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Report 717

Comparing the environmental impact of a nitrifiying biotrickling filter with or without denitrification for ammonia abatement at animal houses

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Abstract
The aim was to assess the environmental impact of a biotrickling filter with nitrification only and with subsequent denitrification. Life cycle assessment was applied to assess greenhouse gases, nitrate, ammonia and fossil fuel depletion. The biotrickling filter with nitrification and denitrification had higher greenhouse gas emission, whereas nitrification only had higher nitrate leaching and ammonia emission from field application of discharge water.

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Preface

Currently several manufacturers of biotrickling filters for ammonia (NH_3) emission abatement at animal houses in The Netherlands are developing a biotrickling filter that includes a denitrification step, aiming to reduce the amount of discharge water. Some studies, however, indicate that application of denitrification may lead to a significant increase of the emission of nitrous oxide (N_2O). With this background the Dutch Ministry of Economic Affairs (EZ) has asked Wageningen UR Livestock Research to assess and compare the life cycle environmental impact of the biotrickling filter with nitrification only and nitrification followed by denitrification. The results of this assessment are reported here.

Summary

Ammonia (NH_3) emission from livestock housing systems contributes to environmental impacts, such as acidification and eutrophication, and to indirect emission of nitrous oxide (N_2O) leading to climate change. One way to mitigate NH_3 emission is cleaning of the exhaust air by means of air scrubbers. 10% of the air scrubbers currently installed in the Netherlands are biotrickling filters, the others are acid scrubbers (chemical scrubbers). A biotrickling filter is a scrubber with a packed-bed in which bacteria convert NH_3 to nitrite (NO_2^-) and nitrate (NO_3^-), i.e. the nitrification step. These nitrogen compounds are dissolved in the water and removed with the discharge water. Recent developments complement the nitrification step with a denitrification step in order to reduce the amount of discharged water and nitrogen the amount of nitrogen that needs to be applied in crop production.

Recent measurements on the denitrification step, however, have indicated considerable nitrous oxide emissions which may increase greenhouse gas emission compared to nitrification only. In order to assess and compare the environmental impact of both filters, it is therefore needed to take a holistic approach that considers all affected processes. In this study the aim was to assess and compare the environmental impact of a biotrickling filter with nitrification and a biotrickling filter with a combination of nitrification and denitrification. This included assessing changes in the environmental impact of downstream and upstream processes, e.g. application of the discharged water and electricity consumption.

We used a change oriented approach to life cycle assessment (consequential), implying that all changes in processes and their environmental impacts are included in the system boundary. For both types of biotrickling filters, we applied a functional unit (FU) of 1 kg NH_3-N removed from the exhaust air, i.e. the exhaust air from the animal house as inlet air of the biotrickling filter. We quantified greenhouse gas (GHG) emission (CO_2, N_2O and methane (CH_4)), NH_3 emission, NO_3^- leaching, and fossil fuel depletion. A sensitivity analysis was done to assess the influence of changes in several parameters and underlying assumptions on the final outcomes and comparisons; showing the solidity of the results.

Results showed that the greenhouse gas emissions were considerably higher when the denitrification step was included, as compared to a system without denitrification (172 vs. 8.41 kg CO_2-eq per kg NH_3-N removed, respectively). Direct NH_3 emission from the biotrickling filter and fossil fuel depletion were equal for both filters, as the same removal efficiencies and energy consumption figures were used.

We conclude that the biotrickling filter with combined nitrification and denitrification results in a higher emission of greenhouse gases than biotrickling filter with nitrification only, when the whole life cycle was considered. Furthermore, biotrickling filters with nitrification only resulted in a higher emission of ammonia and leaching of nitrate from field application of discharge water. The total NH_3 emission from the entire chain, however, remained unchanged. Although the sensitivity analysis showed changes in the environmental impacts, the main observations with regard to the comparison of biotrickling filters with nitrification only and with nitrification and denitrification remained unchanged. It is recommended to compare the environmental performance of biotrickling filters to acid scrubbers, as these are the most commonly used scrubbers for ammonia abatement at livestock housing systems.

Samenvatting

De intensieve veehouderij in Nederland gaat gepaard met de emissie van ammoniak (NH_3). Emissie van NH_3 draagt bij aan de milieubelasting die zich uit in onder andere verzuring, eutrofiëring en in klimaat verandering (dit laatste als gevolg van indirecte productie van N_2O). Luchtwassers zijn een methode om NH_3 emissie uit stallen te verminderen. Ongeveer 10% van de luchtwassers in Nederland bestaat uit biologische luchtwassers of biotrickling filters, de rest betreft zure wassers (chemische wassers). In een biologische luchtwasser wordt NH_3 omgezet naar nitriet (NO_2^-) en nitraat (NO_3^-) met behulp van bacteriën; deze omzetting wordt "nitrificatie" genoemd. Het geproduceerde nitriet en nitraat wordt met het spuiwater afgevoerd. Sinds enige tijd worden biologische luchtwassers soms uitgebreid met een denitrificatie stap, waarbij het de bedoeling is om het gevormde nitraat en nitriet om te zetten in onschadelijk stikstofgas (N_2). Als gevolg hiervan wordt de hoeveelheid stikstof in het spuiwater verminderd en ook de hoeveelheid spuiwater zelf.

