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A systematic literature review to identify an air contaminant removal technology for swine barn exhaust air

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Abstract. *Swine housing can emit substantial amounts of aerial contaminants such as odorous compounds, ammonia, hydrogen sulphide, airborne particulate, bioaerosols and several others volatile compounds. Downwind odours from confined feeding operations are considered to be a nuisance that may lead to a reduced value of living by nearby residents. Technologies allowing the reduction of these contaminants, such as air cleaning, could reduce the level of nuisance*

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caused by pig buildings. To identify an appropriate technology to reduce the nuisance load of barn exhaust air, a procedure described by the National Institute for Health and Clinical Excellence was used. This procedure describes a systematic review of the published information that uses a methodology checklist that is consistent between the published sources. The published material selected from the search was assessed for their methodological rigour and scientific merit against a number of criteria. A systematic review of the studies identified in the literature assessed their quality, synthesized the results, graded the evidence and identified significant gaps in the evidence base. To remove any bias, all the selected papers were assessed by both inclusion and relevance criteria. From the completion of steps 1 and 2, the number of selected titles went from 72,000 to 243. The other steps of the process pointed out the research team towards the 24 selected papers for the review. The information collected throughout the review steps shows that there is no existing technology allowing an effective reduction of all the air contaminants coming from pig buildings. Previous experiments often aim at treating only one or some of the airborne pollutants and they are often carried out under laboratory conditions. However, various configurations of biotrickling filters and bioscrubber filters have been studied and show a very good potential for controlling emissions from pig buildings. According to the knowledge base, most promising technologies will likely emerge from a combination of air treatment principles, and at this point on time, there is no information on the effectiveness of these various technology combinations.

Keywords. Air treatment, biofilter, scrubber, odour abatement, gas removal, emission.

INTRODUCTION

Recent studies show that the environmental issues caused by the global expansion and the intensification of agricultural operations in the last 50 years have become extremely important (Martinez et al. 2008, Godbout and Lemay 2007). The contaminants expelled from pig barns include a number of gases, dust particles (inhalable and respirable), bioaerosols (bacteria, viruses, endotoxins, fungi) and several other volatile compounds such as ammonia (NH₃) and hydrogen sulfide (H₂S). In addition, an increasing importance is given to the odour nuisance associated with swine production. Thus, research in this area has become more important in recent years.

In order to protect the air quality and to reduce potential tension between the residents and the pig producers, municipalities and governments are forced to adopt or strengthen existing regulations. In many places, particularly in North America, the environmental impacts of intensive livestock production have been carefully considered during public consultation processes and often result in the replacement of good practice codes by regulation. Thus, the approach adopted in Québec through the establishment of a public consultation on the sustainable development of swine production reached similar consultations that took place in Wisconsin, Ontario, Alberta and Manitoba. In Quebec, since the submission of the BAPE report in 2003, the swine production has been the subject of political decisions, including legislative and regulatory changes.

Air treatment systems for pig barns may represent a part of the solution to reduce odours and airborne contaminants. A study on the research and development status of concepts used to reduce swine odours (Joncas et al. 2002) identified, among about thirty technologies, the air treatment at the outlet of swine buildings as a promising technology.

In order to gain more information on the research completed on air cleaning treatment, a literature review was to be carried out. This review aims at reviewing the information in the literature on air treatment systems, both with agricultural and industrial applications and to critically analyze and emphasize the strengths and weaknesses of each technique under study. The scientific and technical literature on air treatment systems with potential applications to control airborne contaminants from swine buildings will be reviewed and analyzed using a rigorous approach.

The work done in this context pursues the following objectives:

- Review the latest developments on air treatment systems in order to evaluate the strengths and weaknesses of each technique in a swine building application;
- Set the guidelines to prioritize research work within the framework of a research program on the treatment of air emitted from swine buildings.

STRATEGY AND RESEARCH APPROACH

The research strategy used in this literature review has been developed by the National Institute for Health and Clinical Excellence of United Kingdom (NICE 2007). This approach usually used for health literature review has been adapted for the purpose of this specific literature review. It is presented in six specific steps and allows a rigorous selection of review articles instead of a more intuitive approach.

Step 1: Establish the research question

The first step of the systematic review is to establish a clear and concise research question. In the context of this review, the question chosen was: "What potential air treatment technologies can be used to reduce odour from a grower-finisher swine building?"

All articles selected during the systematic literature review would lead to obtain the information that will answer this question.

Step 2: Bibliographic research and evaluation of inclusion criteria

The search for the scientific literature associated with the research question was then started using electronic databases. To be effective, some parameters were determined beforehand. Thus, only articles with abstracts, from anywhere in the world, in French or English and published between 1993 and today were gathered.

Among the titles, abstracts and keywords of the selected articles, the information was then reviewed by an assessor to judge whether the article should be included or rejected from the study by using a list of inclusion criteria presented in Table 1. At this stage, no complete article has been completely assessed. Studies that did not meet any of the inclusion criteria were excluded, while those that met at least one remained in the evaluation process.

Table 1. List of inclusion criteria for the selection of scientific articles in step 2 of the systematic review

Number	Criterion	State (Y/N)
1	Exhausted air treated from livestock facility	
2	Evaluation of the odour removal	
3	Evaluation of the air contaminants removal	
4	Technology appropriate for the swine industry	

Step 3: Evaluation of the relevance criteria for the titles, abstracts and keywords of the scientific articles

All titles, abstracts, and keywords of the scientific articles that were selected in step 2 were then reviewed by an assessor using the relevance criteria (Table 2). At this stage, no article has been completely assessed. The available information was reviewed to determine if the article has sufficient quality to be part of the papers reserved for the next step. Duplicates and items that did not meet the relevance criteria were rejected in this stage.

