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Review

The multidimensional causal factors of 'wet litter' in chicken-meat production

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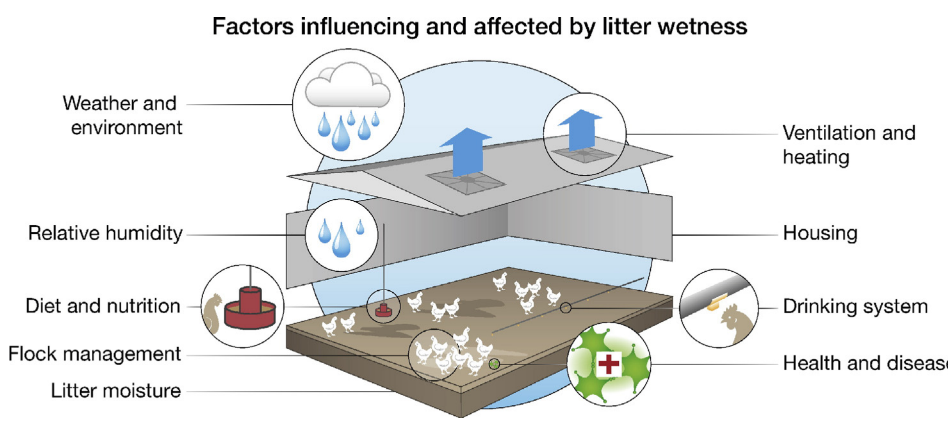
HIGHLIGHTS

- Wet litter in poultry sheds is a complex issue, with many interrelated causes.
- Micro-environment and housing factors contribute most acutely to wet litter.
- Disease and diet/nutrition contribute to wet litter but are less obvious.
- Research and extension are both required to reduce occurrence of wet litter.

GRAPHICAL ABSTRACT



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ABSTRACT

The problem of 'wet litter', which occurs primarily in grow-out sheds for meat chickens (broilers), has been recognised for nearly a century. Nevertheless, it is an increasingly important problem in contemporary chicken-meat production as wet litter and associated conditions, especially footpad dermatitis, have developed into tangible welfare issues. This is only compounded by the market demand for chicken paws and compromised bird performance. This review considers the multidimensional causal factors of wet litter. While many causal factors can be listed it is evident that the critical ones could be described as micro-environmental factors and chief amongst them is proper management of drinking systems and adequate shed ventilation. Thus, this review focuses on these environmental factors and pays less attention to issues stemming from health and nutrition. Clearly, there are times when related avian health issues of coccidiosis and necrotic enteritis cannot be overlooked and the development of efficacious vaccines for the latter disease would be advantageous. Presently, the inclusion of phytate-degrading enzymes in meat chicken diets is routine and, therefore, the implication that exogenous phytases may contribute to wet litter is given consideration. Opinion is somewhat divided as how best to counter the problem of wet litter as some see education and extension as being more beneficial than furthering

Abbreviations: AGP, antibiotic growth promotants; A_w, water activity; DEB, dietary electrolyte balance; FPD, footpad dermatitis; HCl, hydrochloric acid; $NaHCO_3$, sodium bicarbonate; NE, necrotic enteritis; NSP, non-starch polysaccharides; FCR, Feed conversion ratio.

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research efforts. However, it may prove instructive to assess the practice of whole grain feeding in relation to litter quality and the incidence of footpad dermatitis. Additional research could investigate the relationships between dietary concentrations of key minerals and the application of exogenous enzymes with litter quality.

Contents

1. Introduction . . . 767
2. Background . . . 768
3. Environmental and housing factors . . . 768
3.1. Litter material properties . . . 769
3.2. Manure cake formation . . . 770
3.3. Water activity and how it contributes to the symptoms/side effects of wet litter . . . 770
3.4. Housing and ventilation . . . 771
4. Disease and health factors . . . 771
5. Nutritional factors . . . 772
6. Footpad dermatitis (FPD): a consequence of wet litter . . . 773
7. Future directions . . . 774
Acknowledgements . . . 774
References . . . 775

1. Introduction

The occurrence of 'wet litter' in meat chicken sheds is associated with concerns regarding animal welfare, flock health, food safety, environmental impacts and reductions in production efficiency. Mitigating wet litter will only be achieved when there is thorough understanding of the multidimensional causal factors. This will require a multi-disciplinary approach to understand the hydrology in the meat chicken shed micro-environment; the biological response of the chickens to nutrition and the production environment; and the contributions of illness, production equipment/housing design and management, and the intensiveness of chicken meat production on wet litter.

Complexity of the multidimensional causal factors of wet litter is accentuated by the difficulty of reaching an appropriate definition of wet litter. A survey of fifteen people variously connected with the chicken-meat industry, including veterinarians and nutritionists, from Australia and the United Kingdom (UK) was completed to garner background information for this review. Perhaps some of the better responses to the prompt for a definition were: "wet litter is not dry and friable and is unacceptable to the peak welfare body"; and "wet litter is such that the litter is sufficiently moisture-laden to be detrimental to the health and welfare of the birds by way of causing footpad damage". However, neither response constitutes a precise definition of the problem.

One precise definition is that once litter moisture content exceeds 25% (mass of water divided by mass of moist litter, expressed as a percentage, %), its cushioning, insulating and water holding capacity is compromised (Collett, 2012). Or, additionally, Collett (2007) stated that wet litter results when rates of water addition (excreta, spillage) exceed the rates of removal (evaporation). A European Directive requires that "All chickens shall have permanent access to litter which is dry and friable on the surface" (Lister, 2009) and "dry and friable" litter is the recognised, albeit nebulous, benchmark. In the UK, the requirement to keep litter in a well maintained state is enshrined in law and, in the event of non-compliance, growers may be prosecuted (DEFRA, 1994). Also, in Australia, the RSPCA has issued requirements in respect of acceptable litter quality (RSPCA, 2013).

Some 90 years ago, Dann (1923) expressed the opinion that "wet litter in the poultry house is a rather troublesome problem to most poultrymen". Wet litter was deemed to be a favourable medium for the development of colds, catarrh, roup, and like maladies demanding extra labour and litter material due to the necessity of frequent replacements. The author listed six causes of wet litter, all of which were directly related to providing birds with "good housing". Subsequently, James and Wheeler (1949) concurred in suggesting that wet litter is a problem of considerable economic and pathological importance. Quite clearly the situation has changed little, as wet litter remains a troublesome problem for the chicken-meat industry, and the attention the problem is receiving is escalating due to welfare concerns. One of the many relevant aspects is that wet litter is the principal cause of footpad dermatitis (Shepherd and Fairchild, 2010). Moreover, the induction of footpad dermatitis by the deliberate provision of wet litter has been shown to compromise weight gains by 7.75% (1904 versus 2064 g/bird; $P < 0.01$) and feed conversion efficiency by 4.16% (1.68 versus 1.61; $P < 0.05$) at 37 days post-hatch (de Jong et al., 2014). From the standpoints of bird welfare and bird performance in a general context, and from an economic perspective regarding the market demand for chicken paws, the wet litter problem needs to be addressed. Clearly, the identification of the causal factors of wet litter is a precondition for the rectification of the problem.

