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Air Treatment Techniques for Abatement of Emissions from Intensive Livestock Production

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Abstract: Intensive livestock production is connected with a number of environmental effects, including emissions of ammonia (NH_3), greenhouse gases (CH_4 and N_2O), odour, and particulate matter (PM10 and PM2.5). Possible strategies for emission reduction include feed management, adaptation of housing design, and, in case of mechanically ventilated animal houses, the application of end-of-pipe air treatment, *viz* acid scrubbers and bioscrubbers. Air treatment techniques can achieve very high emission reductions (up to 100% ammonia removal for acid scrubbers). Furthermore, air treatment offers the possibility to achieve removal of not just one compound but of a combined removal of a variety of pollutants (ammonia, odour and particulate matter) at the same time. The successful application of scrubbers is of increasing importance as intensive livestock operations have to comply with ever stricter regulations and emission limits. Research is needed to address topics such as reduction of costs (both investment and operational costs), improvement of process control to guarantee stable removal efficiencies, decrease of N_2O production in bioscrubbers, and increase of odour removal efficiency.

Keywords: Air treatment, ammonia, NH_3, odour, acid scrubber, bioscrubber, biotrickling filter, livestock production, animal husbandry.

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) [1]. The Netherlands, with 16 million inhabitants and a population density of almost 400 inhabitants per km^2, houses 11 million pigs and 93 million chickens at approximately 10, 000 and 3, 000 farms, respectively, as per 2005 [2]. The livestock operations are mainly concentrated in the eastern and southern part of the country where in the past opportunities for arable farming were limited by poor, sandy soils.

Intensive livestock production is connected with a number of environmental effects, which include emissions to the air, e.g. ammonia, odour, non-CO_2 greenhouse gases (methane (CH_4) and nitrous oxide (N_2O)) and particulate matter, and discharges to soils and surface waters (e.g. nitrogen, phosphorus, and heavy metals)[1]. The risks of ammonia emissions relate to acidification of soils and waters and high levels of nitrates found in drinking waters. High levels of nitrogen and phosphorus in 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 [4, 5]. The emission of greenhouse gases contributes to increasing global atmospheric concentrations of these gases, which global average net effect leads to global warming [6-8]. 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 [1]. Furthermore, the emission of particulate matter from animal houses has received attention since a few years as the inhalation of dust affects human health.

This paper reviews possible approaches for abatement of gaseous emissions from intensive livestock productions. The application of end-of-pipe air treatment systems, which is one of these approaches, is discussed in more detail.

2. APPROACHES FOR EMISSION ABATEMENT

In order to reduce the environmental impacts of livestock production both national and international regulations went into effect that deal with these issues. This has resulted in the development of a large variety of techniques that aim for reduction of the emission from livestock operations.

Generally speaking, three different approaches can be distinguished in order to reduce the emission of gaseous compounds from animal houses to the atmosphere [1]:

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[1] Ammonia emission contributes minimally to odour emission because the odour threshold of ammonia is relatively high, *viz* 5 ppm [3], which is unlikely to be found outside animal houses. Therefore, emission of ammonia and odour are discussed as separate issues.

(1) feed management

(2) adaptation of housing system design, including inside manure storage

(3) end-of-pipe air treatment

2.1. Feed Management

Nitrogen excreted in urine is predominant in the form of urea, which can easily be converted into ammonia and carbon dioxide by the enzyme urease, which is present in faeces, thus resulting in emission of ammonia. Nitrogen excreted in faeces is mainly present as protein, which is less susceptible to decomposition into ammonia.

Feed management, or nutritional management, aims either to reduce the nitrogen excretion in faeces and urine by matching the amount and composition of feed more closely to animal requirements at various production stages, or by shifting nitrogen excretion from urine to faeces by increasing fibrous feedstuffs in the diet. Furthermore, adaptations of the diet may induce a decrease of urine and slurry pH in. The use of these strategies can reduce the ammonia emission both for pigs [9-13], poultry [14-16] and dairy cattle [17, 18].

