Is SCENA a good approach for side-stream integrated treatment from an environmental and economic point of view?

Stefano Longo[1*]; Nicola Frison[2]; Daniele Renzi[3]; Francesco Fatone[4]; Almudena Hospido[1]

[1]Department of Chemical Engineering, Institute of Technology, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Galicia, Spain

[2]Department of Biotechnology, University of Verona, Strada Le Grazie 15, 37134 Verona, Italy

[3]Alto Trevigiano Servizi Srl, Ufficio Ottimizzazione Processi depurativi, Via Schiavonesca Priula 86, 31044 Montebelluna, Italy

[4]Department SIMAU, Faculty of Engineering, Polytechnic University of Marche, Via Brecce Bianche 12, Ancona, Italy

*Corresponding author email: stefano.longo@usc.es

Nomenclature

Abbreviation	Description
Al	Aluminium
AD	Anaerobic digestion
BOD	Biological oxygen demand
C	Carbon
CAPS	Chemically assisted primary sedimentation
COD	Chemical oxygen demand
DPAO	Denitrifying polyphosphate-accumulating organisms
EBPR	Enhanced biological phosphorus removal
Fe	Iron
FU	Functional unit
GHG	Greenhouse gas
GWP	Global warming potential
LCA	Life cycle assessment
LCC	Life cycle cost
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
N	Nitrogen
P	Phosphorus
PAC	Poly-aluminium chloride
RBS	Rotating belt screen
SBFR	Sequencing batch fermentation reactor
SCENA	Short Cut Enhanced Nutrient Abatement
scSBR	Short-cut sequencing batch reactor
SDT	Sludge dynamic thickening
TS	Total solids
VFA	Volatile fatty acid
WAS	Waste secondary sludge
WWTP	Wastewater treatment plant

Abstract

The environmental and economic benefits and burdens of including the first Short Cut Enhanced Nutrient Abatement (SCENA) into a real municipal wastewater treatment plant were evaluated using life cycle assessment (LCA) and life cycle cost (LCC). The implications of accomplishing nitrogen (N) removal and phosphorus (P) recovery via nitrite in the side stream were assessed taking into account the actual effluent quality improvement, the changes in the electricity and chemical consumption, N_2O, CO_2 and CH_4 emissions and the effects of land application of biosolids, among others. In addition, a case-specific estimation of the P availability when sludge is applied to land, therefore replacing conventional fertilizer, was performed. Furthermore, to account for the variability in input parameters, and to address the related uncertainties, Monte Carlo simulation was applied.

The analysis revealed that SCENA in the side stream is an economic and environmentally friendly solution compared to the traditional plant layout with no side-stream treatment, thanks to the reduction of energy and chemical use for the removal of N and P, respectively. The uncertainty analysis proved the validity of the LCA results for global warming potential and impact categories related to the consumption of fossil-based electricity and chemicals, while robust conclusions could not be drawn on freshwater eutrophication and toxicity-related impact categories. Furthermore, three optimization scenarios were also evaluated proving that the performance of the WWTP can be further improved by, for instance, substituting gravitational for mechanical thickening of the sludge or changing the operational strategy to the chemically enhanced primary treatment, although this second alternative will increase the operational cost by 5%. Finally, the outcomes show that shifting P removal from chemical precipitation in the main line to biologically enhanced uptake in the side stream is key to reducing chemicals use, thus the operational cost, and increasing the environmental benefit of synthetic fertilizers replacement.

Keywords

Short Cut Enhanced Nutrient Abatement (SCENA); Side-stream treatment; Life cycle analysis (LCA); Life cycle cost (LCC); Monte Carlo analysis; Sludge phosphorus availability.

1. Introduction

Within the last decade it has been required that wastewater treatment plants (WWTPs) meet increasing effluent quality standards at affordable cost. Separate treatment of the reject water resulting from dewatering of anaerobic digested sludge at WWTP can be a solution for meeting higher load requirements or stricter effluent standards regarding nitrogen (N) (Malamis et al. 2014). Regarding this issue, several technologies have been developed and successfully implemented at full scale (Lackner et al. 2014). Among them, the implementation of one-stage partial nitritation/anammox, also known as DEMON (Wett 2006), CANON (Third et al. 2001) and OLAND (Kuai and Verstraete 1998), could positively contribute to the optimization of the energy balance of WWTPs by minimizing energy for N removal. As an example, at the Strass WWTP, DEMON in the side stream has reduced electricity consumed per kg of N removed by 44% (Schaubroeck et al. 2015).

Furthermore, as a consequence of the growing awareness of the need to control phosphorus (P) emissions, which is reflected in the increasingly stringent regulations (Gaterell et al. 2000), a boost was given to the existing wastewater industry in order to increase its removal (Hukari et al. 2016). Until now, P has been regarded more as a contaminant than a resource. This perspective has started to change in recent years, since unlike N, P is a limited resource, whose recovery should be promoted as much as possible (Desmidt et al. 2015). However, the most common approach for removing phosphate from wastewater is metal salt precipitation, which makes the precipitate unrecoverable for possible industrial processing into fertilizer (De-Bashan and Bashan 2004, Melia et al. 2017, Torri et al. 2017).

In this regard, the recent introduction of Short-Cut Enhanced Nutrient Abatement (SCENA), for treatment of nutrient-rich reject water, brings an important improvement because P can also be removed from reject water by its enhanced bioaccumulation in the same system (Renzi et al. 2015). In fact, SCENA is a side-stream technology, which combines via-nitrite ammonia oxidation (also known as short-cut nitrification) with denitrifying enhanced biological phosphorus removal (EBPR) processes by the addition of external volatile fatty acids (VFAs) produced on-site (Longo et al. 2015). In this process NH_4 is oxidized to NO_2, which is then reduced to gaseous N_2 by denitrifying polyphosphate-accumulating organisms (DPAO), hence resulting in the potential production of a high added value product (Frison et al. 2016).

As a holistic environmental assessment approach, life cycle assessment (LCA) (ISO 2006) has proved to act as a valuable tool in evaluating the environmental aspects and improvement opportunities of wastewater systems (Corominas et al. 2013, Yoshida et al. 2013, Zang et al. 2015), including most impacts upon the environment, which helps avoid the risk of 'problem transfer' (Guinée 2002). In a LCA study Rodriguez-Garcia et al. (2014) compared different side-stream technologies. The authors emphasized that eutrophication impacts can be significantly reduced by using side-stream technologies, while global warming potential was only marginally reduced. Moreover, there is a certain consensus on the trade-offs between higher N removal achieved by implementation of side-stream technologies and increased direct emissions, with the results being very sensitive to the N_2O emission balance (Schaubroeck et al. 2015, Hauck et al. 2016).