Wet litter is a problem primarily for meat chickens that are grown to market weight but it also extends to the housing of meat chicken breeders. In fact, Mench (2002) stated that because of reduced mobility meat chicken breeders may spend a large proportion of their time lying down and are therefore prone to hock burns and breast blisters from contact with wet litter. Also, excess water intake is a common problem in meat chicken breeder flocks and may need to be restricted in order to maintain litter quality. Carr et al. (1995) evaluated litter samples from flocks of meat chickens and meat chicken breeders with respect to *Salmonella* contamination. These researchers concluded that limiting water activity (A_w) in the litter base reduced the multiplication of *Salmonella* and created a more hygienic environment for poultry production. However, the focus of this review is centred on wet litter in the context of meat chickens.

The objective of this review is to identify and discuss the factors that contribute to wet litter in chicken-meat production. 'Wet litter' is used as a descriptive term for litter with properties that contribute to problematic or detrimental side-effects especially in terms of flock health, welfare, or productivity. Wet litter may also be seen as a contributor to environmental or amenity problems relating to odour or other gaseous emissions. As mentioned, a precise definition of wet litter is difficult and the causative factors are multidimensional including housing, or micro- and macro-environmental factors, disease, health and nutrition. Consideration is given to footpad dermatitis as a consequence, not a causal factor, of wet litter, because of its importance and the incidence and severity of the condition is indicative of litter quality. Finally, consideration is given to the areas where extension and research efforts would be directed to best advantage.

2. Background

As mentioned, a survey of fifteen people was completed to garner background information for this review, to broaden its scope and enhance its objectivity. The respondents included seven practical nutritionists, three veterinarians, three academic nutritionists and two non-professional, experienced poultry-men. Their overall perception was that wet litter was primarily a welfare issue followed by bird performance and chicken-meat marketing. The consensus was that the genesis of wet litter primarily stemmed from environmental factors in the broadest terms with lesser and equal importance being attached to nutrition and disease issues. Within environmental or housing factors, management of drinkers and shed ventilation were considered to be the most important as illustrated in Fig. 1. Amongst the relevant diseases, coccidiosis was the most frequently cited condition followed by dysbacteriosis, mycotoxins and malabsorption. In terms of nutrition there was a focus on minerals including electrolytes and macro-minerals. Some respondents placed importance on an appropriate dietary electrolyte balance (DEB) where:

$$\mathrm{DEB\ (mEq/kg)} = \mathrm{Na}^{+} + \mathrm{K}^{+} - \mathrm{Cl}^{-}.$$

Sodium (Na) is only one component of DEB but it may be pivotal given the variations in Na concentrations in feed grains recorded in Australia. Importance was also placed on the macro-minerals, calcium (Ca) and phosphorus (P), and appropriate Ca:P ratios. More emphasis was placed on Ca and the issue of water quality was raised by a few respondents. The inclusion of NSP-degrading enzymes in meat chicken diets to counter elevated digesta viscosities in wheat-based diets caused by soluble NSP was viewed positively as a routine preventative measure. Alternatively, the inclusion of phytate-degrading enzymes was viewed less positively with 27% of respondents expressing some qualified reservations. Finally, the practice of whole grain feeding was thought to improve litter quality to varying extents by 53% of respondents, which included some very convinced advocates of this approach.

3. Environmental and housing factors

The term 'litter' describes many ages and conditions, from fresh bedding material through to the time after it is removed from the meat chicken shed. In this review the term 'bedding material' will be used to describe the original material, free of any manure, applied at the beginning of a litter use cycle or as a bulking agent during a grow-out period. In contrast, 'litter' will be used to describe the mixture of bedding material and manure. The properties of bedding materials change with the accumulation of manure and therefore data collected on bedding materials may not be applicable throughout a grow-out period or over multiple grow-out periods (Garcês et al., 2013; Meluzzi et al., 2008; Reed and McCartney, 1970; Tucker and Walker, 1992). Even though properties of litter change with manure addition, characteristics of the original bedding materials may be enduring throughout the life of the litter (Andrews and McPherson, 1963; Garcês et al., 2013; Meluzzi et al., 2008).

Litter is used on the floor of meat chicken sheds to absorb moisture and excreta and provide thermal insulation and cushioning from the earth or concrete floor. It supports aerobic decomposition of excreta and allows birds to display natural behaviours such as scratching and dust bathing (Collett, 2012; Shepherd and Fairchild, 2010). In addition to absorbing moisture, litter needs to release moisture readily to permit reasonable drying intervals (Bilgili et al., 2009; Grimes et al., 2002). The beneficial attributes of litter decline as it becomes wet. Litter moisture content changes diurnally, temporally, spatially, within the litter profile and during each grow-out period. The amount of water held by a particular litter material due to its inherent properties will determine when the litter reaches the critical moisture content for it to be defined as 'wet litter'.

The concerns that have been associated with wet litter include: contact or footpad dermatitis (Bilgili et al., 2009; de Jong et al., 2014; Mayne et al., 2007); increased ammonia concentrations in the grower sheds (Elliott and Collins, 1982; Liu et al., 2007; Miles et al., 2011b; Weaver and Meijerhof, 1991); and increased odour generation (Clarkson and Misselbrook, 1991; Homidan et al., 2003). Wet litter also increases risks to food safety (Eriksson De Rezende et al., 2001) and bird health, including dysbacteriosis (Collett, 2012; Hermans et al., 2006), because it enables microbial communities to flourish (Agnew and Leonard, 2003; Wadud et al., 2012). Wet litter has reduced friability (Tucker and Walker, 1992; Bernhart and Fasina, 2009), compresses more easily (Bernhart et al., 2010) and has reduced thermal insulation properties

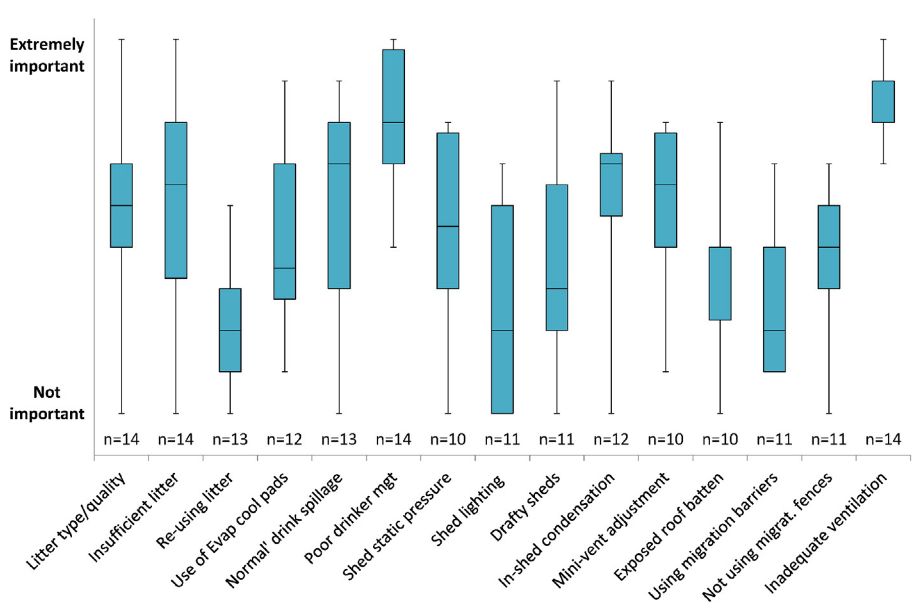

Fig 1. Relative importance of environmental or housing factors contributing to the problem of wet litter as ranked by the industry survey respondents.

