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Strategies to control odours in livestock facilities: a critical review

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Abstract

Odours generated in livestock buildings constitute one of the most relevant air quality issues of intensive livestock production. Reducing nuisance episodes related to odour exposure is therefore essential for a sustainable livestock production. In this study, the state-of-the-art on odour mitigation techniques in livestock housing is critically reviewed. Scientific advances in the last decade are revised and research needs are also identified. The complex nature of livestock odours is firstly reviewed and examined. Then, the most relevant odour control strategies are analyzed in terms of present knowledge and future needs. The strategies considered are: nutritional strategies, manure additives, building design, air filtration, manure covers, manure treatment systems and windbreaks. Finally, future research needs and priorities when establishing mitigation techniques are identified. Despite important recent advances, there are still some challenges for scientists, producers and regulators, particularly related to field evaluation of odours. Therefore, to control livestock odours effectively, using standardized field assessment techniques will be required. Also, investigating measurement and model errors may be useful to better understand the limitations of the current methods, as well as to identify research priorities.

Additional key words: odour emission; odour dispersion; odour mitigation; nuisance; olfactometry.

Introduction

Odour generation is one of the most relevant air quality issues of confined livestock operations. Although odour exposure has been traditionally considered only a nuisance problem, it is now accepted that it can also impair health through direct irritation or psychopathologic mechanisms (Shusterman, 1999; Schiffman & Williams, 2005). For this reason, in recent years intensive research has been conducted to assess and control odours emitted from livestock facilities. There is also a tendency to establish stricter regulations to improve air quality in the surroundings of livestock facilities (Nicell, 2009).

Odour nuisances, however, constitute a concern of very complex nature, in comparison with other air quality issues. Assessing odours is conditioned by the subjective character of nuisances and the intrinsic variability of odour emission and dispersion processes. Thus, measuring odours, developing odour dispersion models and evaluating abatement strategies have been traditionally challenging tasks for farmers and researchers. Much research has been conducted so far in relation to odour measurements and the application of odour dispersion models (Yu *et al.*, 2010). Also, a wide number of odour abatement techniques have been characterized (*e.g.* Powers, 1999). However, our current knowledge seems to be still limited to definitively solve some odour problems of livestock facilities.

The objective of this study is to critically review the state of knowledge on odour mitigation techniques in livestock housing. Firstly, the complex nature of livestock odours is briefly reviewed. Then, we analyze the most relevant odour control technologies, their

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Abbreviations used: CP (crude protein); EF (emission factor); FC (fermentable carbohydrate); FIDOL (frequency-intensity-duration-offensiveness-location); VFA (volatile fatty acid).

strengths and weakness and their efficiency on odour potential reduction. Finally, future research needs and priorities are proposed to establish effective mitigation strategies of livestock odours.

A complex nuisance problem

The complex nature of livestock odours

An odour can be defined as a human sensation that occurs when airborne chemical substances, called odorants, stimulate sensory receptors in the nasal cavity (Schiffman *et al.*, 2001). Livestock odours are composed of a complex mixture of compounds, which varies between animal types. As an example, approximately 330 different odorous compounds have been identified in swine production (Schiffman *et al.*, 2001), whereas 110 compounds were found in dairy facilities (Filipy *et al.*, 2006).

Livestock odours are mainly generated by the microbial decomposition of organic matter contained in the digestive tract of animals and in their manure, under anaerobic conditions. Although odours can also be originated from other sources (*e.g.* from the skin or the feed), studies conducted in this sense suggest that animals themselves constitute a minor source of odour if compared with manure (Verdoes & Ogink, 1997; Kai *et al.*, 2006). Important sources of livestock odours are related to animal houses, manure storage facilities and agricultural application of manure, but the relative odour load of each source is not well determined so far.

Odour formation, concentration and emissions from livestock facilities depend on many factors, which are summarized in Fig. 1. Odour generation is intrinsically determined by the animals themselves, their food and management system of their manure. It may also be affected by daily and seasonal variations, depending on climate and animal activity. Finally, the amount of odour emitted to the atmosphere is determined by the housing ventilation rate and the exhaust odour concentration.

A review of odour emission factors is shown in Suppl. Table 1 [pdf online]. Although a major part of studies on odour emissions have focused on the measurement of odour emission rates, units used in the literature are not always homogeneous. This heterogeneity and the complexity of odour measurements contribute to make comparisons among studies more difficult (Gay *et al.*, 2003).