Table 2. List of relevance criteria for the selection of scientific articles in step 3 of the systematic review

Number	Criterion	Description	Rating of relevance and its definition		
			Excellent (++)	Acceptable (+)	Unacceptable (-)
1	The technology is applicable to the farm	The technology must be applicable to the treatment of exhaust air from livestock buildings	The technology is used on existing farm sites	The technology is on a research or prototype scale	The technology is not applicable
2	Characteristics of the contaminants	The contaminants targeted by the technology must include odour and air contaminants	The odour and the air contaminants are mentioned	The odour or the air contaminants are mentioned	Neither the odour nor the air contaminants are mentioned
3	Performance of the technology	There must be information regarding the performance of the technology	The performance criteria are used	Little information on the performance	No information on the performance
4	Scope of the application	The technology must be applicable for the treatment of air from the barn	Treatment sources from grower-finisher swine buildings	Treatment sources from livestock buildings	Treatment of other sources of air

Step 4: Evaluation of the content of the scientific articles based on the inclusion and relevance criteria

Full versions of the articles that were selected in step 3 were subsequently recovered. Their content was read and evaluated by two evaluators using the same inclusion criteria (Table 1) used in step 2 and the same relevance criteria (Table 2) used in step 3. Only the papers whose content met both the inclusion and relevance criteria were kept for the next step.

Step 5: Evaluation of the methodological validity of the scientific articles

The articles kept from step 4 were then evaluated using a systematic checklist (Table 3). At least two reviewers had read all the materials and completed the evaluation with the checklist for each publication. Since the evaluation criteria may differ depending on the type of study, a checklist was developed to provide a consistent approach for evaluation (NICE 2007). The overall assessment of each study was conducted using a rating (+ +, + or -), based on the level of reduction of bias of the study (Table 3, Section 2). To minimize the bias in the evaluation, step 5 involved a team of two evaluators and a random allocation of articles. In addition, the evaluation was to ensure that there was a causal relationship between the treatments and the data obtained.

Table 3. Evaluation of the validity for scientific articles selected in Step 5 of the systematic review

#	Parameters	Evaluation of the parameter	
SECTION 1 : INTERNAL VALIDITY			
5.1.1	The study clearly and precisely responds to the question.	Well covered Adequately covered Poorly covered	Not covered Not reported Not applicable
5.1.2	A description of the methodology is included.	Well covered Adequately covered Poorly covered	Not covered Not reported Not applicable
5.1.3	The literature review is sufficiently rigorous to identify all relevant articles.	Well covered Adequately covered Poorly covered	Not covered Not reported Not applicable
5.1.4	The only difference between the experimental units is the treatment evaluated.	Well covered Adequately covered Poorly covered	Not covered Not reported Not applicable
5.1.5	All the measurements are made using a valid and reliable method.	Well covered Adequately covered Poorly covered	Not covered Not reported Not applicable
5.1.6	The quality of the study is taken into account.	Well covered Adequately covered Poorly covered	Not covered Not reported Not applicable
SECTION 2 : OVERALL ASSESSMENT			
5.2.1	SECTION 2: OVERALL ASSESSMENT 5.2.1 How the study ensure to reduce bias? Rating +, + or --		
5.2.2	If the rating is + or -, how the bias may have affected the results? (positively or negatively)		
5.2.3	Considering the technological aspects, your assessment on the methodology and accuracy of statistics used, are you sure that the overall effect is due to the interventions made? (high, medium, low)		
5.2.4	Is the treatment the cause of the results? (high, medium, low)		
5.2.5	Are the results of the study directly related to its objectives? (high, medium, low)		

Step 6: Description of the literature retained for the systematic review

The sixteen databases used in the second step of the systematic literature review resulted in 72 000 articles, all based on investigations using the keyword search. A large portion of these articles were not kept after the preliminary evaluation using the formal selection criteria presented above. Of the total number of papers collected in step 2, only 243 were submitted to Step 3. Steps 3 and 4 removed 116 and 91 articles, respectively. The 36 items retained in the last stages were further analyzed for their contents. The evaluation on the validity of the literature

conducted in step 5 then allowed the removal of 12 out of the 36 articles identified in the previous step. Twenty-four papers were selected for the final review. Each of the selected articles provides relevant information associated with the research question and will be used for the systematic analysis.

RESULTS OF THE SYSTEMATIC LITERATURE REVIEW

Introduction

For many years, industrial applications have been using a wide range of air treatment systems. Indeed, the wastewater treatment plants, chemical and petrochemical plants, plastic industries, pulp and paper and food industries are just some examples of the areas that require the development of air treatment systems.

The air treatment methods for odour control are classified into two broad categories, the non-biological treatment (physicochemical) and the biological treatment (Manuzon et al. 2007, Sheridan et al. 2002a Kim et al. 2000, Revah and Morgan-Segastume 2005). Industries use either one of these methods or a combination of both (Devinny et al. 1999, Revah and Morgan-Segastume 2005). The range of contaminants is large, the airflow to deal with reached extremely high values and the temperature and pressure conditions for the treated gas are often very different from ambient conditions.

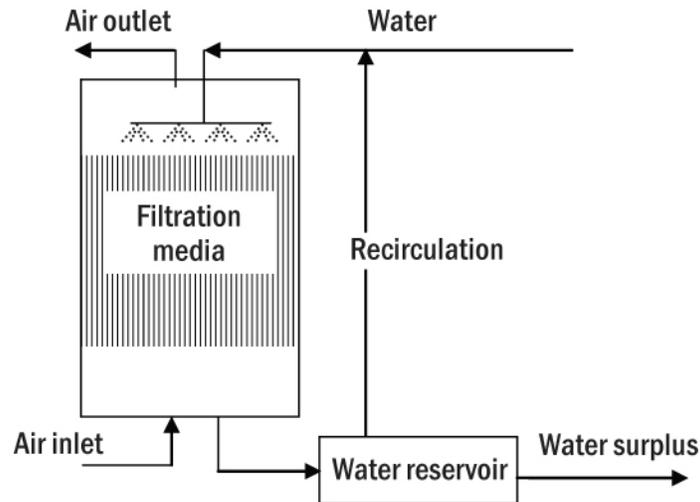
Agricultural applications, such as livestock buildings, require solutions for the treatment of the air emitted. The air volume is high and the concentrations of pollutants are lower as compared from industrial applications. In addition, the systems must be simple and easy to operate and maintain (Devinny et al. 1999). In those applications, the main objectives of the air treatments are the reduction of odours, NH₃, H₂S and dust. The temperature and pressure of the air to be treated are similar to those of the ambient air. However, the climatic factor is sometimes an important element to consider.

