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Control of odour and gaseous emissions from livestock buildings: Recent research and developments

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Abstract: One major challenge in the continuous growth of the livestock industry is the increased emission of odorous gases, which is not just a nuisance but also a cause of serious health and environmental concerns. Several strategies which aim to: (*i*) reduce the formation of odorous gases; (*ii*) enhance dispersion of odour; (*iii*) capture odour and gases to prevent escape to the environment; and (*iv*) reduce odour and gaseous concentrations, are developed. These are achieved with the use or employment of one or more of: (*i*) diet manipulation techniques; (*ii*) additives and adsorbents; (*iii*) covers; (*iv*) shelterbelts or windbreaks; (*v*) ventilation systems; (*vi*) biofilters; and (*vii*) air scrubber. The advantages and limitations of each of these strategies are discussed in this review in order to guide the choice of which strategy to use in a specific livestock application. Moreover, this review also discusses potential researchable areas in the field of odour control in livestock facilities.

Keywords: air scrubber; biofilter; biotrickling filter; diet manipulation; odour control; shelterbelts

Livestock industry is a vital agriculture subsector as it constitutes approximately 13% of the total food calories and 32% of the dietary protein in human food consumption around the world (Smith et al. 2013; FAO 2023). On a global scale, livestock production accounts for 40% of the total agricultural gross domestic product (GDP) (Salmon et al. 2020). Specifically, it employs about 1.3 billion people across the world where an estimated 600 million poor smallholder farmers are from the developing countries (Thornton 2010) where it is a vital source of livelihood, especially for rural dwellers, women and pastoralists groups (Herrero et al. 2012).

In the report of FAO (2023), livestock meat (i.e. pig and cattle meat) constitute a total of 54% of the world meat production which reached 357 million t in 2021. This level of production is approximately 33% higher than the livestock meat production in 2000. Similarly bovine milk production increased by 58% in 2021 relative to its value in 2000. These statistics reveal that the livestock sector is a fast growing agriculture subsector (Delgado 2005). This increase may be attributed to increasing global population, urbanisation, rising incomes, and changing dietary patterns (Robinson et al. 2011; Gerber et al. 2013). However, along with this growth is the problem of excessive odour, particulate matter (PM) and gaseous emissions (Rahman and Borhan 2012; Van der Heyden et al. 2015) which affect the animals, human health, the community and the environment.

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This mini-review briefly tackles the sources of odour and gaseous emissions from livestock facilities as well as the various strategies that have been developed and employed to control them. Different strategies and best available technologies (BAT) are compared based on their effectiveness, applicability and the mechanisms by which odour and emission control is achieved. This also provides information on the knowledge gaps that need to be bridged, hence guiding researchers on the promising research areas in this field.

ODOUR AND AIR POLLUTION

Developing strategies to control odour necessitates a good understanding of its sources, components and the mechanisms by which it is produced, dispersed and emitted to the environment. The odour compounds from livestock facilities are generally classified into: (*i*) volatile fatty acids (VFA); (*ii*) aromatic compounds; (*iii*) nitrogen-containing compounds; (*iv*) alcohols; and (*v*) sulfur-containing compounds (Mackie et al. 1998; Le et al. 2005; Rappert and Müller 2005). Mackie et al. (1998) discuss in greater detail how these odorous components are produced from the livestock facilities and will not be elaborated in this review. Moreover, measurement techniques and dispersion models describing their temporal and spatial distribution are tackled elsewhere (Conti et al. 2020).

The major source of these odour compounds in livestock systems is the manure (Mackie et al. 1998). Odour from manure is generated from the incomplete and slow anaerobic degradation of organic matter (i.e. protein, carbohydrates and fats) (Varel 2002). Aside from manure, odour may also come from animal skin and feed storage (Powers 1999; Kai et al. 2006).

In swine houses and cattle sheds, another source of odour is animal slurry which contains urine, water and feces. Pig slurry emits gaseous pollutants such as methane, carbon dioxide, nitrous oxide, ammonia, hydrogen sulfide and other odorants (Casey et al. 2006; Osorio et al. 2009; Marszałek et al. 2018). In dairy cattle manure, odorous volatile organic compounds (VOCs) often consist of dimethyl sulfide, acetone, formaldehyde and acetaldehyde (Aizawa et al. 2022). Among these gases, ammonia is a major concern because agriculture is considered to be the biggest contributor to ammonia pollution (Guthrie et al. 2018) and it is a good indicator of odour concentration and odour emission (Huang and Guo 2017). It is from the degradation of nitrogenous compounds like uric acid, undigested proteins and urea in the animal excreta (Wood and Heyst 2016; Sousa et al. 2017).

