Sustainable intensive livestock production demands manure and exhaust air treatment technologies

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ABSTRACT

Intensive livestock production is connected with a number of environmental effects, including discharges to soils and surface waters and emissions to the atmosphere. In areas with a high livestock density the low availability of nearby arable land, together with the preferred use of chemical fertilizer by arable farmers, results in high off-farm disposal costs for manure. Furthermore, ammonia abatement technologies, such as treatment of exhaust air, are important as ammonia emissions may account up to a quarter of the total nitrogen flux.

Firstly, the paper describes and discusses the development of manure treatment in the Netherlands since the 1970’s. Manure treatment processes that result in products that compete with and replace the use of chemical fertilizers can (partly) close the nutrient cycle again. From this point of view aerobic treatment of manure (nitrification/denitrification) can not be considered sustainable as nitrogen is taken out of the cycle at high environmental costs.

Secondly, the state-of-the-art of techniques for treatment of exhaust air is presented. Besides ammonia, application of air treatment may also reduce environmental emissions of odour and particulate matter (dust).

Both manure treatment and treatment of exhaust air are considered essential for sustainable livestock operations in areas with a high livestock density.

1. Introduction

Intensive livestock production contributes substantially to the economies of many European countries in terms of employment and export of products. Pig production in Europe is concentrated in several regions characterised by large-scale intensive farms. Main pig producing areas can be found in the north (Denmark, the Netherlands, Belgium, Brittany in France, Niedersachsen in Germany) and in the south (Lombardy in Italy, Cataluña and Galicia in Spain) (EC, 2003). Intensive livestock production is connected with a number of environmental effects which include discharges to soils and surface waters (e.g., nitrogen, phosphorus, and heavy metals) and emissions to the atmosphere. High levels of nitrogen and phosphorus in soil and surface waters may lead to eutrophication which involves excessive algal growth and can lead to potential adverse effects on biodiversity or human uses of waters (Heij and Erisman, 1995, 1997).

The Netherlands, with 16 million inhabitants and a population density of almost 400 inhabitants per km², houses 11 million pigs and 93 million chickens at approximately 10,000 and 3000 farms, respectively, as per 2005 (CBS, 2007). The livestock operations are characterised by large-scale intensive farms which are mainly concentrated in the eastern and southern part of the country where opportunities for arable farming are limited by poor, sandy soils. The increased risk of excess land application of these minerals led to a surplus of manure in some regions and led to national and European Union (EU) legislation that restricts the maximum application of animal manure per hectare. As a result, livestock farmers in these regions experience high off-farm manure disposal costs which consist of sampling and analysis of the manure, transportation, land application, and, in some regions, an acceptance bonus for the landowner.

Besides being a producer of animal manure, livestock farming is an important emitter of airborne pollutants. These pollutants include in particular ammonia, odour and non-CO2 greenhouse gases (methane (CH₄) and nitrous oxide (N₂O)). The risks of ammonia emissions relate to acidification of soils and waters and high levels of nitrates found in drinking waters. The emission of greenhouse gases is related to global warming which means that global temperatures might rise as a result of increasing atmospheric concentrations of certain gases (UNFCCC, 1992, 1997; IPCC, 2001). In recent years, odour emissions from animal housing and land application of manure are being increasingly considered a nuisance in densely populated countries as the scale of livestock operations...
expands and an increasing number of rural residential developments are built in traditional farming areas (EC, 2003).

In order to reduce the mineral surpluses associated with intensive livestock farming in regions with limited availability of nearby arable land, manure treatment technologies have been developed and are still being developed. But besides the abatement of mineral surpluses by manure treatment, it may also be important to take into account the abatement of gaseous nitrogen emissions.

In Table 1 the production of nitrogen as urine and faeces is substantial, i.e., the excretion, by growing-finishing pigs is divided into the part that ends up in the liquid manure that is removed from the farm after storage and the part that is emitted to the atmosphere as ammonia, either from the outside manure storage tanks or by means of the ventilation air of the pig house. Table 1 shows that a significant amount of all nitrogen that is excreted (one quarter) is emitted as ammonia with the exhaust air and three quarters end up in the liquid manure storage. Because 1/4 of all nitrogen is emitted to the atmosphere it can be concluded that abatement technologies for ammonia emissions from animal houses, e.g., by end-of-pipe treatment of exhaust air, are of major importance when we are trying to close nitrogen nutrient cycles in sustainable livestock farming. Furthermore, besides ammonia reduction treatment of exhaust air is also a means of reducing other environmental impacts of livestock production, such as emission reduction of odour and particulate matter (dust).