(Agnew and Leonard, 2003) in comparison to dry litter. Wet litter is prone to the formation of manure 'cake' (or 'cap' or 'crust') that forms on the surface of the litter and sustains a wet surface. Cake is therefore a consequence of wet litter but also sustains surface conditions that increase the risk of the above issues associated with wet litter. 'Wet litter' and 'caked litter' may be considered by some to be separate, but the consequences of both conditions are likely to be similar and interrelated.

Key environmental and management factors that contribute to wet litter are multidimensional (Lister, 2009; Tucker and Walker, 1992; van der Hoeven-Hangoor et al., 2013a,b,c; van der Hoeven-Hangoor, 2014) and have been reasonably well documented in the literature. A summary of the various factors that contribute to wet litter and the relevant references is presented in Table 1. The term 'wet litter' is not always used, but may be described as 'litter deterioration' (Bruce et al., 1990), 'poor litter' (McIlroy et al., 1987), or is inferred during specific discussions implicating wet litter as a key cause of specific conditions including contact dermatitis (de Jong et al., 2014; Shepherd and Fairchild, 2010). It is unlikely that one dominant cause exists given the numerous interrelated contributing factors.

Table 1
Key contributing factors and causes of wet litter and cake.

Key contributing factors	References
Rising damp through floor, leaking walls/roof	Dann (1923); Tucker and Walker (1992)
Drinker spillage (normal)	Bilgili et al. (1999)
Drinker spillage, leaks (mismanagement, pressure, height, design)	Dann (1923); Bilgili et al. (1999); Shepherd and Fairchild (2010); Tucker and Walker (1992)
Normal excretion, varying throughout a grow-out period	Elliott and Collins (1982); Dann (1923); McIlroy et al. (1987); Tucker and Walker (1992); van der Hoeven-Hangoor et al. (2013a, b, c); Weaver and Meijerhof, (1991)
Stocking density	McIlroy et al., (1987); Meluzzi et al. (2008); Shepherd and Fairchild 2010; Tucker and Walker (1992)
Increased water excretion Nutrition imbalance or ingredients, disease e.g. dysbacteriosis, Increased water consumption, water quality feed supply interruption, gut microbiota	Bruce et al. (1990); Collett (2012); Dann (1923); Eichner et al. (2007); Francesch and Brufau (2014); Guardia et al. (2011); LaVorgna et al., (2014); McIlroy et al., (1987); Shepherd and Fairchild (2010); Tucker and Walker (1992); van der Hoeven-Hangoor et al. (2013a, b, c)
Increased in-shed relative humidity Exhaled moisture, wet litter, high ambient humidity, poor in-shed temperature control	Bruce et al. (1990); Dann (1923); Hermans et al. (2006); McIlroy et al. (1987); Payne (1967); Shepherd and Fairchild (2010); Tucker and Walker (1992); Wang et al. (1998); Weaver and Meijerhof (1991)
Season	Bruce et al. (1990); Hermans et al. (2006); McIlroy et al. (1987); Wang et al., (1998)
Condensation on walls, ceilings and in-shed equipment	Dann (1923); Hermans et al. (2006)
Lighting equipment or program	Meluzzi et al. (2008);
Insufficient shed ventilation/air exchange	Dann (1923); Hermans et al. (2006); Tucker and Walker (1992); Weaver and Meijerhof (1991)
Farm biosecurity and cleaning practices	Hermans et al. (2006)
Litter/bedding material type	Andrews and McPherson (1963); Bilgili et al. (2009); Bruce et al. (1990; Davis et al. (2010); Meluzzi et al. (2008); Reed and McCartney (1970); Shepherd and Fairchild (2010); Tucker and Walker (1992)
Insufficient litter depth	Meluzzi et al. (2008); Shepherd and Fairchild (2010); Tucker and Walker (1992)
Excess litter depth	Dann (1923); Ekstrand et al. (1997)
Cool/warm litter and cool/warm in-shed air	Dann (1923);Tucker and Walker (1992)
Litter moisture content/water holding capacity	Andrews and McPherson (1963); Bilgili et al. (2009); Shepherd and Fairchild (2010)

It is suggested that the contribution of the many factors listed in Table 1 is subject to their management. For example, litter type or quantity and wet or moist bedding material may contribute to wet litter if not appropriately managed but may not contribute to wet litter if they are appropriately managed. Additionally, it may be possible to compensate for a deficiency in one of the factors with additional management or investment in others. As an example, poor litter water holding capacity may be compensated by adding more litter or by increasing ventilation or heating. Increasing ventilation, or its effectiveness, may be useful for reducing in-shed humidity or for increasing evaporation when excess water has accumulated from excretion, condensation or direct application (e.g. drinking system or shed leaks). Also, it may be possible to prevent wet litter with changes to on-farm management or equipment maintenance, for example maintaining drinker lines or managing water pressure. Therefore the knowledge, skills and attitudes of farm staff as well as on-farm procedures and maintenance programs contribute to wet litter but are seldom the subject of formal research or investigation. Overall, identifying the exact cause(s) of wet litter is extremely challenging.

3.1. Litter material properties

The volume of water added to litter, evaporated from litter and able to be stored in litter can each contribute to the occurrence of wet litter. A large quantity of water is added to the litter by excretion and normal drinking spillage due to the high water intake and commercial stocking densities of modern meat chickens. Dunlop et al. (2015) estimated that the amount of water added to litter could be as much as 3.2 L/m^2 per day, with a cumulative total of over 100 L/m^2 during a 56 day grow-out. Collett (2012) estimated that a flock of 20,000 birds can excrete up to 2500 L of water per day onto the litter. On its own, this normal quantity of water excretion tends to be manageable with modern farming practices including shed design and ventilation management. However, avoiding wet litter may not be possible if additional water is added to the litter due to ill-health, imbalanced diet, use of certain feed ingredients or if evaporation is reduced by extended periods of high humidity.

Essential properties for all bedding materials to avoid wet litter problems include having good water holding capacity and reasonable drying rates (Grimes et al., 2002; Tucker and Walker, 1992). Litter friability, susceptibility to cake formation and water activity are also important properties (Garcês et al., 2013) as these contribute to the undesirable side-effects associated with wet litter.

The properties of bedding materials and their suitability in meat chicken sheds have been assessed by a number of researchers including Andrews and McPherson (1963), Bilgili et al. (1999), Davis et al. (2010), Garcês et al. (2013), Grimes et al. (2002), Meluzzi et al. (2008), Miles et al. (2011b) and Reed and McCartney (1970). The range of parameters investigated varied but included maximum moisture content, water holding capacity, drying rate, compressibility, bulk density, particle size distribution, thermal conductivity, equilibrium moisture content (water activity), friability and caking. It should be noted that testing of these litter properties is often not undertaken according to a reference standard, and irrespective of methods used, the results from laboratory testing may not be representative of conditions that form within the production setting of a meat chicken shed. Bedding materials used included various pine and other wood products (shavings, sawdust bark, bark and chips, stump chips, pine needles, chopped pine needles), rice hulls, peanut hulls, ground corn cobs, sand, straw (wheat, barley, grasses), sugarcane (tops and bagasse), shredded newspaper and clay. Pine shavings were usually found to be the most suitable bedding material due to high absorbency, reasonable drying time and high friability.

