenario 1 (with AD) was climate change human health, mainly due to fossil carbon dioxide emissions. The use of digested sewage sludge in agriculture positively affected the fossil depletion category. In Scenario 2 (without AD), the weight of climate change categories and particulate matter formation increased significantly.

In terms of subsystems, when the AD is included, air emissions were the most harmful followed by electricity. In the absence of AD, the importance of electricity increased due to the absence of cogeneration. The main credits only from Scenario 1 came from fertilizer avoided due to sewage sludge utilization.

Considering the total impact, results of the LCA analysis clearly showed that the introduction of AD in WWTPs greatly improves the system from the environmental point of view, especially if the digested sludge is used as fertilizer. The quantification analysis carried out with the ReCiPe method indicated a remarkable impact reduction of about 85% with the introduction of AD, confirming that Scenario 1 is the best choice in this study.

ACKNOWLEDGEMENTS

The content of this document summarizes the results of a research project developed during the year 2013. The authors would like to thank the company ACCIONA Agua SA for providing real operation data from an actual WWTP and for the economic support.

REFERENCES

Amores, M. J., Meneses, M., Pasqualino, J., Antón, A. & Castells, F. 2013 Environmental assessment of urban water cycle on Mediterranean conditions by LCA approach. *J. Cleaner Prod.* **43**, 84–92.

Antonopoulos, I. S., Karagiannidis, A., Tsatsarelis, T. & Perkoulidis, G. 2013 Applying waste management scenarios in the Peloponnese region in Greece: a critical analysis in the frame of life cycle assessment. *Environ. Sci. Pollut. Res.* **20**, 2499–2511.

Balmer, P. & Hellström, D. 2012 Performance indicators for wastewater treatment plants. *Water Sci. Technol.* **65** (7), 1304–1310.

Bani Shahabadi, M., Yerushalmi, L. & Haghighat, F. 2009 Impact of process design on greenhouse gas (GHG) generation by wastewater treatment plants. *Water Res.* **43**, 2679–2687.

Bengtsson, M., Lundin, M. & Molander, S. 1997 *Life Cycle Assessment of Wastewater Systems: Case Studies of Conventional Treatment, Urine Sorting and Liquid Composting in Three Swedish Municipalities*. Chalmers University of Technology, Goteborg, Sweden.

Bertanza, G., Canato, M., Heimersson, S., Laera, G., Salvetti, R., Slavik, E. & Svanström, M. 2015 Techno-economic and environmental assessment of sewage sludge wet oxidation. *Environ. Sci. Pollut. Res.* **22**, 7327–7338.

Busetti, F., Badoer, S., Cuomo, M., Rubino, B. & Traverse, P. 2005 Occurrence and removal of potentially toxic metals and heavy metals in the wastewater treatment plant of Fusina (Venice, Italy). *Indust. Eng. Chem. Res.* **44**, 9264–9272.

Carlos-Hernandez, S., Sanchez, E. N. & Béteau, J. F. 2009 Fuzzy observers for anaerobic WWTP: development and implementation. *Control Eng. Pract.* **17**, 690–702.

Corominas, L., Foley, J., Guest, J. S., Hospido, A., Larsen, H. F., Morera, S. & Shaw, A. 2013a Life cycle assessment applied to wastewater treatment: state of the art. *Water Res.* **47**, 5480–5492.

Corominas, L., Larsen, H. F., Flores-Alsina, X. & Vanrolleghem, P. A. 2013b Including Life Cycle Assessment for decision-making in controlling wastewater nutrient removal systems. *J. Environ. Manage.* **128**, 759–767.

Del Borghi, A., Gaggero, P. L., Gallo, M. & Strazza, C. 2008 Development of PCR for WWTP based on a case study. *Int. J. Life Cycle Assess.* **13**, 512–521.

Doorn, M. R. J., Manso, S. M., Irving, W., Palmer, C., Pipatti, R. & Wang, C. 2006 *IPCC Guidelines for National Greenhouse Gas Inventories Intergovernmental Panel on Climate Change 5*.

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D. & Suh, S. 2009 Recent developments in Life Cycle Assessment. *J. Environ. Manage.* **91**, 1–21.

Flores-Alsina, X., Corominas, L., Snip, L. & Vanrolleghem, P. A. 2011 Including greenhouse gas emissions during benchmarking of wastewater treatment plant control strategies. *Water Res.* **45**, 4700–4710.

Gallego, A., Hospido, A., Moreira, M. T. & Feijoo, G. 2008 Environmental performance of wastewater treatment plants for small populations. *Resour. Conserv. Recycling* **52**, 931–940.

Goedkoop, M. J., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J. & Van Zelm, R. 2009 *ReCiPe 2008: A Life Cycle Impact Assessment Method which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level, 1st edn*. ReCiPe Report I: Characterisation. Ministerie van VROM, The Hague, The Netherlands.

