Environmental burdens of nutrient removal technologies for the treatment of anaerobic digestion supernatant and its integration in a sewage treatment plant

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Abstract
The supernatant resulting from the anaerobic digestion of the sludge generated by a sewage treatment plant (STP) is a small flow in terms of volume but very relevant in terms of N and P loads. Its characteristics make it particularly suitable for technologies such as partial nitritation-anammox (CANON), nitrite shortcut (NSC) and struvite crystallization processes (SCP), and removing nutrients under more favourable conditions than in the main water line.
The potential environmental implications of those technologies were assessed using Life Cycle Assessment, both at pilot plant scale and thereafter, integrated in a modelled full STP. Pilot-plant results considered biological N removal technologies as more efficient in environmental terms, distantly followed by SCP. Full-scale modelling, however, highlighted that the differences between technologies were not so relevant once they are integrated in a STP. The addition of these technologies reduced slightly the impacts of the STP in all categories, except for eutrophication, where a substantial reduction was achieved using NSC, SCP and, especially, if CANON and SCP were combined. This study emphasises the need for assessing sewage treatment technologies as part of a WWTP rather than as individual processes and the utility of modelling tools for doing so.

Keywords
CANON; Modelling; Nitrite Short-Cut; side-stream treatment; Struvite crystallization process

INTRODUCTION

The supernatant from anaerobic digestion, also known as side stream, represents about 1% of the total flow of a sewage treatment plant (STP) but it accounts for 10-20% of the total N and 20-30% of the total P entering a wastewater treatment plant (WWTP). These high concentrations of N and P, together with low COD and solids, as well as its warm temperature (~37ºC) allow the implementation of novel technologies such as Complete Autotrophic Nitrogen removal Over Nitrite (CANON), Nitrite Shortcut (NSC) reactors and Struvite Crystallization Processes (SCP) under very favourable conditions.

Life Cycle Assessment (LCA) is a holistic tool that considers the impacts of a process from its cradle to its grave (ISO, 2006). It has been successfully applied both in anaerobic digestion and STP (Hospido et al., 2012). It is used here to quantify the environmental burdens of three technologies for the treatment of the anaerobic supernatant at pilot plant scale. Two of them, a CANON reactor and a Sequential Bioreactor based in the NSC pathway, are N removal technologies while the reactor a SCP is a P removal technology. Later on, the LCA of a full WWTP modelled using BioWin® (www.envirosim.com) where these technologies are implemented is conducted to assess the importance of side-stream technologies within the whole WWTP.

MATERIALS AND METHODS

The individual CANON, NSC and SCP pilot plants assessed are described in Vazquez-Padin et al. (2012), Frison et al. (2012) and Battistioni et al. (2005), respectively. Being all of them nutrient removal technologies, 1 kg of PO_4^{3-} eq. removed as described in Rodriguez-Garcia et al. (2011) was chosen as functional unit (FU). The eutrophication (EP), acidification (AP) and global warming (GWP) potential impacts were assessed using the CML methodology (Guinée et al., 2002) and the analysis of the human toxicity (HTP) and freshwater ecotoxicity (ETP) was performed using the USEtox methodology (Rosenbaum et al. 2008).

The system under study comprises the reactor operation, including background processes associated to the electricity and the chemicals used as well of the treated water's discharge. Sludge treatment, struvite production and their disposal as soil amendments were also considered. Experimental data were used as the main source for the construction of the inventory, complemented with calculations based on literature. Background processes were taken from the Ecoinvent Database (www.ecoinvent.ch).

The full treatment plant presented in BioWin® as an example, treating a medium-strength sewage as described in Tchobanoglous et al. (2002), was used as the baseline scenario (Scenario 0) for assessing the effect that side stream technologies would have in the environmental profile of the overall STP. Over this process, two changes were made: i) $FeCl_3$ was added as a tertiary treatment in order to achieve substantial P removal in the main line and ii) the side-stream reactor was substituted by a black-box model applying the removal efficiencies achieved by the pilot plant assessed: CANON (Sc. 1), NSC (Sc. 2) and SCP (Sc. 3). A fourth scenario, CANON+SCP (Sc. 4), is also considered as the combination of these two alternatives is technologically feasible.