Furthermore, the evaluation of appropriate schemes for wastewater treatment has to consider not only environmental concerns but also economic aspects (Corominas et al. 2013) (e.g., investment, operation and maintenance costs). In this respect life cycle cost (LCC) (Fabrycky and Blanchard 1991) is a useful framework for assessing the economic sustainability of different wastewater treatment schemes over the whole life span of the plant.

Thus, to investigate the holistic environmental and economic life cycle implications of N and P removal through SCENA, this study aims to answer the following questions: i) Is the SCENA system environmentally and economically sustainable? ii) How does SCENA improve the environmental and economic performance of a real WWTP? To provide answers to our questions preliminary results of the first full-scale SCENA system were analysed.

2. Material and methods

2.1. Goal and scope

The goal of the study was to assess the environmental and economic benefits of implementing SCENA in the side-stream treatment of reject water at a real municipal WWTP; the Carbonera facilities (Treviso, Northern Italy).

The system boundary included the WWTP operation with all its associated background processes, such as provision of energy and production and transportation of chemicals, effluent discharge and direct gaseous emissions deriving from the treatment process as well as composting and posterior land application. Regarding the construction phase, only data from SCENA were accounted for in the assessment, as the rest of the facilities remain the same. Upstream wastewater collection and transportation were not included in the analysis although it has been shown that the sewer system makes an important contribution in comparison to the WWTP (Risch et al. 2015); however, these impacts would be the same for each scenario, and are therefore not relevant for comparative purposes.

The functional unit (FU) has been based on the reduction of eutrophication as defined by the CML methodology (Guinée 2002): 1 kg PO_4^{3-} eq. removed. This approach helps with the comparison of different influent wastewater loads by weighting the main pollutants, and reflects the service that the WWTP delivers: the removal of contaminants (e.g., chemical oxygen demand, N and P) (Rodriguez-Garcia et al. 2014).

2.2. Treatment options

The flow diagram of the SCENA system implemented at the Carbonera WWTP is shown in Fig. 1, and an elaborate description of the plant is given in section A of the supplementary file.

In Table 1 are reported the different treatment configurations of the WWTP under investigation. The environmental and economic performance of the plant with no additional nutrient removal from reject water (2015, scenario 0) was compared with the new plant layout (2016, scenario 1) in which the full-scale SCENA is operating in the side stream. Additionally, three different alternative configurations (scenarios 2A-C) for the optimization of the SCENA system and the whole plant performance were simulated. Since the success of EBPR depends on the constant availability of VFAs, the objective of the optimization was to increase the organic loading rate of the SBFR in order to improve and stabilize the VFAs production, which could enable higher rates of biological nutrient removal in the short-cut sequencing batch reactor (scSBR). To do so, in scenario 2A sludge dynamic thickening (SDT) was considered as an effective technology to increase the total solids (TS) concentration of the mixed sludge by up to 5%; in scenario 2B, chemically assisted primary sedimentation (CAPS), consisting of adding chemicals in order to increase the coagulation, flocculation and sedimentation of raw wastewater, was simulated. The application of CAPS was chosen since it does not require any further significant structural intervention, thus saving investment costs and footprint (De Feo et al. 2012); finally, in scenario 2C, the primary sedimentation tank was replaced by a rotating belt screen (RBS) system in order to improve the performance of primary treatment (removal of TS up to 70%) without use of chemicals (Paulsrud et al. 2014). The CAPS system, apart from TS and chemical oxygen demand (COD), can enhance also the removal of P from wastewater. As a consequence scenario 2B will be characterized by a lower effluent discharge for P, despite the fact that all scenarios have the same effluent discharge limits. However, considering the increasingly lower discharge limit policies with regard to P or the spreading of the effluent load tax incentives in Europe (consider, for example, the case of Germany) this scenario is interesting to study for its potential future application. The inventory assumptions for scenarios 2A-C are summarized in section C of the supplementary file.

2.3. Inventory data

2.3.1. Operational data and background processes

Operational data (e.g., water and sludge flow/composition, energy consumption, chemical usage etc.) were directly gathered in-situ and provided by the company that operates the plant from the daily log results of 2015 and 2016, unless mentioned otherwise. Data for the processes of the background system (production of electricity, chemicals and N- and P-based fertilisers) come from the ecoinvent v3.1 database (cut-off system model) (Weidema et al. 2013). A complete discussion of the inventory data collection is given in section B of the supplementary file.

2.3.1. Fertilizer replacement

The benefits of sludge application on arable land can be accounted by crediting for the avoided production of mineral N and P fertilizer. The selection of the replacement ratio at which the N and P in sludge replace mineral fertilizer is challenging and it was shown to be important for the overall LCA results (Heimersson et al. 2017). Contrary to N, the availability of P in chemical and biological solids is an area of on-going research (Menezes-Blackburn et al. 2016), although it is largely accepted that the P in solids containing high levels of aluminium (Al) or iron (Fe) is less available for uptake by plants (Qin et al. 2015). The reason is that metal phosphates (e.g., iron and aluminium phosphates) are unavailable to plants (Melia et al. 2017, Torri et al. 2017), since they are among the most difficult of soil compounds from which to solubilize P, which makes the P removed by metal salt precipitation unrecoverable for possible industrial processing into fertilizer (De-Bashan and Bashan 2004).[1] The substitution should be based on the amount of mineral fertilizer that is actually replaced rather than theoretically, as outlined in several recent LCA studies (Niero et al. 2014, Heimersson et al 2016, 2017). Thus, in this study case specific P replacement ratios were estimated for each scenario to fill this gap (see section E of the supplementary file). On the contrary, due to the much more stable N content in sludge, a replacement ratio of 0.5 was used for N (Foley et al. 2010), which is a ratio widely used in LCA studies (Heimersson et al. 2016). Sludge stabilization treatments may also influence the plant availability of chemical sludge. To the best of our knowledge, only one study (Alvarenga et al. 2017) has tackled the effect of anaerobic digestion (AD) on the P availability of biosolids deriving from chemical precipitation and there, the effect of AD was reported as not significant. Moreover, if biosolids had undergone thermal stabilization during composting, metal-bound P minerals in biosolids is considerably reduced and, consequently, the release of available P is restricted (Hogan et al. 2001). Therefore, based on the reasoning above, we have assumed that the stabilization processes of biosolids produced at the Carbonera WWTP before the application to agriculture (i.e., AD followed by sludge composting) will not alter the P availability. The corresponding synthetic fertilisers considered for substitution were ammonium sulphate ($(NH_4)_2SO_4$) and diammonium phosphate ($(NH_4)_2HPO_4$) as the generic N and P_2O_5 sources, respectively (Rodriguez-Garcia et al. 2011).[2]