Physico-chemical methods

Air scrubbing. Among the non-biological methods for treating the air emitted from livestock buildings, air scrubbing shows good potential because of its simplicity and its performance on reducing dust, NH₃ and H₂S. Indeed, its main advantages are its compact structure, the easiness to control the pH and temperature, the use of inert materials and the rapid adaptation to the change of the gas composition. Air scrubbing allows contact of the gaseous pollutant with a liquid in which it is soluble. The mass transfer from gas to liquid is achieved by using a filler which is the filter of the device (Devinny et al. 1999). Water is often used as the liquid solvent and its pH can be adjusted (basic or acid) depending on the pollutant to increase the solubility of gases.

The most common type of air scrubbing systems is the washing tower, which is a vertical reactor filled with an inert or inorganic material (Figure 1). The material used should have high porosity and large specific surface area (commonly between 100 and 200 m² m⁻³). The solution is sprayed from the top of the device to continuously and uniformly moisten the filling material. The air can flow either horizontally in the device (cross-flow) or from the bottom (counter-current). Once the scrubbing process is done, the liquid must be treated before it will be disposed (Devinny et al.

1999).



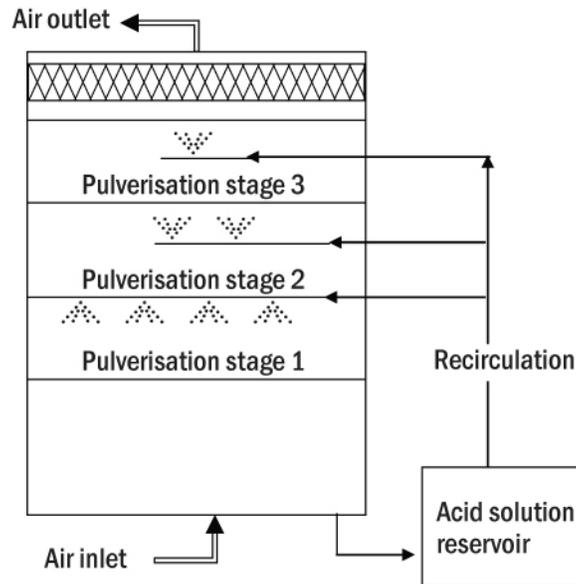
Adapted from Melse and Ogink, 2005

Figure 1. Diagram of a counter-current air scrubber.

Manuzon et al. (2007) consider air scrubbers using acid solution sprayed over the filling material to have the greatest potential for adaptation to livestock buildings. These systems offer a slight reduction of the airflow through the system (reduced pressure loss), the simultaneous reduction of particulate and gaseous pollutants and no generation of waste, as the wastewater can be used as fertilizer.

According to the examples cited by Melse and Ogink (2005), air scrubbers with an acid solution (pH 1.3 to 4.4) used in swine buildings, operating at an airflow rate between 4 000 to 4 500 m³ h⁻¹ and a residence time between 0.5 and 0.9 s, have led to the reduction of ammonia from 77 to 100%. In another example cited by the same study, an air scrubber with an acid solution (pH = 4) which was operated at a maximum air flow of 15 000 m³ h⁻¹ had 3 and 55% reduction in odour for a residence time of 0.6 s.

One solution to increase the performance of this technology is to combine several stages of air treatment. A prototype proposed by Manuzon et al. (2007) was tested for one, two and three stages. In its one-stage configuration, the average reduction of NH₃ ranged from 60% at a concentration of 5 ppm_v of NH₃ to 27% for a concentration of 100 ppm_v of NH₃. Under the same conditions, the average NH₃ reductions in the two-stages were 60 and 35% and they were 63 and 36% in the three-stages. These results were obtained with a superficial air velocity of 6.6 m s⁻¹. Reducing the superficial air velocity to 3.3 m s⁻¹ (residence time of 0.2 to 0.4 s) had a major impact on the performance. By keeping the other conditions similar to the other tests, average reductions of NH₃ were 98 and 46% in the one-stage, 77 and 57% in the two-stages and 70 and 64% in the three-stage configuration. Figure 2 shows the experimental prototype with three stages and position of spray suitable for this application.



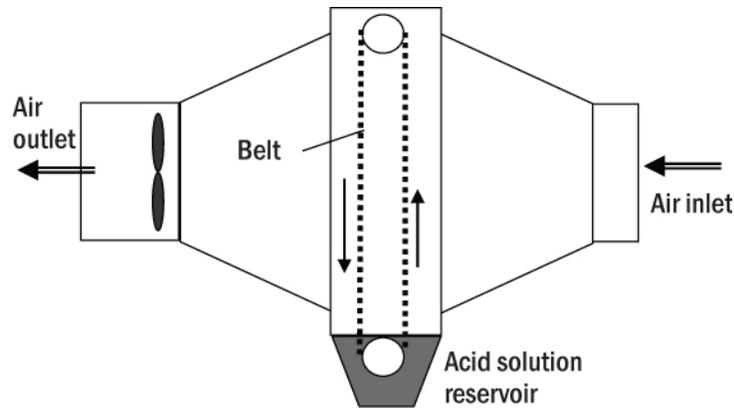
Adapted from Manuzon et al., 2007

Figure 2. Diagram of an air scrubber system with three stages.

