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Removing nitrogen from wastewater with side stream anammox: What are the trade-offs between environmental impacts?

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ABSTRACT

Anaerobic ammonium oxidation (anammox) is a novel way to reduce nitrogen in ammonium rich wastewater. Although aquatic eutrophication will certainly be reduced, it is unknown how other environmental impacts may change by including anammox in the treatment of wastewater. Here, life cycle assessment (LCA) was used to assess the environmental profile of a full scale wastewater treatment plant over its complete life cycle. Changes in the environmental profile by introducing a two-step anammox system in the side stream were assessed based on monitoring data from the full scale Dokhaven wastewater treatment plant (Rotterdam, The Netherlands). Our results confirmed that the two-step anammox technique further reduced life cycle nitrogen emissions compared to the regular treatment of nitrogen in wastewater. This led to a decrease in marine eutrophication potential of 16% for the total wastewater treatment plant. However, our LCA results showed that these ammonium reductions came at the cost of increasing climate change and other environmental impacts. Climate change impacts increased with 9% going from a traditional wastewater plant to the one including two-step anammox, due to increased direct emissions next to electricity use. Our LCA highlights trade-offs when adding two-step anammox for nitrogen removal in wastewater treatment systems. This has significant implications for other WWTPs as these trade-offs should not neglected when implementation of anammox is considered.

1. Introduction

Reducing nitrogen in effluent of wastewater treatment plants is one of the major goals to prevent aquatic eutrophication. The European Water Framework Directive (2000/60/EC) calls for the implementation of the Urban Waste Water Directive (92/271/EEC). According to this directive a discharge limit of 10–15 mg N/l is applicable for European wastewater treatment plants (WWTP) to sensitive areas, depending on the size of the community and that 70–80% of the initial amount of N present in the influent is removed. Half of these (2.3–4 mg N/l) concentrations might be achievable according to the Dutch water research body (Stowa, 2013). In the United States 3 mg N/l for nitrate and nitrite have been discussed (TaskGroup, 2009). According to monitoring reports (CBS et al., 2014) nitrogen concentrations in the North Sea are twice the legal limits, indicating that marine eutrophication should be considered as a relevant environmental problem in this area.

Several authors (Vidal et al., 2002; Foley et al., 2010a; Lederer and Rechberger, 2010; Rodriguez-Garcia et al., 2011) highlighted the trade-off between more nitrogen removal on one hand and higher energy demand, and related greenhouse gas emissions on the other hand when comparing different levels of wastewater treatment. Higher energy and chemical demands generally lead to higher costs.

Anaerobic ammonium oxidation (anammox) has been successfully applied as a cost effective ammonium removal process for wastewater streams with high nitrogen load (e.g. Jetten et al., 2002). During anammox, ammonium and nitrite are directly coupled under anoxic conditions to form dinitrogen gas. Anammox bacteria can perform this transformation without the need for costly aeration or an external carbon source such as methanol. Since their postulation in the 1970s and their discovery in 1990, anammox bacteria have been the focus of a growing body of research (see Kuenen (2008) for an overview). Potential energy benefits have been postulated for anammox in WWTPs that eliminate the trade-off between enhanced nitrogen removal on the one hand and other environmental problems related to energy use on the other hand (Kartal et al., 2010; Joss et al., 2009; Siegrist et al., 2008). Others (Fux and Siegrist, 2004) also estimate economic benefits of anammox over nitrification-denitrification.

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Currently, several full scale anammox reactors are implemented in WWTPs (see Gustavsson, 2010 for an overview). These reactors treat ammonium rich water, mostly reject water from digesters before it is returned to the mainstream water line. The elevated temperature and high nitrogen load of the reject water provides preferable conditions for anammox bacteria. The anammox process is either preceded by aerobic ammonium oxidation to obtain an ammonium and nitrite mixture in about equal quantities (partial nitrification, van Dongen et al., 2001), called two-step anammox, or, increasingly, anammox and aerobic ammonium oxidation are combined in one reactor (one-step anammox).

Several authors have described start-up and nitrogen removal performance of several types of full scale anammox reactors and report NH_4^+-removal efficiencies up to 90% (van der Star et al., 2007; Abma et al., 2010; Rosenwinkel and Cornelius, 2005; Frijters et al., 2007). Joss et al. (2009) also compared greenhouse gas emission from a one-step anammox reactor treating reject water to conventional nitrification-denitrification in the mainstream water line. Although they found slightly higher N_2O emissions from the one-step anammox system, total greenhouse gas emissions were lower due to lower CO_2 emissions from aeration electricity and no carbon source addition. Desloover et al. (2011) investigated treatment of industrial reject water after retrofitting with a combination of partial nitrification, anammox, and nitrification-denitrification. They found dischargeable effluents below 10 mg N/l and reduced energy requirements, but higher N_2O emissions. Not taking into account N_2O emission, Wett and Hell (2008) also found reduced ammonium emissions and energy requirements for two full scale reject water treatment plants.