2.4. Life cycle impact assessment

SimaPro v8.1 software was used for the impact assessment. Excluding global warming potential (GWP), where the last version of the IPCC method (for a 100-year time horizon) (IPCC 2013) was used, impacts were assessed using the Hierarchist ReCiPe(H) (v1.08) which is based on common policy principles including the frame (Goedkoop et al. 2008a). Although endpoint results may be perceived more relevant for decision-making, midpoint assessment directly relates the inventory results into environmental impacts. Moreover, the use of endpoint indicators relies on additional assumptions and introduces greater uncertainty in the modelling process compared to midpoint indicators (Corominas et al. 2013). Therefore, the ReCiPe midpoint method was selected as it complies with all essential aspects for human toxicity (EC-JRC 2011)

[1] For a complete discussion on the availability of P in biosolids, as well as the dynamics of P in biosolids-amended soils, the reader is referred to Torri et al. (2017).

[2] Note that diammonium phosphate provides also N, which has been taken into consideration when calculating the avoided fertilisers.

and includes terrestrial ecotoxicity (Goedkoop et al. 2008a). However, human toxicity assessment is also advised to be estimated using USEtox (Hauschild et al. 2013), hence we also applied the USEtox method (Rosenbaum et al. 2008) solely for the human toxicity, and the results are presented in section H of the supplementary file. Other impacts covered in this study are ozone depletion, terrestrial acidification, photochemical oxidant formation and particular matter formation. Although these impact categories have gained less attention than the others discussed above, they are becoming a standard in the LCA studies (Zang et al. 2015). Land-use related environmental indicators were excluded for their limited relevance in the wastewater treatment sector (Zang et al. 2015). Furthermore, resource depletion categories were excluded since these impacts are not well defined and modelled in LCA methodologies (Hauschild et al. 2013), and there is still no globally agreed method that is sufficiently robust (Drielsma et al. 2016).

Finally, to shows the environmental trade-offs between avoided impact due to wastewater treatment and generated impact by the WWTP's life cycle, the net environmental benefit (NEB) approach (Godin et al. 2012) was also applied and the results are presented in section G of the supplementary file.

2.5. Uncertainty analysis

The importance to test and statically evaluate the environmental impacts in the LCA context has been reported (Nhu et al. 2016). This is particular crucial in the wastewater treatment sector where the large data variability and input data coverage can heavily influence the LCA results (Yoshida et al. 2014). Different types of uncertainty include those relating to parameters (e.g., inaccuracies in measurement, mismatch between the representativeness and use of data, and variability resulting from horizontal averaging), and those concerning the LCA model (e.g., the uncertainties of the characterization factors) and the scenario choices (e.g., choice of functional unit or characterization/weighing methods) (Huijbregts 2002). In this study, we will mainly focus on data uncertainty but will also discuss briefly the influence of some model and scenario choices (section H and G of the supplementary file, respectively). When an uncertainty calculation is performed, it is also important to keep track of the correlations in the data (Nhu et al. 2016). Two kinds of correlation can be identified: (1) correlations between process chains of production systems and (2) correlations within a process record. In this study, only the type of correlation between process chains of production systems is considered, as a comparison Monte Carlo is carried out with SimaPro (in which such issues are excluded).

Based on the uncertainty of the life cycle inventory (LCI) data expressed as probability distributions (see Table S.7 of the supplementary file), the Monte Carlo simulations were run with 1,000 iterations at a significance level of 95%. Clearly, the output distributions generated by any Monte Carlo simulation, and any conclusion derived therefrom, are sensitive to the choice of input distribution. In the current study, when the class of distribution was known a priori we proceeded with direct estimation of the parameters of the distribution (e.g., mean, standard deviation). If the class of the distribution was unknown, default distributions were consulted for possible use based on the range of possible values (Lipton et al. 1995).

2.6. Life cycle cost

In general, costs can be divided into capital and operational costs. The capital cost was estimated by summing the construction, mechanical instrument and consulting costs, as obtained from the WWTP operation office (see Table S.6 of the supplementary file). As major operating costs, the electricity and chemical consumptions, sludge disposal and staff costs were considered. In order to share the same time boundary as the LCA, the time value of money is considered. Net present value (NPV) was adopted as an indicator to evaluate the economic performance of the different scenarios. The NPV for wastewater treatment was calculated based on Eq. (1):

$$\mathrm{NPV} = \mathrm{CAPEX} + \sum_{n} \frac{\mathrm{OPEX}}{(1+i)^{n}}, \tag{1}$$

Where CAPEX and OPEX denote capital cost and operational cost, respectively, *i* refers to discount rate adjusted for inflation, equal to 5% (this is a compromise figure based on market interest rate, cost of capital and time preference considerations (Hermelink and de Jager 2015)), and *n* represents years.

Furthermore, in order to share the same functional unit as the LCA, the total cost is divided into LCC per FU (1 kg PO_4 eq. removed).

3. Results

3.1. Inventory analysis

An overview of the LCI of the treatment options under analysis is reported in Table S.3 of the supplementary file. Once SCENA was operating, the electricity consumed per kg of N removed was reduced from 7.51 kWh in the main line to 3.21 kWh in the side stream. This is consequence of the joint effects of a more efficient N removal pathway (i.e., via nitrite compared to complete nitrification in the main line) and aeration system (i.e., superfine bubble diffusers as opposed to course bubble diffusers in the main line), which make removing N in the side stream more convenient. Besides, energy consumed for aeration in the main line can also be further reduced by about 20% due to the implementation of CAPS and RBS systems (sc. 2B and 2C, respectively), since they can increase the organic matter recovered from wastewater, thus resulting in a reduced COD load entering the biological bioreactor of the main line.

On a process level, the via-nitrite N removal in the scSBR improved the effluent quality of the WWTP in terms of total nitrogen (Table 2), while the benefits regarding total phosphorus were less evident since the additional P removal in the side stream is compensated for by a lower chemical P removal in the main line (i.e., in order to maintain the required effluent quality, thus optimizing costs). However, sc. 2B is characterized by a much better P effluent quality. This is a consequence of the fact that the CAPS system can attain higher P removal (up to 70%) in the primary sedimentation tank due to a significantly higher dosage of poly aluminium chloride (PAC) (Table S.3).