For pigs and poultry, feed management may reduce the emission of ammonia to the atmosphere up to a maximum of about 50% compared to standard feed composition. However, feed management for ammonia abatement may negatively affect the emission of methane and nitrous oxide during storage and after land application of the manure [19]. For pigs it was shown that dietary approaches for ammonia emission reduction may not be effective for odour emission at the same time [20]. However, alteration of feed composition can be an effective tool for abatement of odour emission from pig manure [21, 22]; Le *et al.* [22] reported an odour emission reduction of 80% after a drastic reduction of dietary crude protein feed levels.

For ruminants, feed management can also be used to reduce the emission of methane from the digestive system [23, 24].

2.2. Housing System

The design of a housing system, i.e. the combination of the floor-system, manure collection and the manure removal system, determines to a large extent the level of the emission of gaseous compounds, especially the emission of ammonia. Housing systems that have been developed to reduce ammonia emissions basically involve one or more of the following abatement principles [25][2]:

(1) Reduction of emitting manure surface [29].

(2) Fast and complete removal of the liquid manure from the pit to an external slurry storage [30].

(3) Applying an additional treatment, such as aeration, to obtain flushing liquid [31].

(4) Cooling the manure surface [32].

(5) Changing the chemical/physical properties of the manure, such as decreasing the pH [33].

Housing systems that have been developed on the basis of these principles have proved to be able to reduce their ammonia emissions to the atmosphere from about 30% to 80%. In the Netherlands, animal housing systems and their ammonia emission levels are published in a regulatory list [34].

Brink *et al.* [35] estimated for Europe that animal housing adaptations for ammonia abatement hardly affect the emission of methane but may increase nitrous oxide emissions significantly. The effect of animal housing adaptations on odour emission was demonstrated but is usually limited [36, 37].

Furthermore, control of the indoor climate in terms of reducing air velocity at the manure surface, which decreases mass transfer at the manure-air interface [38, 39], and having relatively low indoor temperatures, which results in less fouling of floors, especially for pigs [40], can reduce ammonia and odour emissions to the atmosphere even further, as emitting surface is reduced.

2.3. End-of-Pipe Air Treatment

Another approach for emission reduction is treatment of the ventilation air of a mechanically ventilated animal house. In such an end-of-pipe technique the house design and management inside the house remains essentially unaffected and is considered as a given emission source. End-of-pipe air treatment techniques that are applied nowadays for treatment of exhaust air in livestock operations include two types of air scrubbers: acid scrubbers and biotrickling filters[3]. The main purpose of these scrubbers is ammonia abatement; the scrubber systems are commercially available and considered as off-shelf techniques in countries such as the Netherlands, Germany and Denmark.

A packed tower air scrubber, or trickling filter, is a reactor that has been filled with an inert or inorganic packing material (Fig. **1**). The packing material usually has a large porosity, or void volume, and a large specific area. Water is distributed on top of the packed bed which is consequently wetted. Contaminated air is introduced, either horizontally (cross-current) or upwards (counter-current), resulting in intensive contact between air and water enhancing mass transfer from gas to liquid phase. Usually a fraction of the trickling water is continuously recirculated; another fraction is discharged and replaced by fresh water [41-46].

For a given compound, the mass transfer rate from gas to liquid phase under equilibrium conditions is determined by several factors, that include the partition coefficient, the concentration difference between gas and liquid phase, the air and liquid flow rate, the size of the contact area between gas and liquid phase, and the contact time of gas and liquid phase [47-49].

[2] For pig and cattle production most of these abatement technologies will result in a higher ammonia content of the liquid manure; this potentially leads to an increase of ammonia nitrous oxide emission from storage and after land application of manure [19, 26-28].

[3] In this paper both the wordings "(bio)scrubber" and "(bio)trickling filter" are used as equivalent for describing a packed tower (bio)trickling filter with an inert packing material, such as is illustrated in Fig. (**1**). The wording "biofilter" is used to describe a system with an organic-based packing material and a low water flow.

