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Research article

Water activity of poultry litter: Relationship to moisture content during a grow-out

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ABSTRACT

Poultry grown on litter floors are in contact with their own waste products. The waste material needs to be carefully managed to reduce food safety risks and to provide conditions that are comfortable and safe for the birds. Water activity (A_w) is an important thermodynamic property that has been shown to be more closely related to microbial, chemical and physical properties of natural products than moisture content. In poultry litter, A_w is relevant for understanding microbial activity; litter handling and rheological properties; and relationships between in-shed relative humidity and litter moisture content. We measured the A_w of poultry litter collected throughout a meat chicken grow-out (from fresh pine shavings bedding material to day 52) and over a range of litter moisture content (10–60%). The A_w increased non-linearly from 0.71 to 1.0, and reached a value of 0.95 when litter moisture content was only 22–33%. Accumulation of manure during the grow-out reduced A_w for the same moisture content. These results are relevant for making decisions regarding litter re-use in multiple grow-outs as well as setting targets for litter moisture content to minimise odour, microbial risks and to ensure necessary litter physical conditions are maintained during a grow-out. Methods to predict A_w in poultry litter from moisture content are proposed.

1. Introduction

Meat chickens (broilers) are commonly raised in open plan sheds on a litter floor. Litter is a mixture of bedding materials (e.g. pine shavings, other wood products, rice hulls or peanut shells) and excreta (Miles et al., 2011). The birds are in constant contact with the litter and therefore the condition of the litter needs to be managed to provide a safe and comfortable environment. One function of litter is to absorb and store water from excreta and drinking-system spillage until the water can be evaporated and removed from the shed by the ventilation system. The amount of water in litter has been found to affect microbial activity (Bessei, 2006; Eriksson De Rezende et al., 2001; Himathongkham et al., 1999; Wadud et al., 2012), thermal insulation (Agnew and Leonard, 2003), ammonia emissions (Miles et al., 2011), odour emissions (Clarkson and Misselbrook, 1991; Murphy et al., 2014) and friability (Bernhart and Fasina, 2009).

'Wet litter' has been described as a multi-factorial problem in poultry production (van der Hoeven-Hangoor et al., 2013) that requires a multi-disciplinary approach to develop solutions (Tucker and Walker, 1992). One definition for wet litter is that it has greater than 25% moisture content and compromised cushioning, insulating and water holding capacity (Collett, 2012). Wet litter has been implicated as a primary cause of contact dermatitis in poultry (Shepherd and Fairchild, 2010) and also negatively affects feed conversion ratio and carcass yields (de Jong et al., 2014). Wet litter can be caused by a combination of diet/nutrition factors (Collett, 2012); shed design, ventilation management and environmental factors (Hermans et al., 2006); and/or flock infections with organisms such as *Clostridium perfringens*, the causative agent of necrotic enteritis (M'Sadeq et al., 2015). Avoiding the consequences of 'wet litter' is one important reason to manage the moisture content of litter during a grow-out.

Water activity (A_w) is arguably a better measure of water in litter than moisture content (mass of water divided by mass of moist

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litter, expressed as a percentage) since it is more closely related to microbial, chemical and physical properties of litter (van der Hoeven-Hangoor et al., 2014). A_W is a thermodynamic property relating to the relative freedom or availability of water in a sample and its tendency to escape. Reid (2007) defined A_W as the ratio of the fugacity of water in a system, and the fugacity of pure liquid water at the same temperature, where fugacity is a measure of the escaping tendency of a substance. A_W can be approximated by the equilibrium relative humidity (ERH, expressed as a %) of a substance (Carr et al., 1995; Reid, 2007). In fact the two terms, A_W and ERH, are effectively interchangeable (A_W = ERH/100). A_W is temperature dependent and generally increases with temperature when moisture content is constant, although the relationship can reverse at high A_W (Labuza and Altunakar, 2007b).