For sc. 0, N_2O emissions were found to be approximately 4.55 kgN-N_2O/d that represents 1.16% of the N influent load. Compared with previous studies (see for example Kampschreur et al. (2009)), N_2O emissions were remarkably high at the Carbonera WWTP. Some operational features employed during the process, i.e., intermittent aeration of the activated sludge process, have been identified as possible features promoting N_2O emissions. However, our emission factor is in accordance with the outcomes for long-term online measurement campaign carried out at the Viikinmaki WWTP[3], which presented an emission factor of 1.9% for influent N (Kosonen et al. 2016). In the scSBR of the SCENA system, the N_2O emissions were 1.42% of the N influent load of the side-stream line, which is in accordance with the range of 0.24-1.49% previously measured by Frison et al. (2015). Moreover, the N_2O emissions were comparable with values in the literature for biological systems accomplishing N removal via partial nitritation/anammox (Schaubroeck et al. 2015).

[3] The process scheme of the Viikinmaki WWTP is different in comparison to the Carbonera WWTP. At Viikinmaki the biological reactions are carried out in six consecutive reactors, while at the Carbonera WWTP, aerated and anoxic phases are performed in the same reactor. However, the two WWTPs share similar operational features, e.g., fluctuating influent flow and intermittent aeration at the activated sludge process.

Thus, shifting N removal from the main stream to the side stream of the WWTP did not increase N_2O emissions as one might expect due to the higher risk of nitrite accumulation.

3.2. Life cycle impact assessment of the treatment options

By integrating the recommendation of Zang et al. (2015), the results are grouped into the following: freshwater and marine eutrophication (Fig. 2); global warming potential (Fig. 3); toxicity and terrestrial ecotoxicity (Fig. 4); and ozone depletion, photochemical oxidant formation, particular matter formation, and terrestrial acidification (Fig. 5). All the impacts are expressed per kg of PO_4 eq. removed.

3.2.1. Eutrophication potential

Eutrophication has been emphasized by earlier studies and is still considered the most relevant impact category when performing environmental evaluation of WWTPs (Corominas et al. 2013, Zang et al. 2015). Thus, is especially important here as eutrophication impacts can be reduced immediately by implementing side-stream treatment technologies to enhance the nutrient removal efficiency. As expected, the impact of wastewater treatment on eutrophication is dominated by the effluent discharge and the nutrient-related emissions during compost land application (Fig. 2).

After the implementation of SCENA, a reduction of 27% of the marine eutrophication has been found (sc. 1) as a consequence of the better effluent quality with respect to N compounds (e.g., NH_4 and NO_3), which could also be further reduced (by an additional 18%) with the optimization of SCENA (sc. 2A-C). The benefits in terms of freshwater eutrophication are less evident since following the installation of the SCENA system the operation of the WWTP was adjusted to guarantee the same P effluent quality. Nevertheless, the substitution of the primary clarification with the CAPS system (sc. 2B) would imply a much lower P in the effluent thanks to the additional dosage of PAC, which translates in the reduction by 43% of the freshwater eutrophication.

Finally, a considerable portion of the marine eutrophication impact (19-21% depending of the scenario) is represented by the N emissions due to land application.

3.2.2. Global warming potential

Impacts on this category are associated mainly with electricity use and direct gaseous emissions during wastewater treatment (Fig. 3).

For sc. 0, electricity accounts for 35% of the total impact and the total plant greenhouse gas (GHG) emissions for 56%. According to our measurements, the N_2O emissions comprised 80% of the total emissions, which is in line with the results reported by Kosonen et al. (2016). Remaining impacts are characterized as follow: composting (4.5%), effluent release (2.3%), transport (1.5%) and production of chemicals used (1.3%). On the beneficial side, i.e., mitigating effects, two elements from compost application to land are contributing here: C sequestration and avoided fertilizers, accounting for 4.1% and 1.9% of the total impact, respectively.

The reduction of electricity consumption and N_2O emissions translates to a reduction of about 14% of GWP, respectively with the following shares: 27% and 65%. The additional energy saving in sc. 2A could further decrease the GWP up to an additional 4%. In terms of avoiding the impact from offset fertilizers, sc. 1 did not show any improvement as the SCENA system was not yet optimized for P removal (Table 2). When the potential optimization is evaluated, the additional P removal in the side stream achieved in sc. 2A results in a lower PAC consumption (12%) in the main line and in a higher P recovered in biosolids (8%) that leads to a benefit from avoided fertilizer. On the contrary, the increased P removal by the CAPS configuration (sc. 2B) did not increase the amount of fertilizer avoided since the P recovered by the chemical process is not available for plant uptake. Besides, sc. 2B and 2C do not result in a net benefit over the other configurations, since their advantages (i.e., better performance of the SBFR and lower energy consumption for aeration) were balanced by the higher chemical consumption in sc. 2B and a slightly higher energy consumption of the RBS system in sc. 2C.

3.2.3. Human toxicity and terrestrial ecotoxicity

Direct emissions of heavy metals dominate toxicity-related impact categories, accounting for half of the total impact of human toxicity and almost the entire impact of terrestrial ecotoxicity (Fig. 4). Once SCENA was up and running, no large variations took place in heavy metals behaviour, which are mostly attributable to anthropogenic activities anyway, such as traffic emissions and weather characteristics (Peña-Fernández et al. 2015). In fact, the lower impact of terrestrial ecotoxicity reported for sc. 1 and followings is principally due to the better effluent quality achieved (i.e., higher FU). Emissions from transport of biosolids increase the human toxicity impact; however, these are overcome by the avoided contaminants due to fertilisers' replacement and their correspondent production. Moreover, emissions associated with chemical manufacture increase the human toxicity and hence shifting P removal from chemical precipitation to biological removal by SCENA entails an additional advantage.

3.2.4. Other impact categories

The impact linked to ozone depletion mainly occurs due to the electricity production and to a lesser extent to transport and chemical manufacturing (Fig 5a). Consequently, implementing SCENA reduced the ozone depletion potential by 9% (sc. 1), which can be further reduced (up to 14%) by sc. 2A and 2B. However, the beneficial effects generated by avoiding fertilizers and chemicals use are offset by emissions from transport of biosolids.

The photochemical oxidant and particular matter formation potentials (Fig. 5b and 5c, respectively) reflect the difference between the impacts due to the electricity and chemicals use for the wastewater treatment and the ones avoided thanks to the land application of biosolids. As seen for ozone depletion, implementing energy efficiency with SCENA is beneficial also for these impact categories. Sc. 1 reduces the photochemical oxidant formation potential by 9%. Furthermore, the increasing of P recovery in sc. 2A has the potential to reduce the impact for the same category up to 13%.