However, experimental results have shown that this type of equipment requires a large amount of optimizations in the type and number of sprayers, pressure and spray area, in the concentration of acid and the residence time according to the inlet concentration of NH_3 . The multi-stage operation also indicates interaction between the stages, which reduces performance. Despite a relatively high efficiency for NH_3 removal, removal efficiency for H_2S is null. The use of acid solutions requires optimal control of pH and of the volatilization of NH_3 . The efficiency of some chemical additives, which were used to improve the absorption of the liquid solution, was weak. Modeling of the transfer phenomena of the gas is not yet available and other tests are still needed.

In another study, Gabriel and Deshusses (2003) considered treating air using a strong alkaline solution ($\text{pH} > 12$) to control emissions of H_2S (low residence time, ranging between 1.3 s and 2.0 s). However the disposal of residues and chemical substances is a big disadvantage of this technique.

A recent study (Shah et al. 2007) presents the development and performance of a new type of chemical air scrubber (wet scrubber) for reducing NH_3 in livestock buildings. This scrubber (Figure 3) consists of a mobile screen filter, which is in the form of a propylene belt that moves continuously with a slow speed (2.7 m min^{-1}) and that is wetted by continuous immersion into a reservoir containing a solution of alum ($\text{Al}_2(\text{SO}_4)_3 \cdot 14 \text{ H}_2\text{O}$). The NH_3 content in the air is absorbed by the acid solution, which is absorbed in the filter material and is then transferred to the liquid in the tank. A regeneration effect of absorbent qualities of the filter is achieved through the continuous immersion of the filter material in the tank.



Adapted from Shah et al., 2007

Figure 3. Diagram of an air scrubber system with a filter-belt.

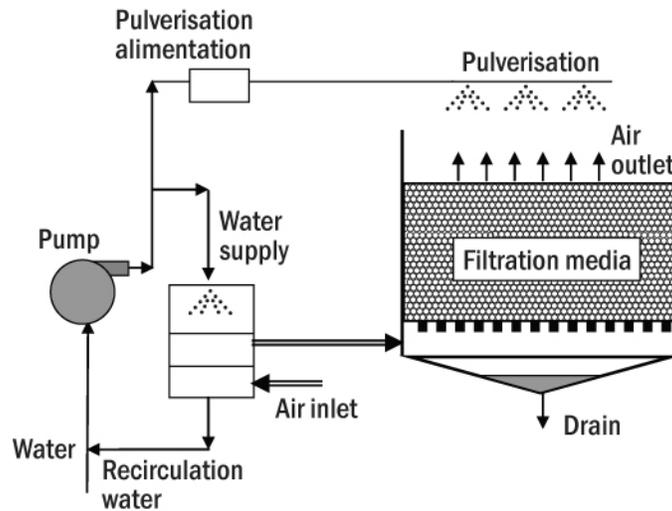
For air coming from a manure pit and from a compost facility, the rate of NH_3 reduction of this type of device varies between 57 and 63%, respectively, for low ($<5 \text{ mg m}^{-3}$) and high (11 to 26.6 mg m^{-3}) NH_3 concentrations. According to the study, the replacement of the scrubbing liquid water ($\text{pH} = 5.77$) by a 1% solution of alum (mean $\text{pH} = 3.46$) allows an increase in efficiency of about 17 times. The disadvantage of such treatment is that it is not effective in reducing H_2S . The water lost in the system was 3.7 l h^{-1} for an airflow rate of $0.93 \text{ m}^3 \text{ s}^{-1}$. There are no results on the reduction of suspended particles. One advantage of this technique is the low pressure drop in ($<100 \text{ Pa}$) compared to conventional solutions for air scrubber ($> 250 \text{ Pa}$).

According to Shah et al. (2007), the use of air scrubbers for livestock buildings remains limited due to technical problems, including water consumption and cleaning requirements.

Biological methods

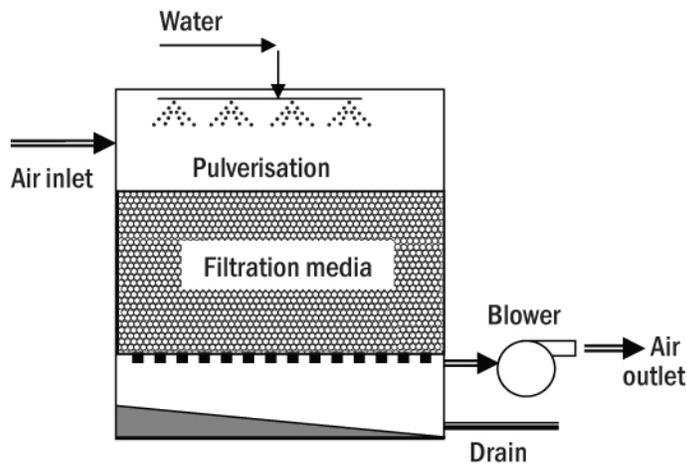
Biofiltration. According to Deviny et al. (1999), the biological treatment of gases started to evolve in 1950s (biofilters using soil as filter bed) in wastewater treatment farms or facilities. In 1970s, interest in biofiltration has increased due to strengthening of air quality regulations. Between 1980 and 1990, biofiltration has progressed rapidly in Europe, but more slowly in North America. Closed systems designed for the treatment of odours and volatile organic compounds (VOCs) have become increasingly computerized. Many recipes for the filter bed were then tested and mathematical models attempted to optimize the process. Today, research in the field of biofiltration focuses mainly on a better understanding on the pathways of biological degradation, the treatment of different mixtures of pollutants, the elimination of overdeveloped biomass and the modeling process.