Other materials ranked in different orders depending on the priority given to different properties measured.

Some bedding materials have properties that require specific management to reduce the risk of wet litter and other problems. For example, sand may require more pre-heating prior to the placement of chicks at the start of the grow-out period to provide the correct temperature and to reduce moisture condensation issues, whereas straw products need to be cut shorter than 2.5 cm to avoid matting of the surface, which can increase cake formation (Grimes et al., 2002). It is suggested that these examples reinforce the concept that materials are not necessarily suitable or unsuitable for litter, but some may require specific management or treatments.

Moisture content is one property that is commonly measured with litter and bedding materials but care is required when moisture content is used to compare the water holding capacity of different bedding and litter materials. This is because the common method for calculating moisture content (mass of water divided by mass of moist litter, expressed as a percentage, %), where the mass of the moist litter is the sum of the mass of the water and the mass of oven dried litter material) is calculated on a mass basis when litter in meat chicken sheds is purchased, distributed across the shed floor, and disposed on a volumetric basis. Differences in the bulk density of the dry material (mass of dry material divided by the volume) may vary. Data collected by Reed and McCartney (1970) can be used to illustrate this issue. Pine sawdust and peanut hulls both had a moisture content at saturation of 67% but had dry bulk densities 211 kg/m^3 and 96 kg/m^3 respectively. While the moisture content was the same, the water holding capacity per square metre of litter on the floor (assuming a 5 cm depth) can be calculated to be 21.4 L/m^2 for pine sawdust and 9.7 L/m^2 for peanut hulls. For comparison, pine shavings at saturation point were found to have a moisture content of 63%, dry bulk density of 98 kg/m^3 and water holding capacity of 8 L/m^2. The calculation is further exaggerated with dense bedding materials such as sand, which have a dry bulk density of 1500 kg/m^3 (Miles et al., 2011b). Despite sand having apparently low moisture content at saturation of 12% (Miles et al., 2011b), the actual water holding capacity for litter depth of 5 cm is 9.8 L/m^2, which exceeds that of pine shavings and is approximately equal to peanut hulls.

Friability is another important litter property because it influences the way that the birds interact with the litter (Lister, 2009) and affects litter drying rate (Collett, 2012; Miles et al., 2011a). Lister (2009) related friability to the ability to reduce a substance into smaller pieces. Therefore, friable litter is not caked or sticky and should fall apart. Friable litter can be 'worked' by the birds as they scratch, dig and forage (Lister, 2009). This maintains aerobic conditions and accelerates moisture loss (Lister, 2009). As an alternative to friability, Bernhart and Fasina (2009) used the term 'flowability' to describe the cohesion between litter particles (i.e. the force between particles causing them to stick together). It is suggested that flowability and friability should be considered similar with respect to the way that individual litter particles hold together and the external forces required to overcome inter-particle bonds. Bernhart and Fasina (2009) concluded that litter moisture content was directly related to the force required to overcome cohesion between particles such that greater force was required for particles to separate as litter became wetter. They also reported that litter flowability reduced as moisture content increased and described litter with a moisture content of 10% as free-flowing, 18% as easy flowing and 22–31% as cohesive. An explanation for the relationship between moisture content and particle cohesion was provided by Roudaut (2007), who related the 'stickiness' and 'caking' of granular or powdery materials to water activity (which is distinctly different to moisture content). Roudaut (2007) explained that 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 the eventual formation of a solid mass with low porosity. Roudaut (2007) further explained that there is a 'critical hydration level' at which caking of granular materials will commence.

3.2. Manure cake formation

Cake is a compressed layer that forms on the top of the bedding material or litter and usually contains most of the moisture and faecal material (Miles et al., 2011a; Shepherd and Fairchild, 2010). Cake is primarily characterised by higher moisture content than surrounding litter although this can vary (Miles et al., 2011a; Miles et al., 2008). Cake is not normally considered the same as wet litter but tends to be described as coinciding with wet litter. Cake contributes to undesirable consequences including contact dermatitis because it increases the surface moisture in contact with birds (Meluzzi et al., 2008; Miles et al., 2008). Miles et al. (2011a) described cake as providing a slippery, disease sustaining surface.

Cake formation is reported to be related to litter moisture content, but is also dependent on bedding material (Andrews and McPherson, 1963; Grimes et al., 2002). Particle size and shape of bedding materials contributes to cake formation with particles larger than 2.5 cm accelerating cake formation as litter particles will tend to 'bridge' or 'mat over' more 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).

It is suggested that reduced friability associated with wet litter (Bernhart and Fasina, 2009; Lister, 2009) reduces the ability of the birds to incorporate fresh excreta into the litter resulting in the formation of an excreta layer on the litter surface. Cake then becomes a physical barrier that prevents fresh excreta being incorporated into friable litter by bird activity and consequently the thickness of cake increases. Sistani et al. (2003) reported cake layers that were 5–10 cm thick.

Miles et al. (2008) reported that cake formation is currently unavoidable in meat chicken sheds and is typically managed or removed between grow-outs by processes known as 'de-caking' or tilling (Miles et al., 2008; Sistani et al., 2003). De-caking removes the cake from the shed and leaves the friable litter for the following flock whereas tilling mechanically chops and incorporates the cake into the friable litter. De-caking and tilling mix and aerate the litter, releasing trapped gases and moisture (Miles et al., 2011a; Topper et al., 2008). It is suggested, however, that cake is likely to reform following mechanical treatment if the litter moisture content is still high enough because the litter will not be friable.

3.3. Water activity and how it contributes to the symptoms/side effects of wet litter

Water activity (A_w) is a thermodynamic property that relates to the relative availability or freedom of water in a material. Reid (2007) described A_w as the ratio of the fugacity of water in a system, and the fugacity of pure liquid water at a given temperature, where fugacity is a measure of tendency for a substance to escape. A_w is determined by placing a sample in a sealed chamber (that is preferably temperature controlled), allowing conditions to equilibrate and then measuring the relative humidity of the chamber headspace. The equilibrium relative humidity (ERH) and A_w are directly related ($A_w = \mathrm{ERH}/100$), and both terms are used interchangeably.

A_w is generally accepted to be more closely related to microbial, chemical and physical properties of natural products, than total moisture content (Chirife and Fontana, 2007), and may be a better measure of litter quality (van der Hoeven-Hangoor et al., 2014). The underlying mechanisms leading to the negative effects of wet litter are related to either pathogenic organisms (bacteria, fungi) or by direct contact with water. A_w directly contributes to these mechanisms.