The particular matter formation and terrestrial acidification (Fig. 5d) follow the trend observed for the photochemical oxidant formation potential, even if in sc. 1 the ammonia emissions from the anaerobic supernatant storage tank increased the particular matter formation and terrestrial acidification impacts. Connecting this plant section to the air treatment system may mitigate these impacts; however, until this is done, these emissions will likely continue to be an issue. For the other scenarios (2A-C), the ammonia emissions may be offset by eliminating the gravity thickener of the digested sludge. Another source of contamination derives from flaring the biogas; this impact contributes about 5% to the particular matter formation potential, and is similar for the different scenarios.

3.2.5. Uncertainty analysis

In Fig. 6, the summation of both blue and grey bars for each category is equal to 100%. The negative portion to the left (blue bars) represents the percentage of cases where $impact_{AssessedScenario} \geq impact_{BaseScenario}$ while grey bars to the right, or the positive portion, represent the inverse situation ($impact_{AssessedScenario} < impact_{BaseScenario}$), being the BaseScenario the sc. 0. This allows understanding whether the differences shown in Fig. 2, 3, 4 and 5 are significant. In general, we can assume that if 90% of the Monte Carlo runs are favourable, the difference may be considered significant (Goedkoop et al. 2008b).

The Monte Carlo simulations suggest that all the scenarios perform better in terms of GWP compared to sc. 0, with Monte Carlo frequency highest for sc. 2B (98.5%), followed by sc. 2A (97.6%), sc. 2C (95.8%) and sc. 1 (92.8%). Regarding eutrophication, the results are less clear, especially in terms of freshwater eutrophication. This is due to the already mentioned compensation effect in total P removal in order to maintain the same quality effluent and, consequently, the role of SCENA was favourable at lower Monte Carlo frequencies of 55-83% and 75-88% with respect to freshwater eutrophication and marine eutrophication, respectively. The benefits of SCENA (e.g., lower energy consumption for N removal and chemical consumption for P removal) are more evident in the fossil-based electricity and chemicals related impact categories, such as ozone depletion (favourable at Monte Carlo frequencies of 86-97%). Among the toxicity-related impact categories, human toxicity shows the highest uncertainty. Even if the negative impacts of these categories are reduced per FU, after the uncertainty analysis robust conclusions could not be drawn on the effect of the SCENA system. This can be explained by the fact that the concentration of heavy metals in the final sludge and the treated effluent is not influenced by SCENA. Although the LCA results show that SCENA is also beneficial in terms of photochemical oxidant formation, particular matter formation and terrestrial acidification, the inclusion of the uncertainty revealed that these differences are favourable with lower Monte Carlo frequencies with respect to GWP. In short, the uncertainty analysis revealed sc. 2A as the most environmentally friendly scenario, having lower impacts for most of the categories with confident level of 90%.

3.3. Economic analysis

Results from the LCC are categorized as investment cost and operational cost, such as cost for electricity and chemical provision, cost for sludge compost and disposal and labour costs (Table 3), and identify sc. 2B as the option with the highest cost per FU (5.75 €).

From an economic perspective, the inclusion of SCENA in the side stream (sc. 1) reduces costs by about 3% per FU, which can be further reduced (up to 5%) by sc. 2A thanks to a further reduction in electricity consumption for aeration and chemical consumption for chemical P removal. Conversely, sc. 2B and 2C increase the total cost due to higher PAC dosing. The investment cost for each scenario does not make a big difference, apart for sc. 2C that is slighter higher, and it is almost negligible in comparison with the operational cost (between 1% and 3% of the total cost). Regarding the cost distribution, this is uniform among the different scenarios under study. On average, 48% of the total cost is associated with energy consumption, 27% with sludge management, 16% with labour and the remaining 7% with chemicals provision. The further reduction of energy use for aeration in sc. 2B and 2C is compensated for by the additional cost of sludge management, which makes these scenarios not recommendable unless energy recovery from the increased biogas production is guaranteed (which is not done at the moment). Moreover, for sc. 2B the additional chemical use of the CAPS configuration has the double drawback of increasing cost for chemical consumption as well as contributing to an increase in the amount of chemical sludge to be disposed of, and as consequence also the cost for its management.

4. Discussion

4.1. Energy efficiency improvements

One of the aims of upgrading the sludge line with side-stream treatment is to improve the energy efficiency of the WWTP. The measurements show lower electricity consumption at a process level, due to a lower need for aeration in the scSBR compared to the main biological reactor. The reduction of electricity consumption per kg N removed for sc. 1 was 57%, which led on a system level to a reduction of the total consumption of about 12%. The fact that about half of the total costs are associated with energy use makes once more evident the importance of energy efficiency both from an economic and an environmental point of view.

Although the integration of SCENA in the side stream has proved to be a good example of energy efficiency improvement, energy self-sufficiency is still a challenge at the Carbonera WWTP. Fully energy self-sufficient WWTPs are possible through improving the energy efficiency as well as harvesting energy from the biogas (Gu et al. 2017). Electrical energy autarchy is already reported to have been achieved for the Strass WWTP (Schaubroeck et al. 2015), where the largest electricity saving was provided through the addition of a co-substrate to the anaerobic digester (e.g., kitchen waste and fat). At the Carbonera WWTP the biogas produced is used only for heating the digester, while the excess is burnt in a torch. However, in light of the fact that after the implementation of SCENA about 10% of the mixed sludge is sent to the fermenter of the SCENA system for the VFAs production, the anaerobic digester in now underexploited. Therefore, the addition of a co-substrate in the digester would imply a better usage of the plant's infrastructure, which could help the Carbonera WWTP moving forward towards energy self-sufficiency, as well as mitigating the negative environmental impacts due to energy use. Finally, it should be noted that when implementing SCENA within a WWTP that uses biogas for electricity production, a reduction of the energy produced should be considered as it might partially offset the energy savings due to SCENA. In this case, when evaluating the WWTP upgrading, the methane yield of the post-fermented sludge should be measured to evaluate the possibility to recycle the residual sludge from the SBFR to the digester, thus limiting the reduction in biogas production.

4.2. Environmental performance improvements

The eutrophication potential impact can be decreased immediately by implementing more sophisticated technologies to enhance the nutrient removal (however, generally associated with increase in other environmental impacts) (Zang et al. 2015). For example, Rodriguez-Garcia et al. (2014) found a substantial reduction of eutrophication associated with side-stream treatments. However, they stated that to reduce significantly the nutrient load of the effluent, side-stream N-removal technologies must be followed by struvite crystallization for P removal, at the cost of increasing electricity and chemical use, which implies higher costs and GWP impacts. In this sense SCENA represents a convenient alternative as it combines N and P biological removal in a single system, which can optimize use of electricity and chemicals. Also Hauck et al. (2016) reported a 16% reduction of eutrophication after the implementation of a two-step anammox in the side stream. This is in line with our findings for marine eutrophication (22-39% depending of the scenario).

