Odour emissions from poultry litter – A review litter properties, odour formation and odorant emissions from porous materials

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ABSTRACT

Odour emissions from meat chicken sheds can at times cause odour impacts on surrounding communities. Litter is seen as the primary source of this odour. Formation and emission of odour from meat chicken litter during the grow-out period are influenced by various factors such as litter conditions, the environment, microbial activity, properties of the odorous gases and management practices. Odour emissions vary spatially and temporally. This variability has made it challenging to understand how specific litter conditions contribute to odour emissions from the litter and production sheds. Existing knowledge on odorants, odour formation mechanisms and emission processes that contribute to odour emissions from litter are reviewed. Litter moisture content and water thermodynamics (i.e. *water activity*, A_w) are also examined as factors that contribute to microbial odour formation, physical litter conditions and the exchange of individual odorant gases at the air-water interface. Substantial opportunities exist for future research on litter conditions and litter formation mechanisms and how these contribute to odour emissions. Closing this knowledge gap will improve management strategies that intercept and interfere with odour formation and emission processes leading to an overall reduction in the potential to cause community impacts.

Keywords :

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Volatile organic compounds (VOCs)

1. Introduction

Emission of odour from litter in meat chicken sheds (broiler houses) can lead to odour nuisance within the surrounding community and potentially result in complaints (Carey, 2004; Guo et al., 2003; Hayes et al., 2014; Radon et al., 2004). Odour is a normal part of meat chicken production due to anaerobic and aerobic microbial activity in the litter and also due to its release from the animals (Pillai et al., 2012). Litter is considered to be the primary source of odour from meat chicken sheds because the majority of odorous compounds are released during the decomposition of organic matter (Hobbs et al., 2004; Mackie et al., 1998). Odour from meat chicken sheds is a complex mixture of odorous compounds typically composed of volatile organic compounds (VOCs) and non-VOCs (e.g. ammonia, hydrogen sulfide, reduced sulfur compounds) (Cai et al., 2007).

Conditions within the litter influence the formation and emission of odorants resulting in changes to the concentration and character of the odour exhausted from meat chicken sheds (Spoelstra, 1980; Wadud et al., 2012). It is suggested that it may be possible to reduce the odour nuisance potential of meat chicken farms by altering this odour mixture in a way that makes the odour less detectable or offensive to the neighbouring community.

Scientific studies and reviews have focussed on general topics about odour from agricultural, industrial and municipal sources (Table 1). This literature provides an understanding of the complexities of odour and odour impacts, but the current specific need is to identify literature that relates to quantifying the properties of meat chicken litter and how these properties influence odour emissions. In this review, the term 'litter' will specifically refer to meat chicken litter.

Relatively little information has been reported about the formation of poultry odour compared to other livestock industries, especially pig production (Cai et al., 2007; Trabue et al., 2010). Litter is a very different odour source than other intensive animal bedding/wastes including those from laying hens, pigs and cattle. As such, literature published for these animals was reviewed but only considered to be relevant if specific aspects were likely to be fundamentally similar to meat chicken litter. Unfortunately, some published research does not specifically identify which animal species were involved, instead referring to ‘animal wastes’ or ‘poultry’, which does not differentiate between meat chickens or laying hens. There are many differences between meat chickens and laying hens in terms of breed, nutritional requirements, feed formulations, length of production cycle and housing design that are likely to support different odour forming mechanisms. Additionally, some published studies refers to odour emissions from poultry manure or poultry litter/manure composting (Petric et al., 2009; Sweeten et al., 1991; Turan et al., 2007). Accumulation of manure/litter within meat chicken sheds may be considered a form of stockpiling/composting and there will be some similarity to in-shed litter, but conditions in terms of the environment, microbial activity, surface to volume ratio, fresh manure addition and mechanical mixing due to chicken activity are likely to be different.

Litter is a porous material and odorants will be released from the surface (Mackie et al., 1998) but will also diffuse through the pores (Schwarzenbach et al., 2003; Thibodeaux and Scott, 1985; Zhang et al., 2002). Release of odorants from litter is therefore complex and requires consideration of gas exchange mechanisms and litter physical properties.

The aim of this review is to describe how conditions within litter influence the formation and diffusion of odorants from litter as well as considering how shed and litter management strategies influence litter conditions. Odorants previously identified at meat chicken farms will be summarised. The effect of litter porosity on the exchange of odorants between the litter and ventilation air will also be examined.

2. Meat chicken litter

2.1. Description and properties

Litter is a friable, absorbent material that is used on the floor of meat chicken sheds to provide thermal insulation, absorb moisture, provide cushioning from the earth/concrete floor and allow birds to demonstrate some natural behaviours such as scratching and dust bathing (Collett, 2012; Shepherd and Fairchild, 2010). In addition to absorbing moisture, litter needs to readily release moisture to enable reasonable drying time (Bilgili et al., 2009; Grimes et al., 2002), it must be free of toxins (Tasistro et al., 2007) and must be suitable for use after it is removed from the shed because it has value as a fertiliser (Sistani et al., 2003; Tasistro et al., 2007).

The term ‘litter’ is used to describe many different conditions and ages of litter from fresh bedding material through to the time after it is removed from the meat chicken shed. From the perspective of investigating how the properties of litter affect odour emissions there is need for more specific terminology. In this review the following terms will be used: bedding materials; litter; cake; (Fig. 1) and reused litter. ‘Spent litter’ is another term that may be used

to describe litter once it is removed from the meat chicken shed and will no longer be used to rear meat chickens.

'Bedding materials' are the base/original materials, free of manure, that are used at the beginning of the litter use cycle. Bedding materials may also be used as a supplement during a grow-out period or end of a grow-out period to increase litter quantity or improve litter properties (*note*: a grow-out period may alternatively be known as a rearing period or batch. For meat chickens, the grow-out period typically lasts for 35–63 days). Bedding materials are usually organic (e.g. wood shavings, saw dust, bark, rice hulls, peanut hulls, straw, shredded paper) but some inorganic materials have also been used (e.g. sand or clay such as vermiculite or bentonite) (Bilgili et al., 2009; Bilgili et al., 1999; Cejiz et al., 2011; Davis et al., 2010; Garces et al., 2013; Grimes et al., 2002; Miles et al., 2011b). Not all bedding materials are equal and the choice of bedding materials has an effect on litter physical properties, structure, ammonia production, water absorption capacity, water release rate, biochemical processes and bird health (Benabdeljelil and Ayachi, 1996; Bilgili et al., 2009; Grimes et al., 2002; Miles et al., 2011a; Miles et al., 2011b; Miles et al., 2008; Shepherd and Fairchild, 2010; Torok et al., 2009).