The threshold value of ammonia concentration that is considered potentially harmful to both animals and humans occupying the facility is 25 ppm, as recommended by Occupational Safety and Health Administration of the United States of America (Groot Koerkamp et al. 1998; Konapathri and Azimov 2024). In sealed broiler and laying hen houses in Taiwan, Cheng et al. (2011) report ammonia concentrations of up to 12.5 ppm while up to 500 ppm at 10 cm above the manure disposal sites. On the other hand, mean ammonia concentrations measured in Northern Europe by Groot Koerkamp et al. (1998) are up to 8 ppm for cattle, 5–18 ppm for swine and 5–30 ppm in poultry houses. Additionally, it was observed in the dairy farms in Poland that maximum ammonia concentration of 16 ppm is usually measured in autumn and winter (Wlazło et al. 2020). Meanwhile, in a swine house in Rongchang, Chongqing, China, ammonia concentration was in the range of 1–21 ppm (Peng et al. 2023). These values are close to the 25 ppm-limit and therefore emphasize the need for odour and gaseous emissions control.

In general, the intensity of odour formation and emission from livestock facilities including manure storage is a function of many factors including temperature, seasonal variations, ventilation rate, period of animal growth, diet of animals, animal activity, type of housing system, feed type, and manure handling systems, among others (Jacobson et al. 2003; Phung et al. 2005; Banhazi et al. 2011; Mihina et al. 2012; Huang and Guo 2017). This immense number of factors and the complex interaction among them make prediction and estimation of odour and gaseous emission difficult, and will not be tackled in detail in this review.

IMPACT OF ODOUR AND AIR POLLUTION

Odour and air pollution negatively affects the health of animals, the farm workers and the immediate and nearby environments. This highlights and justifies the need for an effective odor and gaseous emission control strategies and technologies.

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Animal performance

Odour and air pollution in livestock facilities affect the production performance of the animals. Harmful gases like ammonia may decrease feed efficiency and growth rates among animals (Osorio et al. 2009). These gases may reduce appetite, stress and weaken the animal immune system making them vulnerable to diseases like eye and skin irritation, calluses in the chest, conjunctivitis and respiratory issues, among others. Specifically, Miles et al. (2004) observe that 25 ppm ammonia level in a broiler house results in a significant reduction in the body weight of the broilers (~ 90 g per bird). At 100 ppm concentration, ammonia may cause death even under short-term exposure (Groot Koerkamp et al. 1998). This reduction in weight caused by these harmful gases may lead to economic and financial losses in the production.

Human health

More than the annoyance and stress, unpleasant odour in general may cause adverse effects to human health and overall quality of life (Blanes-Vidal et al. 2012). The first group of people at risk of the health impact of odorous gases and air pollutants in animal raising facilities are the workers (Mulhausen et al. 1987). Risk of respiratory illnesses with symptoms such as chest tightness, wheezing, coughing and excess sputum production increases with constant exposure to odorous gases. Aside from respiratory illnesses, gastrointestinal illnesses and immunologic problems are also possible (Andersen et al. 2004; Thorne 2007). Aside from odorous gases, pollutants such as particulate matter (PM_{10} and $PM_{2.5}$) are hazardous to humans with pre-existing cardiopulmonary conditions like asthma (Schwarze et al. 2006) and may also affect other organs such as liver, kidneys and the nervous system (Koren and Bisesi 2003).

Moreover, airborne antibiotic-resistant bacteria can also be emitted from livestock buildings, harming not just the workers inside the facilities but also the general public (Donham et al. 2006; Gibbs et al. 2006; Guo et al. 2022). Specifically, Donham et al. (2006) and Gibbs et al. (2006) observe that air sampled from areas approximately 4 800 and 150 m from confined animal feeding operations (CAFOs), respectively, contained antibiotic-resistant bacteria while Schinasi et al. (2011) report that people near CAFOs areas show respiratory symptoms typically observed among swine workers and veterinarians.

Environment

Among the gaseous pollutants emitted from livestock buildings are methane, carbon dioxide and nitrous oxide which are considered greenhouse gases (GHGs) and therefore may contribute to greenhouse effect (Dobeic 2011; Marszałek et al. 2018). The livestock sector is known to have an estimated share of 14.5% in the global anthropogenic greenhouse gas emissions (Gerber et al. 2013), but recent analysis of Twine (2021) updated the figure to 16.5% . Although ammonia is not a greenhouse gas, Battye et al. (2003), Faulkner and Shaw (2008) and Groot Koerkamp et al. (1998) report that livestock operations such as cattle, swine and poultry productions are the leading source of ammonia emission in the environment. Approximately 30–55% of the global ammonia emission is from livestock and storage systems (Beusen et al. 2008). Specifically, their ammonia emission rate is estimated at 7–70 kg/cattle/year, 4–17 kg/swine/year and 0.1–0.45 kg/bird/year in the United States for the period of 1994–2003. Moreover, about 75–85% of the total ammonia emission in The Netherlands, United States and Canada is from livestock farming (Groot Koerkamp et al. 1998; Fabbri et al. 2007; Bittman and Mikkelsen 2009). In the 28-member countries European Union, about 75% of the total ammonia emission is from livestock production activities (Webb et al. 2005).

Aside from its atmospheric effect, ammonia emitted from livestock operations causes groundwater contamination and is associated with the eutrophication in water bodies (Groot Koerkamp et al. 1998; Sousa et al. 2017). Moreover, ammonia causes soil acidification and contributes to the deterioration of metal equipment and parts (Sousa et al. 2017).

