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Research Paper

Comparing environmental impact of air scrubbers for ammonia abatement at pig houses: A life cycle assessment

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Intensive livestock production involves environmental emissions and impacts, including emission of greenhouse gases and ammonia leading to climate change and terrestrial acidification. Ammonia emission from animal housing systems can be reduced by introducing air scrubbers for cleaning the exhaust air, but insight into the environmental impact throughout the entire system is lacking. This study aimed to assess and compare the environmental impact of three types of air scrubbers: an acid scrubber and two biotrickling filters, one with nitrification only and one with nitrification and denitrification. Air scrubbers were compared by using life cycle assessment and assessing five environmental impacts: climate change, terrestrial acidification, marine eutrophication, particulate matter formation and fossil fuel depletion. The acid scrubber showed reductions in all environmental impact categories (up to >2000%), whereas the biotrickling filter with combined nitrification and denitrification had highest climate change and fossil fuel depletion. The biotrickling filter with nitrification only had highest terrestrial acidification and marine eutrophication.

1. Introduction

Intensive livestock production results in emissions and environmental impacts, such as ammonia (NH_3) emission leading to acidification, and greenhouse gas emission leading to climate change (CC) (Chadwick et al., 2011). For a great part, NH_3 emission occurs from exhaust air expelled from animal housing systems. One way to mitigate this NH_3 emission from animal houses is to clean the exhaust air by means of air scrubbers (Arends et al., 2008; Melse & Ogink, 2005; Ndegwa, Hristov, Arogo, & Sheffield, 2008). Air scrubbers are currently applied on a large scale in several European countries such as the Netherlands and Germany (Hahne, 2011; Melse, Ogink, & Rulkens, 2009; Melse, Ploegaert, & Ogink, 2012) in order to comply with regulations, such as the National Emission Ceilings (NEC), that limit the emission of NH_3, odour and dust (Melse et al., 2009). In the Netherlands it is estimated that currently about 5000 farm-scale scrubbers are in operation at animal houses of which about 60% are acid scrubbers and 40% bioscrubbers, the latter also referred to as biotrickling filters.

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In acid scrubbers, NH_3 is captured by adding acid, usually sulphuric acid (H_2SO_4), leading to the production of an ammonium sulphate ($(NH_4)_2SO_4$) solution which is discharged (Melse & Ogink, 2005). This solution can be used as nitrogen (N) and sulphur (S) fertiliser for crop production. Acid scrubbers have shown to remove NH_3 from the exhaust air by up to 100% while producing discharge water with a high N concentration (about 30 g[N] L^{-1}).

In biotrickling filters, NH_3 is removed by (de)nitrification and usually shows removal efficiencies of around 70% (Melse & Ogink, 2005). Two types of biotrickling filters can be distinguished: the commonly used biotrickling filter with nitrification only, and the biotrickling filter with both nitrification and denitrification. During nitrification bacteria convert NH_3 to nitrite (NO_2^-) and nitrate (NO_3^-). In a subsequent denitrification step, the aim is to convert NO_2^- and NO_3^- into harmless nitrogen gas (N_2). Compared to acid scrubbers, biotrickling filters with only nitrification produce about ten times as much discharge water at a much lower N concentration (about 3 g[N] L^{-1}). Larger amounts of discharge water may present a problem in areas with high livestock densities, such as the Netherlands, as current disposal costs for discharge water can be 15 € m^{-3} (NVV, 2016). The amount of discharge water and the N concentration is significantly reduced when denitrification is applied. For successful denitrification, however, anaerobic conditions and the presence of an electron–donor or biodegradable carbon source (e.g. molasses or methanol) is required. During the nitrification and denitrification process some nitrous oxide (N_2O), which is a strong greenhouse gas, may be formed (Kampschreur, Temmink, Kleerebezem, Jetten, & Van Loosdrecht, 2009; Melse, Ploegaert, et al., 2012; Melse & Mosquera, 2014; Melse, Van Hattum, Huis in 't Veld, & Gerrits, 2012; Mosquera et al., 2012).