A_w has previously been related to microbial activity in meat chicken litter (Carr et al., 1994, 1995; Eriksson De Rezende et al., 2001; Hayes et al., 2000; Macklin et al., 2006; Opara et al., 1992). The growth of bacteria and fungi can be controlled by keeping the litter A_w below the minimum limit for microbial growth, nominally: 0.86–0.90 for

Staphylococcus spp., 0.92–0.95 for *Salmonella* spp., 0.95 for *Escherichia coli*, 0.9–0.97 for *Clostridium* spp., 0.98 for *Campylobacter* spp. and 0.75–0.85 for *Aspergillus* spp. (Fontana, 2007; Taoukis and Richardson, 2007). Eriksson De Rezende et al. (2001) and Carr et al. (1994) reported that maintaining litter A_w below 0.90 (approximate moisture content 25–35%) was sufficient to minimise viable *Salmonella* and *E. coli*. Hayes et al. (2000) suggested that *Salmonella* spp. could be controlled by maintaining A_w below 0.84 (approximate moisture content 20–25%) and that lowering litter A_w via drying by ventilation or other means could also control other poultry-related microbiota.

Water activity increases non-linearly with litter moisture content. Bernhart and Fasina (2009) reported litter A_w to increase from 0.25 to 0.90 as moisture content increased from 10 to 31%. Data collected by Carr et al. (1995) and van der Hoeven-Hangoor (2014) showed that A_w increased to 0.98–0.99 when litter moisture content reached 38–55%. By comparison, fresh excreta had high moisture content (up to 83%) with correspondingly high water activity 0.96–0.99 (van der Hoeven-Hangoor, 2014). A_w gradients between litter and excreta control the flow of water, therefore if litter has A_w equal or exceeding that of excreta then water will not migrate into the litter and excreta will remain wet. This highlights the need to maintain the litter moisture content below 30–35%.

Labuza and Altunakar (2007) reported that different materials can have the same water activity but have different moisture content. Potential effects of using different bedding materials or additives to reduce A_w in litter have not been explored in the literature; however, Dunlop et al. (2016) recently showed that bedding materials tended to have relatively high A_w that decreased during the grow-out with the addition of excreta and breakdown of the organic materials.

The relationship between A_w and steady state relative humidity has important implications for the management of litter moisture content and the in-shed environment. If in-shed relative humidity is higher than the litter A_w, water will migrate from the air into the surface of the litter. Condensation will also occur if the litter surface is below the dewpoint temperature (Tucker and Walker, 1992). Conversely, water will diffuse through the litter and into the air (raising in-shed relative humidity) if litter A_w exceeds the in-shed relative humidity. External temperature and humidity, shed ventilation rate and shed heating (including heat released from the birds), will each contribute to in-shed relative humidity, litter A_w and litter moisture content.

3.4. Housing and ventilation

Design and management of shed and ventilation are all-important for litter conditions because they control in-shed temperature, humidity and airflow. Controlled laboratory studies have shown that exposure to in-shed relative humidity of 75% was sufficient to cause wet litter (Weaver and Meijerhof, 1991). Similarly, Payne (1967) found that 72% relative humidity resulted in litter surface caking. Payne (1967) further explained that in-shed relative humidity was able to be controlled by regulating in-shed temperature and ventilation rate using adequate shed insulation and a thermostatically controlled ventilation system. Control of in-shed relative humidity reduces water absorption by the litter and also reduces drips from water that condenses on in-shed surfaces (Hermans et al., 2006; Payne, 1967).

To determine the prevalence of wet litter and the predisposing risk factors, Hermans et al. (2006) surveyed meat chicken farms in the UK. Numerous interrelated variables that contributed to wet litter were identified. The only variable associated with the design of meat chicken sheds that contributed to wet litter was side ventilation (where air is drawn into the shed on one side and extracted from the opposite side). Hermans et al. (2006) also reported that inadequate ventilation can lead to high relative humidity in the shed and to poor patterns of air movement such that low incoming air-speed will fall to the ground and create condensation. Conversely, Payne (1967) suggested that too much air flow was not appropriate either because it caused birds to crowd together. What is required is to provide uniform airflow throughout the shed to achieve uniform temperature (Hermans et al., 2006; Payne, 1967) and presumably have uniform litter drying. It is therefore suggested that it is not only the amount of ventilation that is important but the effectiveness of the ventilation system in bringing in air, conditioning it to increase its moisture holding capacity and then getting that air to the litter so it can dry evenly.

With so many housing and ventilation factors that can affect litter moisture, and considering that sheds on different farms are likely to be different, it is unlikely that meaningful and specific solutions to wet litter will be published. Adding further complexity to this issue, Collett (2012) suggested that shed design and ventilation should improve to keep pace with genetics and nutrition that have substantially increased water excretion by birds over recent years. It is suggested that a resolution needs to be found for these two issues. Firstly, are current shed and ventilation system designs adequate and, secondly, can litter moisture control be improved by changing management practices?

4. Disease and health factors

Clearly any disease that triggers diarrhoea is a potential contributor to the problem of wet litter. As mentioned, intestinal coccidiosis was the most frequently cited disease by respondents to the survey, where *Eimeria maxima*, *Eimeria acervulina* and *Eimeria necatrix* hold particular relevance. Chapman et al. (2010) have reviewed the long-standing campaign to control coccidiosis with monensin, other ionophores and pharmacological agents. Necrotic enteritis (NE) is caused by *Clostridium perfringens* but the two quite different disease entities are often interrelated in practice. The integrated control of both entities by ensuring gut integrity has been thoroughly considered by Williams (2005). A variety of antibiotic growth promotants (AGP) are included in meat chicken diets in countries where this is permitted. Very often this practice is essentially an insurance policy to prevent NE outbreaks; however, the usage of AGP is now under increasing pressure on a global basis and it seems likely that it will be discontinued at some point. Very considerable efforts are being directed towards the development of efficacious, safe and inexpensive vaccines to target both coccidiosis and NE and if this objective is realised the discontinued usage of AGP would be far less of a challenge. Such developments would certainly facilitate the maintenance of good quality litter in meat chicken grow-out sheds.

Dysbacteriosis, a non-specific bacterial enteritis, was nominated in the survey by respondents as a relevant disease factor. It has been proposed that dysbacteriosis is an imbalance in intestinal microflora resulting in the malabsorption of nutrients by poultry (Bailey, 2010). Both non-infectious and infectious agents are thought to be involved in the aetiology of dysbacteriosis including soluble NSP, coccidia and *Clostridium perfringens*. The disease is usually seen between 20 and 30 days of age triggering wet and greasy droppings; however, appropriate dietary formulations that include probiotics can ameliorate dysbacteriosis (Teirlynck et al., 2011);.

Several disease entities in addition to coccidiosis, NE and dysbacteriosis were nominated by respondents to the survey. These included Avian Infectious Bronchitis, Infectious Bursal Disease, Transmissible Viral Proventriculitis, Biogenic Amine Toxicity and the runting/stunting syndrome. In Australia, it seems that the incidence of Transmissible Viral Proventriculitis or dilated proventriculi may be increasing, although there is not a consensus on this issue. However, it is noteworthy that whole grain feeding significantly reduced the incidence of dilated proventriculi from 8.4 to 1.1% (unpublished data) in a recent feeding study completed by the University of Sydney. This finding is consistent with the association between whole grain feeding and enhanced gut integrity and, in turn, better litter quality (Liu et al., 2015). The fact that numerous avian diseases can trigger wet litter is irrefutable; nevertheless, they appear to be secondary and somewhat peripheral causative factors.