ODOUR AND EMISSION STRATEGIES

Various strategies are employed in controlling odour and gaseous emission from livestock facilities (Table 1). Their advantages and disadvantages are tackled in order to provide an idea on which strategy or combination of strategies may be best employed for a particular livestock application. These strategies are aimed at: (*i*) reducing the formation of odour; (*ii*) enhancing dispersion; (*iii*) capturing odour and gases to prevent escape to the environment; and (*iv*) reducing odour and gaseous concentrations (Ubeda et al. 2013; Liu et al.s 2014).

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Table 1. Summary of the advantages and disadvantages of the different odour control strategies

Odour control strategy	Advantages	Disadvantages
Diet manipulation	Reduces odour production at the source Easy to employ	Does not completely eliminate the generation and emission of odour Has the potential to negatively affect animal productivity (i.e. carcass traits)
Use of additives	Easy to apply There are inexpensive additives	Pollutant-specific (i.e. may only be effective in mitigating specific pollutants) Short effectiveness period (up to 7 days)
Use of adsorbents	Easy to apply (i.e. either as an additive or a filtering media)	Needs more work to ascertain its effectiveness and to make it practical and economical
Use of covers	Natural covers are inexpensive and may be readily available Synthetic and impermeable covers have long useful life (i.e. 5–10 years)	Natural covers only last up to 6 months hence diminishing odour reduction efficiency Odour reduction efficiency is a function of thickness and uniformity Synthetic covers may be costly Installation of impermeable covers is costly and management requires additional equipment
Shelterbelts	Can provide long-term interception of odour and gaseous emission Can beautify the surroundings	May serve as potential habitat for pest May serve as obstruction during operations involving large farm equipment
Ventilation	May be natural or mechanically ventilated	Requires optimization of the ventilation rate since very high rates may lead to higher ammonia emission to the environment
Biofilter	May employ readily available organic packing materials (i.e. compost, soil, peat, etc.) Effective in reducing particulate matter, cultivable microbes, ammonia and odour	Potential for compaction of the bed that leads to increased pressure drop May incur large physical footprint Unsuitable for exhaust air with high amount of dust particles Applicable only for mechanically ventilated livestock housing
Air scrubber/ biotrickling filter	Can cause adsorption of specific pollutants in gaseous emission that cannot be adsorbed in a conventional biofilter	May require more attention during operation due to the presence of liquid phase that may contain acid Biotrickling filter is more prone to excessive biomass accumulation in the bed that increases pressure drop Synthetic packing material may be more expensive than the organic ones employed in a conventional biofilter Applicable only for mechanically ventilated livestock housing

In selecting the strategy or combination of strategies for odour control, key factors to be considered include the cost, the desired level of odour and pollutant reduction and their suitability to the overall livestock management system (Powers 1999). In particular, some strategies are appropriate only for liquid systems while others are well suited to systems with little or no biological processes involved, while others are only compatible for a specific ventilation system (i.e. mechanical or natural ventilation) (Powers 1999).

Diet manipulation

Since the undigested feed components from animal excreta constitute the major source of odorous compounds (Sec. 2), diets may be modified in order to improve nutrient efficiency among the animals. Specifically, the objective is to minimise overfeeding and excretion of undigested feed that serve as substrates for microbial anaerobic degradations, while ensuring that essential nutrients and energy are still provided for animal growth (Liu et al. 2014; Sharma et al. 2017).

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To achieve the above objective, the amount of crude protein (CP) which is usually fed in excess to ensure animal productivity as well as to satisfy the safety margins recommended by feeding industries, is reduced in new feed formulations. Excessive CP leads to more nitrogen in the manure and subsequent increase in ammonia emission (Vuuren et al. 2015). In swine raising, reducing protein content accompanied with supplementation of essential amino acids results in reduced nitrogen excretion (Nahm 2003; Madrid et al. 2013; Montalvo Bermejo et al. 2013). Hobbs et al. (1996) demonstrate that modifying the diet of growing (35–65 kg) and finishing (65–95 kg) pigs by reducing the amount of nitrogen and providing essential amino acids results in the reduction of their nitrogen excretion as compared to pigs fed with commercial diets. Similar results are observed for nursery pigs (Cho et al. 2008) and finishing pigs (Leek et al. 2007) where reduction in the CP content of the diet also results in decreased ammonia, hydrogen sulfide and VFA emissions in feces. Cho et al. (2015) explain that this is due to the changes in bacterial communities which occur with the reduction of CP levels from 20 to 15%. Specifically, bacteria such as *Ruminococcaceae*, *Bacteroides* and *Pseudomonas* and odorous pollutants such as phenols, indoles, short-chain and branched-chain fatty acids are lowest for slurry and gas samples from treatment with 15% CP as compared to 20% CP (Cho et al. 2015). Hansen et al. (2014) add that reduction of CP levels while supplementing amino acids in the diet has no negative effects on growth, feed utilization and meat percentage of pigs.

Aside from avoiding excessive protein in the diet, dietary supplements like phytase and organic forms of Cu, Zn, Fe and Mg also show potential in reducing nitrogen and phosphorus in the manure (Sutton and Richert 2004). Phytase reduces phosphorus excretion by up to 35 and 60% in chicken and pigs, respectively (Nahm 2002).