Considering the foregoing, in our opinion both manure treatment and treatment of exhaust air are essential when we try to realize sustainable livestock operations in areas with a high livestock density. The first aim of this paper is to describe the experiences we have gathered in the Netherlands with regard to manure treatment since the 1970's, evaluate them and draw some conclusions. The second aim of this paper is to present the state-of-the-art of techniques for treatment of exhaust air, as they are currently applied in the Netherlands and several other European countries.

2. Manure treatment

2.1. General

The aim of manure treatment is usually to reduce mineral surpluses at acceptable financial costs, the latter meaning that manure treatment usually has to compete with transportation of the manure to another region, followed by land application. The two main principles of manure treatment techniques are usually (Melse and Verdoes, 2005):

1. Reduction of transportation costs of liquid manure by volume reduction. Usually one or more components (e.g., phosphorus and dry matter) are accumulated in only a fraction of the original volume. The small fraction can be transported for relatively low costs to another region where it is used for fertilization and the large fraction is applied to nearby arable land.

2. Make manure products that can compete with (base materials for) chemical fertilizer and with untreated manure by adjusting its properties. The formulation (concentration and ratio of nitrogen (N), phosphorus (P), and potassium (K)), texture (solid/liquid/dry matter content) according to the needs of arable farmers.

In the Netherlands manure treatment has been taking place since the 1970's when for the first time measures were gradually introduced to limit the loss of minerals into the environment. Since then, the limiting measures taken by the government have been steadily tightened up and the amount of work in research and development of manure treatment technologies has simultaneously increased. However, the attention on manure treatment is strongly influenced by the disposal costs of untreated manure. Through the years these costs have been shown to be volatile and difficult to predict, being dependent on weather conditions, changes in manure policy, acceptance by crop farmers, and availability of manure (supply-demand).

At present, the driving forces for manure treatment initiatives in the Netherlands can be summarized as:


2. Subsidy on renewable energy (biogas/incineration), which includes energy generated from manure.

3. High off-farm disposal costs for untreated manure: up to EUR 20–30/metric tonne

4. Farm expansion: farmers get a discount of 50% on manure production rights at extending their farm if all manure is processed to products sold outside Dutch agriculture (e.g., export, incineration).

In 2004 a 'quick scan' was performed of available and promising manure treatment techniques for the Netherlands (Melse et al., 2004). In the next few sections some case studies are described of systems that have proven to be successful (case study 1 and 2) or that we believe are promising for the future (case study 3).

2.2. Case study 1: central nitrification/denitrification plant for veal-calf manure

Four large-scale aerobic treatment plants with a nitrification/denitrification process for veal calf slurry have been in operation since 1976 at four locations in the Netherlands (Elspeet, Stroe, Ede, and Putten). The combined treatment capacity of these plants is 660,000 m³ of slurry per year which are operated by the foundation "Mestverwerking Gelderland" (Burton and Turner, 2003; Willers et al., 1993, 1996).

The continuously running systems comprise of three concentric compartments: the outer ring (volume: 2900 m³; liquid surface area: 531 m²) is aerated continuously, whereas the inner ring (volume: 1400 m³; liquid surface area: 261 m²) is not aerated but...
mixed continuously by two mechanical mixers. The central part is a clarifier. In the outer ring nitrification takes place under aerobic conditions, i.e. ammonia is converted to nitrite (NO₂⁻) and nitrate (NO₃⁻) and organic material is converted mainly to carbon dioxide (CO₂), heat and water. Also some lime is added for phosphate removal. In the inner ring denitrification takes place under anoxic conditions, i.e., nitrate is converted mainly to dinitrogen gas (N₂). Fresh slurry is pumped continuously into the denitrification compartment, providing the necessary carbon source for the denitrification process, and next enters the nitrification compartment. A large amount of slurry is recirculated and is led back to the denitrification compartment. Finally, in the clarifier sludge and effluent are separated by gravity (Willers et al., 1996).