Application of acid scrubbers and biotrickling filters affects the environmental impact throughout the complete chain from scrubbing until field application of discharge water. Therefore a comprehensive assessment of impacts between air scrubbers is necessary to provide insight into the overall impact of these air scrubber systems. Life cycle assessment (LCA) is a method to compute the environmental impact of a process or system along the whole life cycle (ISO-14040, 2006). The environmental impact of biotrickling filters for NH_3 abatement at animal houses was compared in 2014 (De Vries & Melse, 2014). Results showed that the biotrickling filter with combined nitrification and denitrification increased emission of greenhouse gases whereas the biotrickling filter, with nitrification only, increased emission of ammonia and leaching of nitrate after application of the discharge water. This study, however, excluded the comparison with an acid scrubber that is currently the most widely applied type of air scrubber. Hence, here we provide a complete and comprehensive overview of biotrickling filters and an acid scrubber.

The aim of this study was to assess and compare the environmental impact of three types of air scrubbers: 1) an acid scrubber, 2) a biotrickling filter with nitrification only, and 3) a biotrickling filter with both nitrification and denitrification. Based on the LCA framework, relevant changes in the environmental impact of upstream and downstream processes were included.

2. Materials and methods

2.1. *Life cycle assessment approach and functional unit*

A change-oriented approach to LCA (consequential) was used, implying that changes in processes and their environmental impacts are included in the system boundary. The processes subjected to change are called marginal processes or suppliers (Weidema, Ekvall, & Heijungs, 2009). In this study, marginal processes included production of electricity and production and use of mineral fertiliser.

The aim of an air scrubber is to remove NH_3 from the exhaust air of animal houses. Therefore, a functional unit (FU) of 1 kg[NH_3-N] entering the air scrubber was applied to compare air scrubbers. In order to relate the functional unit to an air flowrate, the emission factor of a conventional Dutch housing system for fattening pigs was applied, i.e. 3.5 kg[NH_3] per fattening pig place (pp) per year (yr) (IenM, 2012). For each fattening pig place, an average yearly ventilation rate of 31 m^3 pp^{-1} h^{-1} was applied (Infomil, 2010) resulting in an average NH_3-N concentration in the inlet air of 10.6 mg m^{-3}. From this concentration it follows that the functional unit of 1 kg[NH_3-N] requires a total of 94,215 m^3 of air to be ventilated and treated in the air scrubber (De Vries & Melse, 2014).

2.2. *System definition*

Figure 1 shows the processes that are considered for each system: the air scrubber itself, storage of the discharge water, transport and field application as fertiliser, and the avoided use of mineral fertiliser as a result of using N and S in the discharge water as fertiliser. The animal production facility was excluded from the system boundary as this was assumed not to be affected by implementing an air scrubber. Furthermore, molasses is used as an electron donor for the biotrickling filter with nitrification and denitrification.

2.3. *Data inventory and assumptions*

2.3.1. *Air scrubbers*

Emission data and NH_3 removal efficiencies for the acid scrubber and biotrickling filters were taken from literature and databases (Table 1). A mass balance was constructed to calculate the related changes in flows and compositions of air and discharge water. An NH_3 removal efficiency of 90% was applied for the acid scrubber whereas an efficiency of 70% was applied for both biotrickling filters (Melse & Ogink, 2005).

Based on Melse et al. (2011) and Melse, Ploegaert, et al. (2012), it was assumed that during nitrification 0.50% of the NH_3-N entering the scrubber was converted to N_2O-N. Biotrickling filters with nitrification and subsequent denitrification showed N_2O production levels up to 17%, 24%, and 66% of the NH_3-N entering the scrubber, at a NH_3 removal efficiency of 85%, 86%, and 71%, respectively (Melse & Mosquera, 2014; Melse, Ploegaert, et al., 2012; Melse, Van Hattum, et al., 2012; Mosquera et al., 2012). In the baseline calculation for the biotrickling filter including denitrification, an N_2O production figure of 24% of the NH_3-N entering the scrubber was applied, being the median of the aforementioned values. Emissions of