5. Nutritional factors

The role of nutritional factors in relation to wet litter problems has been competently reviewed by Collett (2012) and consideration will be given to more specific factors in this section. Water intake of poultry is obviously a key factor as recently considered by van der Klis and de Lange (2013). Compromised gut integrity will reduce net water absorption from the gastrointestinal tract and manifests as diarrhoea; alternatively, excess nutrients will increase urinary outputs of water. Both factors may, by stimulating both intake and output of water, trigger wet litter. Van der Klis and de Lange (2013) stressed that minimising voluntary water intakes requires dietary regimes that closely meet the nutritional requirements of the flock.

Wheat, a 'viscous grain', is commonly used as the basis of meat chicken diets and the phenomenon of 'new season' wheat and its association with soluble NSP is well documented. Unchecked, the soluble arabinoxylans of wheat would certainly contribute to wet litter problems (Choct and Annison 1992; Collett, 2012); however, this potential issue has been met by the nearly universal acceptance of exogenous NSP-degrading enzymes with predominantly xylanase activity in wheat-based diets (Selle et al., 2003). Anecdotally, an initial reason for the inclusion of exogenous β-glucanases in meat chicken diets based on barley, the other 'viscous grain', in the UK was to maintain good litter quality despite the presence of soluble NSP in barley.

Phytate-degrading enzymes (Selle and Ravindran, 2007) now meet with equal acceptance in meat chicken nutrition irrespective of the grain basis of the diet. Phytate, or *myo*-inositol hexaphosphate (IP_6), is a ubiquitous component of plant-sourced feed ingredients and practical meat chicken diets; however, exogenous phytases have been associated with wet litter as reflected in the following statement: "there has been some commercial experience that the use of phytase may increase excreta moisture and reduce litter quality" (Debicki-Garnier and Hruby, 2003). This association appears to have emerged with the prohibition of meat-and-bone meal in animal diets in Europe circa 2000 and the transition to 'vegetarian' meat chicken diets (Selle et al., 2009a).Vieira and Lima (2005) increased dietary inclusions of soybean meal from 224 to 321 g/kg by eliminating animal by-products as protein sources. This transition significantly increased water intake and excreta moisture by 12.9% and 1.74%, respectively. Thus, to some extent, the implication that phytase is a cause of wet litter is based on a false premise.

In the Debicki-Garnier and Hruby (2003) study, phytase increased excreta moisture at 7 days post-hatch (65.3 versus 62.9%; $P < 0.05$). At 21 days post-hatch there was a subtle but still significant excreta moisture increase (74.4 versus 73.2%; $P < 0.01$) following the dietary inclusion of a fungal 3-phytase at 1000 FTU/kg.

Within the same time-frame, Pos et al. (2003) investigated the effects of two exogenous phytases on litter quality and growth performance to 29 days post-hatch. The outcomes for one of these phytate-degrading enzymes (Natuphos® 5000G. BASF, Ludwigshafen, Germany) are tabulated (Table 2). Litter quality was visually assessed on a scale of 1 (inferior) to 10 (superior). Dietary treatments consisted of a positive control, a negative control (NC; less 1.0 g/kg available P) and three NC plus 500 FTU/kg phytase with reductions of 0, 0.8 and 1.6 g/kg Ca. On the basis of litter scores from Table 2, the addition of 500 FTU/kg phytase to NC diets did not adversely affect litter quality. Phytase improved litter score from 5.3 to an average of 6.9 on day 14; from 6.1 to 6.4 at day 21; but there was a numerical reduction from 6.2 to 5.4 on day 28. Moreover, it is evident in the tabulated results that the dietary removal of 1.6 g/kg Ca was beneficial. Also, it is noteworthy that this dietary Ca removal significantly increased feed intake by 2.97% (2044 versus 1985 g/bird) and weight gain by 2.76% (1453 versus 1414 g/bird) relative to the NC plus 500 FTU/kg phytase diet. The increases relative to the non-supplemented NC diet were 12.6% (2044 versus 1815 g/bird) for feed intake and 12.7% (1453 versus 1289 g/bird) for weight gain. In general terms, the interactions between Ca with both phytate and phytase are profound and complex (Selle et al., 2009a) but they are clearly important in the specific context of wet litter. Predictably, Pos et al. (2003) concluded that litter quality can be improved by reducing dietary Ca levels in meat chicken diets when using phytase. Their findings only emphasise the very real need to apply appropriate matrix values for Ca, P (and Na) in the formulation of phytase-supplemented meat chicken diets.

The importance of Ca in this context is reflected in the Enting et al. (2009) study. In overall terms, increasing Ca levels from approximately 5 to 10 g/kg in diets for meat chickens at 20 days of age tended to increase litter moisture and reduce litter scores; however, phytase supplementation exacerbated the increase in litter moisture. This emphasises the need to apply appropriate Ca matrix values in the formulation of phytase–supplemented diets; however, as mentioned, the interactions between phytate and Ca are not straightforward. It is worth noting that the degradation of IP_6 phytate by exogenous phytase will lead to a step-wise, linear release of P moieties; whereas, the transition from IP_6 to IP_5 and IP_4 will release the majority of Ca bound in mineral-phytate complexes. Consequently the phytase-induced release of P and Ca are not in parallel, which is a complicating factor (Selle et al., 2009a).

Subsequently, Ravindran et al. (2008) investigated the influence of dietary electrolyte balance (DEB) and microbial phytase on excreta quality of meat chickens. Increasing DEB from 150 to 375 mEq/kg significantly increased excreta moisture content from 73.1 to 81.2% (Fig. 2). This translated to a reduction in dry matter from 26.9 to 18.8%. This was reflected in excreta scores, which increased from 2.17 to 4.50 where a score of 5 indicated very watery excreta (Fig. 2). While the effect of DEB on both parameters of excreta quality was highly significant ($P < 0.001$), 500 FTU/kg phytase did not alter excreta dry matter (22.7 versus 22.9%) or excreta score (3.00 versus 2.88). In this study the interaction between DEB and phytase for FCR closely approached significance ($P = 0.06$) with a marked phytase-induced improvement of 5.09% at 150 mEq/kg but a marginal deterioration of 0.88% at 375 mEq/kg. The corresponding calculated dietary sodium (Na) levels were 1.5 and 5.2 g/kg. The outcomes of this study suggest that the

Table 2
The effect of *Aspergillus niger* phytase, dietary phosphorus and calcium levels on litter quality and meat chicken growth performance—litter score were visually assessed on a scale of 1 (inferior) to 10 (superior)—within rows, values with a common superscript do not differ ($P < 0.05$).
Adapted from Pos et al., (2003).