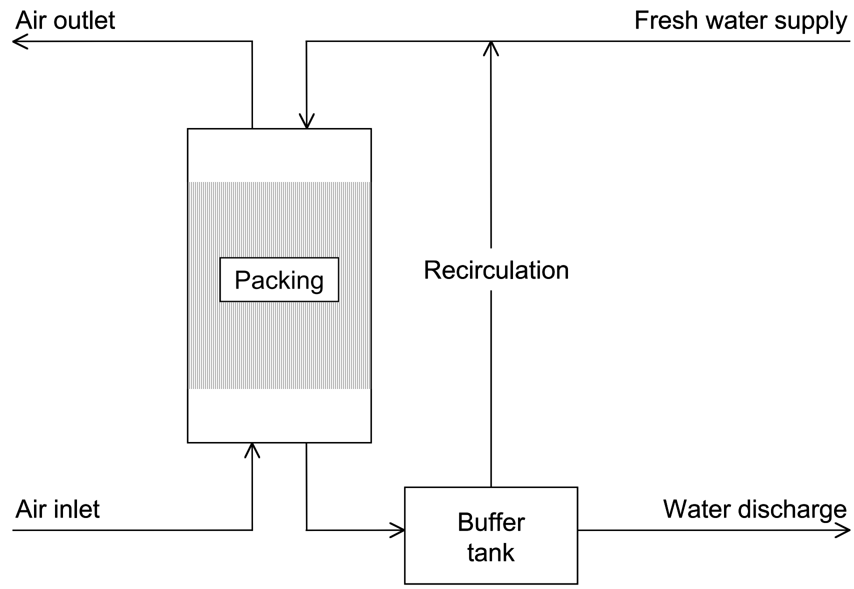

Fig. (1). Schematic of a counter-current packed tower trickling filter.

For ammonia, the concentration in the liquid phase, NH_3 (aq), is mainly determined by the ammonia concentration in the gas phase and the pH driven dissociation into ammonium ($NH4^+$) and hydroxide (OH^-) ions and, if applicable, by the transformation of ammonium into other compounds. In an acid scrubber the pH of the liquid phase is kept at low levels by addition of acid and the ammonium salt is removed from the system with the discharge water. In a biotrickling filter, ammonium is removed by bacterial conversion to nitrite (or nitrous acid) and nitrate (or nitric acid); this process is called nitrification [50, 51]. The bacterial population, or biomass, in the system grows partly as a film on the packing material and is partly suspended in the water that is being recirculated. The accumulated nitrite and nitrate is removed with the discharge water.

The discharge water from a scrubber might be used for nitrogen fertilization of crops; sometimes the water is added to the liquid manure storage. The discharge water from a biotrickling filter might be treated in a denitrification process in order to decrease the nitrogen content which means that the water can be usually discharged at lower costs.

3. SCRUBBER REMOVAL PERFORMANCE

The acid scrubbers and biotrickling filters that have been developed and are in operation for treatment of exhaust air from animal houses are successful in their attempt to achieve emission reductions for ammonia. A review on the performanc of scrubbers shows that acid scrubbers have an average ammonia removal efficiency > 90% an biotrickling filter have an ammonia removal efficiency between 50 and 90% [52].

Besides ammonia, odorous compounds might also be removed by the air scrubber system to some extent. Generally speaking, the odour removal efficiency of an air treatment that has been designed for ammonia removal solely, is on average 30% for acid scrubbers and 45% for biotrickling filters [36, 37, 52], although reported ranges of individual measurements are wide. Especially odorous compounds that are well-soluble, easily biodegradable (in case of a biotrickling filter), or alkaline (in case of an acid scrubber) will be removed from the air relatively easily. The odour removal efficiency of air scrubber systems might be improved by adjustment of design and operational strategy. It is noted that the current design of acid scrubbers and biotrickling filters has been optimized for the removal of NH_3 only and that the removal of odour has been considered as an unintentional, but welcome, circumstance until now. For biotrickling filters it has been suggested that removal of poorly water-soluble odour components might be improved by addition of an organic solvent to the water phase, which increases the availability of the odour component to the bacteria and thus increases biodegradation rates [53-55]. Another approach is to make a multi-stage scrubbing system where each stage aims to remove one type of compounds and the total air residence time increases, e.g. a combination of an acid scrubber and a biotrickling filter (see the section on multi-pollutant scrubbers below). Further analysis of the odour removal performance of air scrubbers is necessary to understand the strong variations and relatively low removal efficiencies. A useful approach would be to combine olfactometric methods using a human panel with advanced analyses of individual compounds by gas chromatography - mass spectrometry (GC-MS).