Meanwhile, as compared to a diet based on cereals, a high-fiber diet based on sugar beet pulp reduces ammonia emission but increases methane emission in gestating sows and fattening pigs. However, a high-fiber diet adversely affects the growth performance and carcass traits, specifically of the fattening pigs (Philippe et al. 2015). Nahm (2002) add that improving the digestibility of raw materials in feed through grinding and reduction to the correct particle size through expanding or pelleting can contribute to the reduction of nitrogen, phosphorus and other odour contents of both chicken and pig manure.

In summary, diet manipulation is advantageous because it minimises odour production at the source, by reducing nitrogen input (Chadwick et al. 2011). Nevertheless, this does not completely eliminate the generation and emission of odour from livestock buildings, hence other strategies may be necessary.

Use of additives

The reduction of odour and gaseous emissions during transport, storage, agitation and land application of manure may be accomplished with the use of chemical or biological additives. These additives either aid in oxidising volatile organic compounds or modify the biochemical pathways leading to odour production (Janni 2020). Generally, an additive must be safe to the environment, easy to apply and inexpensive (Varel 2002). Common additives used in the livestock industry include water, salt water, artificial spices and essential oil (Kim et al. 2008; Cheng et al. 2011).

Occasional water spraying employed by Cheng et al (2011) in sealed broiler and laying hen houses results in 30–50% ammonia removal efficiencies. On the other hand, salt water reduces up to 35% of ammonia generation while artificial spice reduces odour intensity and offensiveness by up to 80% and essential oil reduces sulfuric compounds for 24 h after spraying (Kim et al. 2008).

Chemical additives may also be used to deodorize livestock facilities. Yan et al. (2016) employ an enzyme lignin peroxidase with either hydrogen peroxide (H_2O_2), calcium peroxide (CaO_2), or sodium percarbonate ($2Na_3CO_3{\cdot}3H_2O_2$) as electron acceptor in reducing odour from pig manure. Reduction of 16–90% in ammonia and hydrogen sulfide as well as other odorous compounds such as propionic acid, isobutyric acid, isocaproic acid, isovaleric acid, phenol, p-Cresol, indole, and skatole is obtained and lasts for 72 hours.

Although relatively easier to employ as compared to other odour control technologies (Maurer et al. 2017), chemical additives are expensive and may only be effective in mitigating specific pollutants and the effectiveness period is usually short and can only be up to 72 hours (Rahman and Borhan 2012). Other chemical additives used for disinfecting include chlorine, hydrogen cyanamide, potassium

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permanganate, and ozone (McCrory and Hobbs 2001; Rahman and Borhan 2012).

Alternatively, microbial additives may also be used for deodorisation of animal housing (Gutarowska et al. 2014; Choi et al. 2015; Borowski et al. 2017). Borowski et al. (2017) employ microbial additives in three forms: (*i*) spray-dried microcapsules; (*ii*) mineral carrier and (*iii*) freeze-dried powder, composed of microorganisms such as *Pseudomonas fluorescens, Enterococcus faecium, Bacillus subtilis, Bacillys megaterium, Leuconostoc mesenteroides* and *Lactobacillus plantarum*. With the addition of perlite-bentonite mixture as sorbent to the mineral carrier and spray-dried microcapsules, the ammonia and hydrogen sulfide concentration in exhaust air is reduced by over 90 and 60%, respectively.

Kalus et al. (2017) demonstrate that while microbial-mineral litter additive consisting of 20% bacteria powder and 80% mineral carrier can reduce VOC levels by up to 96%, its efficacy is relatively short as indicated by decreasing VOC reduction efficiency on day 7^{th} day after application. On the other hand, the commercial microbial additive used by Rahman et al. (2011) is not effective in the reduction of ammonia, odour and hydrogen sulfide emission from farrowing-gestation swine operation, thereby recommending the test of an application rate higher than what was recommended by the manufacturer (Digest3+3) (~ 23 kg/month).

Another additive that can be directly applied to the surface of manure is the non-activated, non-functionalized biochar, which can yield ammonia reduction by up to 23%, accompanied by 25% increase in methane generation (Maurer et al. 2017). In composting, biochar aids in microbial activity (Sánchez-García et al. 2015), particularly favoring the growth of fungi and reducing the composting time without significant nitrogen losses (Jindo et al. 2012; Sánchez-García et al. 2015). Due to its high sorption characteristics, it may contribute to the absorption of VOCs (Kumar et al. 2019) that are in the gaseous emission. Overall, the use of biochar is an economically feasible option for odour and gaseous emission control (Maurer et al. 2017).