A_W provides a measure of the thermodynamic forces driving the movement of water within and between media (including air). Water will migrate from higher A_W to lower A_W until equilibrium is achieved and A_W is constant throughout the system (assuming isothermal conditions). Different materials can have the same A_W but different moisture content (or vice-versa), but it is A_W that regulates water movement (Labuza and Altunakar, 2007a). A_W theory can be used to explain the movement of water between excreta, litter and air in poultry sheds, but is a guide only because A_W applies only to equilibrium conditions (constant temperature, no air velocity and no air exchange), which do not occur in commercial poultry sheds. If temperatures are unbalanced, with the litter surface being below the dewpoint temperature, then water will also condense on the litter surface (Tucker and Walker, 1992). Additionally, the effect of increasing air velocity in the poultry shed may reduce water absorption into the litter surface, resulting in lower litter moisture content for a given relative humidity condition (Foong et al., 2009).

It has been demonstrated that the microbiological properties of poultry litter are directly related to A_W, and that maintaining litter below a critical A_W value corresponds with reduced growth of pathogens including *Salmonella* and *Escherichia coli* as well as other microbiota (Carr et al., 1995; Chinivasagam et al., 2012; Eriksson De Rezende et al., 2001; Hayes et al., 2000; Himathongkham et al., 1999; Macklin et al., 2006; Payne et al., 2007). A_W has also been related to physical handling properties of litter including cohesion, adhesion, compressibility and flowability (Bernhart and Fasina, 2009; Reed and McCartney, 1970; Roudaut, 2007).

The purpose of this study was to explore the relationship between A_W and moisture content of litter from a meat chicken shed throughout a grow-out period. The relationship between A_W and litter moisture content during a grow-out has implications for litter management, the microbial properties of poultry litter and the potential for environmental impacts with the formation of nuisance odours. These are relevant for making decisions regarding litter re-use for multiple grow-outs, setting targets for litter moisture content to minimise microbial risks and to ensure necessary litter physical conditions are maintained during a grow-out.

2. Materials and methods

2.1. Farm description and collection of litter and bedding materials

Litter samples were collected in a previous study (Dunlop et al., 2015). In brief, litter samples were collected from a commercial broiler shed that was stocked with Ross 308 meat chickens at a stocking density of 19.4 birds/m^2. Pine shavings were used at the start of the grow-out at a depth of 5 cm. Litter samples were collected on days 0 (pine shavings), 10, 17, 24, 31, 38, 45 and 52 of a grow-out. Samples were stored at 4 °C until the end of the grow-out period.

Samples of bedding materials (not containing excreta) including hardwood sawdust, rice hulls and peanut shells were also tested and compared with pine shavings. These materials were stored in as-received condition until testing.

2.2. Sample preparation

A 0.5–1.0 L sample from each litter collection day and each bedding material was dried in an oven at 40 °C until a constant mass was reached. Each sample was then divided into seven sub-samples that were designated with a target moisture content value: 10.0, 16.3, 22.5, 28.8, 35.0, 47.5 and 60% (wet basis; mass of water divided by mass of moist sample). Target values were arbitrarily chosen to represent the normal range of litter moisture content found in meat chicken production. The required amount of water to achieve each target moisture content value was then added to each sub-sample, which were then mixed and sealed in individual containers for 24–48 h prior to A_W analysis.

2.3. Water activity analysis

A_W was measured using an AquaLab® dewpoint water activity meter (model 4TE, Decagon Devices Inc., Pullman, WA, USA—measurement range 0.030–1.000 A_W, accuracy ±0.003 A_W, repeatability ±0.001 A_W). The temperature controlled sample chamber was set to 25 °C. Between each A_W measurement, dry activated charcoal was placed in the sample chamber to remove any residual moisture or volatiles.

Litter samples for each of the seven moisture contents from each of the eight sampling days were analysed in random order in triplicate. The experimental design (7 × 8 × 3) produced a total of $n = 168$ measurements. Bedding material samples for each of the seven moisture contents for each of the four materials were analysed in random order in duplicate. The experimental design (7 × 4 × 2) produced a total of $n = 56$ measurements. When each A_W measurement was complete, the litter sample was placed in a pre-weighed tray and dried in an oven (model 8150, Contherm, Hutt City, New Zealand) at 65 °C to determine matching moisture content value for each A_W value.