A full description of the reactors under study, their complete Life Cycle Inventories as well as a complete explanation of the calculations required for its construction and a detailed discussion of the impacts of these reactors can be found in Rodriguez-Garcia et al. (submitted).

RESULTS AND DISCUSSION

LCA of pilot plant reactors

The most relevant differences between reactors at inventory level are found in the influent and effluent quality (Rodriguez-Garcia et al., submitted). According to these results, NSC is the technology removing the largest amount of these substances, not only achieving almost complete N removal but also removing a substantial fraction of P. The CANON has a slightly lower overall removal, presenting also a very high N removal, but, due to the small growth of anammox biomass, P removal is almost non-existent. Finally, the SCP presents a high P removal but, due to the stoichiometry of the struvite precipitation reactor, N removal is very limited. This overall ranking can be seen in Figure 1a.

Electricity use is by far the single most relevant item due to its effect in the majority of the categories (Fig. 1b-d). Gaseous emissions generated during the water treatment play a very important role in the GWP of N removal technologies (due to N_2O, Fig. 1b) and on the AP of SCP (due to NH_3, Fig. 1c). Both HTP and ETP presented identical tendencies and thus only the latter is presented there (Fig.1d). In these categories, the use of acetic acid affects significantly the NSC profile while some benefits (negative values) can be seen in these categories related with the production of struvite.

In summary, NSC can be considered as the best alternative, closely followed by the CANON, while SCP is considered the least sustainable technology, mainly due to its low eutrophication removal.

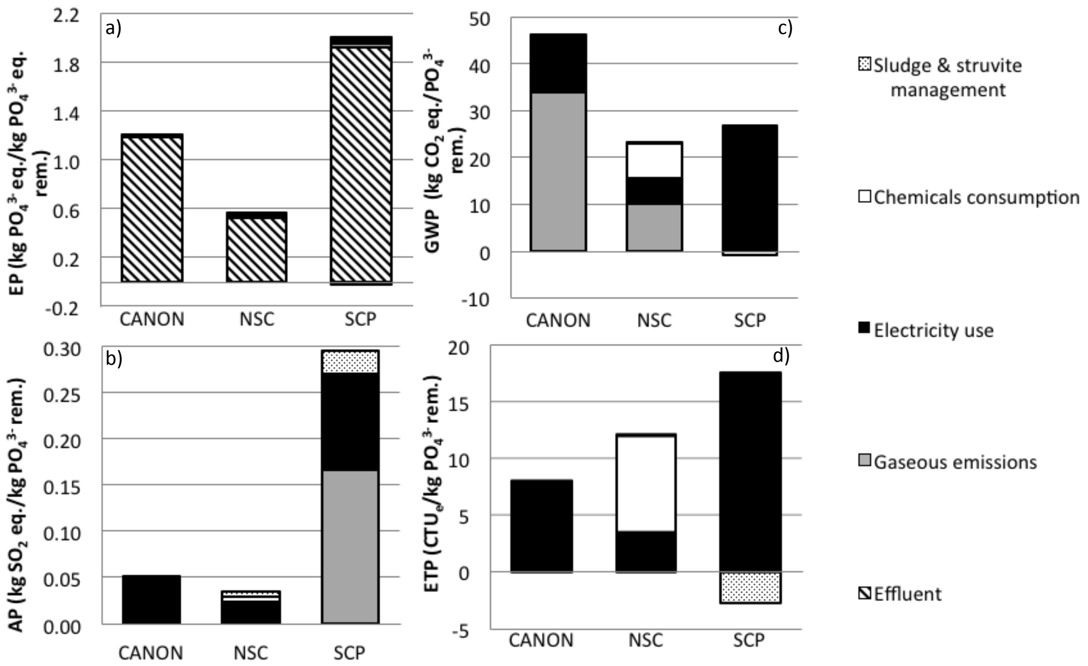

Figure 1. a) Eutrophication, b) Global Warming, c) Acidification, d) Freshwater Ecotoxicity Potential Impacts per FU (1 kg PO_4^{3-} eq. rem.)