Other additives used to reduce ammonia volatilisation and nitrogen losses during composting include: wood fly ash, lime, jaggery, phosphorgypsum, polyethylene glycol (Gabhane et al. 2012), zeolite (Cai et al. 2007), and bentonite (Li et al. 2012). Jaggery and polyethylene glycol help in facilitating microbial growth and cellulose activity thereby producing higher quality compost than other additives tested (Gabhane et al. 2012). Li et al. (2012) demonstrate that up to 2.5% bentonite (by weight) as additive may aid in organic matter degradation, increase Total Kjeldahl Nitroten (TKN) content and decrease C/N ratio. However, none of these studies specifically looked into the ability of these additives to mitigate ammonia volatilisation. Zeolite addition of up to 10% by weight reduces odour in a simulated poultry manure storage by up to 67% (Cai et al. 2007) while ammonia emission is reduced by up to 70% at the same zeolite concentration in the study of Liang et al. (2005). Moreover, the adsorptive characteristics of zeolite aid in the adsorption of VOCs in the gaseous emissions (Liang et al. 2005; Cai et al. 2007).

Use of adsorbents

Adsorbents like zinc oxide (ZnO) nanoparticles also show potential in reducing hydrogen sulfide from odorous gases. These nanoparticles can either be directly added to the manure or be used in the ventilation system as a filtering media for exhaust gases (Predicala et al. 2012). When used as a filtering media, the performance of the adsorption systems is a factor of gas flow rate, hydrogen sulfide concentration, temperature and particle size of ZnO nanoparticles (Awume et al. 2017). Specifically, when used in the fluidised bed air filtration system (FBAFS) at a loading rate of 0.28 $g \cdot cm^{-2}$ filter area, 65 and 40% hydrogen sulfide and ammonia reductions are achieved, respectively (Alvarado and Predicala 2017).

When used as an additive in swine manure at a rate of 3 $g \cdot L^{-1}$ manure slurry, ZnO nanoparticles show significant reduction in hydrogen sulfide and ammonia and the effectiveness last up to 15 days. Moreover, the performance of the pigs and the properties of the manure were not negatively affected by its addition (Alvarado et al. 2014). Other adsorbents tested for odour reduction in manure include zinc silica nanogel, copper silica nanogel, and silver nanoparticles which reduce odorous gases by inhibition of microbial activities as shown by up to 90% reduction in aerobic and anaerobic microbial populations (Sarker 2018). Although, nanoparticles show potential for odour control, it has not been widely used for livestock applications as more work needs to be done to make its application practical and economical.

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Use of covers

Covering materials can also be used in controlling odour and gaseous emissions from manure storage facilities. The covers are either made of natural or synthetic materials, and may either be permeable or impermeable with varying degree of flexibility and rigidity (Janni 2020). Permeable covers include straw, geotextile, clay balls, perlite, rigid foam, oil, natural crust, and other residuals like corn stalks, sawdust, wood shavings, rice hull, corncobs and grass clippings (Nahm 2003; English and Fleming 2006; Hudson et al. 2006).

Depending on the permeability of covering materials, covering the manure storage with litter materials like sawdust can reduce nitrogen by over 20% and consequently reduce odour production (Nahm 2003). In addition, supported straw cover surfaces and non-woven, spun fibre polypropylene weed control material reduce odour emission by up to 8 times than the uncovered anaerobic pond (Hudson et al. 2006). Similarly, synthetic covers like geotextile and polyurethane foam also show potential in reducing emission of odour and total reduced sulfur (TRS). Moreover, these two covers show better performance in terms of reducing hydrocarbon emissions than the natural ones (Regmi et al. 2007). Geotextile membrane which is made from nonwoven fabric composed of polypropylene filaments, is a promising covering material due to its resistance to moisture and chemical attack, its self-floating characteristics and its effectiveness in odour and hydrogen sulfide emission reduction (Nicolai et al. 2004). Moreover, the biofilm growth on its surface can self-seal the cover (Clanton et al. 1999). However, Bicudo et al. (2004a) argue that this biofilm growth may lead to gas buildup and gas exit along the sidewalls, thereby reducing the effectiveness of the cover with time. Although not as effective as straw and geotextile, another floating cover used in livestock odour control are clay balls (with 1.9 to 2. 5 cm diameter) which are impermeable to water and other fluids (Clanton et al. 1999).

Although natural covers are less costly than the synthetic ones, natural permeable covers do not last long (i.e. 2–6 months) (Bicudo et al. 2004b). In particular, the odour reduction efficiency of straw cover diminishes with time due to saturation and sinking (Bicudo et al. 2004b). Moreover, its efficiency depends on the thickness and uniformity, with thicker layers having higher reduction efficiency (Clanton et al. 2001; Nicolai et al. 2004). Although costly, the usable life of synthetic cover like geotextile can be up to five years (Nicolai et al. 2004) while perlite which can also reduce odour and ammonia emission by up to 90% has 10 years of useful life (Hörnig et al. 1999).

On the other hand, impermeable covers may completely prevent emission of odorous gases but its installation is costly and additional equipment may be necessary to manage the gases generated inside, the precipitation on top and the insects and animals that may walk on the cover (Janni 2020). Impermeable covers include plastics which can either be inflatable, floating, or suspended. It can also be made of concrete, wood or steel (English and Fleming 2006). Although expensive, the plastic impermeable cover can have life expectancy of up to 10 years (Nicolai et al. 2004). Concrete, wood and steel lids are also capital intensive but can last up to 15 years (Nicolai et al. 2004). Steel, however is rarely used due to the potential of corrosion when exposed to ammonia (English and Fleming 2006).