The most common type of this kind of air treatment is the open biofilter (Figure 4). This equipment can be exposed to atmospheric conditions and can be installed at ground level. Moreover, it usually uses packing materials readily available and affordable (soil, compost). The usual height of the filter bed of an open biofilter is between 1.0 and 1.5 m. Open systems are ideal for applications where space is not a constraint and they are known to be the least expensive solutions for odour control (Deviny et al. 1999).



Adapted from Revah and Morgan-Segastume, 2005
Figure 4. Diagram of an open biofilter system.

Closed biofilters (Figure 5) are generally more complex and may have either a circular or rectangular section. These air treatment systems allow a better control of some operating parameters (temperature, moisture, nutrients, pH) while being less sensitive to climatic factors. The filter bed used in closed biofilters generally has a height that varies between 1.0 and 1.5 m and is composed of organic and/or inorganic materials. An air plenum at the inlet and the outlet of the biofilter facilitate uniform distribution of air through. For most applications with closed biofilter, a circulation of the air downwards is more efficient than an upward one as the moisture control material filtration is better in the first case (Revah and Morgan-Segastume 2005).



Adapted from Devanny et al., 1999
Figure 5. Diagram of a closed biofilter system.

A study by Nicolai and Janni (2001) recommends maintaining moisture content between 35 and 65% in the filter material. The average reductions of H₂S for low, medium and high relative humidity were 3, 72 and 87 %, respectively. Under the same conditions, the odour reductions were 42, 69 and 79%, respectively and the ones for ammonia were 6, 49, and 81%, respectively.

The optimal ratio of compost to wood chips recommended by the study for the treatment of air coming from swine buildings is 30% compost and 70% wood chips (on a weight basis).

Sheridan et al. (2002a) studied a pilot-scale biofilter to determine the optimum operating conditions. The filter bed had a height of 0.5 m and was built using wood chips of 20 mm and above. The moisture content of the filter bed varied between 64 and 69%. Preliminary tests have shown that the installation of a mechanical filter at the air inlet of the biofilter can reduce over 99% of airborne particles with an odour reduction of 19%. During the experiment, the system had achieved a removal efficiency between 73 and 87% for NH_3 . When the load of ammonia is increased from 967 to 2 057 mg h^{-1} and a maximum volumetric load of 1 898 $\text{m}^3_{\text{air}} \text{m}^{-3}_{\text{filter}} \text{h}^{-1}$, the removal efficiency was reduced by 19%. The study shows that the wood chips over 20 mm are recommended for biofilters that are used to treat air emitted from swine production facilities. The maximum recommended volumetric load is 1 350 $\text{m}^3_{\text{air}} \text{m}^{-3}_{\text{filter}} \text{h}^{-1}$ in order to ensure an effective odour removal greater than 90%. In summer operating conditions, the size of the biofilter is 0.148 $\text{m}^2 \text{pig}^{-1}$. Reduced pressure drop was possible through the kind of material used and the filter bed height of only 0.5 m. The study recommends that the humidity in the filter bed should be at least 63%. An efficient humidification system (humidifier at the inlet and a spraying device above the bedding material) and an adapted air distribution system are determining factors for the design and the operation of treatment solutions for large volumes of air.

In another study, Sheridan et al. (2002b) compared the effectiveness of two pilot-scale biofilters for treatment of air from pig barns. The first biofilter used wood chips with more than 20 mm and the second one used wood chips with dimensions between 10 and 16 mm. The humidity in the filter bed was maintained at 69% and the volumetric load varied between 769 and 1847 $\text{m}^3_{\text{air}} \text{m}^{-3}_{\text{filter}} \text{h}^{-1}$ for a trial period of 63 days. Both biofilters had reduced the odour in the range of 88 to 95%. The reduction of ammonia was in the range of 64 to 92% for the first biofilter and 69 to 93% for the second. H_2S was reduced by 9 to 66% for the first biofilter while the results for the second range from an increase of 147% to a decrease of 51%. The pH was maintained between 6 and 8. Investigations show that there is a risk of formation of anaerobic zones (second biofilter) and release of sulphur compounds. The study concluded that biofiltration is an interesting technology for the removal of odour and ammonia from the air emitted from swine production facilities.

Hartung et al. (2001) conducted a study on two open type biofilters similar to those commonly used to treat the air from pig barns in Germany. The filter beds had a surface of 18 and 30 m^2 and a height of 0.5 m. The filter material was composed of a mixture of coconut and peat fibers. The removal efficiency for ammonia was 15% for the first biofilter and 36% for the second. In terms of odour reduction, the efficiencies of the two biofilters were respectively 78 and 81%. In conclusion, the study seems to contradict the other previous researches, because the removal efficiency of ammonia increases (15 to 39%) with the increasing inlet load volume of ammonia at the entrance (1 000 to 6 000 $\text{mg m}^{-3} \text{h}^{-1}$).

Hoff and Harmon (2006) attempted to combine a strategy of minimum ventilation and biofiltration. A minimum air flow rate of 75 $\text{m}^3 \text{h}^{-1} \text{pig}^{-1}$, which corresponds to the conditions of summer nights, was established as a reference. The tests were made on a biofilter using wood chips, having a filter bed height of 27 cm and an area of 80 m^2 . The results showed an average removal efficiency of 44% for ammonia, 58% for H_2S and 54% for odours. The results are quite

modest but are partially due to reduced volumes of the treated air.

Kaligan et al. (2004) studied the efficiency of biofilters in reducing ammonia emitted from livestock buildings. The aim of the research was to test a filter bed composed of non-expensive organic and inorganic materials in combination with a diverse microbial population (multiculture). The tests were conducted on a bench-scale device with a closed-type reactor having a height of 500 mm. The packing media was composed of peat (91% organic), vermiculite and perlite (ratio 3:1:1). In the second series of tests, the filter material was made from peat and polystyrene (3:1 ratio). The results of the study show that removal efficiency of ammonia can be very high (99 to 100%) under conditions where the NH_3 inlet concentration is 200 ppm_v and flow rates are between 0.03 to 0.06 m³ h⁻¹.