Impact of the side-stream technology in the environmental performance of the full WWTP

Moving from the particular analysis to a boarder scope, the implementation of these technologies significantly increases the removal of N and P of the whole WWTP (Fig. 2.a), thus reducing the EP impact category (Fig. 2b).

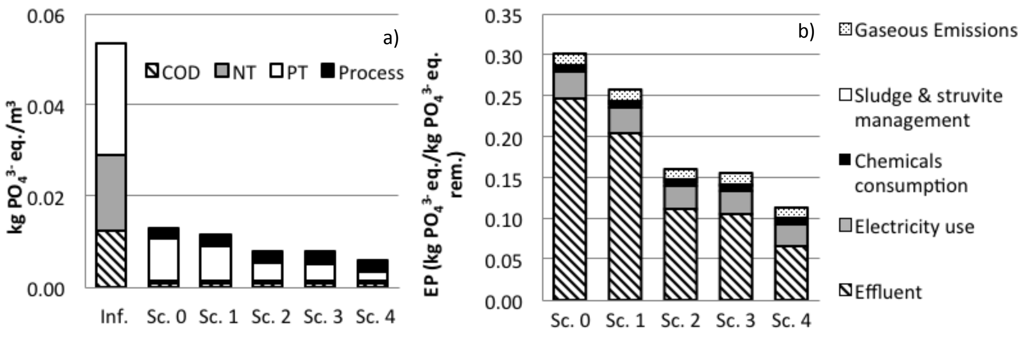

Figure 2. a) Eutrophication impact of the influent (Inf.) and the effluent + the process of the different scenarios per (per m^3) b) Eutrophication Potential Impact per FU (1 kg PO_4^{3-} eq. rem.)

Considering the other impact categories, Table 1 reports the environmental reduction associated to the inclusion of the different side-stream technologies. The largest benefits are found in the EP category, while smaller reductions are found in all the other categories for all reactors but GWP in Sc. 1, where there is an increase in the impact due to the N_2O emissions of the CANON. In general terms, the higher removal of eutrophying substances per m^3 as we go from Sc.0 to Sc. 4 is responsible for the lower impact in the non-EP impact categories rather than a reduction in the consumptions or the emissions per m^3 of sewage treated.

According to these results, the addition of a technology for the treatment of the anaerobic supernatant would make a WWTP more sustainable, reducing the impacts associated in all the items evaluated.

Table 1. Total impacts per FU of the baseline scenario and changes achieved by the alternative scenarios

	EP (kg PO_4^{3-} eq.)	**GWP (kg CO_2 eq.)**	**AP (kg SO_2 eq.)**	**HTP (CTU_h)**	**ETP (CTU_e)**
Sc. 0	0.30	12.31	0.28	0.001	841.22
Sc. 1	-15%	5%	-3%	-3%	-3%
Sc. 2	-47%	-5%	-11%	-11%	-11%
Sc. 3	-47%	-10%	-11%	-11%	-11%
Sc. 4	-61%	-4%	-16%	-15%	-15%

CONCLUSIONS

The LCA of individual processes for the treatment of the anaerobic digestion supernatant recommend N removal technologies, CANON and NSC, leaving SCP as the least preferable one. However, these differences are not so relevant once these technologies are assessed as part of the whole plant. P removal technologies, namely CANON+SCP were found to be the best upgrade that could be made for the treatment of anaerobic digestion. Finally, modeling has shown to be a valuable tool for the LCA of WWTP as a first approach when no information from full-scale plants is available.

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