The resulting product of the process is a sludge that has about 15% of the original slurry volume and an effluent (about 85% of the original slurry volume) that is discharged into the municipal sewer system. Typical removal efficiencies of the systems are 95% for COD, 99% for BOD₅, 94% for TKN, 97% for NH₄-N, and 95% for P resulting in these effluent concentrations: COD = 0.7 g/L, BOD₅ = 0.1 g/L, TKN = 0.02 g/L, NH₄-N = 0.002 g/L and P = 0.02 g/L (Willers et al., 1996).

Nitrification and denitrification of animal manure might result in the production of nitrous oxide (N₂O) (Burton et al., 1993; Melse and Verdoes, 2005; Osada et al., 1995) which is an undesirable by-product as nitrous oxide is a potent greenhouse gas. For the continuous system described above it was found that the ammonia emission was 0.1–0.2% and the nitrous oxide emission was 9% of the total Kjeldahl nitrogen content of the fresh slurry (Willers et al., 1996).

Currently farmers have to pay EUR 9.50/tonne for treatment (excluding transport of slurry to treatment facility), which includes sewer discharge levy of EUR 0.50/tonne.

### 2.3. Case study 2: farm-scale biogas plant

In the Netherlands about 100 farm-scale biogas plants are currently in operation. An example of such a farm is the experimental pig farm in Stekkel, the Netherlands, where a farm-scale biogas plant has been in operation since 2002. The biogas plant is used both for research purposes and for capital gains (Timmerman and Claessen, 2005). The biogas plant has been expanded in 2006 and is operated mesophytically (at 40°C). The current plant consists of storage facilities for manure and co-substrates, mixing tanks, two vertical stainless steel CSTR (continuous stirred tank reactors) digesters (volume: 1310 m³ and 620 m³) with integrated gas storage, biogas scrubber for removal of hydrogen sulphide (H₂S) and a combined heat and power (CHP) unit consisting of a 330 kWe gas engine and a 60 kWe micro-gasturbine.

In the biogas plant a mixture of sow and growing-finishing pig manure is co-digested with organic products such as energy crops and by-products from the food processing industry. The slurry from the pigs is removed periodically from the houses through a sewage system to the storage tanks. The co-substrates are all off-farm material which are delivered by truck. Both digesters are automatically fed with a mixture of manure and co-substrates several times a day. The manure that enters the digesters is relatively fresh (on average 3 weeks old) due to the use of the sewage system in the houses.

The digestate is pumped to two manure storage bags and later on trucked to arable land in other parts of the Netherlands. The produced electricity is used in the pig farm and the surplus is sold to an energy company. Part of the produced heat is used to keep the digester temperature at 40°C and for heating of the animal houses and offices. Currently a research project is underway that aims to use the surplus heat for treatment of the digestate. Table 2 gives an overview of the results of the biogas plant in 2007.

### Table 2: Operational parameters of farm-scale co-digester plant in Stekkel, Netherlands, for the year 2007 (Timmerman and Claessen, 2005)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment capacity</td>
<td>9471 tonne/year (46% manure and 40% co-substrates)²</td>
</tr>
<tr>
<td>Dry matter loading rate</td>
<td>3.3 kg dry matter/m³ digester/day</td>
</tr>
<tr>
<td>Average retention time in digester tanks</td>
<td>65 days</td>
</tr>
<tr>
<td>Biogas production</td>
<td>1,297,630 m³/year or 860 m³/digester/m³</td>
</tr>
<tr>
<td>Average methane content</td>
<td>54%</td>
</tr>
<tr>
<td>Running hours</td>
<td>8397 (96% of the time)</td>
</tr>
<tr>
<td>Full load hours</td>
<td>7130 (81% of the time)</td>
</tr>
<tr>
<td>Electricity production</td>
<td>2353 MWh</td>
</tr>
</tbody>
</table>

² Average manure DM and VS content is about 75 and 58 g/kg, respectively; about 38% of the manure VS is degraded (Timmerman et al., 2005). DM content of co-substrates varies from 13 to 89%.