A first series of experiments helped to develop a bench-scale device for an open biofilter type that uses wood chips of small dimensions (2 to 5.6 mm) (Sunghyoun et al. 2007). The retention times were 5, 7 and 9 s and the moisture content of the filter media was between 40 and 63%. The removal efficiency of ammonia recorded ranged from 92.7 to 95.2%. The inlet concentration of ammonia ranged from 3.0 to 24.2 ppm (average 6.5 ppm). The height of the filter bed was 60 cm, the residence time was 7 s and the moisture content of the filter media was maintained at a level higher than 50%. The removal efficiency of ammonia ranged from 67 to 97% (average 89%) for air from a manure pit and 68 to 96% (average 86%) for air from of a fermentation. The study did not estimate the reduction of odour or of H₂S.

A study on a pilot-scale plant had enabled Luo (2001) to investigate the performance of biofilters on odour reduction using different filter materials such as sand, bark and wood mixtures soil and bark. The reduction of odours analyzed by olfactometry technique was between 29 and 99.9% with odour concentration at the inlet ranging between 143 100 and 890 000 OU m⁻³. The study highlighted the presence of leachate resulting from wetting the bed filtration. This fluid plays a very important role in maintaining the moisture, but it may also have other effects on the quality of the filter bed, such as washing phenomena, accumulation of large amounts of pollutants, interference with the airflow, formation of preferential paths, formation of anaerobic zones and release of NH_3 and H₂S. The study demonstrates the need for further research to clarify these aspects that have a direct influence on the performance and longevity of the biofiltration system.

In a study aiming at the control of air pollution by using biofiltration, Deviny et al. (1999) analyzed in detail the aspects of this technology. They demonstrated that the choice of an optimized solution for a particular application requires a further understanding of the theoretical knowledge and results validated by experiments conducted on a wide range of aspects as the filtration material, the control and operation parameters of the biofilter and the microbial ecology. Consistent with the results of several other researchers, the study demonstrates the importance of controlling the moisture content in the biofilter. If a biofilter is not irrigated, moisture should be controlled by the humidity of the air that feed the device. This type of control on the moisture content of the filter media is not always effective and the variations in the humidity and temperature of the incoming air can affect the performance of the biofilter.

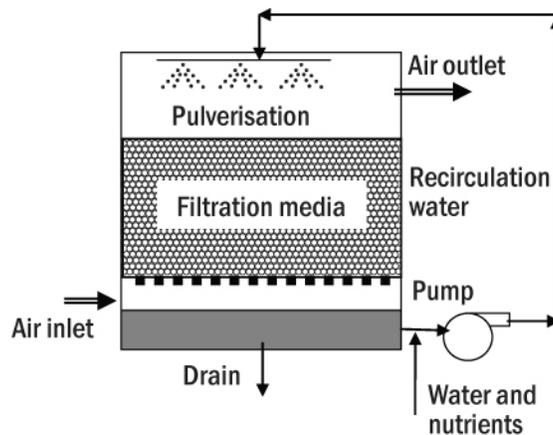
On the other hand, when the amount of water exceeds the capacity of the filter bed, water drains under the force of gravity. The leachate contains cells, undegraded pollutants, residual products, humic materials, nutrients, acids and salts. The loss of the nutrients reduces the performance of

the biofilter, but poor drainage can also reduce acidification and accumulation of salts and biomass and clogging of the filter bed. Leachate often requires treatment prior to its disposal.

Further studies on the effects of leachate in biofilters in correlation with the accumulation of nitrogen compounds and water application rate were investigated by Armeen et al. (2008a and 2008b). These studies tried to identify the physical and chemical factors that influence the long-term performance and stability of biofilters for the removal of air contaminants. According to these authors, the efficiency of a bioreactor is influenced mainly by factors such as the inlet concentration of the pollutant, pH and moisture content and temperature of the filter bed.

In response to the questions raised regarding the accumulation of nitrogen compounds in the filter bed due to high inlet concentrations of ammonia, a study by Japanese researchers (Kim et al. 2000) proposes the use of a new bacterium (*Vibrio alginolyticus*), which is able to effectively degrade high concentrations of ammonia. The study demonstrated the feasibility of using this marine bacterium for concentrations of ammonia between 120 and 2 000 ppm_v with a removal efficiency greater than 85% for more than 60 days of operation.

Biotrickling filters. According to Deshusses and Gabriel (2005), biotrickling filters involve biological techniques that are more promising for controlling odour and VOCs. Unlike biofilters that use mostly organic materials for the filter bed and operate with a minimum water flow rate, biotrickling filters use only inorganic materials and the water flow is achieved by continuous percolation. In biotrickling filters, the air passes through an inert filter in which the liquid is continuously recirculated (Figure 6). The filter material is similar to that used in chemical scrubbers and must have high porosity and specific surface area (100 to 400 m² m⁻³). The residence time is about 30 s, but it can go down to lower values particularly in H₂S removal (1.2 s; Revah and Morgan-Segastume 2005).



Adapted from Revah and Morgan-Segastume, 2005
Figure 6. Diagram of a biotrickling filter.

Air treatment by biotrickling filters is a relatively new technology and majority of the experimental results are from the tests carried out on pilot-scale plants (Iranpour et al. 2005). Various filter media, such as lava rock, random plastic packing, structured blocks of plastic and polyurethane foam were used. The high porosity of these materials allows minimal pressure drop

on the airflow. Higher airflow rates are, therefore, achievable. One of the main characteristics of biotrickling filters is the continuous flow of the liquid in the filter bed. It is, therefore, possible to improve the control by the addition of nutrients, adjustment of the pH and the temperature or by removing the residual products. In the case of odour reduction and H₂S removal, production of sulfuric acid and reduction of pH and/or accumulation of sodium sulphate are the key controlling parameters of a biotrickling filter.