Item	Positive control	Negative control less 1 g/kg P	NC + 500 FTU/kg phytase	NC + 500 FTU/kg less 0.8 g/kg Ca	NC + 500 FTU/kg less 1.6 g/kg Ca
Litter score					
Day 14	7.7^{e}	5.3^{a}	6.2^{b}	6.9^{bcd}	7.5^{de}
Day 21	7.1^{b}	6.1^{a}	6.2^{a}	6.5^{ab}	6.9^{b}
Day 28	5.8^{a}	6.2^{a}	5.3^{a}	5.6^{a}	5.4^{a}
Growth performance					
Weight gain (g/bird)	1482^{d}	1289^{a}	1414^{b}	1441^{bc}	1453^{cd}
Feed intake (g/bird)	2087^{d}	1815^{a}	1985^{b}	2028^{bc}	2044^{cd}
FCR (g/g)	1.453^{a}	1.459^{a}	1.451^{a}	1.453^{a}	1.452^{a}

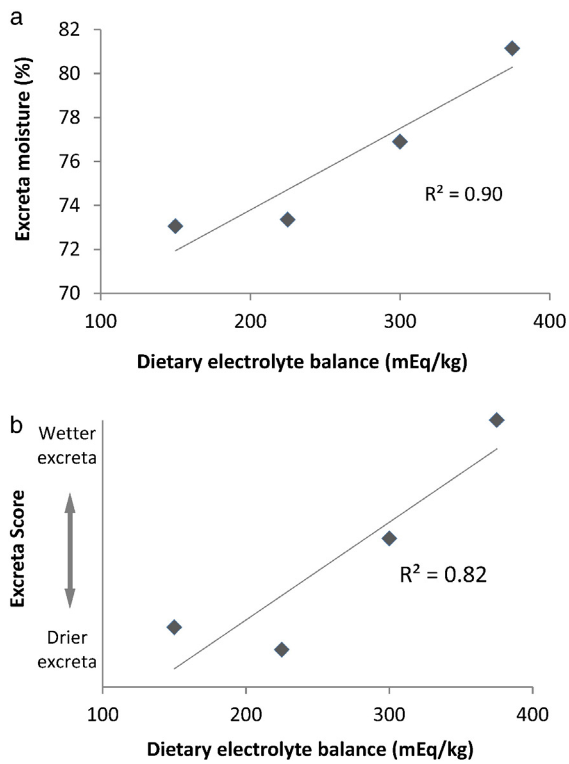

Fig. 2. a. Linear relationship between dietary electrolyte balance and excreta moisture (adapted from Ravindran et al. (2008)). b. Linear relationship between dietary electrolyte balance and excreta score (adapted from Ravindran et al. (2008)).

positive impact of exogenous phytase is diluted by increasing dietary Na levels and, axiomatically, increasing DEB.

Phytate and phytase impact on the Na status of meat chickens (Cowieson et al., 2004). The profound effect of phytase on Na digestibility in the small intestine was initially demonstrated by Ravindran et al. (2006; 2008). Subsequently, Selle et al. (2009b) reported that 500 FTU/kg phytase increased ileal Na digestibility coefficients from −0.52 to −0.04 in wheat-based diets. Further, the addition of 2000 XU/kg xylanase and 500 FTU/kg phytase in tandem marginally enhanced Na recovery from −0.52 to +0.04 at the terminal ileum. More recently, Truong et al. (2014) investigated the effects of 1000 FTU/kg phytase on Na digestibility coefficients in four small intestinal segments in meat chickens offered maize-, sorghum- and wheat-based diets. As a main effect, phytase significantly increased Na digestibility by 21.8% (−2.800 versus −2.190) in the proximal jejunum, 23.4% (−1.462 versus −1.120) in the distal jejunum, 38.0% (−0.983 versus −0.609) in the proximal ileum with a numerical increase of 3.68% (−0.299 versus −0.288) in the distal ileum.

The relevance of increasing DEB and therefore dietary Na levels, to excreta characteristics and, in turn wet litter, is illustrated in Fig. 2. It appears that exogenous phytase has the potential to effectively increase DEB and/or dietary Na levels by attenuating endogenous losses of Na into the gut. The likelihood is that the bulk of these Na losses is as $NaHCO_3$ being secreted into the duodenum primarily by the pancreas as a buffering agent to counter HCl secretion by the proventriculus (Selle et al., 2012). That phytase has the capacity to enhance the retrieval of Na along the small intestine almost certainly has important implications for the absorption of glucose and amino acids via Na^+-dependent transporters and sodium pump activity (Truong et al., 2014). However, in the context of wet litter, it follows that dietary Na levels should be adjusted via appropriate matrix values with phytase supplementation.

That appropriate Ca, P and Na matrix values should be taken into consideration in the formulation of phytate-supplemented diets is illustrated by the data of Huang et al. (2011). In this study litter moisture reduced from 53.2 to 48.1% following average reductions in dietary Ca levels of 1.00 g/kg (8.33 versus 9.33 g/kg), available P levels of 0.50 g/kg (4.07 versus 4.57 g/kg) and Na levels of 0.44 g/kg (1.43 versus 1.87 g/kg). On balance, it seems unlikely that exogenous phytases will contribute to wet litter problems provided appropriate dietary formulations are employed.

The standard dietary Na level is 1.8 g/kg and the maize-, sorghum- and wheat-based meat chicken diets in the Truong et al. (2014) study were formulated to meet this requirement (Liu et al., 2014) but the respective analysed Na levels were 1.18, 1.42 and 1.60 g/kg. It seems likely that the low 1.18 g/kg Na level in the maize-based diets may have contributed to the more robust responses to phytase reported by Liu et al. (2014) in the companion paper. However, in this context the suggestion is that Na levels in grains are generating variations in dietary Na levels that are not being taken into account. In as yet unpublished data, The University of Sydney is finding extraordinary differences in Na levels in grain sorghum samples with a coefficient of variation in excess of 100%. While speculative, it seems likely that sorghums and other grains with excessive, unidentified Na levels could contribute to wet litter.

An insight into the importance of Na, K, Ca and P to a lesser extent, in relation to wet litter, may be gleaned from the Smith et al. (2000) study in laying hens. Elevating dietary Na from 1.6 to 5.5 g/kg increased excreta moisture by 12.7% in association with a 36% increase in water intake. Increasing K from 2.3 to 5.0 g/kg increased excreta moisture by 20.1% with a modest 7.3% increase in water intake. Broadly similar increases in Ca and P did not have equivalent impacts.

Finally, water quality should be taken into consideration in this context, and Carter and Sneed (1996) and Water quality is important but often overestimated (2002) have considered this issue. High levels of Ca and Mg are associated with 'hard water'. Soft water may contain 0.2 Ca and 0.1 mg/100 mL Mg, whereas hard water may contain 6.7 Ca and 4.3 mg/100 mL Mg (Hankin et al., 2002). In the Vieira and Lima (2005) study, water intake exceeded feed intake by factors of 1.93 to 2.13 in meat chickens from 21 to 35 days post-hatch. Consequently, water quality and 'hardness' should not be overlooked as a possible contributing factor to wet litter.

6. Footpad dermatitis (FPD): a consequence of wet litter

Footpad dermatitis (FPD), pododermatitis or 'foot-burn', is essentially a consequence of excessive litter moisture content and high ammonia concentrations. Moreover, FPD is increasingly being recognised as a major welfare issue in chicken-meat production quite apart from its adverse economic consequences. The condition of FPD has been thoroughly reviewed by Shepherd and Fairchild (2010). Instructively, these researchers point out that in the USA, chicken paws are the third most important part of the bird following breast and wings from an economical stand-point.