Odour nuisances

The processes by which odours are formed, released to air, dispersed in the atmosphere, perceived by individuals and cause nuisance in a population are complex not fully understood. Van Harreveld (2001) defined some essential words for a sound scientific

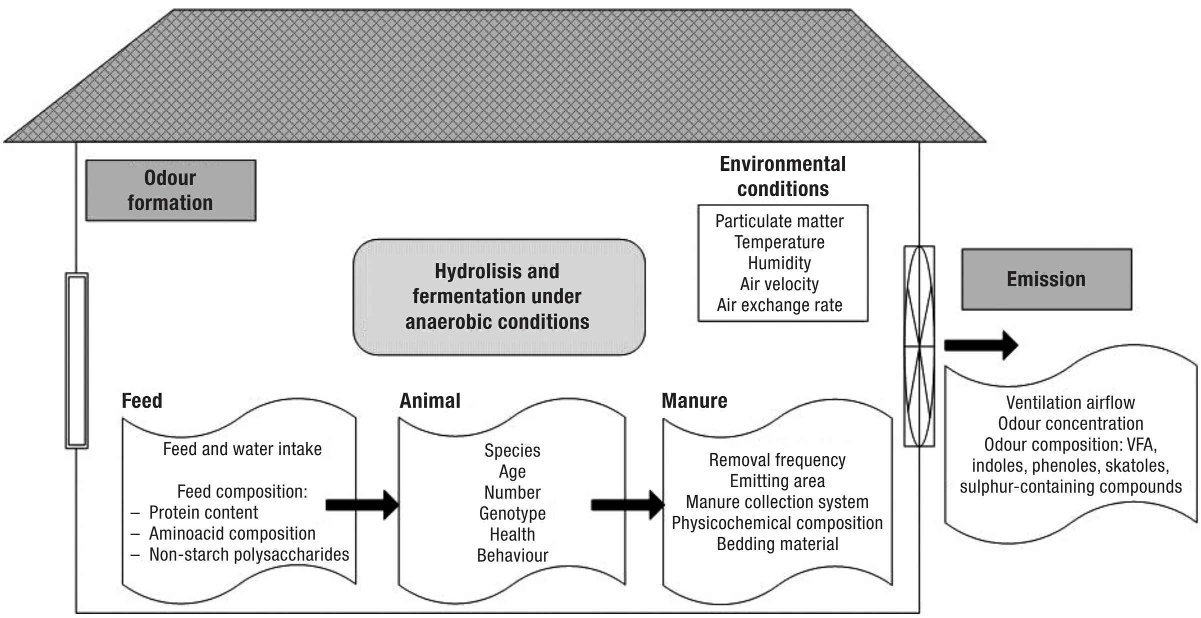

Figure 1. Overview of sources and relevant factors affecting odour concentration and emission from livestock houses. VFA: volatile fatty acid. *Source:* Adapted from Le *et al.* (2005).

discussion. So, "annoyance" can be defined as a set of complex human reactions resulting from an immediate exposure to an ambient stressor (*e.g.* an odour). On the contrary, "nuisance" is caused by repeated events of annoyance over an extended period of time, which leads to modified or altered behaviour and can have a detrimental effect on well-being and health. Therefore, the annoyance potential is an attribute of a specific odour or mixture of odorants, whereas nuisance potential is a much broader concept that describes the probability of nuisance occurrence in a particular location.

Human responses to odours, however, are also highly variable, and must be understood as a combination of five interrelated components, known as a whole as FIDOL (Nicell, 2009). The FIDOL components refer to the Frequency (how often), Intensity (how strong), Duration (how long), Offensiveness (how unpleasant), and the Location (sensitivity of neighbours with regards to livestock operation). Since these components are difficult to monitor, some countries (*e.g.* Germany, The Netherlands, Switzerland, Austria, Belgium and Canada) have developed land use planning guidelines based on minimum separation distances between livestock units and residential areas. This setback distance is calculated considering four main factors, according to the following general equation (Nicolas *et al.*, 2008):

$$D = \alpha f_D f_R \sqrt{N f_A f_T} \qquad [1]$$

where the setback distance (D) is calculated as a function of the following factors: the dispersion conditions (f_D), receptor characteristics (f_R), animal species (f_A) and technical factors such as abatement strategies (f_T). The equation also considers the farm size (N) and a fitting factor to real farm conditions (α).

Odour measurement

Odour measurement techniques arise from the fundamental premise that odours must first be measured objectively and reproducibly measured before they can be effectively subjected to regulation and before the effectiveness of odour control technologies can be assessed (Nicell, 2009). Despite recent advances, obtaining precise odour measurements remains an elusive target for researchers and regulators.