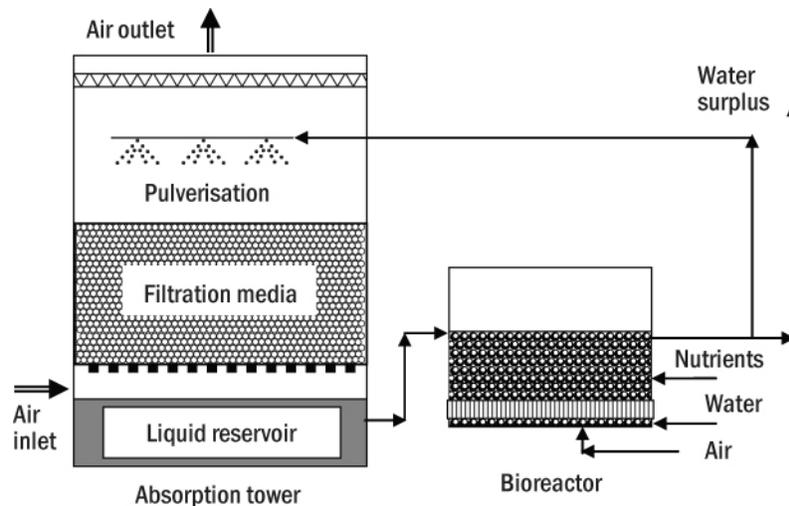
The examples cited by Iranpour et al. (2005) show that these reactors have good removal efficiencies for high concentrations of H₂S at low residence time (EBRT). Biotrickling filters seem a good option for treatment of gases with high concentrations of H₂S and possibly for other sulfur compounds. Experiments on industrial applications have shown the potential of biofilters and biotrickling filters on the simultaneous removal of odour, H₂S and VOCs. On a total of eight cases of biotrickling filters used for the removal of H₂S and for inlet concentrations of 1 to 1000 mg m⁻³, the reduction efficiency was from 95 to 99%. In the case of five of those and for the reduction of odours, the efficiency was 65 to 99%.

Biotrickling filters have some advantages over the other biological treatments in controlling air pollutants (Deshusses and Gabriel 2005). These includes the height of the filter bed, the longer life of the filter media (above 10 years), the ease of control and the ability to treat air containing dust and grease.

In the case of biotrickling filters, the addition of nutrients becomes a tool for optimizing the performance of the reactor. In fact, the biotrickling filters should be inoculated with a variety of microorganisms, since the initial charge does not contain bacteria. The nutrients requirement depends on the type of pollutant to be treated, its concentration, the pollutant loading and operating conditions of the reactor. Excess nutrients can lead to overproduction of biomass and clogging of the reactor. The biotrickling filters used for the removal of H₂S are less exposed to the risk of clogging, probably due to the relative ineffectiveness of autotrophic organisms.

Some research that deals with the conversion of air scrubbers to biotrickling filters (Gabriel and Deshusses 2003, Deshusses and Gabriel 2005) have shown that it is possible to use a biotrickling filter in the same operation range than air scrubbers (comparable residence time of 1 to 2 s), but with the advantage of being able to degrade, in addition to inorganic pollutants, organic compounds without using toxic chemicals and dangerous. The results of long-term tests show an efficiency of over 97% for the H₂S removal when the inlet loading was 15 to 95 g m⁻³ h⁻¹. Concentrations higher than 100 g m⁻³ h⁻¹ cause a gradual reduction in efficiency to below 80%.

Bioscrubbers. Bioscrubbers use a design that includes an absorber in which the gaseous pollutant is transferred to a liquid solvent and a bioreactor in which biological degradation occurs in the liquid phase. According to the schematic diagram shown on Figure 7, the absorption is carried out in a tower spray (absorber) and the biodegradation in a reservoir (bioreactor) containing suspended biomass (activated sludge). Singh et al. (2005) reported several types of absorber like the tower with a filler, the wet cyclone, the spray tower and the venturi scrubber type.



Adapted from Revah and Morgan-Segastume, 2005

Figure 7. Diagram of a bioscrubber.

The flow of air and water can either be counter-current, co-current or cross-current. The air velocity can vary between 1.5 m s^{-1} and 20 m s^{-1} in the spray tower, it can reach 25 m s^{-1} for the wet cyclone and between 40 and 50 m s^{-1} for the venturi. The bioscrubbers have the same space, flexibility and control than biotrickling filters and they offer the possibility of dealing with poorly water soluble compounds (Henry coefficients $H < 0.01$) or toxic for microorganisms.

The bioscrubbers have increased the scope of application for biological treatment of waste gases. The bioscrubbers can be defined as a unit composed of two reactors and a system of recirculating water that runs between the two reactors (Kraakman 2005). In the first unit, which is the absorber, the pollutant is absorbed by the liquid phase. Mass transfer then takes place between the vapor and liquid phase. In the second unit, the liquid-phase bioreactor, the pollutant is degraded by microorganisms that are suspended in the liquid or fixed on a filter material.

The greatest advantage of bioscrubbers compared to biofilters and biotrickling filters is the ability to produce and maintain large amount of active microbial mass in a smaller units. On the other hand, Kraakman (2005) considers that bioscrubbers and biotrickling filters present a greater construction and operation complexity.