Harms et al. (1977) investigated the relationship between FPD and litter moisture content, and found that meat chickens reared on wet litter displayed significant increases in the incidence of footpad dermatitis. Meat chickens reared on artificially induced damp litter had an average footpad score of 2.26 compared to a score of 1.22 for their counterparts reared on dry litter (the scoring system rated 1 as no lesions, 2 as the presence of lesions and 3 as the presence of severe lesions). Interestingly, the addition of biotin decreased the incidence of FPD lesions from 70.4 to 66.4% of birds reared on damp litter; however, an examination of footpad tissue indicated that the birds offered control diets were biotin deficient. The average incidence of FPD lesions was 14.9% for birds on dry litter irrespective of biotin supplementation.

McIlroy et al. (1987) completed a longitudinal survey to investigate the epidemiology of contact dermatitis of breast, hocks and feet involving 986 flocks containing 12.6 million birds over a 2 year period in Northern Ireland. Stocking density, feed manufacturer, average age of birds at removal and sex of birds impacted on the incidence of contact dermatitis. The condition was more prevalent during the winter months and there was a strong positive correlation between relative humidity and hock burn. McIlroy et al. (1987) concluded that the incidence of contact dermatitis, including footpad dermatitis, was closely associated with the presence of poor litter conditions.

More recently, Cengiz et al. (2011) investigated the influence of bedding or litter type and transient elevations in litter moisture on the incidence and severity of FPD in meat chickens. The incidence of FPD was significantly increased when litter moisture was increased by wetting at 14 days post-hatch, but not at 56 days post-hatch, and the severity of FPD was reduced with improvements in litter quality. Early exposure to wet litter increased the incidence of FPD from 8 to 53% at day 14. At 34 days post-hatch, exposure to wet litter significantly compromised weight gain by 6.25% (1769 versus 1887 g/bird) and FCR by 2.58% (1.55 versus 1.51 g/g). Cengiz et al. (2011) concluded that litter moisture level and particle size may be crucial factors in the aetiology of FPD. They considered that the condition was occurring early in the grow-out period but subsequent improvements in litter quality could reverse the severity of lesions in market-age meat chickens.

Ekstrand et al. (1997) investigated the foot-health status of meat chickens in Sweden using a classification method to estimate the prevalence of FPD. Data were collected from 101 commercial meat chicken flocks at slaughter. Mild FPD lesions (discoloration, erosions) were observed in 32% of birds, 6% had severe lesions (ulcers) and the remaining birds were classified as being free of FPD. The prevalence of FPD was significantly higher in houses equipped with small water cups than in grow-out sheds equipped with water nipples. Also, litter layers thinner than 5 cm were associated with less FPD than thick layers of litter, regardless of litter material used.

Pagazaurtundua and Warriss (2006) assessed samples of 100 birds from each of 190 flocks slaughtered at two UK processing plants in 2002 and 2003. Only 12 of the flocks, or 6.3% per cent, did not present with signs of FPD. In the majority of flocks, FPD lesions differed in their prevalence and severity. In affected flocks, 16.0% of birds had some evidence of FPD with lesions involving >20% of the area of the foot in the worst examples. The prevalence of FPD and its influential factors in The Netherlands were considered by de Jong et al. (2012) in a survey involving 386 flocks and eight processing plants. They found that 26.1% of meat chickens had mild lesions while 38.4% of birds had severe FPD lesions. In a subsequent study, de Jong et al. (2014) concluded that increased litter moisture not only triggered severe FPD but also compromised meat chicken performance, carcass yield and negatively impacted on bird welfare. Clearly, footpad dermatitis is an important negative consequence of wet litter.

Interestingly, Ask (2010) found genetic variation between and within lines of meat chickens for FPD (and hock-burn) which indicates that selection against FPD is possible. Ask (2010) argued that it is important to select against FPD but such selection should not negatively influence genetic improvements in bodyweight; however, continued selection for increased weight gain while ignoring FPD could lead to an increased propensity to develop FPD. Earlier, Kjaer et al. (2006) had concluded that the relatively high heritability of FPD and its low genetic correlation to bodyweight suggested that genetic selection against susceptibility to FPD should be possible without negatively influencing weight gain.

It is noteworthy that a validated FPD scoring system has been developed for monitoring the incidence and severity of this condition in chicken processing plants (Michel et al., 2012). This researcher recommended that management approaches to reducing these conditions should concentrate on minimising moisture accumulation in litter, particularly in the early rearing period. Michel et al. (2012) concluded that FPD is a major welfare issue in chicken meat production as it was associated with a reluctance to walk in motivational tests.

The development of validated FPD scoring systems and the automated scanning of chicken feet in processing works is clearly a valuable tool to monitor the prevalence and severity of this condition; however, this data is also an indicator of litter quality and could possibly be employed in large-scale evaluations of strategies to improve litter quality more readily than direct assessments of litter in the field.

7. Future directions

In the survey, respondents were asked to nominate where future research effort would be best directed to avoid the problem of wet litter. Interestingly, a proportion of respondents did not believe additional research and development was really needed and held the view that the quest to enhance litter quality should revolve around education and extension. In this connection, Czarick (2008) made a number of practical recommendations to improve litter quality when it is used for successive meat chicken flocks. These recommendations are valuable as they almost certainly focus on the prime causes of wet litter despite the complexity of the problem and could be readily incorporated into extension programs. The central point is that keeping litter dry is all about prevention. For example, the drinker system should be managed properly in respect of drinker height, water pressure and the lines should be flushed and maintained or replaced on a regular basis. Also, to ensure that ventilation is adequate and effective in removing litter water, the relative humidity within the grower shed should be monitored where a relative humidity of 50–60% is considered ideal. These views were supported by one particular survey respondent who believed that it was imperative that growers are better educated so that they understand the mechanics of drinker systems. In his opinion nipple drinker systems have a limited life span, require regular maintenance, water quality should receive greater attention and, overall, nipple drinker systems could be far better utilised by the chicken-meat industry.

There was little uniformity in the survey responses insofar as the research and development directions that should be adopted were concerned. However, the most consistent suggestions did revolve around "minerals" in a broad sense. Seemingly, Ca was considered the most important mineral with one suggestion that a comparison of limestone and dicalcium phosphate as Ca sources in the context of wet litter should be drawn. Other suggestions indicated there was a need to determine actual mineral levels, in both feed and water, variously including Ca, P and Na. Some suggested that the relationship between DEB and wet litter should be investigated further with something of a focus on sodium levels. Others suggested that the role of exogenous enzymes, both NSP- and phytate-degrading feed enzymes, in the genesis of wet litter still should be explored. Finally, it was also suggested that studies into the selection of litter material, its depth and re-use were justified.

To research any specific factor within the frame-work of wet litter could be frustrating and not particularly fruitful given the complexity of the causes of this condition. Nevertheless, the general and increasing importance of footpad dermatitis to the chicken-meat industry is sufficient to encourage future research activities. Somewhat ironically, the prevalence of this condition can be monitored accurately in processing plants and could provide an additional vehicle to assess litter quality and facilitate future research. It may be valuable to assess the practice of whole grain feeding in relation to litter quality and the incidence of FPD. Such studies may well confirm the merits of whole grain feeding in this context but also shed light on the relationships between whole grain feeding, heavier and more functional gizzards, gut motility and reverse peristalsis, and 'gut integrity'.

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