Recente metingen aan biologische luchtwassers met denitrificatie hebben laten zien dat bij deze systemen de productie van lachgas (N_2O) aanzienlijk verhoogd wordt ten opzichte van biologische luchtwassers met alleen nitrificatie. Het is echter niet duidelijk hoe de N_2O emissie en andere milieu-indicatoren van deze twee typen biologische luchtwassers zich verhouden ten opzichte van elkaar wanneer de gehele keten onder de loep wordt genomen. Om duidelijk inzicht te verschaffen in de milieubelasting is het daarom nodig om een holistische aanpak toe te passen. Het doel van deze studie was om inzicht te verschaffen in de verandering van de milieubelasting van biologische luchtwassers met alleen nitrificatie ten opzichte van biologische luchtwassers met nitrificatie en denitrificatie. Een holistische aanpak betekend dat alle relevante processen uit de gehele keten worden meegenomen, zoals de toediening van het spuiwater en de productie van elektriciteit die nodig is voor de luchtwassers.

Om de verandering in de milieubelasting van de biologische luchtwassers te vergelijken is gebruikt gemaakt van de levenscyclusanalyse methodiek (LCA); gekozen is voor een veranderingsgerichte oftewel *consequential* LCA aanpak. De milieubelasting is vergeleken op basis van de verwijdering van 1 kg NH_3-N uit de stallucht die de luchtwasser in gaat (de functionele eenheid). De milieubelasting werd uitgedrukt in broeikasgasemissie (BKG, als optelsom van CO_2, N_2O en methaan (CH_4)), NH_3 emissie, NO_3^- uitspoeling en gebruik van fossiele energie. Een gevoeligheidsanalyse werd uitgevoerd met als doel om de invloed van veranderingen in belangrijke parameters op de berekende milieubelasting en de vergelijking van de milieubelasting tussen de luchtwassersystemen weer te geven.

De resultaten van de vergelijking van de milieubelasting lieten zien dat de BKG emissie van de biologische luchtwasser met nitrificatie en denitrificatie steeg ten opzichte van de biologische luchtwassers met alleen nitrificatie wanneer de gehele keten in acht werd genomen (172 vs. 8.41 kg CO_2-eq). De directe emissie van NH_3 uit de wasser en het gebruik van fossiele energie van de wasser was gelijk voor de beide luchtwassystemen, omdat dezelfde verwijderingsefficiëntie en hetzelfde energiegebruik werd aangenomen.

Geconcludeerd wordt dat de biologische luchtwassers met nitricatie en denitrificatie leidt tot een hogere emissie van broeikasgassen dan de biologische luchtwasser met alleen nitrificatie wanneer de gehele keten in acht wordt genomen. De biologische luchtwassers met alleen nitrificatie had een wat hogere ammoniak emissie en nitraatuitspoeling tijdens en na toediening van het spuiwater. De totale NH_3 emissie uit de keten bleef echter onveranderd. Ondanks het feit dat de gevoeligheidsanalyse veranderingen in de milieubelasting liet zien, had dit nauwelijks invloed op de resultaten van de vergelijking tussen de twee typen biologische luchtwassers. Aanbevolen wordt om de milieubelasting van de biologische luchtwassers ook te vergelijken met chemische wassers, aangezien dit de meest gebruikte luchtwassers zijn voor het verminderen van ammoniakemissie uit stallen.

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1 Introduction

Intensive livestock production involves a number of environmental impacts which include ammonia (NH_3) emission leading to acidification, and greenhouse gas emission leading to climate change. NH_3 emission occurs from exhaust air from the animal housing systems. One way to mitigate this NH_3 emission is cleaning of the exhaust air by means of air scrubbers (Ndegwa et al., 2008; Melse et al., 2009a). Air scrubbers are applied on a large scale in several European countries, like the Netherlands and Germany (Hahne, 2011; Melse et al., 2009b; Arends et al., 2008, Melse et al., 2012a), in order to comply with current regulations, e.g. National Emission Ceilings (NEC) (. In the Netherlands, in about 90% of the cases, acid scrubbers are used to remove the NH_3 from the air and in about 10% of the cases biotrickling filter (sometimes also referred to as bioscrubbers) are used.