The only standardized approach which is internationally accepted in odour measurement is the dynamic olfactometry (CEN, 2003). This technique determines odour concentrations using the dilution-to-threshold principle, but still poses some challenges for measurements in field conditions (Smith *et al.*, 2007). Odour concentrations are directly related to odour intensity, but this relationship is not straightforward because intensity refers to an individual's perception of odour strength (Nicell, 2009). More specific information on the FIDOL components related with odour nuisances can be obtained only with alternative methods, which at present are not standardized. It would be therefore convenient to normalize field assessment techniques at an international level. In this sense, the Sniffing Team Method or plume measurements such as those established by the German VDI 3940 could be more realistic to evaluate the impact of livestock odour sources, which are by nature variable and discontinuous in time (Nicolas *et al.*, 2008).

Obtaining objective odour indicators seems crucial to identify effective mitigation strategies. To this aim, the relationship between odour perception and chemical compounds has been subject of intense research. This is a complex task because analytical techniques may fail to characterize the synergic effects among odorants. In addition, particulate matter could play an important role in odour perception (Bottcher, 2001; Nicell, 2009). Contrarily, some gases such as NH_3 and SH_2 are odour constituents, but they cannot be easily used as odour indicators, since their odour detection is relatively high (Smeets *et al.*, 2007; Blanes-Vidal *et al.*, 2009a) and their emission process may differ from the release pathways of most odorants (Le *et al.,* 2005; Blanes-Vidal *et al.*, 2009a). Recent studies have achieved high relationships (R^2 ~ 90%) between olfactometric measures and analytic analyses using gas chromatography – mass spectrometry (Blanes-Vidal *et al.*, 2009a; Zhang *et al.*, 2010). However, odorants may differ considerably among livestock species, and therefore using a generalized analytical measurement method for livestock odours seems at the moment not feasible.

Odour dispersion modelling

Fig. 2 summarizes the main factors which determine odour dispersion from livestock facilities. Weather conditions (mainly wind speed and direction, and atmospheric stability) constitute the main factor determining odour dispersion. Furthermore, other factors such as vegetation and topography also influence in a relevant way.

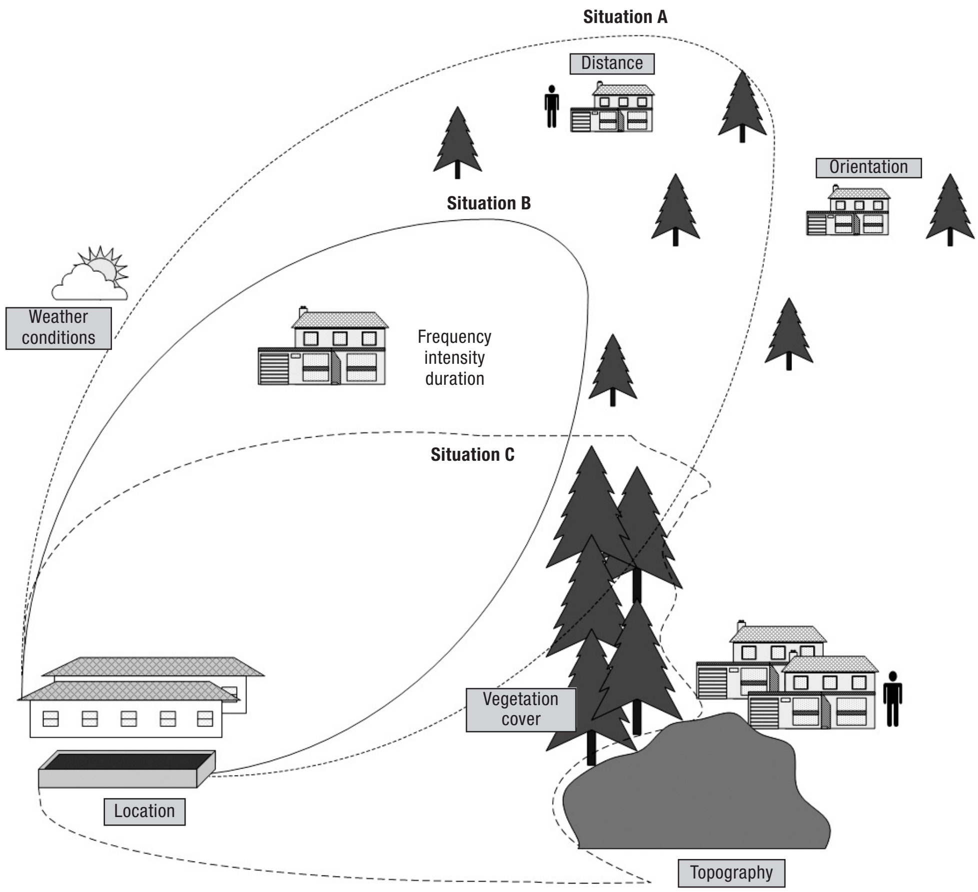

Figure 2. Elements affecting odour dispersion process in livestock confining operations. The odour plume under three hypothetical situations (A, B and C) illustrates the variability of odour exposure as a function of weather conditions, topography, vegetation and location.