The properties and suitability of a variety of bedding materials for meat chicken production have previously been investigated (Bilgili et al., 2009; Bilgili et al., 1999; Cejiz et al., 2011; Davis et al., 2010; Garces et al., 2013; Miles et al., 2011b; Reed and McCartney, 1970). There has been interest in how various bedding materials have different moisture holding capacity and physical properties (Grimes et al., 2002; Reed and McCartney, 1970); contribute to bird health and production parameters such as feed conversion ratio, weight gain and carcass properties (Bilgili et al., 2009; Bilgili et al., 1999; Cejiz et al., 2011; Davis et al.,

2010; El-Wahab et al., 2012; Malone et al., 1983); or influence ammonia and other gaseous emissions (Miles et al., 2011b; Tasistro et al., 2007).

'Litter' is a friable mixture of bedding materials, fresh excreta, partly decomposed manure, spilt feed, feathers and water (Miles et al., 2011a; Sistani et al., 2003). The amount of excreta in the litter increases during a grow-out period and correspond with changes in physical and chemical properties of the litter over time (Dunlop et al., 2015; Miles et al., 2011a; Miles et al., 2008). Miles et al. (2011a) differentiated litter conditions according to 'friable litter' or 'heavy cake'.

'Cake' is a compacted layer/crust that forms on the surface of the bedding materials or litter that may be 5–10 cm thick (Miles et al., 2011a; Sistani et al., 2003). It tends to form in high-traffic areas (Miles et al., 2008) (presumably due to localised high stocking density) and on litter with higher moisture content (Grimes et al., 2002). Particle size and shape of bedding materials also contributes to cake formation with particles larger than 2.5 cm accelerating cake formation because the litter particles tend to 'bridge' or 'mat over' quickly (Grimes et al., 2002). Materials such as straw, rice hulls, wood fibre products, bagasse and pine needles have been reported to contribute to more severe caking than pine shavings (Grimes et al., 2002; Tasistro et al., 2007). Cake can be broken up by bird scratching (Grimes et al., 2002) or by mechanical turning/cultivating with machinery. Sistani et al. (2003) reported that at the end of a 49 day grow-out period 43% of the mass of floor material was cake with the remaining 57% being friable litter.

Presence of cake has been found to coincide with reduced gas emission rates compared to friable litter and it has been hypothesised that this is related to the formation, thickening and

compaction of cake due to bird excretion and traffic (Lin et al., 2012; Miles et al., 2011a; Miles et al., 2008; Tasistro et al., 2007). It has also been shown that gas emission rates and litter properties vary spatially across the floor of a meat chicken shed (Miles et al., 2011a; Miles et al., 2008).

Cake has been described as having high moisture content (relative to the friable litter around it). Sistani et al. (2003) reported cake with moisture content 44.0–47.7% compared to 25.6–29.7% for litter. Miles et al. (2008) and Miles et al. (2011a) reported cake with moisture content 55–60%, which was influenced by location, with cake that formed between feeder/watering lines having lower moisture content than surrounding litter while cake that formed near the exhaust fans had higher moisture content than the surrounding litter. Some of the inconsistency regarding reported cake/litter moisture content is possibly due to the cake formation processes and yet these have not been explained in detail in the literature. The litter formation/development process will likely also affect odour and gas formation and emission and is therefore pertinent to this review.

‘Reused litter’ is litter that is used for multiple grow-out periods. In some growing areas litter may be re-used multiple times, for example 8–10 flocks (Sistani et al., 2003). Litter re-use is so common in some countries (i.e. United States of America) that reference to litter in published literature commonly refers to re-used litter that has been used for multiple grow-out periods (even though it is not clearly distinguished). This needs to be recognised because differences in the properties between re-used litter and litter that commenced as bedding material may affect odour emissions (Dunlop et al., 2010; Wathes et al., 1997), especially during the first weeks of a grow-out period (Brewer and Costello, 1999).

2.2. Formation processes for friable litter and cake

2.2.1. Effects of cohesion

Water affects cohesiveness (the attractive forces between particles) and consequently compaction and flowability in granular materials such as litter. Water both lubricates and provides cohesion between soil particles (Burger et al., 1985) and assists with agglomeration in food ingredients (Roudaut, 2007). Compaction will be enhanced or inhibited at particular moisture contents and high moisture contents will allow deformation to occur with less resistance (Burger et al., 1985). Agnew and Leonard (2003) reported that moisture content affects porosity and thermal conductivity and aids compaction/compression in composts. The effect of water on cohesion and compaction can also be applied to litter.

Bernhart and Fasina (2009) measured the cohesiveness and compaction of litter for moisture contents ranging from 10.3% to 30.9%. They observed that drier litter (10.3% moisture content) was less compressible and had higher flowability (as a result of requiring lower ultimate yield stress to shear litter samples) compared to wetter litter (30.9% moisture content). They described litter with 10.3% moisture content as ‘easy-flowing’ whereas litter with 30.9% moisture content was described as ‘non-flowing’. In another application involving litter, Way et al. (2013) found that litter based on wood shavings flowed well when moisture content was less than 35% but adhered and clogged parts in an implement when moisture content was greater. It is suggested that the increased compressibility and cohesiveness along with decreased flowability that occur with increasing moisture content contribute to cake formation.

The moisture content of litter at the time of compaction also influences the amount of energy required to break up a piece of compacted litter once it has dried. Bernhart et al. (2010) reported that the force required to break compacted samples of litter increased substantially when the moisture content was higher at the time of compaction. They concluded that moisture acted as a natural binder during the agglomeration process because the coating of moisture on particle surfaces improved cohesion between the particles. This suggests that the difficulty in breaking up the cake by the birds (Grimes et al., 2002) is related to the strong adhesion between particles described by Bernhart et al. (2010) that forms when litter/cake is compressed while wet.

2.2.2. Formation of friable litter

Poultry excreta is a mixture of faeces and urine (Collett, 2012) and has a moisture content ranging from 55% (Miles et al., 2011b; Stephens and Hampson, 2002) to 83% (van der Hoeven-Hangoor et al., 2014) (for birds that were free from illness or disease). Excreta is deposited on the surface of the litter but what happens to it from this point depends on the litter properties, especially moisture content.

Excreta will be worked into the litter and dispersed by bird activity and scratching if the litter is near the ‘optimal’ moisture content of 25% (Collett, 2012), is friable and the surface of the bedding material is not matted or compacted. When this occurs, the average moisture content of the combined excreta/litter mixture will be less than that of the fresh excreta and the litter will develop a texture that might be described as a moist crumble. The final moisture content will be proportional to the volumes of excreta and bedding that are combined. The litter will likely remain friable and uncompacted because the birds can readily scratch and dig

in the litter (because of litter flowability and lower ultimate yield stress required to shear litter particles (Bernhart and Fasina, 2009)). This aids the drying process by maintaining porosity and exchanging litter particles at the litter surface where they are most effectively dried by shed ventilation.

2.2.3. Formation of caked litter

If the rate of excretion increases (e.g. due to disease or localised high stocking density), if the litter is moist (e.g. greater than 35–45% moisture content) or if the litter/bedding material has a matted or compacted surface then it is possible that the litter will have insufficient capacity to absorb the moisture being applied and the birds may not be able to mix the excreta into the litter. If this occurs, the surface of the litter may ‘slick’ over (Miles et al., 2008) and cake will begin forming on the litter surface. While friable litter remains uncompacted and dries readily, cake has low porosity (Lin et al., 2012; Miles et al., 2008) and dries slowly (slow drying of cake was inferred by Topper et al. (2008) who reported that cake is removed in the inter-batch period to allow litter to dry).