In terms of GWP, other elements contribute besides electricity consumption and there is a certain consensus in the literature on the importance of N_2O emissions, which can be more important than electricity use (Schaubroeck et al. 2015, Hauck et al. 2016). At the Carbonera WWTP, shifting N removal from the main line to the side stream has the advantage of reducing the N_2O emissions in the main line as result of more favourable process conditions in the biological reactor of the mainline, i.e., a higher degree of N removal and more stable conditions (Parravicini et al. 2016).

The total heavy metals load of untreated wastewater ends up in the sludge or remains in the treated effluent, as consequence no metal biodegradation is achieved during the wastewater treatment. The Carbonera WWTP is a significant source of heavy metals to both aquatic and terrestrial recipients. The impact of terrestrial ecotoxicity was found to exceed the benefit of avoided fertilizers. The latter was already acknowledged in the literature (Schaubroeck et al. 2015).

Finally, it can be seen that the impact categories of ozone depletion, photochemical oxidant formation, particular matter formation, and terrestrial acidification are mostly attributed to the consumption of electricity and chemicals, and thus the results reveal an improvement in the environmental performance of the new layout compared to the old configuration.

4.3. Phosphorus considerations on land application of biosolids

Selecting a P replacement ratio is challenging and especially important in this study where the additional biological P removal by SCENA is expected to reduce the intensity of the chemical P removal. The prediction of the P fertilizer value from sludge characteristics is possible through modelling. For example, Falk Øgaard and Brod (2016) developed a multiple linear regression model to predict the P fertilizer value using Fe and Al content in activated sludge as predictors and reported a significant negative effect of both Al and Fe on the fertilization effect. The results of this study contribute considerably to the understanding of P availability in biosolids. However, we were not able to check for the model prediction accuracy due to data unavailability.

The results of the P replacement ratio estimation are reported in Table 2. Apart from sc. 2B, these values are in line with the values commonly used in the literature (50-70%). Sludge containing high levels of P does not necessarily imply a greater potential for P supply. In sc. 2B, the dosage of PAC used for the increasing of the organic matter recovery has the additional effect of increasing the total P removal from 54% to 73% (compared to sc. 1). Much more P is recovered in this scenario, even if the majority is in the form of aluminium phosphate, and hence not available for plant uptake. Furthermore, as a result of the higher organic matter removal (through the CAPS system) the growth activities of activated sludge are also reduced (and as a consequence the P removal) in comparison to the other scenarios. For these reasons, the P availability of biosolids in sc. 2B is only 9.5%. These findings are in line with Falk Øgaard and Brod (2016) who demonstrated that the concentration of the precipitation salts in sludge are inversely correlated with the P fertilization effect of sludge. Thus, considering that an economically feasible process for recovering P from metal salt compounds does not yet exist (Wilfert et al. 2015), these results suggest that in the perspective of P recovery from wastewater, biological P removal should be preferred to a chemical process if the destiny of the sludge produced during treatment is land application to agriculture.

5. Conclusions

Updates to process improvements of existing WWTP, i.e., integration of SCENA as side-stream treatment, imply changes in the plant operating conditions that affect effluent and sludge quality, electricity and chemical use, GHG emissions and total cost. Hence, this study emphasizes the need to evaluate all of these elements by means of a holistic approach based on environmental and economic indicators. The main findings of the study are:

- SCENA was identified as a more sustainable option for providing a greater degree of environmental protection at lower cost. In particular, SCENA induced significant improvement in terms of (i) reduction of GHG emissions, mainly due to increased energy efficiency, (ii) reduction of eutrophication, due to a higher level of N abatement and (iii) reduction of total cost, due to the lower amounts of electricity and chemicals consumed.
- Moreover, the performance of the Carbonera WWTP can be further improved if the operation of the whole plant is optimized, i.e., substituting gravitational with mechanical thickening of the sludge (sc. 2B). Although a significant reduction of freshwater eutrophication as well as further energy savings could be obtained changing the operational strategy to the chemically enhanced primary treatment, due to the higher consumption of chemicals the operational cost will increase by 5%.

- The uncertainty analysis proved the validity of the LCA results for GWP and impact categories related to the consumption of fossil-based electricity and chemicals, while robust conclusions could not be drawn on freshwater eutrophication and toxicity-related impact categories.
- From a methodological point of view, the suggested method for the estimation of the P availability of biosolids, in contrast to the classical approach consisting in the application of a fixed P replacement ratio, provided a better picture of the real situation and revealed that improving P recovery by chemical precipitation does not give rise to an environmental benefit by replacement of synthetic fertilizer.
- Although results from different LCA studies depend on the assumptions, this case study confirms the dominant role of N_2O emissions on the GWP and emphasizes once again that more consideration should be paid to N_2O emissions at WWTPs.

The conclusions presented here have partially motivated the Horizon 2020 'SMART-Plant' action[4], which will allow for the optimization of the best scenario for SCENA integration in the Carbonera WWTP.

Acknowledgements

S. Longo and A. Hospido belong to the Galician Competitive Research Group GRC2013-032 and to the CRETUS strategic Partnership (AGRUP2015/02), co-funded by FEDER (EU). Besides, S. Longo and A. Hospido are supported by 'ENERWATER' Coordination Support Action that has received founding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 649819, while N. Frison, F. Fatone and D. Renzi are supported by 'SMART-Plant' Innovation Action that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690323. The authors would also like to thank the reviewers for their valuable comments.

[4] www.smart-plant.eu

References

Alvarenga, E., Øgaard, A.F. and Vråle, L., 2017. Effect of anaerobic digestion and liming on plant availability of phosphorus in iron-and aluminium-precipitated sewage sludge from primary wastewater treatment plants. Water Science and Technology 75(7), 1743-1752.

Corominas, L., Foley, J., Guest, J., Hospido, A., Larsen, H., Morera, S., Shaw, A., 2013. Life cycle assessment applied to wastewater treatment: state of the art. Water research 47(15), 5480-5492.

De Feo, G., De Gisi, S., Galasso, M., 2012. Chemically assisted primary sedimentation: A green chemistry option. In Green Technologies for Wastewater Treatment, Lofrano, G., ed. Springer, Dordrecht, Heidelberg, New York, London, 1-18.