With regard to ammonia removal, two types of biotrickling filters can be distinguished: biotrickling filters with only nitrification, and biotrickling filters with a combined nitrification and denitrification step (Figure 1 and 2). A biotrickling filter is a packed-bed scrubber in which bacteria convert NH_3 to nitrite (NO_2^-) and nitrate (NO_3^-), i.e. the nitrification step. Water is distributed on top of the packed-bed; usually a fraction of the wash water is continuously recirculated and another fraction is discharged and replaced with fresh water. The discharged water can be used as N-fertilizer in crop production.

In case of a biotrickling filter with denitrification, the nitrite and nitrate is subsequently converted to nitrogen gas (N_2). The aim of denitrification is to reduce the amount of N that needs to be discharged with the discharge water. Volume of discharge water is especially important in regions with intensive livestock production (e.g. the Netherlands), as off-set costs can run up to >15 euro per ton. For successful denitrification, anaerobic conditions and the presence of an electron donor or carbon source (e.g. molasses or methanol) are required. As a result of denitrification, usually some N_2O is formed which leads to greenhouse gas emissions. Besides, some N_2O can also be produced during nitrification, but usually this amount is much smaller. It should be noted that the climate change impact of N_2O equals 298 CO_2-eq which means that 1 kg of N_2O has the same impact as 298 kg of CO_2 on a 100-year timescale (IPCC, 2006).

Recently, measurements were carried out at three animal houses where the exhaust air was treated by a biotrickling filter with an additional denitrification step (Melse et al., 2012c, 2012d; Mosquera et al., 2012; Melse and Mosquera, 2013). The results showed that addition of denitrification resulted in a considerable production of N_2O compared to nitrification only. As expected, denitrification resulted in a reduction of the amount of nitrogen that was discharged with the water and of the amount of discharge water. However, the change in N_2O emission and other environmental indicators in the whole chain of the application of biotrickling filters remains unclear. In order to consider all related changes in the environmental impact and to make a comparison between the two types of filters, a holistic perspective is required that considers all affected processes and environmental impacts. Such a comparison has not been conducted on air scrubbers and specifically biotrickling filters before in the literature.

Life cycle assessment (LCA) is a holistic method to compute the environmental impact of a process or system delivering a predefined function or service (ISO-14040, 2006). According to the methodology, all related environmental impacts are included from the production system, i.e. the production of resources, transport, and on-farm impacts.

Our aim in this study was to assess and compare the environmental impact of a biotrickling filter with nitrification only and a biotrickling filter with a combination of nitrification and denitrification. This included assessing changes in the environmental impact of downstream and upstream processes, e.g. application of the discharged water and electricity consumption. We also aim to analyse the sensitivity of the results related to changes in the main operating parameters and emissions of the filters. LCA is used as a tool to quantify the environmental impact.

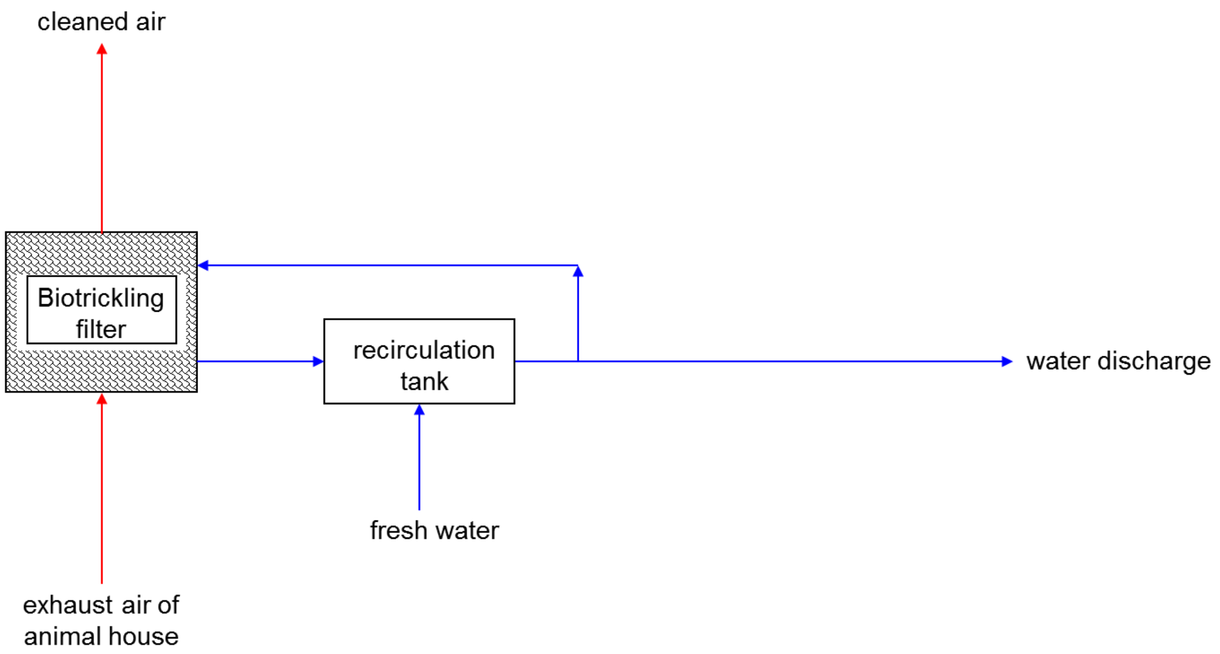

Figure 1. Schematic overview of biotrickling filter with nitrification only.