If there is cake already on the surface of the litter, any added excreta will be unable to mix with the friable litter and will remain on the surface. If the rate of excretion exceeds the rate at which the ventilation system can remove the moisture then the cake will grow thicker and remain wet. On the other hand, if the rate of excretion is less than the evaporation rate due to ventilation, the surface of the litter will dry and eventually the moisture in the wet cake will be evaporated from the litter surface and the entire layer of cake will slowly dry. With wet cake being greater than 55–60% water by mass (Miles et al., 2011a) a substantial volume of

the cake is water and therefore drying the cake will reduce cake thickness and overall litter volume.

Another important consideration in litter/cake formation is in-shed ventilation. Average litter moisture conditions are similar, in general, from day to day (Dunlop et al., 2010; Miles et al., 2011a; Miles et al., 2008), which suggests that 24 hour average evaporation rates generally match the amount of water deposited on the litter in the same period. However, ventilation rates fluctuate diurnally in meat chicken sheds to match cooling requirements and ambient conditions. Ventilation rates have been observed to fluctuate from 20 m³/s at night to 80 m³/s during a single day (Dunlop et al., 2010; Sohn et al., 2010). In this review it will be assumed that meat chickens do not have a preferred time of day for excretion (no information was found in the literature on this subject). Consequently, litter moisture content is likely to increase at night due to higher relative humidity and lower ventilation rates (low potential for evaporation) and decrease during the day due to lower relative humidity and higher ventilation rates (high potential for evaporation). Because excreta are applied at the surface of the litter, any deficit in evaporation will result in the surface moisture content increasing and a wetting front will move in a downward direction through the litter. This will likely contribute to an increased tendency for cake to form at night. Scheduling the timing for measurement of litter properties and gas emission rates during experimental studies is therefore critical, even within the course of a day, due to anticipated diurnal fluctuations in litter conditions (Powers et al., 2005).

It is evident that existing litter conditions, bedding material properties, excretion rates, bird activity and ventilation all contribute to litter conditions and cake formation. Miles et al. (2008) stated that formation of cake in meat chicken sheds is ‘unavoidable’. Additionally, it

must be recognised that the majority of water and excreta addition and evaporation occur at the litter surface and therefore it is likely that there will be differences in conditions at the surface of the litter compared to the rest of the litter profile.

2.3. Relating litter and cake formation to water activity

Water activity (A_w) is a thermodynamic property defined as “the ratio of [the fugacity of water] in a system, and the fugacity of pure liquid water at the same temperature” (Reid, 2007) and can be approximated by the equilibrium or steady state relative humidity of a substance (Carr et al., 1994; Reid, 2007). Fugacity is a measure of the escaping tendency of a substance (Reid, 2007). Water activity is generally accepted to be more closely related to microbial, chemical and physical properties of natural products than total moisture content and has been associated with changes in colour, aroma and texture (Chirife and Fontana Jr., 2007). Water activity of litter has previously been measured by Carr et al. (1994), Carr et al. (1995), Eriksson De Rezende et al. (2001), Hayes et al. (2000), Macklin et al. (2006) and Opara et al. (1992) who used it to explain microbial activity while Bernhart and Fasina (2009) related water activity to structural and handling properties. Additionally, van der Hoeven-Hangoor et al. (2014) measured water activity in excreta and litter as a response to different diet formulations. More recently, Dunlop et al. (2016) showed that the relationship between water activity and litter moisture content changed during a grow-out, with fresh bedding having the highest water activity.

Water activity can be directly related to the mixing of fresh excreta with bedding/litter, litter cohesion, cake formation, and relationships between in-shed relative humidity and litter properties (Bernhart and Fasina, 2009; van der Hoeven-Hangoor et al., 2014). Labuza and

Altunakar (2007) explained that different materials can have the same water activity but have different moisture content. When this occurs, no water will transfer between the different materials because they are in thermodynamic equilibrium. Additionally if the materials are in a sealed, isothermal chamber, the relative humidity in the chamber will equalise with the water activity (e.g. if $A_w=0.75$, relative humidity is 75%) and no more water will transfer from the air to the materials or vice-versa. Conversely, water will migrate from a region of higher water activity to a region of lower water activity (Labuza and Altunakar, 2007).

‘Stickiness’ and ‘caking’ of granular or powdery materials has been related to water activity (Roudaut, 2007), especially for materials with high levels of sugars, minerals or proteins (excreta is approximately 20% crude protein (van der Hoeven-Hangoor et al., 2014)). Roudaut (2007) described the process in which increasing water activity (as a result of increasing moisture content) causes the surfaces of particles to plasticise and this contributes to inter-particle bridging, cohesion and eventual formation of a solid mass with low porosity. Roudaut (2007) explained that there is a ‘critical hydration level’ at which caking will commence and suggested that one strategy to prevent caking is through competition for water (i.e. mixing material with low water activity with materials with high water activity to force water to migrate from the material with high water activity).

Fresh excreta has a high moisture content (up to 83%), which corresponds to a water activity of 0.96–0.99 (van der Hoeven-Hangoor et al., 2014). The water activity of litter is more variable and depends on the moisture content. Bernhart and Fasina (2009) reported water activity to increase non-linearly from approximately 0.25–0.90 as moisture content increased from 10.3%–30.9%. Fresh excreta have high water activity, which is likely to be above the ‘critical hydration level’ for cohesion and compaction. Comparatively, dry litter

has lower water activity. When the two come into contact and are mixed, moisture from the fresh excreta will migrate to the litter and the resulting water activity of the mixture will be less than the initial water activity of the fresh excreta but higher than the initial water activity of the litter. But if litter is wet, the water activity will be higher and possibly match that of fresh excreta. This will result in little exchange of moisture between the excreta and litter, because they will be at or near thermodynamic equilibrium, and consequently the fresh excreta and litter will remain wet.

Relative humidity of the in-shed air also needs to be considered. Water exchange between the litter and in-shed air will occur until the water activity of the litter matches the relative humidity of the air (assuming isothermal conditions) (Labuza and Altunakar, 2007). Consequently, if the relative humidity of the air at the litter surface is less than the water activity of the litter (or fresh excreta) the moisture will diffuse from the litter into the air. If the situation is reversed, moisture will migrate from the air into the litter until thermodynamic equilibrium is reached. When high in-shed relative humidity results in water migrating into the surface of the litter (which may also occur when water vapour condenses on cool litter), the increased water activity at the surface of the litter increases cohesion between the litter particles resulting in a higher tendency for cake formation.

The relative differences in water activity between bedding materials and litter reported by Dunlop et al. (2016), especially higher water activity in fresh bedding than older litter, has implications for managing litter moisture and surface conditions at different stages of a grow-out, and for re-using litter for multiple grow-outs. Additional research is required to explain litter properties, drying and cake formation in terms of water activity and how these relate to odour emissions.