Singh et al. (2005) concluded that bioscrubbers offer the greatest efficiencies in the removal of H_2S , NH_3 and organic sulphur compounds. The performance analysis of bioscrubbers used in the industry for H_2S removal show efficiencies of over 98%, as much for low, medium and high inlet concentrations (between 0 and 75 mg m^{-3} , $2\,000 \text{ mg m}^{-3}$, between $10\,000$ and $15\,000 \text{ mg m}^{-3}$). The results cited for the reduction of odours show an efficiency of 80% (for the reduction of organic sulfides with inlet concentrations between $4\,000$ and $22\,000 \text{ OU}$). Kraakman (2005) confirms the performance obtained with bioscrubbers in reducing H_2S , for flow rates of about 160 , 450 and $6\,000 \text{ m}^3 \text{ h}^{-1}$ and for odour reduction for air flows of $40\,000 \text{ m}^3 \text{ h}^{-1}$.

General discussion

There are many methods aiming at the reduction of the air contaminants and odours. The choice of a specific technology must be determined by considering the technical and environmental aspects as well as the impact on public health. The difficulty of using one of the existing technologies for the treatment of air comes from the specific constraints of the application. According to the literature review, the livestock buildings in general, especially swine production facilities, are characterized by a very large number of parameters that influence the application of air treatment.

The analysis of the advantages and disadvantages of current air cleaning techniques (acid or basic solutions) shows that technologies under investigation provide only partial removal of certain pollutants, such as dust and NH_3 or dust and H_2S . Indeed, since NH_3 and H_2S have completely opposite solubility, it is impossible for this technology to treat these two gaseous pollutants simultaneously. In addition, the effect of air scrubbing on reducing odour concentrations is rather limited. Air scrubbing could therefore be an interesting pre-treatment, but should be combined with another method to effectively reduce all airborne contaminants.

Biofiltration has been the subject of many publications in science and technology and several units are currently installed throughout the world. Current researches show that this technology partly meets the requirements for swine productions. Its efficiency has been demonstrated in reducing odour and to a lesser extent, in the reduction of NH_3 and H_2S emitted from the barn. However, despite its advantages of being simple, problems like the accumulation of pollutants, the potential for clogging, the high pressure losses and the relatively rapid degradation of the filter bed, cannot conduct to the conclusion that biofiltration is an effective and easy solution.

Biotrickling filters have better features compared to biofiltration, especially by their rapid response to changes in operating conditions and a longer life time. The use of a trickling liquid allows a more precise control on the conditions within the biofilter. For example, the concentration or type of bacterial population could be modified directly through the liquid. The biotrickling filters can simultaneously and effectively treat more pollutants emitted from the buildings, such as dust, odours, H_2S , and VOCs, while presenting low losses.

Bioscrubbers also offer interesting advantages over biofiltration. They can treat several pollutants emitted from the building, such as NH_3 , H_2S , and several other sulfur compounds. In addition, they are stable and have a longer life time than biofilters. Yet, these technologies are slightly more complex than biotrickling filters since they are composed of two separate reactors.

However, even if they are very interesting, biotrickling filters and bioscrubbers have not been the subject of many experimental studies on a full-scale system. In addition, applications for swine production facilities are virtually nonexistent. Experimental research on these two technologies has just started and only specific solutions for specific applications and partial results are available.

The systematic analysis of all the literature demonstrates that currently there are no technologies that could effectively reduce odours, dust, NH_3 , H_2S and VOCs. Several technologies have configurations that are similar to each other though different in terms of operating principle. It

would therefore be possible to convert some of these equipments to perform a treatment different from the one they were intended for. However, the technologies that would have the greatest potential to reduce the contaminants should, in all likelihood come from the combination of different treatment systems. A combination of an air scrubber and a biotrickling filter or a combination of a biofilter and a biotrickling filter could be a more interesting solution than the technologies used individually. However, there is no information in the literature on the efficacy of these different combinations of technologies.

Answers to the research question and current knowledge gaps

The analysis of various research results on air treatment technologies allowed us to answer the question of this systematic literature review: "what potential air treatment technologies can be used to reduce odour from a grower-finisher swine building?"

The systematic literature review shows that there is currently no single technology that can effectively control all air contaminants from a swine building. However, if we consider the pressure loss through the system, specific capacity, the life length of the equipment, the ability to simultaneously control odour, particulates and other contaminants, the biotrickling filter seems to have a great potential for development and application. It becomes clear that effective control of pollutants can be obtained by combining several technologies sequentially. An air treatment system composed of a biotrickling filter, coupled to an air scrubber or a biofilter could probably lead to an effective air cleaning at the exhaust of livestock buildings.

However, analysis of selected studies has also shown that trials are often conducted under laboratory conditions and they do not take into account the great variability of the factors that characterize livestock buildings. Therefore, coefficients of performance do not likely reflect the behaviour of the equipment under real operating conditions.

Another weakness identified in the experimental data presented in the studies is that performance analysis corresponds, in many facilities, to the efficiency of treating a single type of pollutant. Under current conditions, it is more appropriate to determine the efficacy of the technologies of treating a wider range of pollutants.

New developments in biological treatments are still at the research laboratory or pilot plant level. The validation of these concepts in actual operations and on a long term basis remains to be done.

CONCLUSIONS AND DIRECTIONS FOR RESEARCH

The technological development and advancement of scientific research made in the air treatment for industrial applications are an important resource for the future development in agricultural applications. Among the potential technologies for air treatment in reducing odour from swine production facilities, the current treatments provide partial solutions that do not meet all the technological requirements.

However, there seems to be a strong potential for the development and improvement of some new technologies such as biotrickling filters and bioscrubbers. Finally, air treatment technologies

based on a combination of several treatment methods, including mechanical filtration, air scrubber and biotreatment, have high potential for application.

Some research directions must be prioritized to ensure the development of air treatment technology for pig barns. The knowledge base must be first developed concerning the biotrickling filter system for their effectiveness in controlling odours, dust and gas that leave the livestock buildings. Then, research protocols should be planned for and developed to measure the effectiveness of an air treatment under conditions similar to real buildings. Finally, an economic analysis must be completed to ensure that the most interesting technologies from a technical point of view are also relevant from a cost benefit perspective.

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