Hischier, R., Weidema, B., Althaus, H. J., Bauer, C., Doka, G., Dones, R., Frischknecht, R., Hellweg, S., Humbert, S., Jungbluth, N., Köllner, T., Loerincik, Y., Margni, M. & Nemecek, T. 2010 Implementation of Life Cycle Impact Assessment Methods Data v2.2. Ecoinvent Report No. 3. Swiss Centre for Life Cycle Inventories, Zurich, Switzerland.

Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K. & Johnson, C. A. 2001 *Climate Change 2001: The Scientific Basis.* Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

Iranpour, R., Cox, H. H. J., Kearney, R. J., Clark, J. H., Pincince, A. B. & Daigger, G. T. 2004 Regulation for biosolids land application in U.S. and European Union. *J. Residuals Sci. Tech.* **1**, 209–222.

Jenicek, P., Bartacek, J., Kutil, J., Zabranska, J. & Dohanyos, M. 2012 Potentials and limits of anaerobic digestion of sewage sludge: energy self-sufficient municipal wastewater treatment plant? *Water Sci. Technol.* **66** (6), 1277–1281.

Jenicek, P., Kutil, J., Benes, O., Todt, V., Zabranska, J. & Dohanyos, M. 2013 Energy self-sufficient sewage wastewater treatment plants: is optimized anaerobic sludge digestion the key? *Water Sci. Technol.* **68** (8), 1739–1743.

Johansson, K., Perzon, M., Fröling, M., Mossakowska, A. & Svanström, M. 2008 Sewage sludge handling with phosphorus utilization – life cycle assessment of four alternatives. *J. Cleaner Prod.* **16**, 135–151.

Lassaux, S., Renzoni, R. & Germain, A. 2007 Life cycle assessment of water from the pumping station to the wastewater treatment plant. *Int. J. Life Cycle Assess.* **12**, 118–126.

Lundin, M., Bengtsson, M. & Molander, S. 2000 Life cycle assessment of wastewater systems: influence of system boundaries and scale on calculated environmental loads. *Environ. Sci. Technol.* **34**, 180–186.

Lundin, M., Olofsson, M., Pettersson, G. J. & Zetterlund, H. 2004 Environmental and economic assessment of sewage sludge handling options. *Resour. Conserv. Recycling* **41**, 255–278.

Manfredi, S. & Christensen, T. H. 2009 Environmental assessment of solid waste landfilling technologies by means of LCA-modeling. *Waste Manage.* **29**, 32–43.

Manzoor, D. & Haqiqi, I. 2012 Impact of energy price reform on environmental emissions; a computable general equilibrium approach. *J. Environ. Stud.* **37**, 1–12.

Muñoz, I., Rodríguez, A., Rosal, R. & Fernández-Alba, A. R. 2009 Life Cycle Assessment of urban wastewater reuse with ozonation as tertiary treatment. A focus on toxicity-related impacts. *Sci. Total Environ.* **407**, 1245–1256.

Murray, A., Horvath, A. & Nelson, K. L. 2008 Hybrid life-cycle environmental and cost inventory of sewage sludge treatment and end-use scenarios: a case study from China. *Environ. Sci. Technol.* **42**, 3163–3169.

Nakakubo, T., Tokai, A. & Ohno, K. 2012 Comparative assessment of technological systems for recycling sludge and food waste aimed at greenhouse gas emissions reduction and phosphorus recovery. *J. Cleaner Prod.* **32**, 157–172.

Nowak, O., Keil, S. & Fimml, C. 2011 Examples of energy self-sufficient municipal nutrient removal plants. *Water Sci. Technol.* **64** (1), 1–6.

Remy, C., Lesjean, B. & Waschnewski, J. 2013 Identifying energy and carbon footprint optimization potentials of a sludge treatment line with Life Cycle Assessment. *Water Sci. Technol.* **67** (1), 63–73.

Rodriguez-Garcia, G., Molinos-Senante, M., Hospido, A., Hernandez-Sancho, F., Moreira, M. T. & Feijoo, G. 2011 Environmental and economic profile of six typologies of wastewater treatment plants. *Water Res.* **45**, 5997–6010.

Singh, R. P. & Agrawal, M. 2008 Potential benefits and risks of land application of sewage sludge. *Waste Manage.* **28**, 347–358.

Spriesma, R. 2004 *SimaPRO Tutorial and Database Manuals*. Pré Consultants, Amersfoort, The Netherlands.

Svardal, K. & Kroiss, H. 2011 Energy requirements for waste water treatment. *Water Sci. Technol.* **64** (6), 1355–1361.

Yoshida, H., Christensen, T. H. & Scheutz, C. 2013 Life cycle assessment of sewage sludge management: a review. *Waste Manage. Res.* **31**, 1083–1101.

First received 8 May 2015; accepted in revised form 8 October 2015. Available online 29 October 2015