2.4. Variability in the properties of litter

Litter environments in meat chicken sheds are rarely at equilibrium and this creates many challenges for measuring, understanding or mitigating the formation and emission of odours from the litter. Litter properties change diurnally, temporally and spatially during each grow-out period and are affected by manure accumulation; moisture addition (bird excretion, condensation and leaking drinkers); moisture loss due to ventilation; and bird activity (scratching, sitting, mixing and preferential use of some parts of the shed).

Physical and chemical properties of litter that are typically measured during in-shed investigations are temperature, moisture content, pH, nitrogen (N) and carbon (C) content. These have been found to change during the grow-out period (Dunlop et al., 2010; Miles et al., 2006; Tasistro et al., 2007). Koerkamp and Groenestein (2008) reported that the history of litter conditions during the growing cycle—including the litter structure (friability), presence of cake and stratification of the litter—had such a strong influence on the emission of ammonia that the most important parameters controlling ammonia emissions (pH, moisture, temperature and ammonia concentration) were not able to be related to the emission rates. Historical records of litter conditions in research papers are seldom reported.

Miles et al. (2008) stated that a lack of homogeneity in litter conditions creates difficulties in accurately estimating gas volatilisation from the litter surface. Spatial non-homogeneity of litter conditions, in particular, has been reported to significantly affect gaseous emissions in different locations across the floor in a meat chicken shed (Brewer and Costello, 1999; Miles et al., 2011a; Miles et al., 2008). Miles et al. (2011a) concluded that the “highly variable

spatial distribution of most parameters cannot be adequately characterised by average values”.

The formation of a ‘crust’ or ‘cake’ also needs to be considered because it results in a duplex structure in the litter with friable litter and caked layers having substantially different physical and chemical properties that can affect odorant formation and emission (Miles et al., 2011a). Consequently, there will be changes through the depth profiles of the litter in addition to the diurnal, temporal and spatial changes previously mentioned.

3. Odorant measurement, properties and origins

Litter is considered to be the primary source of odour from meat chicken sheds because it is the source of most odorous compounds (Mackie et al., 1998; Trabue et al., 2010; Wadud et al., 2012) while some odours may be emitted from the birds themselves (Lacey et al., 2004). Meat chicken shed odour is a mixture of hundreds of odorous compounds (odorants) (Lacey et al., 2004; Murphy et al., 2014; O'Neill and Phillips, 1992; Trabue et al., 2010; Trabue et al., 2008) that exist in the gas phase or attached to particulates (Heber et al., 1988; Mackie et al., 1998). These odorants may be VOCs or non-VOCs (e.g. ammonia, hydrogen sulfide, reduced sulfur compounds) (Parker et al., 2013b). VOCs are molecules that contain at least one carbon and one hydrogen atom (i.e. organic compounds) that vaporise easily at room temperature (i.e. volatile) (Ni et al., 2012). Trabue et al. (2010) reported that the five most abundant compounds in meat chicken sheds were acetic acid, 2,3-butanedione, methanol, acetone and ethanol. Murphy et al. (2014) reported that the most important compounds for predicting odour from meat chicken sheds were dimethyl disulfide, dimethyl trisulfide, 2,3-butanedione, 3-methyl-1-butanal, 1-butanol, 3-methyl-1-butanol, 2-butanone and acetoin.

These are just a few of the many compounds previously reported in meat chicken odour (Table S1 in the Supplementary Data).

3.1. Odour measurement

Odours are measured and characterised using instrumental and/or sensorial techniques (Capelli et al., 2013b; Lebrero et al., 2011; Zarra et al., 2012). Instrumental techniques include gas chromatography–mass spectrometry (GC–MS), proton transfer reaction–mass spectrometry (PTR–MS) or selected ion flow tube–mass spectrometry (SIFT–MS) whereas sensorial techniques include dilution olfactometry or field-based odour panels (Capelli et al., 2013a; Lebrero et al., 2011). Instrumental techniques are used to characterise an odour in terms of chemical composition by identifying and quantifying the chemical concentration of specific odorants (Capelli et al., 2013a; Lebrero et al., 2011). Instrumental techniques tend to be objective, repeatable and accurate, however they provide little information about how the odour may be perceived by human receptors (Akdeniz et al., 2012; Lebrero et al., 2011), especially given that the characterisation of nuisance odour is often subjective (Zavaleta and Wilson, 1976).

Sensorial techniques allow odours to be characterised in terms of the way an odour may be perceived and how it may contribute to odour annoyance. Specifically, sensorial methods allow an odour to be characterised using four dimensions: concentration, intensity, quality and hedonic tone (Lebrero et al., 2011; Nimmermark, 2011). A detailed discussion of these four dimensions of odour is provided in the Supplementary information (S2) along with a discussion about odour threshold values for individual odorants. Odour thresholds for selected odorants are provided in Table S1 and Figure S1.1 of the Supplementary Data.

3.2. Measurement of odour emissions from a litter surface

Studies have evaluated wind-tunnels and flux chambers/hoods as area source enclosures to measure the specific emission rate of individual gases or odorous gas mixtures from liquids and porous media (Capelli et al., 2012; Gholson et al., 1991; Gholson et al., 1989; Hudson and Ayoko, 2008; Jiang and Kaye, 1996; Kienbusch, 1986; Leyris et al., 2005; Smith and Watts, 1994; Witherspoon et al., 2002; Zhang et al., 2002). The focus of most of these studies has been to evaluate these enclosure devices for their relation to actual emission rates. Smith and Watts (1994) and Zhang et al. (2002) concluded that wind tunnels and flux chambers/hoods are suitable for comparative studies but will not provide accurate measurement of true emission rates because the conditions created within the enclosure will regulate emissions. A method to address this shortcoming for selected compounds has recently been proposed and tested by Parker et al. (2013a), who simultaneously measured water evaporation inside and outside a sampling enclosure and used the difference in evaporation to scale the measured emission rates.

3.3. Microbial production of odorants

The majority of odorants in meat chicken sheds are produced by microbial degradation of organic matter, especially manure (Mackie et al., 1998). The process can occur aerobically or anaerobically (Powers, 2002) and produces a large number of odorous and intermediate compounds (Mackie et al., 1998; Powers et al., 1999; Zhu, 2000). Odorants are also produced in the gastro-intestinal tract of the chickens by microbiota during anaerobic fermentation of carbohydrates, proteins and amino acids (Rinttilä and Apajalahti, 2013). This is essential in

the digestive tract of all animals to recover energy for the host and microflora (Mackie et al., 1998).