Furthermore, air scrubbing might partly remove dust or particulate matter (PM) from the air. Especially the removal of PM10 and PM2.5[4] is relevant as the inhalation of these fractions affect human health. Recent indicative measurements of particulate matter removal by air scrubbers treating animal house exhaust air showed an average removal efficiency ranging from 62 to 93% for PM10 and from 47 to

[4] PM10 (also called thoracic particles) represents the fraction of particles that have an aerodynamic diameter of 10 µm or less; PM2.5 (also called fine 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/m^3 that has the same terminal settling velocity in the gas as the particle of interest.

90% for PM2.5 [56-59][5]. These data suggest that end-of-pipe air treatment may be of major importance for compliance with current and future PM10 and PM 2.5 emission limits.

In the past, also biofilters with organic-based packing materials were tested and applied for ammonia and odour removal from exhaust air from livestock operations in several European countries. However, at air residence times that are normally applied in biofilter systems, packing life span is limited due to the relatively high NH_3 and dust concentrations of this air, and uniform humidification of the packing is difficult. That is why nowadays mostly trickling systems with inorganic packing are applied for treatment of exhaust air from animal houses in Europe. However, after ammonia has been removed from the air, biofiltration can be effectively used as a polishing step for effective odour removal [52].

Because of the low solubility of methane, usually scrubber systems do not affect the methane concentration of the treated exhaust air. At high air residence times, however, significant removal of methane from this air might be achieved by bacterial oxidation in a biofilter system [60]. Furthermore, some nitrous oxide (N_2O) might be formed as a by-product of nitrification and denitrification in biological air treatment systems [61, 62].

4. NEW DEVELOPMENTS

4.1. Multi-Pollutants Scrubbers

In order to meet the increasingly stringent emission levels that livestock operations have to comply with, a new development is the application of multi-pollutants scrubbers. Whereas acid and biological air scrubbers have been designed for ammonia removal multi-pollutant air scrubbers also aim to achieve significant emission reduction of odour and particulate matter (PM 2.5 and PM 10). Usually multi-pollutant scrubbers are multi-stage systems where each stage aims for the removal of one type of compounds. The first prototypes of multi-pollutant scrubbers for pig and poultry farms, combining the concepts of acid scrubbing, bio-scrubbing, water-curtains, and biofiltration, are in operation now on a limited number of farms; research and development in this field has started recently [63-66]. Multi-pollutant scrubbers may become of major importance for compliance with current and future emission standards. However, further research and development will be necessary to keep investment and operational costs at an acceptable level.

4.2. Scrubber Market Size

For about 25 years air scrubbers have been applied in the Netherlands in intensive livestock farming, in particular for the emission reduction of ammonia. In 2004 biotrickling filters were operated on about 45 farms and acid scrubbers on about 160 farms, in total just over 200 locations [67]. However, during the last five years the application of air scrubbers has been multiplied; recent data show that in early 2008 scrubbers were operated on almost 900 farms (Table **1**).

[5] These measurements were carried out on so-called multi-pollutant air scrubbers. Data on PM removal by current acid scrubbers and biological air scrubbers that have been designed for ammonia removal solely is currently not available.

Table 1. Scrubber Application for Ammonia Removal in Pig and Poultry Operations in the Netherlands, Based on Statements from Manufacturers, as per January 1st, 2008) [65]

	Installed Ventilation Capacity (m^3 $Hour^{-1}$)	Number of Farms (-)
Acid scrubbers	64 million	790
Biotrickling filters	14 million	90
Total	79 million	880
Pig	76 million[a]	850
Poultry	3 million[b]	30
Total	79 million	880

[a] This equals 10% of the exhaust air of all pig farms nationwide.
[b] This equals 0.4% of all exhaust air of all poultry farms nationwide.

This market growth coincides with a general trend of increasing the scale of livestock operations in order to reduce costs. This increase of scale facilitates parties to invest in air-scrubber systems. It is expected that the coming years the implementation of air scrubbers will also expand in other intensive livestock production areas in Europe, besides the Netherlands, in order to comply with European regulations for protection of natural ecosystems and ambient air quality.