According to Smith (1993), the dispersion of livestock odours differs from other atmospheric pollutants because of important particularities of odour sources, the nature of odours and the receptor characteristics. In contrast to industrial sources, livestock odour sources usually cover a large area at or near ground level and the plume rise is normally irrelevant. Furthermore, in livestock buildings odours are emitted from openings or fans in walls and roofs, forming complicated structures which are difficult to model (Yu *et al.*, 2010). Model validation is also complicated because of the challenges of odour measurements, as well as the spatial and temporal variability in emission rates. Finally, receptors may be relatively close to the source of emissions, and in this case conventional dispersion models are not reliable. For all these reasons, specific odour dispersion models are necessary.

In a recent review on livestock odour dispersion modelling, the major research gaps of research were examined (Yu *et al.*, 2010). Apart from the particularities of odour dispersion indicated above, these authors questioned the traditional use of Pasquill-Gifford coefficients in the Gaussian dispersion models. Atmospheric stability has a large influence on the dispersion results, but it seems too simplistic to describe it using the Pasquill's stability classification scheme. Finally, Yu *et al.* (2010) identified that the main drawback of most models is the long-time integration periods, normally from 10 to 60 minutes. Using these time integration periods, short-time concentration fluctuations are usually ignored by dispersion models. However, short-time fluctuations may influence considerably the nuisance potential (Nicell, 2009) and therefore should be considered when predicting the odour plume (Sykes & Gabruk, 1997; Mussio *et al.*, 2001).

In recent years, advances in computation have allowed the development and use of numerical dispersion models (Lin *et al.*, 2009; Hong *et al.*, 2011). However, a major challenge of odour modelling remains to be the proper validation between modelled data and real nuisance perceived by the population.

Abatement and control strategies in livestock housing

Overview of odour abatement strategies

A wide variety of odour prevention and control strategies have been studied in recent years. For every odour control strategy, it is necessary to consider the costs and the desired mitigation level, as well as the applicability to the overall farm management (Powers, 1999; Ullman *et al.*, 2004). Also, it must be accepted that only a partial reduction of odours can be achieved (Nahm, 2003). Three main ways are possible to minimize odour impact from livestock houses: reducing odour formation, using end of pipe techniques and enhancing dispersion. Odour formation can be reduced by means of dietary manipulation, additives, low-emission livestock housing and manure management systems. However, the effectiveness of these strategies may differ for different animal species. End-of-pipe techniques, such as air scrubbing, and manure covers have proved to be very effective to reduce odour emission. It is also possible to promote the dispersion of odours in the farm surroundings to reduce the nuisance potential at sensitive areas.

Dietary manipulation

Despite being relatively inexpensive, dietary strategies in livestock production may achieve important environmental benefits. It has been demonstrated that reducing crude protein (CP) can effectively reduce the proportion of excreted nitrogen, which is associated to lower ammonia emissions, not only at the housing level, but also during manure storage and land application of manure (Hayes *et al.*, 2004; Le *et al.*, 2007). However, the cause and effect relationship between feed characteristics and the excretion of odorous compounds is not so evident. Thus, there is no agreement about the effect of low-protein diets on odour compound profile.

Some studies such as those conducted by Hobbs *et al.* (1996) and Kerr *et al.* (2006), showed a decrease of odorant concentrations in growing and finishing pigs when using low-CP diets with amino acid supplementation. Feeding pigs with low crude protein diets reduced odour concentration from 30 to 80%, according to Hayes *et al.* (2004) and Le *et al.* (2007). On the other hand, some authors reported that odour concentration and offensiveness increased when low-CP diets supplemented with synthetic amino acids were used (Otto *et al.*, 2003; O'Connell *et al.*, 2006). Finally, other studies could not find differences in odour composition and magnitude when low-CP diets were used (Sutton *et al.*, 1999; Clark *et al.*, 2005; Leek *et al.*, 2007).

Some studies have evidenced the influence of the enteric microbial community on the excretion of odorous substances. O'Shea *et al.* (2011) found that chitosan inclusion in diets inhibited *lactobacilli* populations and this was associated to increased *Enterobacteriaceae* populations and odour emissions from manure. This suggests that lactic-acid bacteria may play an important role in mitigating manure odour emissions. Mc Alpine *et al.* (2012) found that the inclusion of xilanase (an enzyme which degrade beta-xylan into xylose) effectively reduced manure odour emissions. However, the inclusion of a protease did not influence odour emissions. Also, growth-promoting substances help to reduce odour emissions from pig slurry in a 53-56% (Nahm, 2002). However, as indicated by McCrory & Hobbs (2001) digestive additives do not constitute an alternative until a thorough understanding of microbial processes in livestock wastes is achieved and therefore more research is still needed on the effects and modes of action of specific microorganisms and enzymes.