Specific bacterial genera have been identified in the lower gastro-intestinal tract and fresh excreta of meat chickens as well as litter. Lu et al. (2003a) and Wei et al. (2013) reported that the microbiota of the lower gastrointestinal tract (ileum and caeca) were dominated by *Lactobacillus*, *Streptococcus*, *Clostridium*, *Ruminococcus*, *Bacteroides* and *Eubacterium*, whereas litter microbiota was dominated by *Staphylococcus*, *Salinicoccus*, *Virgibacillus*, *Faklamia*, *Brevibacterium*, *Bacillis*, *Brachybacterium*, *Aerococcus* and *Corynebacterium* (Lu et al., 2003b; Wadud et al., 2012) (determined using aerobic culturing methods). These organisms produce some of the odorants associated with meat chicken production. Table S3 in the Supplementary Data is a summary of selected odorant-producing microbiota observed in excreta and litter along with information about their preferred environmental conditions.

There are similarities between bacterial genera in the lower gastro-intestinal tract and litter. This is not surprising considering meat chickens are known to consume litter as part of their diet (Malone et al., 1983) and this influences the microbial diversity in the gastro-intestinal tract (Torok et al., 2009). Microbiota in the lower gastro-intestinal tract are then deposited in the litter and this influences microbial diversity in the litter (Wadud et al., 2012). Microbial diversity has also been observed to change during the grow-out period in the intestines (Lu et al., 2003a), excreta and litter (Fries et al., 2005).

Microbial interactions between the litter and gastro-intestinal tract can be cyclic with wet litter conditions leading to high bacterial counts in the litter (Fries et al., 2005). This may contribute to dysbacteriosis or other intestinal upset because of an apparent overgrowth of

some gastro-intestinal bacteria (Hermans et al., 2006). The result is wet excreta perpetuating wet litter conditions (Guardia et al., 2011). Additionally, susceptibility of the birds to bacterially induced gastric upset is greater in the first 3–4 weeks of a grow-out period (Guardia et al., 2011; Torok et al., 2009), which can exacerbate wet excreta and litter conditions.

Microbial survival and diversity in the litter are influenced by pH, temperature and moisture content (Lovanh et al., 2007; Wadud et al., 2012), bedding material type (Fries et al., 2005) and stocking density (Guardia et al., 2011). Changes in these conditions and resulting microbial activity can occur within very short distances (a few centimetres) (Lovanh et al., 2007). With respect to odour formation, changes in conditions that affect microbial diversity and activity (pH, moisture content, temperature, manure content) will influence the formation of specific odorants (Spoelstra, 1980; Wadud et al., 2012). In beef feedlot manure, Woodbury et al. (2015) reported that warm, wet, anaerobic conditions resulted in greater emission rates of sulfide compounds, which have offensive character and are more likely to contribute to odour impacts due to low odour threshold values. Zhu (2000) concluded that aeration can be effective in reducing offensive odours because it supports aerobic bacteria that actively decompose odorous compounds.

Odorant emissions change spatially within a chicken shed and temporally during each grow-out period (Miles et al., 2011a); however, it is not possible in a practical sense to link the formation of specific odorants to specific microbial activity because of the complexity of the microbial processes and properties of the waste substrate (Spoelstra, 1980). It is suggested that there are at least three microenvironments with different microbial diversity that

contribute to odour from litter. These should to be considered specifically when investigating the origins of odour from litter: 1–fresh excreta; 2–dry friable litter; and 3–wet/caked litter.

Odour from fresh excreta is not well represented in the literature due to ‘litter decomposition’ historically being seen as the primary odour source. Le et al. (2005a) reported the direct release of indole and phenol compounds from fresh excreta. Because of the differences in microbial diversity between fresh excreta and litter it is likely that fresh excreta and litter will produce different mixtures of odorants (Table S3 in the Supplementary Data). Dominant bacteria in fresh excreta are known to produce many of the odorants in meat chicken shed odour (Murphy et al., 2014). It is therefore suggested that fresh excreta should receive more focus as an odour source in meat chicken sheds.

The potential contribution of odour from fresh excreta can be viewed in context with the manure accumulation processes previously discussed. When fresh excreta mix with dry, friable bedding/litter, the mixing process reduces moisture content (and water activity) of the excreta, exposes the manure to oxygen and supports aerobic microbial activity. Conversely, excreta will remain intact and wet for longer if it mixes with sticky, wet litter or cake. The result is a moist micro-environment that supports anaerobic microbial activity and production of odorants with offensive characters and low odour thresholds.

4. Gas exchange from porous media

Formation of odorants within meat chicken litter is one issue that needs to be considered. A second is the mechanisms controlling the emission or flux of odorants from the litter into the air above it and then exhausted from the shed through the ventilation fans. To investigate

these mechanisms it is necessary to understand the factors controlling transfer of odorants from the litter to air. A detailed discussion of the fundamental diffusion and emission processes from porous materials is provided in the Supplementary Material (S4).

Litter is a porous medium comprising solid, liquid and vapour phases. There are complexities of litter that need to be considered, from a gas exchange perspective, with respect to odour emissions including porosity, moisture content, effects of turbulence from ventilation and interactions of the birds with the litter.

4.1. Effects of litter porosity on odorant emissions from porous litter

Emission of odorants from porous surfaces is a more complex process than from liquids due to phenomena of diffusion within pores and the effects of turbulence above the rough surface (Capelli et al., 2012). When considering porous sources, such as litter, it is commonly assumed that movement of volatile compounds within the pores occurs by the process of random molecular diffusion and then flux from the porous material into the airstream above occurs by convective mass transfer (Zhang et al., 2002).

Schwarzenbach et al. (2003) explained that diffusion through pores occurs by molecular diffusion because the small diameter of pores suppresses turbulence. Flux of odorants will be less from a porous medium compared to a homogenous fluid or gas (assuming the pores of the porous medium are filled with the same fluid/gas) because the relatively longer and non-linear nature of pores compared to fluids (i.e. air or water) increases the distance that molecules need to travel before they are emitted. This resistance is described in terms of the diffusivity of molecules in the porous medium compared to diffusivity in free air, and is

termed ‘tortuosity’. In all situations, molecular diffusion within the pores will be less than flux into free air due to resistance that occurs because of the tenuous path through the pores (Zhang et al., 2002).

Litter has a variety of pore sizes ranging from large cracks and pores that exist between particles down to micro-pores that exist between fine particles or within particles (e.g. pores within the grain structure of wood shavings). Porosity varies spatially, through the litter profile and during the grow-out cycle. This variability occurs as a result of litter compaction due to bird activity (Miles et al., 2008), grinding down of litter particles and the presence of cake or greater manure content (Miles et al., 2008), which can happen for a variety of litter, shed, ventilation and flock management related reasons. Layers in the litter with different porosity, for example cake vs friable litter, will affect the rate of diffusion of compounds through the litter profile (Fig. 2).

Litter porosity reduces during the grow-out cycle due to the increasing proportion of very fine manure particles and ‘grinding’ of the coarser bedding materials that support macro-pores within the litter. Different bedding materials will have a different ability to support pores within the litter and will also have different durability and longevity. Reducing macro porosity increases tortuosity and will slow rates of diffusion of odorants through the litter medium (Schwarzenbach et al., 2003).