2.4. Data analysis

2.4.1. Non-linear regression analysis

The relationship between A_W and moisture content of bedding and litter materials was investigated using grouped non-linear (exponential) regression analysis with a grouping factor for bedding material or litter sampling day, respectively. *GenStat* 16th Edition (VSN, 2014) was used to fit the exponential function (Eq. (1)). Significance of the grouping factor on curve parameterisation was assessed when *p*-values were less than 0.05.

$$A_W = A + B \times (R^m) \tag{1}$$

where: A_W is water activity; m is litter moisture content (wet basis, expressed as a decimal value); and A, B & R are parameters to be estimated.

2.4.2. Application of the empirical 'Henderson' model

Theoretical and empirical models have previously been used to describe the relationship between A_W and dry basis moisture content (Maia et al., 2011). (Note the use of *dry basis* moisture content in this section, where moisture content is calculated from the mass of water divided by the mass of the dry solids. Equations to convert moisture content between wet and dry basis are provided in the supplementary material.) One such empirical model, the 'Henderson model' (Henderson, 1952), has been used extensively to describe the water sorption behaviour of biological materials

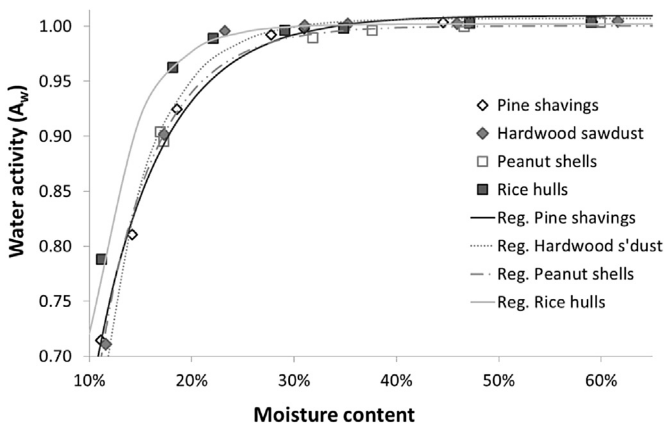

Fig. 1. Mean experimental values and exponential regression curves for bedding materials showing water activity (A_w) as a function of moisture content (wet basis).

because of frequent high correlation with experimental data and small number of model parameters (Maia et al., 2011). The model is expressed in Eq. (2) and Eq. (3) depending on whether A_W or moisture content is the subject, respectively.

$$A_W = 1 - e^{(-Tk(M^n))} \tag{2}$$

$$M = [(ln(1 - A_W))/(-kT)]^{1/n} \tag{3}$$

where: A_W is water activity (expressed as a decimal); M is the equilibrium litter moisture content (dry basis); k and n are experimentally derived parameters; T is the temperature (K); e is exponential of the natural logarithm (ln).

To describe the relationship between moisture content and A_W, the Henderson model (Eq. (2)) was fitted for each day separately using non-linear regression with no linear terms. An exponential curve was then fitted to the parameter estimates of k and n from the fitted Henderson models for each day, allowing these parameters to be estimated on any day of the grow-out.

3. Results and discussion

3.1. Relationship between A_W and moisture content for bedding materials and litter

Exponential relationships between water activity (A_W) and moisture content (%, wet basis) were observed for bedding materials with curves differing ($P < 0.01$) among materials (Fig. 1; $R^2 = 0.983$; regression parameters provided in Table 1). A_W increased from 0.70 to 1.00 as moisture content increased from 11 to 60%. The increase of A_W as a function of moisture content was most rapid for rice hulls. Compared to equilibrium relative humidity (ERH) values published by Reed and McCartney (1970), our A_W values for pine shavings and rice hulls were similar although our A_W values for peanut shells appeared to be lower. This comparison was limited due to Reed and McCartney (1970) measuring ERH to a maximum of 93% ($A_W = 0.93$), which had corresponding litter moisture content of 16–19%.

All the bedding materials displayed high A_W (>0.99) when moisture content was greater than 30%, but rice hulls exhibited higher A_W than the other bedding materials when moisture content was less than 25%. This may make rice hulls more prone to caking and supporting more microbial growth at the early stages of a grow-out. Further testing would be required to confirm whether the relatively higher A_W of rice hull continues during the grow-out when manure is added.

