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Life cycle assessment of nutrient removal technologies for the treatment of anaerobic digestion supernatant and its integration in a wastewater treatment plant

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HIGHLIGHTS

- LCA was used to compare different side-stream treatment technologies.
- At pilot plant scale, N removal technologies had the lowest environmental impact.
- If part of a full WWTP, P-crystallization technologies presented the lowest impact.
- Eutrophication impacts were reduced significantly using side-stream technologies.
- Global warming, acidification, and toxicity impacts were only marginally reduced.

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ABSTRACT

The supernatant resulting from the anaerobic digestion of sludge generated by wastewater treatment plants (WWTP) is an attractive flow for technologies such as partial nitritation–anammox (CANON), nitrite shortcut (NSC) and struvite crystallization processes (SCP). The high concentration of N and P and its low flow rate facilitate the removal of nutrients under more favorable conditions than in the main water line. Despite their operational and economic benefits, the environmental burdens of these technologies also need to be assessed to prove their feasibility under a more holistic perspective.

The potential environmental implications of these technologies were assessed using life cycle assessment, first at pilot plant scale, later integrating them in a modeled full WWTP. Pilot plant results reported a much lower environmental impact for N removal technologies than SCP. Full-scale modeling, however, highlighted that the differences between technologies were not relevant once they are integrated in a WWTP. The impacts associated with the WWTP are slightly reduced in all categories except for eutrophication, where a substantial reduction was achieved using NSC, SCP, and especially when CANON and SCP were combined. This study emphasizes the need for assessing wastewater treatment technologies as part of a WWTP rather than as individual processes and the utility of modeling tools for doing so.

1. Introduction

Anaerobic digestion is among the most common alternatives for the treatment of the sludge produced in wastewater treatment plants (WWTP). The supernatant resulting from the dewatering of biosolids, also called *side stream*, presents high concentrations of nutrients, nitrogen (N), and phosphorus (P), but low amounts of biodegradable organic matter in comparison with the WWTP influent. This flow, representing less than 1% of the total influent, accounts for 10–20% of the N and 20–30% of the P found in a WWTP (Gujer, 2010; Bilyk et al., 2011). These

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characteristics allow the implementation of technologies with additional benefits over conventional processes:

- Nitritation–anammox combines ammonia-oxidizing bacteria (AOB) with anammox bacteria, and removes N through the combined oxidation of NH_4^+ and the reduction of NO_2^-. The use of these two cultures in the same reactor has received different names, CANON (completely autotrophic nitrogen removal over nitrite) being the most accepted (Campos et al., 2010). This process is entirely autotrophic, and thus the low COD concentrations found in the side stream would not reduce the growth of N-removing bacteria, something that would occur in a conventional nitrification–denitrification process.
- Nitritation–denitritation, also called nitrite short-cut (NSC), promotes the growth of AOB and denitrifiers in the same reactor, removing N without oxidizing it first to NO_3^-, hence reducing oxygen (O_2) and organic matter requirements together with sludge production (Van Kempen et al., 2001). Since denitrifiers are heterotrophs, this process might demand an external source of carbon. Due to the high N concentration and relatively small flow of the supernatant, if implemented there, NSC would require less additional carbon per unit of N removed than if applied in the main water line.
- Struvite crystallization removes N and P producing a mineral fertilizer with virtually no heavy metals (Ueno and Fujii, 2001). Struvite (magnesium ammonium phosphate hexahydrate, $NH_4MgPO_4 \cdot 6H_2O$) crystallizes when equimolar mixtures of NH_4^+, Mg^{2+} and PO_4^- are found in wastewater (Le Corre et al., 2009). This process would benefit from the lower concentrations of organic solids and the high NH_4^+ and PO_4^{3-} concentrations found in the digester supernatant (Rittmann et al., 2011).