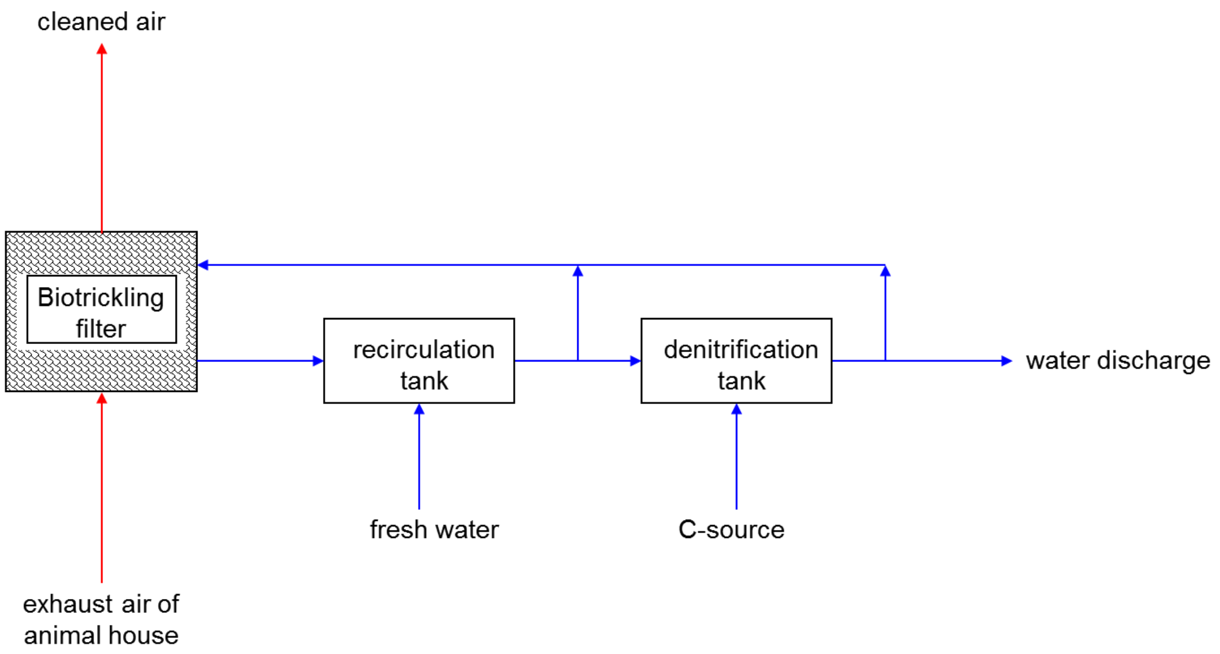

Figure 2. Schematic overview of biotrickling filter with combined nitrification and denitrification.

2 Materials and Methods

2.1 LCA approach

We used a change oriented approach to LCA (consequential), implying that all changes in processes and their environmental impacts are included in the system boundary. The processes subjected to change are also called marginal processes or suppliers (Weidema et al., 2009). Marginal processes included electricity production and mineral fertilizer production and were based on De Vries et al., (2012a).

The aim of the biotrickling filters is to remove NH_3 from the exhaust air of the animal housing systems. For comparison, we therefore, applied a functional unit (FU) of 1 kg NH_3-N removed from this air for both biotrickling filters, i.e. the exhaust air from the animal house as inlet air of the biotrickling filter. In all modelled scenarios, the same composition of the inlet air was assumed. The average NH_3 inlet concentration that was used in the model was calculated from the emission factor of a conventional housing system, i.e. 3.5 kg NH_3 per fattening pig place per year (IenM, 2012). This includes a year round average ventilation rate of 31 m^3 per hour (Infomil, 2010). The average NH_3-N inlet concentration was 10.6 mg NH_3-N per m^3 of inlet air. With an applied NH_3-N removal efficiency of 70% , 1 kg NH_3-N removal equals an average ventilation rate of 93,000 m^3 per hour for a pig house with about 3,000 fattening pigs.

We quantified the following environmental impacts related to exhaust air treatment with biotrickling filters: greenhouse gas (GHG) emission (CO_2, N_2O and CH_4), NH_3 emission, nitrate (NO_3^-) leaching, and fossil fuel depletion. We modelled the environmental impacts in SimaPro v. 7.3.3 (PréConsultants, the Netherlands). GHG emissions and fossil fuel depletion were quantified by using the ReCiPe v.1.04 impact assessment method (Goedkoop et al., 2009).