Exponential relationships were also evident between A_W and moisture content for litter samples (regression curves for selected days shown in Fig. 2; $R^2 = 0.989$; regression parameters provided in Table 1 and a method to estimate the regression parameters for litter on any day is provided in the supplementary material). Curves differed ($P < 0.001$) among sampling days with A_W reaching an asymptote most rapidly (i.e. at the lowest moisture content) for the pine shavings (moisture content approx. 28%) and less rapidly (i.e. at higher moisture contents) as the grow-out progressed. In other words, we observed a general trend for A_W to decrease for the same value of moisture content as the grow-out progressed and the manure content in the litter increased (evident by the curves in Fig. 2 shifting downwards and to the right as the number of days during the grow-out increased). This trend has relevance for microbial activity in the litter as well as the management of litter physical properties and moisture content.

One consequence of the trend for A_W to decrease during a grow-out (Fig. 2), is that litter later in the grow-out will absorb more water and equilibrate at higher moisture content for the same relative humidity (evident in Fig. 2 by exchanging the name of the vertical axis from 'Water activity' to '[Equilibrium] relative humidity'). This phenomenon is most evident at very high relative humidity, and litter moisture content could be maintained below, for example 25%, if relative humidity at the litter surface remains below 92% (and assuming there are no other water inputs).

The curvilinear relationships observed in this study between A_W and moisture content were similar to those reported by Bernhart and Fasina (2009) and Eriksson De Rezende et al. (2001);

Table 1
Regression analysis parameters (Eq. (1)) for bedding and litter materials (parameter value ± standard error (s.e.)).

Materials	Regression parameters		
	A	*B*	*R*
Bedding materials			
Pine Shavings	1.010E+00 ± 4.83E-03	−1.562E+00 ± 1.90E-01	3.040E-07 ± 3.23E-07
Hardwood sawdust	1.007E+00 ± 4.95E-03	−2.993E+00 ± 6.23E-01	2.270E-09 ± 4.04E-09
Peanut shells	1.000E+00 ± 5.00E-03	−2.206E+00 ± 3.42E-01	1.540E-08 ± 2.06E-08
Rice Hulls	1.002E+00 ± 4.81E-03	−3.180E+00 ± 1.21E+00	2.930E-11 ± 1.01E-10
Litter collected during grow-out			
Day 0 (Pine shavings)	1.010E+00 ± 3.47E-03	−1.562E+00 ± 1.36E-01	3.040E-07 ± 2.32E-07
Day 10	9.956E-01 ± 3.38E-03	−1.284E+00 ± 1.28E-01	5.890E-07 ± 5.09E-07
Day 17	9.899E-01 ± 3.36E-03	−1.241E+00 ± 1.23E-01	9.310E-07 ± 7.67E-07
Day 24	9.908E-01 ± 3.56E-03	−1.268E+00 ± 1.23E-01	1.740E-06 ± 1.34E-06
Day 31	9.901E-01 ± 3.91E-03	−9.872E-01 ± 7.15E-02	1.315E-05 ± 7.97E-06
Day 38	9.959E-01 ± 4.94E-03	−5.993E-01 ± 3.60E-02	2.840E-04 ± 1.56E-04
Day 45	9.888E-01 ± 4.00E-03	−1.010E+00 ± 7.35E-02	2.310E-05 ± 1.34E-05
Day 52	9.909E-01 ± 4.32E-03	−8.687E-01 ± 6.47E-02	5.860E-05 ± 3.41E-05

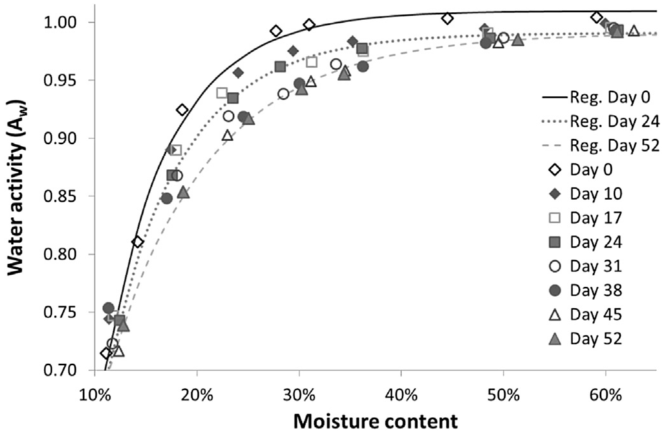

Fig. 2. Mean experimental values and selected exponential regression curves for poultry litter showing water activity (A_w) as a function of moisture content (wet basis). Pine shavings were used as bedding at the start of the grow-out, Day 0, and regression curves shown for Days 0, 24 and 52.