The main operational problem that are encountered are: excessive foaming in the digesters, failure of equipment, and contamination of manure and co-substrates with rocks, plastic and ear tags. The latter causes problems with the pumping and mechanical mixing equipment.

The total revenue for the sold 'green' electricity that has been produced from biogas, i.e., the sum of governmental subsidy and market value, was about EUR 0.158 per kWh in 2007. Several studies have been done after the economic perspectives of on-farm biogas plants, e.g. Timmerman et al., 2005. The direct costs for purchase of co-products, disposal costs for the extra slurry (digestate) produced and maintenance cost for the CHP was about EUR 0.085 per kWh.

It is expected that only a few new biogas plant will be built on farms in the Netherlands because of a decrease in the governmental subsidy for electricity produced from biogas.

### 2.4. Case study 3: central incineration plant for poultry manure

In August 2006 the construction of a central incineration plant for poultry manure was started in Moerdijk, the Netherlands (BMC Moerdijk BV). The plant aims to produce electricity and fly ash. March 2008 the first tests with incineration of poultry manure were commenced and late 2008 the plant was in semi full-scale operation. It took a period of more than 10 years between the feasibility study and final realization of the power plant, partly due to the legal procedures that needed to be followed, appeals that were lodged etc. before all required allowances could be obtained. The plant has a capacity of about 440,000 tonnes of stackable poultry manure (around 60% DM) per year.

The different freights of poultry manure are mixed and then transported to the dosing tank of the incinerator. The incinerator is a fluidised bed boiler. The steam of the boiler is used to drive a steam turbine with a generator of 36.5 MWe. The generated 'green' electricity is sold to the national electricity grid. The flue gases are purified before they are released to the atmosphere. The fly ashes are used by the fertilizer industry as a base material for the production of fertilizers.

A cooperative association of poultry farmers (DEP) is responsible for the delivery of poultry manure to the incineration plant. The DEP currently has 616 members which have signed 10-year delivery contracts for over 340,000 tonnes of poultry manure; these farmers pay a price of currently EUR 17.5 per tonne of manure, including transport costs. DEP is also one of the four shareholders of BMC Moerdijk BV.

The average dry matter content of the delivered poultry manure was around 57% in 2008. The main operational problem that was encountered in 2008 was the great difference in calorific values or energy densities between truck loads of poultry manure. The net
caloric value of the poultry manure needs to be between 6 and 10 MJ per kilogram with an average value of 7.9 MJ/kg for stable operation of the incineration furnace. Average net caloric values in the manure were: broilers 7.7 MJ/kg, turkeys 7.5 MJ/kg, rearing chickens 8.1 MJ/kg, breeders 6.3 MJ/kg, and laying hens 5.8 MJ/kg. Most extreme values (by exception) were 2 MJ/kg and 17 MJ/kg. Due to the lower net caloric value of the poultry manure, especially from broiler breeders and laying hens, the returns of the incineration plant is lower than expected. Therefore BIC Moerdijk BV is in the process of improving the manure quality in conjunction with farmers and feed companies (Weemen, 2009).

3. Discussion

In the Netherlands we have a long history of development and application of manure treatment techniques. However, many techniques that were developed never made it to successful long-term application on a full-scale basis, being either farm scale or centralized processing. We will try to explain why many treatment technologies were not successful on the long term.

3.1. Centralized processing

An important and expensive learning experience was the case of a centralized liquid pig manure treatment facility that was built in Helmond, the Netherlands in the late 1990’s, called “Promit”. The unit operations included anaerobic digestion, mechanical separation, stripping, nitricification, ultra-filtration, reverse osmosis, evaporation/condensation and also included air cleaning. The products were a granular fertilizer and clean water that could be discharged to the sewer system or to surface water. The process was tested since 1988 in a facility with a treatment capacity of 100,000 tonnes/year and was scaled up to a capacity of 600,000 tonnes/year in 1993. The investment costs were about EUR 60 million and the processing costs were about EUR 25 per tonne liquid manure. Medio 1995 the facility was closed down due to bankruptcy without ever having run on full capacity. Besides this facility another five large-scale manure treatment initiatives (Melmon, Scarabee Vefinex, Ferm-O-Feed, Mestverwerking Geklolland) were realized between 1985 and 1995 (Feyaerts et al., 2002).