2.2 System definition

Figure 3 shows the considered system with included processes: the biotrickling filter, storage of the discharged water, transport and field application as fertilizer, and the avoided mineral fertilizer, as a result of using N in the discharge water as fertilizer. The animal production facility was excluded from the system boundary as this was assumed not to be affected by implementing the biotrickling filter. Furthermore, with denitrification, molasses is used as an electron donor. In the baseline situation we excluded any impacts related to the production of molasses.

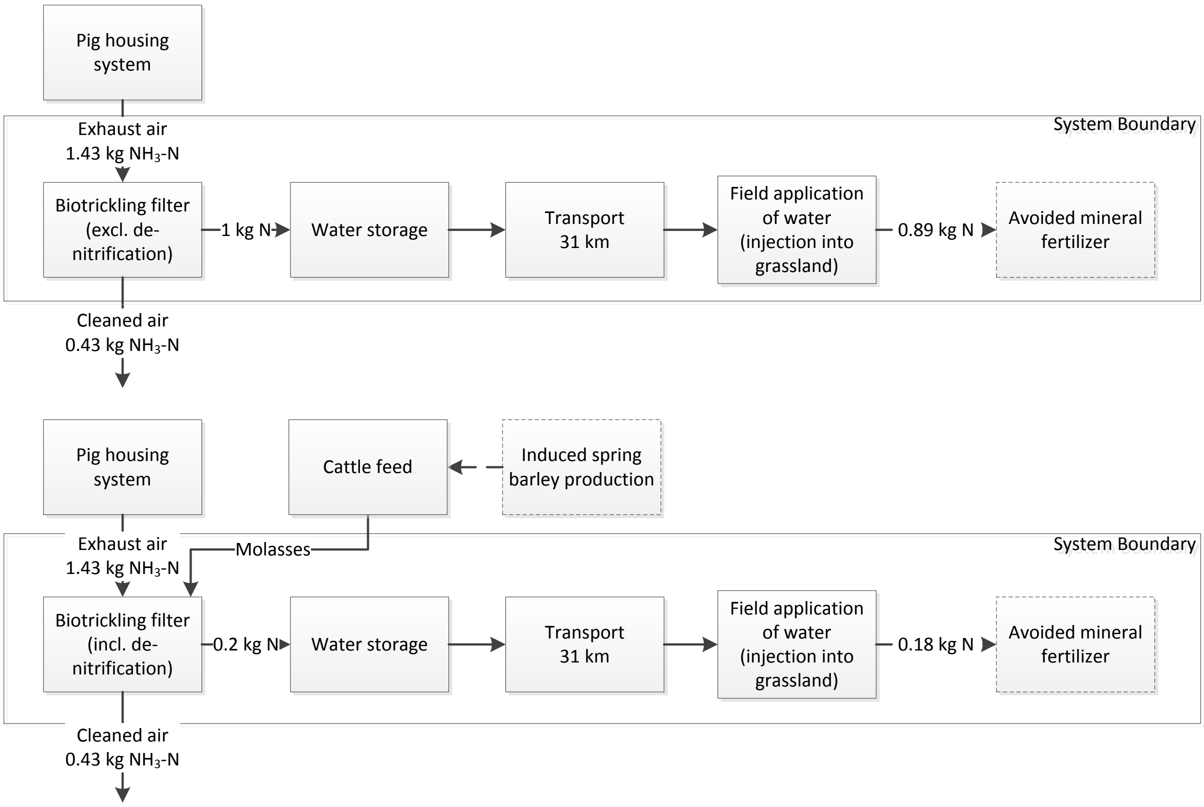

Figure 3. Defined system and system boundary for the situation of a biotrickling filter with only nitrification and including denitrification. Dotted boxes and lines represent avoided or induced production processes.

2.3 Data inventory and assumptions

2.3.1 Biotrickling filters

Emission data for the biotrickling filters were taken from recent studies and literature (Table 1). We constructed a mass balance to calculate all related changes in flows and compositions. For both types of biotrickling filters an NH_3 removal efficiency of 70% was applied as this is the average removal efficiency that is found in practice (Melse and Ogink, 2005).

During the nitrification step, a relatively small amount of N_2O is supposed to be produced. Based on previous studies (Melse et al., 2011; Melse et al., 2012a) it was assumed that 0.50% of the NH_3-N entering the filter was converted to N_2O-N. We assumed that the N in the discharge water existed of 50% NH_4-N and 50% NO_3^--N + NO_2-N, representing a liquid ammonium nitrate fertilizer.

During the denitrification step, a considerably larger amount is supposed to be produced. In the above mentioned studies (Melse et al., 2012c, 2012d; Mosquera et al., 2012; Melse and Mosquera, 2013) it was found that for three biotrickling filter systems that were investigated the N_2O production amounted to 17%, 24%, and 65% of the NH_3-N entering the filter, at a NH_3 removal efficiency of 85%, 86%, and 71%, respectively. As a baseline we applied the middle value of 24% of NH_3-N to be converted to N_2O-N. We assumed N_2O-N and NH_3-N emissions in the storage system to be negligible.