The use of fermentable carbohydrates (FC) is effective to reduce ammonia volatilization, but they may also affect the odour emission profile (Le *et al.*, 2005). The increase of feed FC stimulates microbial activity in animal gut and in the manure, shifting the nitrogen balance from urine to faeces (Sutton *et al.*, 1999; Clark *et al.*, 2005). It has been widely demonstrated that FC incorporated into pig diets increases the volatile fatty acid (VFA) content in manure (Clark *et al.*, 2005; Kerr *et al.*, 2006; O'Connell *et al.*, 2006), but it remains unclear whether the odour profile is affected. Whereas Lynch *et al.* (2008) obtained a 41% increase of odour emissions when sugar beet pulp was added to pig diets, a non-significant effect of FC was found by Clark *et al.* (2005) and Le *et al.* (2007). As acknowledged by Leek *et al.* (2007) and Le *et al.* (2008), the balance between dietary FC and CP plays an important role on odour production and emission. However, this relationship must be further explored.

Manure additives

Manure additives are potentially effective tools to reduce atmospheric emissions from livestock production, particularly odours and ammonia. To be useful, these additives must be safe in the environment, inexpensive and easy to apply (Varel, 2002). These properties are appreciated by manufacturers and farmers, but in some cases the commercial confidentiality may involve a lack of standard, independent tests. McCrory & Hobbs (2001) reviewed the use of manure additives regarding ammonia and odour reduction. They concluded that only short-term odour control can be achieved using masking, disinfecting, and oxidizing agents. Frequent reapplication of additives is therefore required to maintain an acceptable odour reduction.

Wheeler *et al.* (2011) classified manure amendments into five categories: microbial, chemical, disinfectant, masking and adsorbents. As indicated by Mackie *et al.* (1998), livestock wastes constitute a dynamic environment in which aerobic and anaerobic microbial reactions occur. As a result of these reactions, VFAs are formed, most of which are offensive odorants. Therefore, manure additives corresponding on the first three categories above mentioned focus on inhibiting some of these microbial processes. According to Varel (2002) anti-microbial plant-derived oils may play a role in inhibiting odours. However, Amon *et al.* (1997) found no significant effect of using a manure additive based on an extract of *Yucca shidigera*, and similar results were obtained by Wheeler *et al.* (2011) for other additives. Also, masking agents (essential oils) and adsorbents (zeolites) have been reported to have limited odour reduction potential (Amon *et al.*, 1997; Wheeler *et al.*, 2011).

Animal housing

Animal housing and management systems influence the emission of odours. However, in contrast to the currently well defined "low-ammonia emission" housing systems, it is difficult to distinguish "low-odour emission" housing systems. The reason for this is the large variability within housing systems (Mol & Ogink, 2004). Generally, low-ammonia emission housing systems also reduce odour formation, but this relation is not always straightforward.

In pig production, reducing the surface contact between slurry and the air has been demonstrated to be effective to reduce not only ammonia, but also odour emissions by up to 50% (Ogink & Koerkamp, 2001). These systems include partial slatted floors, triangular-shaped gutters and frequent slurry removal by flushing.

It is generally accepted that odorous compounds are mainly produced when animal wastes are subjected to anaerobic conditions (Mackie *et al.*, 1998). Therefore, reducing moisture content of manure is effective to reduce odour production. This can be achieved by using bedding materials with a proper management (O'Neill & Phillips, 1991). Contrarily to ammonia emissions, specific research regarding the effect of bedding material on odour generation is scarce, and contradictory results have been obtained for pig and cow production (Ngwabie *et al.*, 2010; Wang *et al.*, 2011). For laying hens those systems including frequent removal, drying or mixing up with litter involved relevant odour reductions with respect to the conventional, long term manure storage (Ogink & Koerkamp, 2001). Finally, in broilers, a proper regulation of drinkers and refrigeration foggers is effective to control litter moisture. Establishing proper ventilation flows can also contribute by eliminating the excess of water and reduce odour generation (Ullman *et al.*, 2004).

Air cleaning systems

Air cleaning systems such as biofilters, scrubbers and biotrickling filters have been developed in the last decades to remove airborne pollutants from livestock facilities. In these systems the exhaust air is forced to pass through one or more sets of wet packing material in which certain pollutants are retained and eliminated. Despite their high investment and function costs, they are very effective to remove pollutants and their characterization is relatively easy in comparison with other odour mitigation techniques. However, these systems cannot be applied in naturally ventilated buildings.