In any medium (solid, liquid or gas) molecules of a compound will diffuse in a random manner due to molecular forces until a state of equilibrium is reached. This is known as molecular diffusion. Any movement or mixing of the medium, for example due to ventilation airflow, will introduce another mechanism of diffusion known as turbulent diffusion. Rates of

diffusion vary by orders of magnitude depending on the medium and the type of diffusion. Molecular diffusion rates in gas-phase media are in the order of 10^4 times greater than in liquids and turbulent diffusion leads to rates of diffusion 10^8 – 10^{13} times greater than molecular diffusion (Schwarzenbach et al., 2003).

Litter pores may be filled with air, water or both depending on the litter moisture content (Schwarzenbach et al., 2003). Litter porosity reduces with increasing moisture content due to an increasing amount of water in the pores but also because litter particles swell as they absorb water. It has been observed that the volume of litter particles increases at a greater rate than the mass increases as the litter particles absorb water (Bernhart and Fasina, 2009). As litter becomes wetter, more of the inter- and intra-particle pore space fills with water. Molecular diffusion of gases through the litter will be greatly reduced because diffusivity is orders of magnitude slower in liquids than air, and because the reduction in pore size will increase tortuosity. Consequently, increasing water content in litter reduces porosity and the flux of odorous gases diffusing through the litter pores, which will in turn reduce the flux of odorants being released from the surface (Schwarzenbach et al., 2003; Thibodeaux and Scott, 1985; Zhang et al., 2002). Zhang et al. (2002) concluded that reduced porosity reduces the maximum flux rates and this leaves a greater quantity of odorants in the litter matrix that can sustain a longer enduring flux.

4.2. Effects of ventilation and in-shed aerodynamics on odorant emissions from porous litter

Different ventilation conditions are used in meat chicken sheds to optimise the comfort of the birds (especially in removing heat) and manage litter conditions. Air temperatures are reduced during the grow-out period to provide a thermo-neutral environment for the birds.

The recommended 'effective' temperature starts at approximately 31 °C (at the start of the grow-out period) and reduces linearly to 20 °C on day 27 where it is kept constant until the end of the grow-out (Aviagen Inc., 2014). The 'effective' temperature is not dry-bulb air temperature, but is a comfort temperature considering relative humidity and wind-chill due to air speed (Aviagen Inc., 2014; Cobb-Vantress Inc., 2012).

Many meat chicken sheds, for example in the south-eastern region of Australia, are mechanically ventilated. Tunnel-ventilated sheds are a specific type of mechanically ventilated shed that are typically long (100–150 m) and narrow (13–18 m) and use a system of inlet vents, extraction fans, stirring fans, heaters, evaporative cooling cells and environmental sensors (differential pressure, temperature, humidity, ammonia (NH₃) and/or carbon dioxide (CO₂)) that are all connected to a programmable automatic controller (Fig. 3). Farm managers vary ventilation programs according to prevailing conditions using their experience and interpretation of biological responses displayed by the birds, such as panting and congregating behaviours.

Air is drawn into tunnel-ventilated sheds using negative pressure (typically 10–40 Pa) through evenly spaced wall-mounted vents (mini-vent inlets), large vents at the front of the shed (tunnel inlets), or both types of vent simultaneously. Air entering the shed through mini-vent inlets is projected across the ceiling where it mixes with warm air lingering near the roof apex. Warming the incoming air reduces its relative humidity thus increasing its moisture-holding capacity and allowing more moisture to be removed from the litter. Air entering the shed through mini-vents creates turbulence and mixing of the in-shed air but produces minimal air velocity at the litter surface. This minimises wind-chill on the birds, which is essential during the early stages of a grow-out period. When a higher degree of cooling is

required, mini-vents are closed and air enters the shed through tunnel inlets at the front of the shed. This air may or may not be cooled using evaporative cooling cells. The air then moves linearly through the shed towards the tunnel fans, reaching air speeds of up to 2.0–3.5 m/s depending on the shed design. At these velocities, the air is turbulent. Ventilation strategies are designed to maximise the evaporation potential of the air, either by increasing its moisture-holding capacity or reaching moderate air velocities. Due to the relationships between water evaporation and odorant emissions (Parker et al., 2013a), it is likely that the conditions created by ventilating the shed are likely to influence odour emissions from the litter (Barth et al., 1984).

4.3 Effects of moisture on odorant emissions from porous litter

A substantial quantity of water is added to litter and evaporated from litter on a daily basis during a grow-out cycle (Collett, 2012). This is balanced by evaporation rates that vary throughout the day. As such, litter moisture content is constantly changing. The presence of water in litter has multiple effects on the emission of odorants by reducing porosity of litter (physical resistance) and by altering the emission potential of odorants from the liquid phase within litter.

The rate of water evaporation is influenced by litter porosity and the internal mass transfer resistance of water to the evaporation surface (Ghaly and MacDonald, 2012; Yusheng and Poulsen, 1988). The rate of evaporation reduces as the litter dries (Dunlop et al., 2015) due to its resistance to diffusion of water vapour through litter pores as the drying front moves from the litter surface down through the litter profile (i.e. increasing thickness of the sub-surface

boundary layer) and eventually due to unavailability of free water for evaporation (Aminzadeh and Or, 2013).

Many odorants are water soluble (Table S1 and Figure S1.2 in the Supplementary Data) and therefore the water held within the litter will absorb and retain odorants (Cai et al., 2006; Woodbury et al., 2015) that are then subject to air–water exchange processes. Relatively large amounts of water are added and evaporated from litter daily (kilograms of water per m² per day (Dunlop et al., 2015)) and it is suggested that this contributes to the substantial movement of odorous molecules within the litter (molecular diffusion within litter water and air-filled pores) and from the litter into the ventilation air. Woodbury et al. (2015) concluded that additional research is required to evaluate the effects of wetting and drying cycles on emissions.

Litter is unlikely to be completely saturated, i.e. all pores filled with water, with the exception of wet cake. If saturated, compounds diffuse slowly through the liquid-filled pores to the litter surface where they would be available for emission into the ventilation airstream above the litter. The tortuous path through the pore spaces provides resistance to diffusion from the litter depths. More commonly litter may be damp, in which case it could be expected that a film of water would be present within and around each litter particle, creating an extensive emission surface, with greater surface-to-volume ratio than may exist in a body of water (Valsaraj, 1994). Valsaraj (1994) explained that the increased surface-to-volume ratio of water film in a non-saturated zone changes the rate of gas exchange at the liquid–air interface, which can result in considerable adsorption or release of gases. Additionally, Valsaraj (1994) suggested that water molecules compete with VOCs for sorption sites on mineral surfaces. It is suggested that in the case of litter this may result in the release of

VOCs that are bound to dry litter surfaces. Gases emitted from dry surfaces or from the liquid film into air-filled pores or at the litter surface are subject to random molecular diffusion through the litter pores (Schwarzenbach et al., 2003; Thibodeaux and Scott, 1985; Zhang et al., 2002).