Electricity consumption was 14.6 kWh or 53 MJ per kg NH_3-N removed for both systems (based on KWIN, 2012) and was included in the analysis.

Table 1. Applied nitrogen emission factors and energy use during air treatment and field application of discharged water; BF = biotrickling filter, '-' = not included

Life cycle stage	NH_3-N	N_2O-N	N_2-N	NO-N	NO_3^--N	Energy (MJ/FU)
BF, nitrification only	30% of NH_3-in	0.50% of NH_3-in	0	-	-	53
BF, nitrification + denitrification	30% of NH_3-in	24% of NH_3-in	32% of NH_3-in	-	-	53
Field application of discharge water	6.04% of N applied[a]	0.45% of N applied[b]	-	0.55% of N applied	14% of N applied[c]	5.6[d]
Avoided mineral fertilizer application[f]	2.5% of N applied	1% of N applied	-	0.55% of N applied	14% of N applied[c]	2.3[d]

[a] Adjusted according to Groenestein et al. (2012) and Huijsmans and Hol (2010) in De Vries et al. (2012a); related to the dewatered liquid fraction: 19% NH_3 from injected manure in grassland x 0.3182 = 6.04% of the applied N.
[b] Adjusted according to Velthof and Mosquera (2010) and Velthof and Hummelink (2011) in De Vries et al. (2012a); related to the dewatered liquid fraction: 0.3% N_2O from injected manure in grassland x 1.5 = 0.45% of the applied N.
[c] Based on Dekker et al. (2009).
[d] Based onEcoinventCentre (2007). Assuming 170 kg N application per ha from animal manure or discharge water.
[e] FU = functional unit, i.e. kg NH_3-N removed.
[f] As mineral fertilizer calcium ammonium nitrate (CAN) is assumed.
[g] 1 kWh = 3600 kJ.

Fresh water use for the biotrickling filters with nitrification and including denitrification was 535 and 287 kg per kg NH_3-N removed, respectively, as a results of water discharge and humidification of the air. The water use for humidification was based on the assumption that the relative humidity of the ventilation air (inlet air temperature = 20°C) increased from 60% to 100% (outlet air temperature = 15°C).

Furthermore, the main materials used for the filters include high density polyethylene (HDPE). According to several manufacturers on average 2.6 tons of HDPE is used for a standard biotrickling filter unit with a treatment capacity of 45,000 m^3 per hour. Converting this to the FU and assuming a depreciation rate of 10 years this leads to 0.09 kg of HDPE per kg of NH_3-N removed. We included the environmental impact of producing the HDPE in the analysis based on data from the Ecoinvent database (EcoinventCentre, 2007).

2.3.2 Transport and field application

Transport distances of the discharge water and mineral fertilizer were assumed equal in both situations, i.e. 31 km and 150 km, respectively (De Vries et al., 2012a). Transport occurred by lorry; for the discharged water a lorry a 32-ton lorry and for the mineral fertilizer a 16-32 ton lorry was used. Data were taken from the Ecoinvent database (EcoinventCentre, 2007).

In practice, field application of the discharged water of biotrickling filters occurs on grassland as well as on arable land (e.g. as fertilizer for potatoes). In our assessment we assumed injection into the soil on grassland for comparing both biotrickling filters. Emissions of N_2O and NH_3 during field application were assumed to be similar to emissions from dewatered liquid fraction produced by separation of manure (De Vries et al., 2012a). We assumed the application of N from discharge water to substitute mineral N fertilizer. The marginal source for mineral fertilizer was calcium ammonium nitrate (CAN). The nitrogen fertilizer replacement value (NFRV) of the N in the discharge water was assumed to be 90% compared to mineral fertilizer (Versluis et al., 2005).

2.4 Sensitivity analysis

A sensitivity analysis was done to obtain insight in the effect of assumptions and uncertainty on the final results and conclusions. We selected three parameters for testing: NFRV of the discharge water applied to the field, including environmental consequences for producing a substitute for cattle feed for the molasses used in denitrification, and the effect of varying N_2O emission during the denitrification step.

2.4.1 NFRV

The nitrogen fertilizer replacement value of the discharge water is mainly important for the amount of fertilizer replaced and depends on various factors, including weather conditions, crop uptake, and soil type (Schröder, 2005). We assumed that the N in the discharge water could be as effective as mineral fertilizer so the NFRV was put at 100% instead of 90% in the baseline situation.