The exhaust air of confined livestock buildings has normally high concentrations of ammonia, which is volatilized from the breakdown of urea and other nitrogen compounds of urine and faeces. To remove the ammonia from the air, chemical scrubbers have been designed, which use acid solution. Melse & Ogink (2005) reported an average ammonia removal efficiency of 96%, and according to Ogink & Aarnink (2007) they can also remove particulate matter by up to 90%. However, these systems are relatively inefficient to remove odours (typically about 30%) because only soluble compounds are removed, which does not include many odorants (Melse & Ogink, 2005). Recent studies have suggested that the addition of an organic solvent to the water phase could increase the availability of odour components to the bacterial population, enhancing the biodegradation of odour (Melse *et al.*, 2009). Biotrickling filters, despite the lower ammonia efficiency, are on average more effective to reduce odours than chemical scrubbers (Melse *et al.*, 2009).

Biofiltration is the most effective end-of-pipe technique to reduce odours. When the air passes through a wet organic packing material, odours are first retained in the material surface and then decomposed by microorganisms (Revah & Morgan-Sagastume, 2005). The reported efficiency lies within the range from 80% to 99%, depending on the packing material, its moisture content and the empty bed retention time (Chen & Hoff, 2009). To obtain maximum odour and ammonia reductions, these systems should be installed after a chemical scrubber, thus removing NH_3 and odours in two separate stages (KTBL, 2006).

Manure storage and treatment

Manure storage and treatment is considered a significant source of odour emissions in livestock facilities. However, the relevance of this source in comparison with livestock houses and land application is not well quantified in literature.

Among the available techniques for odour control in manure storage facilities, the use of covers to reduce gaseous emissions has been widely studied in recent years (VanderZaag *et al.*, 2008). These authors classify covers according to their origin. Covers of natural origin include naturally occurring crusts, straw and other crop residues, woodchips and sawdust, expanded clay, perlite, vegetable oils and aeration foam. Synthetic covers include permeable covers (plastic granules, rubber granules, hydrophobic powder) and impermeable covers such as plastic films. Finally, composite covers combine the best aspects different materials. The use of covers is attractive because of their low cost compared to other abatement strategies.

According to the revision conducted by VanderZaag *et al.* (2008), average odour reduction of different covers ranges between 40% and 90%. Several studies (Hudson *et al.*, 2008; Blanes-Vidal *et al.*, 2009b) support the idea that the main mechanism for odour reduction is that covers act as a physical barrier obstructing the free exchange of volatile compounds from the underlying liquid to the atmosphere. Moreover, these studies also indicate that natural covers may also reduce odours as a result of a biofiltration action of the cover itself.

However, further research seems necessary to overcome two main gaps of knowledge on the use of covers. On the one hand, the cross effect of different cover materials on greenhouse gas emissions should be better characterized. On the other hand, the overall performance of covers should be tested under a wide variety of conditions derived from different manure types, climate conditions or cover ageing. The use of covers may be of highest interest in those regions where large lagoons are used (*i.e.* intensive pig farming in Southern Europe and the USA). Maintenance of these covers may be a critical aspect of these covers, according to the tests made by Aguilar *et al.* (2012) for permeable and impermeable covers.

Other manure treatments, despite not being specifically designed to abate odours, may lead to odour emission reduction if they alter the anaerobic conditions or eliminate the precursors of odorous compounds. Solid-liquid separation can reduce odour emission, both as a stand-alone technique (Zhang & Westerman, 1997) or combined with anaerobic digestion (Hansen *et al.*, 2006). However, it can only be considered a mitigation technique if the separation process can remove the finest fraction of solids (particles smaller than 75 μm) to which VFAs are attached (Ndegwa *et al.*, 2002).

The aerobic treatment oxidizes manure organic materials into stable products by aerobic bacteria (Westerman & Zhang, 1997). This process stabilizes the manure and does not allow the accumulation of VFAs and other odorants. When the waste is stabilized, it can be stored for a long period without emitting relevant odours. In this technique, the main decision is to balance the need of a minimum aeration time with the increasing cost of long aeration times (Westerman & Zhang, 1997; Zhang *et al.*, 2004).

In contrast to the aerobic treatment, anaerobic digestion promotes the production of VFA as a substrate for methane and carbon dioxide production. Because the degradation of VFAs is enhanced during this process, the odour release potential of the digestate during subsequent storage and land application is lower than the undigested materials (Hansen *et al.*, 2006). Considering the low odour emission potential of digested materials, the management of undigested materials (slurries and co-substrates) becomes crucial to complete an effective odour mitigation strategy in the farm.