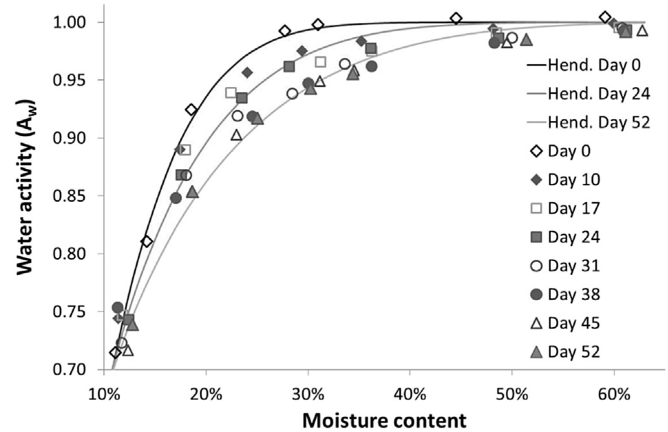

Fig. 3. Mean experimental values and selected Henderson model curves (Days 0, 24 and 52) for poultry litter showing water activity (A_w) as a function of moisture content (wet basis).

however, we have demonstrated that the relationship changes during the grow-out. Bernhart and Fasina (2009) explained that the observed curvilinear relationship is typical for materials that absorb moisture by capillary forces and for materials that contain significant amounts of soluble components such as sugars and salts. A_w measured in this study compared well with some published values (van der Hoeven-Hangoor et al., 2014), but was higher than others by about 0.05 A_w (Bernhart and Fasina, 2009; Carr et al., 1995; Eriksson De Rezende et al., 2001; Hayes et al., 2000). We suggest that differences observed between studies may be due to differences in the bedding materials, A_w testing conditions (e.g. temperature), or due to some of the previously tested litter being used for multiple grow-outs. The possibility of measuring lower A_w in previously used litter is supported by Chinivasagam et al. (2012), who found that litter used for multiple grow-outs tended to have lower A_w compared to litter being used in its first grow-out (fresh bedding material used at the start of the first grow-out). This further supports our observation that A_w decreases over the course of a grow-out and also demonstrates that A_w is likely to be even lower when litter is used for multiple grow-outs.

3.2. Empirical 'Henderson' model A_w isotherms

The Henderson model (Eq. (2)) described the relationships between A_w and moisture content for each day with R^2 values ranging from 0.975 to 0.994 (Table 2, with selected model curves in Fig. 3). The strong fit of the model to the experimental data in this study further supports the application of the model to a variety of biological/agricultural materials as previously demonstrated by Henderson (1952) and Maia et al. (2011). Parameter estimates for k and n decreased exponentially during the grow-out with $R^2 = 0.973$ and 0.928, respectively (Table 2), which implied that the litter properties did indeed change. (Day 38 data were excluded from the exponential regression analysis between the parameter estimates and day because it had a poor fit with these relationships. We speculate that the litter sample collected on day 38 may not have been characteristic of the litter in the shed.)

The thermodynamic basis of the Henderson model enables the A_w isotherms to be estimated for other temperatures (Henderson, 1952). We speculate that the parameter estimates developed in this study will allow the relationships between A_w and moisture content to be estimated for pine shavings based poultry litter at any stage of a grow-out and for different temperature conditions, although further testing is required to verify this.

3.3. Water activity (A_w) and the transfer of water between excreta, litter and humid ventilation air

Fresh excreta contain a diverse microbial community from the gastrointestinal tract of the birds (Lu et al., 2003; Singh et al., 2014) and rapidly reducing A_w of excreta may have a positive effect on reducing microbial growth within the litter. Theoretically, the two main factors controlling moisture transfer between porous materials (i.e. excreta and litter) are A_w and resistance to diffusion (Labuza and Altunakar, 2007a). Resistance to diffusion increases when there is low porosity or the path that the water vapour needs to travel is long or tortuous (Schwarzenbach et al., 2003). A_w of

Table 2
Henderson model (Eq. (2)) parameters n and k for litter materials (parameter value ± s.e.) and regression equations to estimate these parameters.