2.4.2 Including consequences of using molasses

In the baseline results the environmental consequences of using molasses were excluded. Molasses results from the sugar processing industry and is normally used for cattle feed purposes as an energy component (Vellinga et al., 2009). Using the molasses for the biotrickling filter, therefore, requires a substitute for cattle feed. The marginal source for carbohydrate in animal fodder was earlier indicated to be spring barley (Weidema, 2003). Therefore, in the sensitivity analysis we include the environmental impact of producing spring barley for replacing molasses based on the carbohydrate value of molasses and barley. We calculated that 7 kg of molasses requires 5.5 kg of barley based on an energy value of 772 VEM (Dutch energy value, *voeder eenheid melk*) for molasses and 975 VEM for barley (CVB, 2010). The environmental impact data for barley production were taken from De Vries et al, (2012b). This included CO_2 emission from land use change (LUC) based on the same assumptions, i.e. the expansion of land as a result of producing additional barley.

2.4.3 N_2O emission from denitrification

In the above mentioned studies it was found that the fraction of the NH_3-N entering the biotrickling which is eventually converted to N_2O-N during denitrification, largely varies between the scrubber systems that were investigated. We applied a range for N_2O production from 13 - 52% of the NH_3-N inlet to show the effect on the final results and comparison between filter types.

3 Results and discussion

3.1 Comparison of biotrickling filter with or without denitrification

Table 2 presents the baseline results of the analysis for both biotrickling filters. Results show that the greenhouse gas emissions are considerably higher when the denitrification step is included, as compared to a system without denitrification (172 vs. 8.41 kg CO_2-eq per kg NH_3-N removed, respectively).

Nitrate leaching was slightly higher in the scenario with nitrification only. More N was retained in the discharge water and subsequently applied to the field. For the discharge water a NFRV of 90% was assumed (compared to 100% for CAN) meaning that the avoided CAN and NO_3^- from CAN was slightly lower leading to a net increase of NO_3^-. The higher N concentration in the discharge water also explained the higher emissions of NH_3 and GHGs during field application and higher amount of avoided mineral fertilizer. Furthermore, emissions for transport were higher also in the scenario with nitrification only, as more discharge water and thus weight was transported. NH_3 emission and fossil fuel depletion for the biotrickling filter were equal, as the same removal efficiencies and energy consumption figures were used.

3.2 Sensitivity analysis

Results from the sensitivity analysis (Table 3) showed that increasing the NFRV of the discharge water reduced the environmental impacts in the case of nitrification only compared to the baseline results. This was because more mineral fertilizer was avoided. In the case of nitrification with denitrification, no considerable change was found compared to the baseline results. This is because less N (only 0.18 kg) is retained in the discharge water compared to water from the nitrification unit only (0.89 kg of N, figure 1).

Furthermore, including the environmental impact of producing barley as substitute for the molasses used for denitrification increased the environmental impact compared to the baseline results. This was related to the emissions that are associated with the production of the barley. This illustrates that the inclusion of such consequences may have an important effect on the final results and should be taken into account in LCA studies.

Reducing and increasing the N_2O emission from the denitrification step considerably affected GHG emissions (up to a factor of 2.1). NO_3^- leaching varied between -0.01 and 0.02 kg and fossil fuel depletion varied between 3.95 and 4.63 kg oil-eq mainly as a result from changed N application and less or more avoided mineral fertilizer production and application.

Although the sensitivity analysis showed that the calculated values of the environmental impacts may vary depending on the input parameters (Table 1), the main observations with regard to the comparison of nitrification only with nitrification and denitrification (see previous section 3.1) remained unchanged.

Table 2. Results of the environmental impact for biotrickling filters excluding and including denitrification (excluding environmental impact of using molasses)

Environmental impact	Unit/ FU	Biotrickling filter	Transport	Field application of discharge water	Mineral fertilizer application and production	Total (sum of preceding columns)[b]
Nitrification only						
GHGs[a] emission	kg CO_2-eq	16.6	0.99	3.27	-12.4	8.41
NH_3 emission	kg NH_3	0.52	0	0.07	-0.04	0.57
NO_3^- leaching	kg NO_3^-	0	0	0.62	-0.57	0.05
Fossil fuel depletion	kg oil-eq[c]	4.26	0.38	0.14	-1.18	3.60
Nitrification + denitrification						
GHGs emission	kg CO_2-eq	174	0.20	0.66	-2.45	172
NH_3 emission	kg NH_3	0.52	0	0.01	-0.01	0.54
NO_3^- leaching	kg NO_3^-	0	0	0.12	-0.11	0.01
Fossil fuel depletion	kg oil-eq	4.26	0.08	0.03	-0.22	4.14

[a] GHGs = greenhouse gases. FU = functional unit (kg NH_3-N removed).
[b] Totals do not always correspond to the sum of rows due to rounding.
[c] 1 kg oil-eq = 42 MJ.