With the exception of the last one (which has been discussed in Section 2.2, Case study 1) these large-scale initiatives failed, despite the enormous amounts of time and money invested. There were various reasons for these large-scale failures, such as an excessively high processing price in relation to competing options such as transport to another area followed by land application (the animal farmers were not under obligation to deliver their manure to the facility); problems with the choice of location and licences, and uncertainty with regard to the market prospects for the end product (Anon., 1998).

Furthermore, in 1995 the EU prohibited the continuation of subsidies for large-scale manure processing and long-distance transportation. These negative developments gave rise to a climate of considerable scepticism concerning central manure processing, and in the pig farming sector, in particular, people started to look for solutions to the manure problem at farm level (Anon., 1998).

3.2. Farm scale processing

Since 1995 the attention moved from centralized to farm-scale manure treatment technologies. Four examples of techniques that were realized on farm scale are described by Melse and Verdoes, 2005. However, many farm scale applications (including the ones described by Melse and Verdoes) were closed down after some time due to one or several of the following reasons:

- Production capacity of nutrient concentrates for replacement of fertilizers was too small on farm scale. In order to be able to compete on the fertilizer market much higher product amounts are necessary. Furthermore, because landowners are used to receive a bonus for application of untreated manure, it is difficult to convince them to pay for manure products (e.g., nutrient concentrates) anyway.
- Technology was sometimes too complex for day-to-day operation by the farmer alone (maintenance and trouble shooting efforts).
- After having invested in a manure treatment facility, prices for transport followed by land application of untreated manure dropped and became lower than manure processing costs. Therefore manure processing was terminated on these farms.

3.3. Lessons learned

As a summary, the following conclusions can be enumerated:

1. Manure processing that focuses on replacement of chemical fertilizers by production of liquid or granular concentrates requires complex combinations of technologies. More simple treatment techniques, e.g., mechanical separation, will not result in products that have the value that arable farmers associate with chemical fertilizer. Because of the technical complexity of the treatment processes (need for professional operators and maintenance services in order to guarantee product quality) and the need of large manure product volumes for successful marketing, this is only possible with large-scale treatment facilities, implying centralized manure processing plants. This does not rule out the possibility, however, that in some individual cases a close cooperation between animal farmer and end user of the manure products may result in successful manure treatment on farm-scale, in this way bypassing the chemical fertilizer market.

2. Centralized manure processing requires long-term contracts on delivery of manure and sales or export of the end products. Only then the return on investment can be guaranteed.

3. Technologies for manure processing are abundantly available and documented. However, documentation is often available as ‘grey’ literature and often in other languages than English.

4. At least for European conditions, manure policy and legislation is of major importance for the success or failure of manure treatment systems. Legislation on acceptable land application levels for nitrogen accepts higher levels for application of chemical fertilizer than for animal manure or its products. If manure products (e.g., nutrient concentrates) would be legally considered as equivalent to chemical fertilizer this would greatly enhance the market potential of manure products as chemical fertilizer replacements.

Table 3

<table>
<thead>
<tr>
<th>Type of Manure</th>
<th>Installed capacity (m³/h)</th>
<th>Number of farms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acid scrubbers</td>
<td>64 million</td>
<td>790</td>
</tr>
<tr>
<td>Biogas digesters</td>
<td>14 million</td>
<td>90</td>
</tr>
<tr>
<td>Total</td>
<td>79 million</td>
<td>880</td>
</tr>
<tr>
<td>Pig</td>
<td>70 million²</td>
<td>850</td>
</tr>
<tr>
<td>Poultry</td>
<td>3 million³</td>
<td>30</td>
</tr>
<tr>
<td>Total</td>
<td>73 million</td>
<td>880</td>
</tr>
</tbody>
</table>

¹ This equals 10% of the exhaust air of all pig farms nationwide.
² This equals 0.4% of the exhaust air of all poultry farms nationwide.
4. Air treatment

4.1. Ammonia scrubbers

Since the 1990’s, packed-bed air scrubbers have been implemented on intensive livestock operations in the Netherlands mainly to minimize ammonia emissions for the protection of nearby located sensitive ecosystems. Two types of scrubbers have been generally applied: (1) acid scrubbers, (2) bio-scrubbers or biotrckling filters. They are mainly applied in mechanically ventilated pig housings with central ventilation ducts; only in a few cases they are applied in poultry houses because of the high dust content of the ventilation air which increases the risks of blockage of the packing bed causing high pressure drop and thus increased energy use.