De-Bashan, L.E., Bashan, Y., 2004. Recent advances in removing phosphorus from wastewater and its future use as fertilizer (1997–2003). Water research 38(19), 4222-4246.

Desmidt, E., Ghyselbrecht, K., Zhang, Y., Pinoy, L., Van der Bruggen, B., Verstraete, W., Rabaey, K., Meesschaert, B., 2015. Global phosphorus scarcity and full-scale P-recovery techniques: a review. Critical Reviews in Environmental Science and Technology 45(4), 336-384.

Drielsma, J.A., Russell-Vaccari, A.J., Drnek, T., Brady, T., Weihed, P., Mistry, M. and Simbor, L.P., 2016. Mineral resources in life cycle impact assessment—defining the path forward. The International Journal of Life Cycle Assessment, 21(1), 85-105.

EC-JRC, 2011. International Reference Life Cycle Data System (ILCD) Handbook ‐ Recommendations for Life Cycle Impact Assessment in the European context. European Union, Luxemburg.

Fabrycky, W.J., Blanchard, B.S., 1991. Life-cycle cost and economic analysis, Pearson Prentice Hall, New Jersey, USA.

Falk Øgaard, A. and Brod, E., 2016. Efficient Phosphorus Cycling in Food Production: Predicting the Phosphorus Fertilization Effect of Sludge from Chemical Wastewater Treatment. Journal of agricultural and food chemistry, 64(24), 4821-4829.

Foley, J., De Haas, D., Hartley, K., Lant, P., 2010. Comprehensive life cycle inventories of alternative wastewater treatment systems. Water research 44(5), 1654-1666.

Frison, N., Chiumenti, A., Katsou, E., Malamis, S., Bolzonella, D., Fatone, F., 2015. Mitigating off-gas emissions in the biological nitrogen removal via nitrite process treating anaerobic effluents. Journal of Cleaner Production 93, 126-133.

Frison, N., Katsou, E., Malamis, S., Fatone, F., 2016. A novel scheme for denitrifying biological phosphorus removal via nitrite from nutrient‐rich anaerobic effluents in a short‐cut sequencing batch reactor. Journal of Chemical Technology and Biotechnology 91(1), 190-197.

Gaterell, M., Gay, R., Wilson, R., Gochin, R., Lester, J., 2000. An economic and environmental evaluation of the opportunities for substituting phosphorus recovered from wastewater treatment works in existing UK fertiliser markets. Environmental technology 21(9), 1067-1084.

Godin, D., Bouchard, C. and Vanrolleghem, P.A., 2012. Net environmental benefit: introducing a new LCA approach on wastewater treatment systems. Water Science and Technology, 65(9), 1624-1631.

Goedkoop, M., De Schryver, A., Oele, M., Durksz, S., de Roest, D., 2008a. Introduction to LCA with SimaPro 7. PRé Consultants. Amersfoort, The Netherlands.

Goedkoop, M. J.; Heijungs, R.; Huijbregts, M.; Schryver, A. D.; Struijs, J.; Zelm, R. V., 2008b. ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level; Report for Pre Consultants, CML University of Leiden, Radboud University, RIVM Bilthoven: Netherlands.

Gu, Y., Li, Y., Li, X., Luo, P., Wang, H., Wang, X., Wu, J., Li, F., 2017. Energy Self-sufficient Wastewater Treatment Plants: Feasibilities and Challenges. Energy Procedia 105, 3741-3751.

Guinée, J.B., 2002. Handbook on life cycle assessment operational guide to the ISO standards. The international journal of life cycle assessment 7(5), 311-313.

Hauck, M., Maalcke-Luesken, F.A., Jetten, M.S., Huijbregts, M.A., 2016. Removing nitrogen from wastewater with side stream anammox: What are the trade-offs between environmental impacts?. Resources, Conservation and Recycling 107, 212-219.

Hauschild, M.Z., Goedkoop, M., Guinée, J., Heijungs, R., Huijbregts, M., Jolliet, O., Margni, M., De Schryver, A., Humbert, S., Laurent, A. and Sala, S., 2013. Identifying best existing practice for characterization modeling in life cycle impact assessment. The International Journal of Life Cycle Assessment, 18(3), 683-697.

Heimersson, S., Svanström, M., Cederberg, C., Peters, G., 2017. Improved life cycle modelling of benefits from sewage sludge anaerobic digestion and land application. Resources, Conservation and Recycling 122, 126-134.

Heimersson, S., Svanström, M., Laera, G., Peters, G., 2016. Life cycle inventory practices for major nitrogen, phosphorus and carbon flows in wastewater and sludge management systems. The International Journal of Life Cycle Assessment 21(8), 1197-1212.

Hermelink, A.H., de Jager, D., 2015. Evaluating Our Future: The crucial role of discount rates in European Commission energy system modelling. Available: http://www.eceee.org/policy-areas/discount-rates/evaluating-our-future-report [2017, March, 05].

Hogan, F., McHugh, M. and Morton, S., 2001. Phosphorus availability for beneficial use in biosolids products. Environmental technology 22(11), 1347-1353.

Huijbregts, M., 2002. Uncertainty and variability in environmental life-cycle assessment. The International Journal of Life Cycle Assessment, 7(3), 173-173.

Hukari, S., Hermann, L., Nättorp, A., 2016. From wastewater to fertilisers—technical overview and critical review of European legislation governing phosphorus recycling. Science of the Total Environment 542, 1127-1135.

IPCC, 2013. Climate change 2013: the physical science basis. Summary for policymakers contribution of Working Group I to the IPCC Fifth Assessment Report. Twelfth Session of Working Group I, 27 September 2013.

ISO, 2006. ISO 14040:2006 Environmental management–life cycle assessment–principles and framework. International Standards Organization, Geneva.

Kampschreur, M.J., Temmink, H., Kleerebezem, R., Jetten, M.S., van Loosdrecht, M.C., 2009. Nitrous oxide emission during wastewater treatment. Water research 43(17), 4093-4103.

Kosonen, H., Heinonen, M., Mikola, A., Haimi, H., Mulas, M., Corona, F., Vahala, R., 2016. Nitrous Oxide Production at a Fully Covered Wastewater Treatment Plant: Results of a Long-Term Online Monitoring Campaign. Environmental science, technology 50(11), 5547-5554.

Kuai, L., Verstraete, W., 1998. Ammonium removal by the oxygen-limited autotrophic nitrification-denitrification system. Applied and Environmental Microbiology 64(11), 4500-4506.