Volatile compounds are emitted from the water held within litter in a similar way to larger bodies of water (such as liquid waste ponds), with the main difference being that the amount of liquid surface available for emission depends on the moisture content of the litter (Thibodeaux and Scott, 1985; Valsaraj, 1994). The emission of these compounds is governed by the properties of the liquid and air above the liquid, and the rate of emission will depend on the specific compound. Liang and Liao (2004) measured the effective diffusion rate of odorants from pig manure and found that Henry's law constants for specific compounds affected their emission rate as manure moisture content changed. Henry's law constants enable the definition of a steady-state ratio in the concentration of a compound in the liquid phase to the concentration of the specific compound in the gas phase above it (Parker et al. 2010a). Specifically, the diffusion rate of a compound with a small Henry's law constant (p-Cresol, dimensionless Henry's law constant value $1.0 \times 10^{-4.5}$, which makes it an air phase-controlled compound) increased as moisture content of the manure increased while the diffusion rate of other compounds with larger Henry's law constant (toluene and p-xylene, dimensionless Henry's law constant value $\sim 1.0 \times 10^{-0.53}$, which makes them liquid phase controlled compounds) decreased as moisture content increased. It is suggested that this finding reinforces the application of the emission theories and Henry's law to moist porous materials and also indicates that litter moisture content is likely to influence the diffusion rate (and therefore the emission rate) of individual odorants, which in turn will lead to differences

in odorant concentration. Henry's law constants for selected meat chicken shed odorants are provided in Table S1 and Figure S1.3 in the Supporting Data.

4.4 Effects of ventilation on odorant emissions

Tunnel ventilated meat chicken sheds are effectively a large area-source enclosure that can be operated like a wind tunnel or dynamic flux hood depending on the inlet vents that are used (tunnel or mini-vent inlets respectively). Use of specific inlets and ventilation programs depends on the cooling requirements of the birds. Conditions in the shed are similar to a wind tunnel when operated in tunnel ventilation mode due to turbulent linear air movement or are similar to a dynamic flux hood when operated in mini-vent ventilation mode due to random air movement/turbulence and negligible air speed.

With meat chicken sheds being similar to area source enclosures, it is likely that the airflow conditions within the shed will influence odour emission rates, especially for odorants that are gas phase controlled (relating to Henry's law constant, Table S1 and Figure S1.3 in the Supporting Data). It is suggested that changing the mode of ventilation from tunnel ventilation to mini-vent ventilation may reduce odour emission rate, but it is unlikely that this strategy could be used in a practical way due to considerations of heat stress. Nonetheless, it is surprising that no literature was found specifically relating the air speed or mode of ventilation in meat chicken sheds to odour emissions, although some researchers have reported that higher ventilation rates correspond with higher ammonia and odour emission rates (Dunlop et al., 2010; Le et al., 2005b; Ndegwa et al., 2008; Zhu et al., 2000). Jiang and Kaye (1996) and Hafner et al. (2012) reported that emissions of gas phase controlled VOCs and water from porous media (manure and silage) increased with increasing turbulence and

airspeed of the air over the surface. This again highlights the relevance of Henry's law constants for individual compounds (Table S1 and Figure S1.3 in the Supplementary material) when investigating the effects of ventilation air speed and turbulence on odorant emissions from litter. There is a need for further investigation into the effects of ventilation rate and air speed on the emission of individual odorants from meat chicken litter.

4.5 Effects of the birds on odour emissions from the litter

The birds deposit manure and moisture onto the litter surface and then mix it in. Nutrients in the excreta are the catalyst to odorant emissions and some odorants will be emitted directly from the excreta. The addition of nutrients to the litter also fuels the degrading/composting processes that release odorants (Mackie et al., 1998).

The birds produce substantial heat and warm the litter when they sit down. It is suggested that warming the litter will accelerate evaporation from the litter and will also increase the rate of microbial activity. Changes to temperature of an emission source can influence the emission or re-absorption rate of specific odorants (Woodbury et al., 2015).

Resistance to emission of gas phase compounds through pores in the litter is reduced when emitting surfaces (i.e. manure particles and liquids) are raised to the surface of the litter. This is because the odorants are not subjected to the tortuous path through the pores (Zhang et al., 2002). Normal bird activities such as scratching and dust-bathing will increase the exposure of emission sources at the litter surface, which in turn will likely result in higher emission rates from those sources. Trabue et al. (2010) reported that the presence of birds in a meat chicken shed corresponded with seven-fold higher VOC concentrations than an area of

a shed without birds. Trabue et al. (2010) concluded that this demonstrated the importance of characterising odour emissions from animal facilities while the animals are present because there were distinct differences in both odorant diversity and concentrations in the presence or absence of birds.

The presence of birds affects the airspeed and turbulence at the litter surface, which in turn may affect emission rates of certain odorants (Trabue et al., 2010). No information could be found regarding or quantifying the specific effect that the birds have on micro-turbulence at the litter surface. It is suggested that they may reduce air velocity at the litter surface but would increase turbulence. The overall effect of this on the air boundary layer and mass convection of odorants from the litter is unknown and requires investigation.

4.6. Management strategies that interfere with or inhibit odorant formation and emission from litter

There has been limited studies of management strategies that reduce the formation and emission of odorants from meat chicken litter. Few investigations, if any, have considered the “litter physical and chemical properties, gas evolution, bird effects, as well as meat chicken house management and structure” as recommended by Miles et al. (2011a) for the development of “comprehensive mitigation strategies”.

A review by Ullman et al. (2004) focussed on the use of litter amendments but mostly from the perspective of reducing ammonia emissions. In their review, the discussion of odour reduction strategies primarily focussed on air scrubbing, misting, filtering, ionizing, oxidising and dispersing technologies. Bouzalakos et al. (2004) also focussed on misting technologies

combined with the use of masking agents, counteractants, neutralisers and surface-enhanced absorption agents to reduce airborne odours. These end-of-pipe strategies target airborne odours and have not necessarily been shown to be effective at reducing odour formation or emissions from litter, i.e. the source of the odour, and are beyond the scope of this review; however, they warrant further investigation and development for when strategies to reduce odour from the litter are ineffective. Table 2 list selected odour reduction management strategies and expected efficacies.

In a broader context, absorption and adsorption of odorants onto organic material for microbial degradation have been investigated with respect to biofiltration of odours (Chen and Hoff, 2009; Kennes et al., 2009; Ralebitso-Senior et al., 2012). Biofiltration is an odour reduction technology in which odorous air is passed through a moist, biologically active and commonly organic medium. Microbes within the biofilter consume and convert the odorant compounds into less odorous compounds thereby reducing the concentration and intensity of the released odour. Interestingly, the review by Chen and Hoff (2009) highlighted the importance of moisture content, porosity, temperature, microbial activity, pH and VOC diffusion on the odour removal efficiency of biofilters. If conditions within the biofilter bed are sub-optimal, for example anaerobic, odorant removal efficiency is reduced and the biofilter may emit its own odours (Chen and Hoff, 2009). It is suggested that biofilters, like litter, are a porous organic medium that is interacting with volatile odorants and therefore further review of the literature concerning biofiltration may reveal knowledge that can be used to develop new strategies to reduce the emission of odorants from litter.