5. DISCUSSION

5.1. Removal Efficiency

In comparison with the emission reduction principles of feed management and adaptation of housing system design, which can be considered as source measures, an advantage of end-of-pipe technique air treatment techniques is that very high reductions of ammonia emission can be achieved, up to 100% for acid scrubbers [52]. This aspect makes application of air scrubbing systems suitable even for situations with very stringent emission limits. Furthermore, air scrubbing techniques offer the possibility to achieve removal of not just one compound but of a combined removal of a variety of pollutants (ammonia, odour and particulate matter) at the same time. The application of air treatment techniques is limited to mechanically ventilated animal houses but as an end-of-pipe technique air treatment may also be applied in addition to feed management measures and housing design adaptations. Different emission reduction measures, both source measures and end-of-pipe measures, can be combined so higher emission reductions and/or an increase of the overall cost-efficiency might be achieved. However, the odour removal efficiency of air scrubbing systems is relatively low as compared to the ammonia removal efficiency.

5.2. Process Control

Since scrubber technology was introduced in the Netherlands about 25 years ago, the manufacturing costs of scrubbers have been reduced as manufacturers have optimized and upscaled their production processes. Also the choice of construction materials and equipment (pumps, spray nozzles, measuring devices etc.) has been optimised to some extent. However, the pollutant removal process and control itself have virtually remained unchanged and an increase of robustness and process stability, resulting in long-term reliable removal efficiencies, are aspects that still need further research and development.

Especially bioscrubbers experience quite often operational problems in day-to-day practice, which on the long run will result in decreased ammonia removal efficiencies. Often this is caused by too low discharge flow rates resulting in accumulation of inhibiting compounds (ammonium and/or nitrite) [52, 68]. After discharge the water might be treated in a denitrification reactor and partly reused in the scrubber; this might drastically reduce the net discharge water flow rate from the combined bioscrubber-denitrification system. In order to guarantee successful NH_3 removal process control and monitoring of bioscrubbers needs to be improved. This might be done by obligatory installation of an electrical conductivity (EC) meter that controls the water discharge flow rate from the bioscrubber. In this way the discharge water flow rate can be adjusted conditional on the monitored accumulation of salts.

5.3. Costs

Investment and operational costs of scrubber systems for livestock operations [64, 69] are generally considered as high and therefore it is desirable to improve and further develop the currently commercially available techniques. The main elements determining the yearly costs of air scrubbing are fixed costs (depreciation, interest, maintenance) and energy use. The fixed costs are correlated to the size of the scrubber installation; the energy use is determined by the (continuously) running spraying pumps and the increased energy use of the mechanical ventilation system, which has to compensate for the additional backpressure caused by the scrubber system. In addition to these cost factors, the costs of chemical use for acid scrubbers. i.e. sulphuric acid, and water discharge costs for biotrickling filters are the next important elements [69] [6].

In order to reduce investment and operational costs Melse *et al.* [70] developed a new scrubber design approach that focuses on high *average* ammonia removal efficiencies whereas *incidental* low emission removal efficiencies are accepted. This partial-air-cleaning system has been successfully tested on an acid scrubber on an experimental pig farm [71]. However, in order to make the application of scrubber systems economically more attractive it might be necessary to further scale up intensive animal operations to enable a cut in costs.

CONCLUSION

With ever stricter emission limits the successful application of end-of-pipe air treatment technologies is of increasing importance for intensive livestock operations. End-of-pipe air treatment offers the possibility to achieve removal of not just one compound but of a combined removal of a variety of pollutants (ammonia, odour and particulate matter) at the same time. However, especially for bioscrubbers, process control needs to be improved in order to guarantee stable removal efficiencies.

Important future research topics are how to control or prevent of N_2O formation during degradation of ammonia in bioscrubbers and how to increase odour removal efficiency. Furthermore, considerable research and development efforts are needed to keep operational costs at acceptable levels.

[6] The costs of water discharge, if any, largely depends on the local situation. Melse and Willers [69] assume a discharge cost of EUR 12.60 per m^3 for the Netherlands, both for discharge water from biotrickling filters and acid scrubbers. For other countries different cost figures might apply.

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