Windbreaks

It has long been demonstrated that windbreaks alter the air turbulence (Seginer, 1975), but their effectiveness to enhance odour dispersion and reduce nuisances has not been studied until the last decade. Windbreaks and shelterbelts around livestock units are normally vegetation systems that redirect wind and reduce wind speed. This effect on wind modifies environmental conditions upwind and downwind sheltered zones, and thus changes the dispersion of odours (Tyndall & Colletti, 2007). Windbreaks not only enhance dispersion by promoting air turbulence, they also serve as a filtration barrier where particulate matter and odours are partly retained. A wind-break positioned near an odour source can reduce the downwind length of the odour dispersion plume, as evidenced by field measurements and model simulations (Lin *et al.*, 2006). They are also applicable at reasonable costs (Tyndall & Grala, 2009).

Quantifying the odour mitigation potential of windbreaks is extremely complicated, and depends on shelterbelt characteristics and weather conditions. This has been studied using numerical models (Lin *et al.*, 2007; 2009) or scaled wind tunnel tests (Ikeguchi *et al.*, 2003). Odours are better dispersed using dense and high windbreaks, located near the odour emitting source (Lin *et al.*, 2007).

The potential reduction of odour dispersion by windbreaks is evident and, considering its low implementation cost, this technique can be recommended to reduce odour nuisances. However, standardizing this technique in practice is challenging. There is still a lack of scientific knowledge measure in practice how the specific environmental conditions are affecting the wide range of possible windbreak types and dispositions.

Research needs and future priorities

Recent research on odour science in livestock production has significantly improved our knowledge on odour nature, measurement techniques, dispersion modelling, and mitigation techniques. It is remarkable that the range of available mitigation techniques is nowadays not significantly different from those proposed a number of years ago (O'Neill & Phillips, 1991; Powers, 1999). As it is now accepted, these authors also considered the relevance of feeding strategies, livestock housing, air filtering, additives, manure covers, manure management systems and windbreaks, among others. Many of these abatement techniques were primarily developed to reduce ammonia emissions. However, research so far has given us an insight into the fundamentals and potentials of those techniques to abate odours. The combination of more accurate measurement methods and computer advances has provided the opportunity to quantify the potential odour mitigation of different strategies and to assess the nuisance potential in farm surroundings using numerical dispersion models. However, efforts are required to overcome some aspects for which scientific knowledge is still incomplete, such as odour measurements and error analysis.

Despite the advances in odour science, odour measurement still poses a challenge for researchers. Similar to other atmospheric pollutants of agricultural origin, odour emissions are highly variable and in many cases difficult to trace because of the diffuse nature of their sources. In contrast to other atmospheric pollutants, which can be analytically determined with precision, the subjective component of odour perception makes progress more difficult. The relationship among odorant substances, odour concentration and odour intensity is now better understood, but measurement errors are still too large to detect relatively small effects of abatement techniques (Clanton *et al.*, 1999; Boeker & Haas, 2007; Banhazi *et al.*, 2009). It is also still necessary to quantify more precisely and at reasonable costs the other components of nuisance potential, namely frequency, duration and offensiveness. It is reasonable that adopting standardized field olfactometry techniques would allow obtaining better estimations of the odour impact in the surroundings of diffuse sources. In this sense, adopting an internationally standardized field assessment method seems an essential requirement to adopt a common strategy (for example at the European Union level) to abate odour nuisances.

Quantifying errors of odour estimations may be of highest interest for scientists and policy makers. To this aim, uncertainty analysis can be performed according to the concepts and procedures defined by the *Guide to the expression of uncertainty in measurement* (ISO, 1995). Although for odour emissions such an analysis is at present missing, potential uncertainty sources of odour impact assessment are outlined in