Nahm (2005) suggested that reducing moisture content, changing pH or adding fresh shavings or zeolite (or other clay materials with high adsorption properties) can be effective

at reducing emissions of gases such as ammonia. Unfortunately, these treatments may not be effective for reducing the emission of all of the odorants that contribute to odour impacts downwind from the shed (Barth et al., 1984). Pillai et al. (2012) tested several litter additives to reduce odorant emissions and found adsorbent materials including activated carbon and silica gel to be effective on some odorants, but not all. Loyon et al. (2016) reported strategies to reduce emissions (especially ammonia) from meat chicken sheds, which were based on good housekeeping and litter management practices including the reduction of water loss from drinking systems and using forced manure drying (with ventilation air). This further supports the strategy of maintaining dry and friable litter to minimise odour emissions. Further research and development is required to translate this strategy into practical techniques that will assist meat chicken growers to achieve these dry and friable litter conditions in sheds. Improved techniques are also required to reverse wet and caked litter so that dry and friable conditions can be maintained.

5. Conclusions

Litter is considered the primary source of odour in meat chicken sheds. Odour emissions from litter are complex due to the existence of multiple odorant sources within litter (i.e. fresh excreta, friable litter and cake), formation and emission of numerous odorants, and significant spatial and temporal variability of moisture content, porosity, pH, ventilation air-flow, temperature, humidity and bird activity. There is limited published information relating odour and odorant emissions to specific litter conditions.

We have compiled a reference list of more than 130 odorants that have been observed in meat chicken sheds or litter along with selected properties including odour threshold value, odour

character, Henry's law constant, water solubility and vapour pressure (Table S1 in the Supplementary Data).

Litter formation mechanisms are not well described in the literature despite the fact that the resulting conditions, especially friable litter or cake, are known to significantly affect odours. In this review, we have proposed mechanisms for the formation of cake and friable litter using information available on litter friability, flowability, moisture content, water activity and compaction. Opportunities exist to further research litter formation mechanisms and to develop management strategies to reduce the formation and emission of odorants.

Many challenges remain in understanding odour formation processes and emissions from porous meat chicken litter. Research is required to specifically identify and quantify the emission rate of odorants from litter with known physical conditions and history. Research is also required to develop practical litter management techniques that maintain dry and friable litter, which is likely to minimise odour emissions and reduce the potential for odour impacts.

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[FIGURE 1. – 2 column width]

Fig. 1. Photographs of bedding material (*left*, pine shavings), litter (*centre*) and cake (*right*).

Note: litter and cake images show the top surface and exposed side surface following excavation

[FIGURE 2. – 1.5 column width]

Fig. 2. Diffusivity and concentration profiles through litter (*top*) and caked litter (*bottom*)

[FIGURE 3. – 2 column width]

Fig. 3. Selected components of a meat chicken shed ventilation system (*top* – inside shed with roof removed, *bottom* – outside shed). Note: the long axis of the shed has been drawn at $\frac{1}{3}$ to $\frac{1}{2}$ scale for improved presentation

Table 1

Overview of selected studies on odour from agricultural, industrial and municipal sources

Odour research topics	References
Odour metrics (concentration, intensity, hedonic tone, character)	Fournel et al. (2012); Lebrero et al. (2011); Nimmermark (2011)
Odour measurement (olfactometry)	Hamon et al. (2012); Jacobson et al. (2008); Lebrero et al. (2011); van Harreveld et al. (1999)
Instrumental odorant measurement such as gas chromatography–mass-spectrometry/olfactometry (GC-MS/O), selected ion flow tube–mass spectrometry (SIFT-MS) or proton transfer reaction–mass spectrometry (PTR–MS)	Cai et al. (2006); Hamon et al. (2012); Hansen et al. (2012); Heynderickx et al. (2013); Lebrero et al. (2011); Muñoz et al. (2010); Ni et al. (2012); Van Huffel et al. (2012); Zhang et al. (2010)
Odour sampling methodologies (e.g flux chamber versus wind tunnel methods for area sources, and sample storage prior to analysis)	Brockreis and Steinberg (2005); Capelli et al. (2012); Capelli et al. (2013a); Capelli et al. (2013b); Guillot (2012); Hudson and Ayoko (2009); Hudson et al. (2009); Jiang and Kaye (1996); Lebrero et al. (2011); Parker et al. (2013a); Parker et al. (2010a); Parker et al. (2010b)
Odorant chemistry and composition, formation and emission (flux)	Cai et al. (2006); Hamon et al. (2012); Hudson and Ayoko (2008); Hudson et al. (2009); Mackie et al. (1998); Ni et al. (2012); O'Neill and Phillips (1992); Trabue et al. (2010); Turan et al. (2007)
Odour impacts (frequency, intensity, offensiveness, duration, location/receptor characteristics)	Lebrero et al. (2011); Mackie et al. (1998); O'Neill and Phillips (1992)
Odour management or treatment	Hamon et al. (2012); Lebrero et al. (2011); Massé et al. (2013); Ullman et al. (2004);

Table 2

Selected management strategies to reduce odour emissions from litter

Strategy	Reported or expected efficacy
Maintaining dry litter and friable litter	<p>Expected efficacy:</p> <ul style="list-style-type: none"> • Less offensive odour due to aerobic conditions (Barth et al., 1984) • Lower emission of water soluble odorants due to lower water evaporation rates (Barth et al., 1984; Woodbury et al., 2015) • Reduced odour formation due to less microbial activity (Wadud et al., 2012).
Litter in-situ aeration	<ul style="list-style-type: none"> • Odour concentration reduced by 6–36% (not significant or consistent)
In-shed windrowing/pasteurising (only applicable for litter-reuse in subsequent batches or land application of spent litter)	<p>Compared to non-windrowed litter (Harmel et al., 2014):</p> <ul style="list-style-type: none"> • 58–65% reduction in odour concentration • Changed odour character from ‘manure’ to ‘earthy’ • Reduced odour offensiveness when land applied • Some odorant compounds decreased but others increased
Acidifying litter additives	<ul style="list-style-type: none"> • Inconsistent reduction of volatile fatty acids by 14–83% (Kim et al., 2011) • Reduced ammonia (considered an odorant) by up to 99% (Ullman et al., 2004)
Litter adsorbent addition	In laboratory trial conditions (Pillai et al., 2012):

(activated carbon, silica gel or zeolite)	<ul style="list-style-type: none"> • Reduced emission of some odorant compounds but not all. Concluded that no one product was universally effective.
Enzyme addition combined with heated incubation	Greatly reduced odour (but economic viability unknown) (Enticknap et al., 2006)
Clinoptilolite addition to feed and directly to litter	<ul style="list-style-type: none"> • No odour reduction (Amon et al., 1997)
Yucca extract based feed additive	<ul style="list-style-type: none"> • No odour reduction (Amon et al., 1997)