Acid scrubbers are based on the entrainment of ammonia in acid liquid that is recirculated over a packed-bed and the frequent discharge of the resulting ammonium salt solution at a concentration of about 150 g/L. Usually sulphuric acid is applied and pH is kept between 2 and pH 4. Melse and Ogink (2005) reported average ammonia removal efficiencies of 96% for farm-scale operated acid scrubbers. Reported average removal efficiency for odour was only 31% and showed a large variation. In bio-scrubbers, or biotrckling filters, bacteria convert ammonia into nitrite and nitrate. Nitrogen concentrations in the water are kept below inhibiting levels by regular discharge of the recirculation liquid. The biomass is partly attached to the packed-bed and partly suspended in the recirculation liquid. As compared to chemical scrubbers the discharge volume of biotrckling filters is about 8–10 times higher. Average ammonia removal efficiency at farm operations amounted 70%, whereas for biotrckling filters is about 8–10 times higher. Average ammonia liquid. As compared to chemical scrubbers the discharge volume of the recirculation liquid. The biomass is partly attached to the packed-bed and partly suspended in the recirculation liquid. As compared to chemical scrubbers the discharge volume of biotrckling filters has a higher odour removal potential than acid scrubbers because a wide array of odour components dissolved in the circulation water are broken down by the biomass, whereas in chemical scrubbers only part of the odour components are kept in solution due to a low pH. A disadvantage of bio-scrubbers is that part of the nitrogen might be converted to nitrous oxide (Trimborn, 2006) which is a potent greenhouse gas.

In several European countries (Germany, Denmark, Netherlands) ammonia scrubbers are considered off-the-shelf techniques for effective removal of ammonia from exhaust air from pig houses and, to less extent, for poultry houses and odour removal. In Table 3 the market size of air scrubbers is shown for livestock operations in the Netherlands as per January 1st 2008.

4.2. Multi-pollutant scrubbers

As the scale of livestock operations expands and an increasing number of rural residential developments are built in traditional farming areas reducing odour nuisance and particulate matter (PM10 and PM2.5) emission is of increasing importance. For odour, usually local or national legislation exists. For particulate matter, air quality regulations from the World Health Organization and European Union impose limits on PM10 and PM2.5 emissions on all major sources, including farms, to keep PM concentration in ambient air below critical standards to protect human health (EC, 1999, 2005; WHO, 2006). In the Netherlands, approximately 20% of the primary PM10 production is estimated to originate from poultry and pig operations (Chardon and van der Hoek, 2002); furthermore, it is known that ammonia is a precursor of secondary particulates.

Currently, a new generation of scrubbers is being developed for livestock operations that, besides ammonia, also addresses odour and particulate matter emission abatement. These so-called multi-pollutant scrubbers usually consist of two or more scrubbing stages, each stage aims for the removal of one type of compounds. The first prototypes of multi-pollutant scrubbers for pig farms, combining the concepts of acid scrubbing, bio-scrubbing, water-curtains, and biofiltration have been tested in Germany (Arends et al., 2008) and the Netherlands (Aarnink et al., 2007, 2009a, b) and are in operation now at a limited number of farms.

Recently, an innovation and implementation program has been set up by the Dutch national government that aims to stimulate the development and introduction of multi-pollutant air scrubbers. The program includes farm-scale research on five pilot locations where experimental multi-pollutant scrubber are tested during a three-year period. In Table 4 the operational parameters and in Table 5 the preliminary results of the measurement program on these multi-pollutant scrubbers are given.