Shelterbelts/windbreaks

A strategy that aims to enhance dispersion of gases coming from livestock facilities involves the introduction of shrubs and trees arranged and designed in a manner that intercepts, disrupts and dilutes odour and gaseous emissions, and is known as shelterbelts or windbreaks (Tyndall and Colletti 2007). In diluting odour and gaseous emissions, these shelterbelts act as permeable filter for dust particles coming out of the livestock facilities (Powers 1999). Moreover, shelterbelts may change wind directions and/or reduce wind speed, thereby affecting the dispersion of gases and reducing nuisance odour to the nearby community (Brandle et al. 2004). VOCs may also be adsorbed and absorbed by the leaves of the shelterbelts (Reischl et al. 1989) and may be degraded by the microbial community.

The ability of the shelterbelts to perform the above functions is a function of external characteristics such as height, width, number of rows, species of trees and shrubs, length, orientation and continuity (Heisler and Dewalle 1988; Tyndall and Colletti 2007). Moreover, the porosity which is defined as the ratio of the perforated area to the total area also greatly influences the effectiveness of the shelterbelts (Heisler and Dewalle 1988), with 40–60% as the ideal value (Brandle et al. 2002). Shrubs and trees with height of 6–9 m (Heisler and

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Dewalle 1988) and conifers that have complicated geometry and large circumference to area ratios are ideal as shelterbelts (Smith 1993).

Overall, shelterbelts can intercept odour and gaseous emissions on a long-term basis (Tyndall and Colletti 2000), beautify the surroundings and can limit the view of livestock operations which is otherwise nuisance for the community (Powers 1999). However, aside from the added maintenance labor in the form of branch trimming, shelterbelts may serve as a potential habitat for pests and may serve as obstruction when farm equipment are used (Tyndall and Colletti 2000).

Ventilation

A basic engineering approach to control odour and gaseous emission is the installation of mechanical ventilation system in the animal housing. A ventilation system dilutes the concentration of the pollutants in the air through introductionof fresh air into the indoor environment (Wood and Heyst 2016). The dilution and the concentration of particulate matter and other gases inside the facility varies depending on the location of the air inlets of the ventilation system (Tan and Zhang 2004). Hence, if a more uniform dilution is desired, more air inlets need to be installed at different locations in an animal housing.

The ventilation rate is also a primary parameter that affects the effectiveness of a ventilation system. Higher ventilation rate results in lower PM concentration but caution should be observed as increase in PM concentration may occur beyond a threshold ventilation rate, potentially due to the resuspension of PM from surfaces (Wang et al. 2002). Moreover, although higher ventilation rates dilutes ammonia concentration inside the livestock building, it does not significantly reduce its emission to the environment (Wood and Heyst 2016). As a matter of fact, higher ventilation rates can even lead to higher ammonia emission rates as observed by Gallmann et al. (2003) who compare ammonia emissions from a mechanically-ventilated and naturally-ventilated swine houses. The former has 47% higher emission than the latter, potentially due to the higher indoor temperatures in the former which promotes the biological conversion of urea to ammonia. This is the drawback of relying on ventilation systems as the sole means of controlling odour and gaseous emissions. Hence, other engineering approaches are employed as discussed in the succeeding sections.

Biofilters

An engineering technology which can be coupled to the mechanical ventilation system of a livestock facility is a biofilter. Biofilter is a biological system that consists of a bed of organic media which allows the growth of microorganisms (primarily bacteria and fungi) that degrade the organic matter in the gaseous emissions (Ottengraf and Konings 1991). Aside from microbial degradation, another mechanism by which biofilter achieves pollutant removal is through adsorption and absorption by the organic media (McNevin and Barford 2000). As a matter of fact, in the nitrogen mass balance performed by Jinanan and Leungprasert (2015) with biofilter for ammonia removal in livestock farms, it was shown that the 99% ammonia removal efficiency is primarily attributed to media adsorption (67%) while bacterial degradation contributes to only 15% of the total removal.

Kurc and Sisman (2017) discuss the parameters that must be considered when operating a biofilter. These are: (*i*) moisture content of the media; (*ii*) the microbial community; (*iii*) oxygen; (*iv*) temperature; (*v*) pH; (*vi*) medium depth and pressure drops; (*vii*) nutrient availability; (*viii*) pollutant load and (*ix*) the toxic and inhibitory by-products of degradation. These parameters are influenced by the selection of the organic media as bed packing for the biofilter.