Table 3. Results of the sensitivity analysis compared to the baseline results (see Table 2)

		Baseline results		NFRV of discharge water = 100% instead of 90%		Substituting molasses with barley	N_2O emission (instead of 13% of NH_3-N emitted as N_2O)	
		Nitrification only	Nitrification+ denitrification	Nitrification only	Nitrification+ denitrification	Nitrification+ denitrification	Nitrification+denitrification;	
Impact category	Unit/ FU						13% of NH_3-N as N_2O	52% of NH_3-N as N_2O
GHGs[a]	kg CO_2-eq	8.41	172	7.02	172	197	97.1	363
NH_3 emission	kg NH_3	0.57	0.54	0.56	0.53	0.54	0.54	0.52
NO_3^- leaching	kg NO_3^-	0.05	0.01	-0.01	0.00	0.08	0.02	-0.01
Fossil fuel depletion	kg oil-eq	3.60	4.14	3.47	4.12	6.36	3.95	4.63

[a] GHGs = greenhouse gases, FU = functional unit (kg NH_3-N removed), NFRV = nitrogen fertilizer replacement value.

3.3 General Discussion

3.3.1 Shifting of nitrogen emissions

The results of the analysis showed that adding a denitrification step to a nitrifying biotrickling filter increased GHG emissions as a result of increased N_2O emissions, but reduced the leaching of NO_3^-. This shows that the inclusion of a denitrification step results in the swapping of N compounds from NO_3^- leaching to N_2O emission meaning that one compound may be avoided, but another can be emitted. This underlines the essence of a holistic assessment including all environmental consequences. It also highlights that tactical decisions have to be made regarding to which type of pollution should be prevented most when implementing air scrubbers or other NH_3 abatement technologies, for example by weighting of environmental impacts (Goedkoop et al. (2009)). This weighting will depend on the local circumstances to which it applies, such as Natura 2000 areas or the intensity of NO_3^- leaching in the area, but also on the system borders that are considered (e.g. global or national). Weighting can be applied as an additional step in the life cycle impact assessment phase but is not taken into account in this study.

Besides the biotrickling filters that were evaluated in this study, other technologies for treatment of animal exhaust air are available. In fact, in most cases not a biotrickling filter but an acid scrubber ('chemical scrubber') is applied (90% of the cases). It would, therefore, be of great interest to extend this LCA to acid scrubbers and to assess other types of NH_3 abatement techniques. This could provide insight into the extent to which NH_3 mitigation techniques lead to increased environmental impacts in other categories or other processes in the system.

An environmental impact that may be important with regard to air scrubbers or biotrickling filters involves the use of fresh water. The biotrickling filter with nitrification only has a higher water use than the biotrickling filter with nitrification and denitrification, 540 and 290 liter per kg NH_3-removed, respectively. On the one hand, this aspect may play a role when the application of biotrickling filters is considered in areas where water is a scarce resource. On the other hand, the higher amount of discharge water for the biotrickling filter with nitrification only can be used for crop production purposes limiting the need of irrigation water.

Another impact not considered is the reduction on particulate matter emission by application of biotrickling filters. Such impact reductions may be of considerable relevance for human health issues near livestock facilities and require further investigation.

3.3.2 Sensitivity of the results

The sensitivity analysis highlighted the effect of changing several important parameters on the results and comparison of the biotrickling filter systems. Other sources of uncertainty, not considered here, can include the type of housing system, feeding regime of animals, and field application strategies. Although these sources will have an effect on the calculated total environmental impact, they are not expected to affect the comparison between the scrubbers with and without denitrification.

Including barley as a substitute for the molasses used in denitrification increased the environmental impact. This included land-use-change (LUC) emissions. LUC emission, however, are highly uncertain and may have a strong effect on the end results (De Vries et al., 2012b). Here, however, the contribution of LUC was very small (17 kg CO_2-eq) and did not cause a change in the comparison of the filters. Changing dairy cattle feed from molasses to barley might also affect the enteric methane production and emission; higher methane production will increase GHG emissions (Van Zanten et al., 2013). However, no change in the results of the comparison of the filters is expected because of the relatively small change in this study.

4 Conclusions and recommendations

The aim of this study was to assess and compare environmental impacts of a biotrickling filter with nitrification only and a biotrickling filter with a combination of nitrification and denitrification.

We conclude that the biotrickling filter with combined nitrification and denitrification results in a higher emission of greenhouse gases than biotrickling filter with nitrification only, when the whole life cycle is considered; this is mainly due to the emission of N_2O from the denitrification process. The use of biotrickling filters with nitrification only, resulted in a higher emission of ammonia and leaching of nitrate from field application of discharge water. The total ammonia emission, however, remained unchanged. Although the sensitivity analysis showed varying environmental impacts when changing important parameters, the main observations with regard to the comparison of nitrification only with nitrification + denitrification remained unchanged

It is recommended to compare the environmental performance of biotrickling filters to acid scrubbers, as these are the most commonly used scrubbers for ammonia abatement at livestock housing systems.

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