However, for assessing the environmental benefits of adding anammox for reject water treatment, the overall environmental performance of a wastewater treatment plant has to be assessed. Life cycle assessment (LCA) is a well-suited method to include all environmental impacts, also those arising for provision of materials and energy (Corominas et al., 2013; Guinée et al., 2002). Beyond above assessments of nitrogen and greenhouse gas emissions and energy use during nitrogen removal and one paper by Thibodeau et al. (2014), no life cycle assessments on anammox are known to us. Information on environmental performance can help municipal wastewater treatment boards to decide on investing in this new technology or indicate focus points for further optimization.

The aim of this research was to assess the environmental life cycle implications of nitrogen treatment by a full scale wastewater plant including two-step anammox in the sidesteam. Long-term data from a two-step anammox process in the reject water treatment in Rotterdam, The Netherlands, was used for this purpose. Comparison to the same WWTP with no extra nitrogen removal from the reject water before recirculation to the mainstream water line is also included to assess environmental benefits and trade-offs.

2. Materials and methods

2.1. System description

The WWTP in Rotterdam Dokhaven was built in 1987 and currently treats about 620,400 person equivalents municipal wastewater. The local river that receives the Dokhaven WWTP effluent is a branch of the River Rhine close the North Sea. The WWTP is an activated sludge plant with biological nutrient removal. Within the mainstream water line there is an activated sludge system divided in two steps and chemical phosphorus removal (with iron chloride dosing). The first step, a highly loaded A-stage (Adsorption) with mainly BOD removal, is followed by a B-stage ("Belebung": Aeration) with low sludge load where nitrification can occur. The sludge is treated at a separate sludge line located nearby (called Sluisjesdijk). Sludge is digested before transport to an incineration plant. Reject water is recycled to the mainstream wastewater treatment plant. Biogas produced during digestion is used to generate heat for the digester and electricity for internal use. In case heat supply by the biogas is insufficient to fulfil heat needs, natural gas is added. A SHARON (Stable High rate Ammonia Removal Over Nitrite) reactor was in full operation from 1999 to 2004 in the side stream. The current two-step anammox process, with the SHARON reactor running as partial nitrification reactor, was at full load in 2005. A schematic overview of the WWTP including sludge line and two-step anammox and the system boundaries of the LCA, is given in Fig. 1.

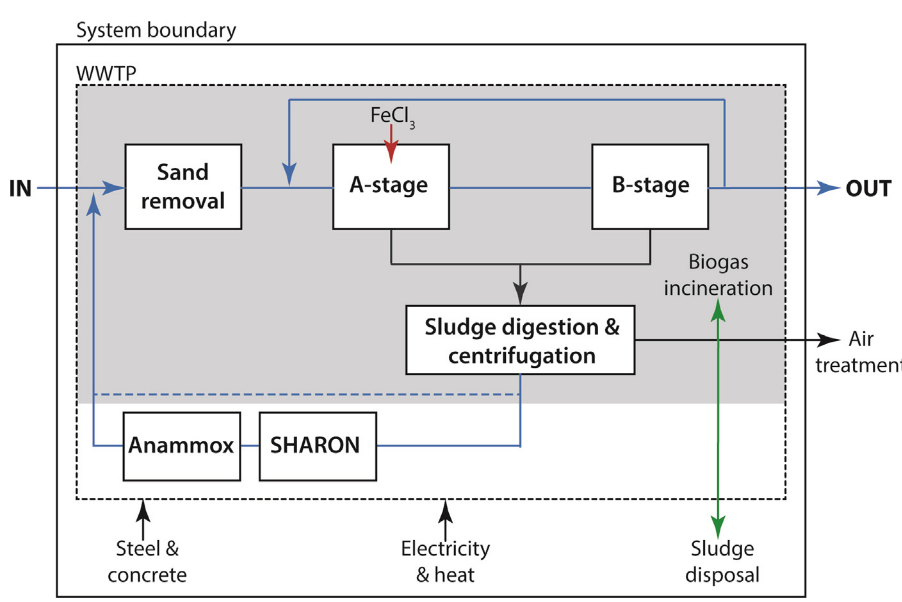

Fig. 1. Schematic representation of the WWTP in Dokhaven with the nitrogen removal configuration investigated in this research (foreground system) and the system boundaries employed. The grey box indicates the WWTP Dokhaven situation in 1998, used for the comparison of a WWTP without nitrogen removal with the two-step anammox system. The stripped blue line represents effluent recirculation before implementation of sludge line treatment. Blue lines indicate water, brown lines sludge, green lines biogas, red lines chemical input.