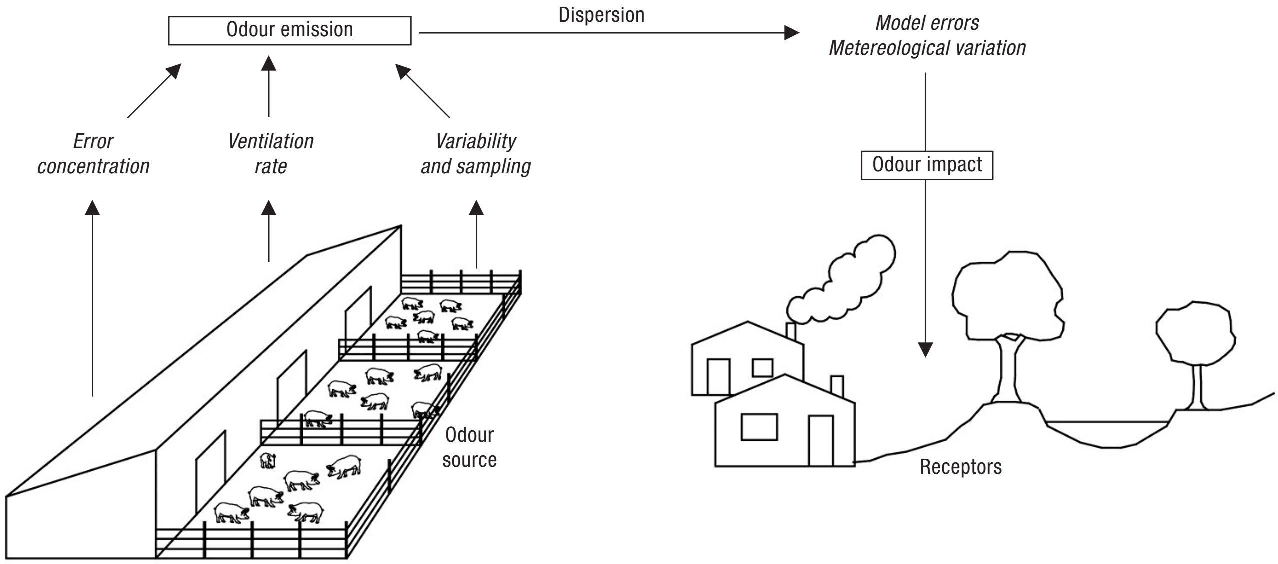

Figure 3. Overview of uncertainty sources in the determination of odour impacts.

Fig. 3. As an example, Boeker & Haas (2007) found that lower and upper limits of measurement uncertainty, expressed as a percentage of the odour concentration, were 25% and 400% respectively. Obviously, this level of uncertainty makes difficult establishing comparisons among alternatives to reduce odour emissions at farm level.

Apart from measuring odour concentrations, researchers find other two important sources of uncertainty when determining odour emissions from livestock buildings. The first source is the intrinsic variability of odour emissions as a function of interrelated factors such as air temperature and manure management, among others. Because of this variability it is complicated to obtain a representative air sample, which leads to important sampling errors. The second source of uncertainty is the measurement of ventilation rates. In mechanically ventilated buildings this uncertainty has been reported to be at best 5-10% of the measured ventilation, but in naturally ventilated buildings measurement errors may be considerably higher (Van Buggenhout *et al.*, 2009). Very open, naturally ventilated livestock houses are currently an interesting alternative against intensively controlled buildings, particularly in cattle and pig buildings. However, in these systems measuring ventilation flows and odour emission rates is extremely uncertain, and therefore it is a challenge for researchers to characterize these systems in terms of odour production.

When determining odour nuisance potential using dispersion modelling, the corresponding modelling errors are added to the aforementioned odour emission uncertainty. However, the contribution of each individual uncertainty source to the final error of modelled nuisance potentials is to the moment unknown. Quantifying the uncertainty of modelled odour nuisance potentials and determining the contributions of each individual source would contribute to establish research priorities conducting to reduce the most relevant errors. This would also undoubtedly lead to a better understanding of the problem by researchers, farmers and policy makers.

Conclusions

The range of available mitigation techniques is nowadays similar to those proposed a number of years ago. However, recent research on livestock odours has significantly improved our knowledge on odour nature, measurement techniques, dispersion modelling, and mitigation techniques. Accepted odour abatement strategies at farm level are: feeding strategies, livestock housing, air filtering, digestive and manure additives, manure covers, manure management systems and windbreaks. Although these techniques are known for years, research so far has given us an insight into the fundamentals and potentials of those techniques. Despite this increasing knowledge of odour abatement strategies, their effective implementation at farm level needs a definite commitment of farmers and regulators. Research also indicates that odour problems must be considered from a global perspective because odours are emitted through all the manure management system.

As reviewed in this work, recent advances are unquestionable. However, further research efforts are required to overcome some aspects for which scientific knowledge is still incomplete. Measurement methods are still strongly conditioned by the subjective character of odour perception. Livestock odours are variable and discontinuous by nature, and therefore the existing standard methods of odour assessment may be inadequate. Although livestock odours constitute a local problem, a standardized field assessment method could be the basis of an internationally accepted odour regulation strategy, which allows comparisons among studies. As a consequence of the subjective nature of odours and the intrinsic variability of emissions and climate conditions, determining odour nuisances is usually associated to high uncertainties. Quantifying these uncertainties and identifying the most relevant uncertainty sources can be useful for scientists to establish research priorities and policy decisions.

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