Nutrient removal technologies, and WWTPs in general, are end-of-pipe technologies designed to deal with a particular environmental issue, i.e. pollutants present in wastewaters. As engineering moves from the end-of-pipe approach to sustainability, a broader perspective is required to avoid exporting environmental problems over time or space. This perspective needs to consider additional environmental impacts to those that WWTPs were designed to deal with (Balkema et al., 2002; Davidson et al., 2007). This holist viewpoint is an integral part of life cycle assessment (LCA). This methodology has been widely used within the field of wastewater treatment, giving also substantial attention to sludge treatment (Hospido et al., 2012). To the best of our knowledge, a dozen papers have been published regarding sludge treatment in the last decade (Beavis and Lundie, 2003; Lundin et al., 2004; Hospido et al., 2005; Houillon and Jolliet, 2005; Tarantini et al., 2007; Hara and Mino, 2008; Murray et al., 2008; Peters and Rowley, 2009; Hong et al., 2009; Pasqualino et al., 2009; Carballa et al., 2011; Nakakubo et al., 2012). Among them, only Beavis and Lundie (2003) and Nakakubo et al. (2012) consider the supernatant, indicating that it returns to the main water line and thus it can be accounted as internal flow within the plant, not having a quantifiable effect on the environment. In addition, the only LCA study dealing with P-removal technologies in the side stream is that of Nakakubo et al. (2012). The present study is, to the best of our knowledge, the first LCA focusing on side stream technologies that remove both nutrients.

The analysis of environmental impacts from the cradle to the grave is at the core of LCA. As such, special attention should be given to the effect that a particular technology has on the environmental profile of the whole WWTP. For this reason, we conducted an LCA on three side stream technologies at two different levels: first, examining them as independent processes, and later as part of a modeled WWTP.

2. Materials and methods

2.1. Goal and scope

The goal of this study is to evaluate the environmental profile of three different options for the treatment of the anaerobic supernatant: a CANON reactor, a sequencing batch reactor based on the NSC, and a struvite crystallization process (SCP) reactor. These technologies will be assessed first as individual processes; afterwards, the contribution of the supernatant treatment will be considered for the evaluation of a whole WWTP where these different technologies are implemented.

2.2. Treatment options

The three technologies under study have been the focus of intensive research in recent years (Ueno and Fujii, 2001; Peng and Zhu, 2006; Joss et al., 2009). Most of this research, and therefore most of the information available regarding these technologies, concerns lab and pilot plants rather than full-scale facilities. For this reason, the three pilot plants described in Appendix A were considered for the first part of this study.

2.3. Functional unit and impact assessment methodology

The main objective of side stream technologies is the removal of eutrophying substances, namely N and P compounds. For this reason, we chose, as functional unit (FU), the reduction of the eutrophication potential (EP) as defined by the CML methodology v.2.05 (Guinée et al., 2002), 1 kg PO_4^{3-} eq. removed. As seen in Rodriguez-Garcia et al. (2011), this FU reduces the effect influent quality has on the environmental profile of a WWTP, giving more importance to the effort made by the plant than to the actual effluent quality. As a result, this FU allows a better comparison between reactors whose influents present different characteristics. Like those FU based on volume (e.g. 1 m^3), it does not show how a technology would behave with a different influent.

Global warming (GWP), acidification (AP), EP, photochemical oxidation (POP) and toxicity-related impact categories are, according to Corominas et al. (2013), those most widely assessed. As such, we evaluated those impacts, excluding POP, since previous studies had shown that the effect of WWTPs in this category was negligible (Beavis and Lundie, 2003; Hospido et al., 2005).

GWP, AP and EP were assessed using the last updated version (v.2.05, November 2010) of the CML methodology (Guinée et al., 2002). According to Corominas et al. (2013), this is the impact method most commonly used in LCA of WWTP. The toxicity-related categories of human toxicity (HT) and freshwater ecotoxicity (ETP) were evaluated using USEtox, including both recommended and interim substances (Rosenbaum et al., 2008). USEtox is considered a state-of-the-art methodology thanks to the large consensus achieved by model developers, including those from CML, during its design.

2.4. System boundaries

For a full-scale WWTP, the life cycle entails construction, operation and dismantling. The impact of the former has been found to be significant, especially in terms of GWP (Tangsubkul et al., 2005; Doka, 2009). However, due to lack of data regarding the construction of the pilot plant reactors and to the small correlation between the materials used at pilot plant and at full-scale, this stage was not taken into account. The impacts of the dismantling stage are likely to be negligible unless long-term emissions from landfills are considered (Larsen et al., 2010). Thus, only the operation stage was assessed, including the background processes associated with the provision of the energy and chemicals used, the final disposal of the sludge, the production of struvite, as well as the discharge of the treated water. In a full plant, treated water would go back to the head of the WWTP. However, for the studied pilot plants, the effluent was assumed to be directly discharged to the river in order to include its impacts.