Organic media that may be used include soil, compost, peat, activated carbon, municipal waste, bark, trimmings and/or leaves (Ullman et al. 2004). Williams and Miller (1992) and Swanson and Loehr (1997) describe a good biofilter media to have the following characteristics: (*i*) adequate nutrients and moisture for growth of microorganisms; (*ii*) large surface area for microbial attachment and sorption capacity; (*iii*) ability to resist media compaction and channeling; (*iv*) high moisture holding capacity; and (*v*) high porosity to maximize empty bed residence time (EBRT) and minimise pressure drop. Two of the commonly used media include compost (Tanaka et al. 2003), wood chips (Chen et al. 2009a; Lim et al. 2012; Hong and Park 2013) or a combination of the two with 20–30% compost and 70–80% (by weight) wood chips (Sun et al. 2000; Nicolai and Janni 2001). The main drawback with the use of pure compost as biofilter media is its tendency for compaction brought about by fast degradation rates (Swanson and Loehr 1997) which leads to increase pressure drop and the need for high-capacity fans that increases cost

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of operation (Garlinski and Mann 2003). Therefore, a combination of compost and wood chips is usually employed (Nicolai and Janni 2001). Moreover, several studies have also employed organic media in combination with inert bulking agents like plastic saddles (Das et al. 2004), perlite and vermiculite (Kalingan et al. 2004) to minimise compaction and channeling, and therefore extend the useful life of the biofilter.

In terms of application, biofilter has been in use in Europe since 1970s and in the US since 1990s (Nicolai and Lefers 2006), specifically in confined animal feeding operations (CAFOs) (Sheridan et al. 2002a; Tymczyna et al. 2007; Chen et al. 2009b). Among others, it has been used in swine houses (Sheridan et al. 2002b; Chang et al. 2004; Chen and Hoff 2012; Lim et al. 2012) and poultry houses (Shah et al. 2003; Lau and Cheng 2007; Melse and Mosquera 2014). A more thorough list of biofilter application in livestock facilities is available elsewhere (Chen et al. 2009b) and it is noteworthy that among the odor mitigation strategies reviewed by Banskota et al. (2021), biofiltration technology emerged as a valuable and environment-friendly odor control approach in both the developed and developing countries.

Biofilter is effective in reducing both particulate matter, cultivable microbes, ammonia and odour (Martens et al. 2001; Wood and Heyst 2016). Specifically, biofilters employing different media such as biochips, coconut peat, wood bark, pellets and compost reduce bacteria and fungi by 60–95% while reducing odour by 40–80% (Martens et al. 2001). Ferguson et al (2015) demonstrate over 90 and 85% reduction in airborne methicillin-resistant *Staphylococcus aureus* (MRSA) and dust particles, respectively, in biofilters with hardwood chips and western red cedar shredded bark as packing materials.

Since the performance of the biofilter largely depends on the microorganisms (Kurc and Sisman 2017), it is important that optimum moisture content (35–80%), temperature (20–40 °C) and pH of 7 to 8 are maintained in the media and a minimum EBRT is employed (Chen et al. 2009b; Dumont et al. 2014). Guo et al. (2022) noted that the pH in a biofilter is difficult to control which may result in degradation of packing materials that would eventually affect microbial processes. To minimise pressure drop, the media depth is recommended to be in the range of 0.25–0.50 m (Chen et al. 2009b). Depths ranging from 0.3 to 0.75 m have been used for higher removal efficiency but typically results in higher pressure drop, which increases energy consumption (Chen et al. 2009b). How these parameters affect the performance of a biofilter is tackled in greater detail by Chen et al. (2009b).

In terms of configuration, the two main design configurations for biofilters are the flat-bed type and the vertical biofilter, where the former offers ease of construction and less capital cost. However, flat-bed type biofilter has higher physical footprint. For vertical biofilters, leaking problem is a common drawback due to the tendency of biological materials to settle, hence multiple layers are recommended for such configuration (Harmon et al. 2014). In general, the drawback in the use of biofilter is its unsuitability for long-term treatment of exhaust air that contains high amount of dust particles due to their excessive accumulation on the packing media that contributes to the increase in pressure drop and channeling as they accumulate in the organic packing media (Melse and Ogink 2005).

Air scrubber/biotrickling filter

Another end-of-pipe technology that can be employed in controlling gaseous emission from mechanically-ventilated livestock facilities is the biotrickling filter or air scrubber. Similar to a conventional biofilter, a biotrickling filter consists of a bed of organic/synthetic packing materials but is continuously irrigated through water spraying (De Vela and Gostomski 2018). The same biological processes with biofilter take place in biotrickling filter (Van der Heyden et al. 2015). Contaminated air is introduced either cross-currently or counter-currently with the liquid phase, enabling adequate contact and mass transfer between gas and liquid phases. A portion of the liquid phase is recirculated to the packing material while another portion is discharged and replaced by fresh water (Melse and Ogink 2005).

Deng et al. (2022) employed BTFs which employed volcanic rocks and ceramsite as packing materials and it was observed that the BTF with ceramsite had higher removal efficiencies than the one which used volcanic rocks. Specifically, the BTF with ceramsite removed NH_3, total volatile organic compounds and odour with approximately 89, 70 and 88% efficiency, respectively. This shows that the physical and chemical properties of the packing material influence BTF's performance

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and stability as it is where the biofilm growth occurs (Guo et al. 2022). The microbial community that thrives in the packing material is the primary factor that determines the effectiveness of a BTF (Deng et al. 2022). For example, the high NH_3 removal in the BTF used by Deng et al. (2022) is related to the high relative abundance (~85%) of Proteobacteria. The same was observed by Kim et al. (2021) who associated the high NH_3 and H_2S removal from a livestock wastewater treatment facility to the 76% relative abundance of Proteobacteria which are known to promote nitrification process (Maeda et al. 2011). In the BTF used by Kristiansen et al. (2011) for air treatment in a swine house, greater than 70% carboxylic acid reduction, up to 50% organic sulfur compounds reduction and 48–81% reduction of several aromatic compounds were achieved through the microbial population dominated by Actinobacteria with some representatives from Flavobacteria and Sphingobacteria which all thrived in porous corrugated cellulose pads as packing materials.