Future measurements will be carried out in the coming two years in order to get reliable data on long-term performance of ammonia, odour, and particulate matter removal by the multi-pollutant scrubber systems. Based on the results additional research will be formulated in order to improve performance, reliability, and stable operation of the systems. Although the multi-pollutant scrubbers are running at farm-scale size, they are still being considered as experimental systems at present.

Table 4 Operational parameters of experimental multi-pollutant scrubbers that are included in research program.

<table>
<thead>
<tr>
<th>Pilot location</th>
<th>Animal category</th>
<th>Installed ventilation capacity (m³/h)</th>
<th>EBRT (s)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30,000 broilers</td>
<td>75,000</td>
<td>0.43</td>
<td>Biotrickling filter (cross-flow) + denitrification unit</td>
</tr>
<tr>
<td>2</td>
<td>182 farrowing sows + 2640 piglets</td>
<td>81,000</td>
<td>0.29</td>
<td>Acid scrubber + water scrubber (cross-flow)</td>
</tr>
<tr>
<td>3</td>
<td>400 dry and pregnant sows</td>
<td>60,000</td>
<td>1.0</td>
<td>Acid scrubber + water scrubber (cross-flow)</td>
</tr>
<tr>
<td>4</td>
<td>2600 fattening pigs</td>
<td>160,000</td>
<td>1.6</td>
<td>Biotrickling filter (counter-current flow) + denitrification unit</td>
</tr>
<tr>
<td>5</td>
<td>21,000 broilers</td>
<td>180,000</td>
<td>0.12</td>
<td>Acid scrubber + water scrubber (counter-current flow)</td>
</tr>
</tbody>
</table>

4 Average values of 2-h measurements.

b Average values of 24-h measurements.

Table 5 Preliminary results of the measured removal efficiencies for ammonia, odour, and particulate matter (PM) by five farm-scale multi-pollutant scrubbers.

<table>
<thead>
<tr>
<th>Ammonia removal</th>
<th>Odour removal</th>
<th>PM10 removal</th>
<th>PM2.5 removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>5–99% Average: 66%</td>
<td>0–86% Average: 42%</td>
<td>21–90% Average: 50%</td>
<td>28–90% Average: 57%</td>
</tr>
<tr>
<td>n = 28</td>
<td>n = 26</td>
<td>n = 17</td>
<td>n = 9</td>
</tr>
</tbody>
</table>

4 Average values of 24-h measurements.

b Average values of 2-h measurements.

1 PM10 (also called inhalable particles) represents the fraction of particles that have an aerodynamic diameter of 10 μm or less; PM2.5 (also called respirable particles) is used to describe the particles fraction with an aerodynamic diameter of 2.5 μm or less. The aerodynamic diameter is the diameter of a spherical particle having a density of 1 kg/m³ that has the same terminal settling velocity in the gas as the particle of interest.
5. Conclusions and recommendations

An important aspect of sustainable livestock farming is closing nutrient cycles, including the nitrogen cycle. In regions with high animal density and limited availability of arable land not only manure treatment but also air treatment of mechanically ventilated housings is necessary for closing nutrient cycles (e.g., a quarterly refreshment of all nitrogen excreted by pigs is emitted as ammonia). Furthermore, treatment of exhaust air is a means of reducing other environmental impacts of livestock production caused by the emission of ammonia, odour and particulate matter (dust). Therefore both manure treatment and treatment of exhaust air are essential for sustainable livestock operations in areas with a high livestock density.

For manure treatment, we think that research in this field should focus on the production of concentrates that are competitive with chemical fertilizers and can (partly) replace their use. In most cases this implies large-scale processing facilities, in our opinion, because of the complexity of the processes and the need for high product volumes. Furthermore, we think that aerobic treatment of manure (nitrification / denitrification) can not be considered as sustainable, as this process uses a lot of energy, emits nitrous oxide, and finally destroys nitrogen by converting it to a form (dinitrogen gas) that can not be utilized anymore for fertilization of crops.

Technologies for manure processing and ammonia scrubbing technologies are well researched and ready for use in practice. However, costs are high and cost reduction options need to be further investigated. The benefits of scrubber application may be enhanced by development of scrubbers that not only successfully remove ammonia but also reduce environmental impact by achieving high odour and particulate matter removal efficiencies.

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