Lackner, S., Gilbert, E.M., Vlaeminck, S.E., Joss, A., Horn, H., van Loosdrecht, M.C., 2014. Full-scale partial nitritation/anammox experiences–an application survey. Water research 55, 292-303.

Lipton, J., Shaw, W.D., Holmes, J., Patterson, A., 1995. Short communication: selecting input distributions for use in Monte Carlo simulations. Regulatory toxicology and pharmacology 21(1), 192-198.

Longo, S., Katsou, E., Malamis, S., Frison, N., Renzi, D., Fatone, F., 2015. Recovery of volatile fatty acids from fermentation of sewage sludge in municipal wastewater treatment plants. Bioresource technology 175, 436-444.

Malamis, S., Katsou, E., Di Fabio, S., Bolzonella, D., Fatone, F., 2014. Biological nutrients removal from the supernatant originating from the anaerobic digestion of the organic fraction of municipal solid waste. Critical reviews in biotechnology 34(3), 244-257.

Melia, P.M., Cundy, A.B., Sohi, S.P., Hooda, P.S. and Busquets, R., 2017. Trends in the recovery of phosphorus in bioavailable forms from wastewater. Chemosphere. http://dx.doi.org/10.1016/j.chemosphere.2017.07.089

Menezes-Blackburn, D., Zhang, H., Stutter, M., Giles, C.D., Darch, T., George, T.S., Shand, C., Lumsdon, D., Blackwell, M., Wearing, C., 2016. A holistic approach to understanding the desorption of phosphorus in soils. Environmental science, technology 50(7), 3371-3381.

Nhu, T.T., Schaubroeck, T., Henriksson, P.J., Bosma, R., Sorgeloos, P., Dewulf, J., 2016. Environmental impact of non-certified versus certified (ASC) intensive Pangasius aquaculture in Vietnam, a comparison based on a statistically supported LCA. Environmental Pollution 219, 156-165.

Niero, M., Pizzol, M., Bruun, H.G. and Thomsen, M., 2014. Comparative life cycle assessment of wastewater treatment in Denmark including sensitivity and uncertainty analysis. Journal of cleaner production, 68, 25-35.

Parravicini, V., Svardal, K., Krampe, J., 2016. Greenhouse Gas Emissions from Wastewater Treatment Plants. Energy Procedia 97, 246-253.

Paulsrud, B., Rusten, B., Aas, B., 2014. Increasing the sludge energy potential of wastewater treatment plants by introducing fine mesh sieves for primary treatment. Water Science and Technology, 69(3), 560-565.

Peña-Fernández, A., Lobo-Bedmar, M.C. and González-Muñoz, M.J., 2015. Annual and seasonal variability of metals and metalloids in urban and industrial soils in Alcalá de Henares (Spain). Environmental research, 136, 40-46.

Qin, C., Liu, H., Liu, L., Smith, S., Sedlak, D.L., Gu, A.Z., 2015. Bioavailability and characterization of dissolved organic nitrogen and dissolved organic phosphorus in wastewater effluents. Science of the Total Environment 511, 47-53.

Renzi, D., Longo, S., Frison, N., Malamis, S., Katsou, E., Fatone, F., 2015. Short-cut enhanced nutrient removal from anaerobic supernatants: Pilot scale results and full scale development of the SCENA process. In Sewage Treatment Plants: Economic Evaluation of Innovative Technologies for Energy Efficiency. Integrated Environmental Technology Series. Stamatelatou and Tsagarakis Ed. IWA Publishing.

Risch, E., Gutierrez, O., Roux, P., Boutin, C., Corominas, L., 2015. Life Cycle Assessment of urban wastewater systems: Quantifying the relative contribution of sewer systems. Water research 77, 35-48.

Rodriguez-Garcia, G., Frison, N., Vázquez-Padín, J.R., Hospido, A., Garrido, J.M., Fatone, F., Bolzonella, D., Moreira, M.T., Feijoo, G., 2014. Life cycle assessment of nutrient removal technologies for the treatment of anaerobic digestion supernatant and its integration in a wastewater treatment plant. Science of The Total Environment 490, 871-879.

Rodriguez-Garcia, G., Molinos-Senante, M., Hospido, A., Hernández-Sancho, F., Moreira, M.T., Feijoo, G., 2011. Environmental and economic profile of six typologies of wastewater treatment plants. Water research 45(18), 5997-6010.

Rosenbaum, R.K., Bachmann, T.M., Gold, L.S., Huijbregts, M.A., Jolliet, O., Juraske, R., Koehler, A., Larsen, H.F., MacLeod, M., Margni, M. and McKone, T.E., 2008. USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. The International Journal of Life Cycle Assessment 13(7), 532-546.

Schaubroeck, T., De Clippeleir, H., Weissenbacher, N., Dewulf, J., Boeckx, P., Vlaeminck, S.E., Wett, B., 2015. Environmental sustainability of an energy self-sufficient sewage treatment plant: improvements through DEMON and co-digestion. Water research 74, 166-179.

Torri, S.I., Correa, R.S. and Renella, G., 2017. Biosolid application to agricultural land—a contribution to global phosphorus recycle: A review. Pedosphere 27(1), 1-16.

Third, K., Sliekers, A.O., Kuenen, J., Jetten, M., 2001. The CANON system (completely autotrophic nitrogen-removal over nitrite) under ammonium limitation: interaction and competition between three groups of bacteria. Systematic and applied microbiology 24(4), 588-596.

Weidema, B., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C., Wernet, G., 2013. The ecoinvent database: overview and methodology, data quality guideline for the ecoinvent database version 3.

Wett, B., 2006. Solved upscaling problems for implementing deammonification of rejection water. Water science and technology 53(12), 121-128.

Wilfert, P., Kumar, P.S., Korving, L., Witkamp, G., van Loosdrecht, M.C., 2015. The relevance of phosphorus and iron chemistry to the recovery of phosphorus from wastewater: a review. Environmental science, technology 49(16), 9400-9414.

Yoshida, H., Christensen, T.H., Scheutz, C., 2013. Life cycle assessment of sewage sludge management: a review. Waste management & research 31(11), 1083-1101.

Yoshida, H., Clavreul, J., Scheutz, C. and Christensen, T.H., 2014. Influence of data collection schemes on the Life Cycle Assessment of a municipal wastewater treatment plant. Water research 56, 292-303.

Zang, Y., Li, Y., Wang, C., Zhang, W., Xiong, W., 2015. Towards More Accurate Life Cycle Assessment of Biological Wastewater Treatment Plants: A Review. Journal of Cleaner Production 107, 676-692.