Aside from the packing material, the pH and the electrical conductivity of the aqueous phase that flows into a BTF also influence its performance, specifically in NH_3 removal. This was shown theoretically by Dumont et al. (2020) who emphasised that the aqueous phase should have a pH close to neutral in order to promote transfer of NH_3 and nitrification process. Hence, an efficient BTF theoretically requires fresh water that will similarly control the thermal conductivity of the aqueous phase.

Acid or bases can be added to the liquid phase in order to cause adsorption of specific pollutants in the gaseous emission (Janni 2020). For example, dilute sulfuric acid may be added to the recirculating water, making it an acid scrubber with pH < 4 and enhancing ammonia removal (>90%) as compared to a typical biotrickling filter (50–90%). On the other hand, Abdi et al. (2020) use hydrogen peroxide as oxidant and yield up to 99% ammonia removal. Apart from low odour removal at 27–43%, the discharge of acidic water from acid scrubber tends to be more costly than a typical biotrickling filter or air scrubber (Melse and Ogink 2005). Hence, a multi-pollutant scrubber which consists of a scrubber coupled with a biofilter is developed by Zhao et al. (2011) where 60–93% PM10 removal, 45–90% PM2.5 removal, 45–85% total bacteria removal and 70–100% ammonia removal are obtained. The design of this three-stage scrubber is based on the observation that acid scrubbers are more effective in ammonia and airborne microorganism reduction while the biofilter is more effective at reducing odour (Zhao et al. 2011).

In summary, the selection of the appropriate strategies for control of odour and gaseous emissions in livestock buildings is influenced by the type of pollutant or gaseous emission to be removed, the range of pollutant concentration, the type of ventilation and other factors pertaining to the site of livestock facility.

Future research directions

Until now, accurate quantification of pollutant emissions (both odour and gases) from livestock and poultry buildings remains a challenge since many factors are at play. Some of these include animal type and species, stocking density and age, time of year and day, weather conditions, ventilation rates, type of housing and characteristics of manure, to name a few. Weather condition, in particular, includes temperature, humidity, wind speed and solar intensity (Casey et al. 2006; Cheng et al. 2011). For example, emission rate of ammonia from broiler and laying hen houses during summer ranges from 0.24–0.42 kg ammonia/hen/year and decreases to 0.15–0.19 kg ammonia/hen/year in winter (Cheng et al. 2011). Moreover, odour readings are usually higher after the rain (Ismail et al. 2014).

Another challenge in odour and gaseous emission research is the lack of standards in collecting, measuring and calculating pollutant content in the air emitted by livestock facilities, thereby resulting in significant variability in data available in literature (Casey et al. 2006). For European and Northern American countries, research studies aimed at evaluating pollutant emissions are relatively easy because most of the livestock facilities are closed and confined (Osorio-Saraz et al. 2014). However, in tropical and subtropical regions, most of the livestock facilities are kept open and naturally ventilated, making the determination of emissions more complex (Mendes et al. 2014) as it is influenced by wind currents and other uncontrollable factors (Osorio-Saraz et al. 2013).

With the advent of information and communication technology (ICT), the monitoring and control of odour in livestock facilities may automatically be done. This is demonstrated in the work of Yoon et al. (2021) who developed a livestock odor

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monitoring system which consists of an ammonia sensor, communication equipment, server, database management system and user operating program. The sensor measures the ammonia and such data are transmitted using a communication equipment and are used in planning and implementing odor reduction strategies. This automation of odor monitoring and control constitute a good area for future research especially in the age of artificial intelligence.

Despite the ill impacts of livestock odour to health, environment and general well-being of the neighbouring communities, livestock, odour control regulations are often lacking in many countries. Policymakers need adequate science-based information on how livestock odour may be controlled to guide them in formulating informed decisions and policies that balance the welfare of the livestock producers, the community and the environment.

CONCLUSION

The continuous growth of the livestock industry poses increasing problem of odour and gaseous emission which causes nuisance, health problems and environmental concern to the community. Hence, strategies to control odour are developed and employed. These strategies either reduce odour generation through diet manipulation, minimise the odour emission through the use of covers and additives, dilutes and disperses gases through shelterbelts and reduces the concentration of odorous gases through ventilation and end-of-pipe technologies like biofiltration and air scrubbing. These strategies exhibit different level of odour reduction efficiency and no single strategy is appropriate to all livestock and poultry production systems. The selection of the appropriate strategies for control of odour and gaseous emissions in livestock buildings is influenced by the type of pollutant/gaseous emission to be removed, their concentration range, the desired odour reduction level, the type of ventilation, cost and management system and other factors pertaining to the site.

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