Materials	Henderson model parameters		
	k	n	R^2
Day 0 (Pine shavings)	0.0438 ± 0.0064	1.1271 ± 0.0799	0.975
Day 10	0.0293 ± 0.0013	0.9005 ± 0.024	0.994
Day 17	0.0255 ± 0.0018	0.8397 ± 0.0411	0.980
Day 24	0.0250 ± 0.0015	0.8606 ± 0.0348	0.985
Day 31	0.0202 ± 0.0010	0.7539 ± 0.0305	0.983
Day 38	0.0156 ± 0.0006	0.5764 ± 0.0223	0.984
Day 45	0.0187 ± 0.0008	0.7469 ± 0.0283	0.986
Day 52	0.0173 ± 0.0005	0.6918 ± 0.0200	0.991
Parameter estimation equations (where d is the day of the grow-out ($0 \le d \le 52$)	$k = 0.01727 + 0.02613 \times (0.9359^d)$	$n = 0.6991 + 0.4173 \times (0.9434^d)$	k: 0.973 n: 0.928

excreta was previously reported by van der Hoeven-Hangoor et al. (2014) to be 0.96–0.99. Therefore, A_W of the litter needs to be less than this for there to be a thermodynamic gradient to drive the diffusion of water from the excreta into the litter. If not, water will not diffuse from the excreta to the litter and there will be complete reliance on water to diffuse from excreta into the ventilation air. We speculate that would slow drying of the excreta and sustain high A_W, which supports microbial growth and increases excreta/litter cohesion that leads to litter caking. In contrast, excreta that is worked into friable litter with low A_W is broken into smaller pieces by bird activity (walking, scratching, dust-bathing and foraging) and become coated in dry litter particles that draw water out of the excreta (due to the thermodynamic gradient generated by difference in A_W). The resulting litter will have lower A_W compared to the fresh excreta, will be less likely to commence caking and as a result will more likely remain friable. Maintaining friability may also prevent anaerobic conditions and associated nuisance odours. Further testing is required to measure the diffusion rate of water between excreta and litter, and to accurately describe cake formation processes.

3.4. Litter rheological properties relating to A_W

Roudaut (2007) theorised that A_W is directly related to the flowability, stickiness and caking of granular materials. When A_W increases in a material, a '*critical hydration level*' will be reached and this will commence a process whereby the surface of individual particles will plasticise and bond with neighbouring particles through inter-particle liquid bridging. The strength of this bond depends on the particle size and composition but also the length of time allowed for bonds to form. Eventually, inter-particle bonding/bridging leads to agglomeration and/or cake formation that produces a compacted material with reduced porosity.

Bernhart and Fasina (2009) related the cohesiveness and flowability of poultry litter to moisture content and A_W. They showed that the cohesive strength of litter rapidly increased (the observed change in cohesive strength also depended on the consolidation pressure applied to the litter), and the litter changed from 'free-flowing' to 'cohesive' when the moisture content increased from 18.0% to 22.1% (~0.75 to ~0.85 A_W, respectively). Based on the theory of Roudaut (2007) and observed properties of poultry litter by Bernhart and Fasina (2009) (and taking into consideration that our values of A_W were approximately 0.05 greater than theirs), we suggest that poultry litter reaches the *critical hydration level* when A_W is between 0.75 and 0.90. Based on our data, this corresponds with moisture content ranging from 12 to 24% depending on the day during the grow-out. It is therefore likely to be beneficial to keep the A_W of litter below the *critical hydration level* so the litter remains friable, enabling excreta to be worked into the litter to maximise the rate of moisture transfer away from the excreta.

3.5. Effect of A_W on microbiota

Fontana (2007) and Taoukis and Richardson (2007) have previously established that microbiota growth can be reduced by limiting A_W and summarised nominal A_W values for selected microbiota (based on testing of food materials) that have relevance in poultry production: 0.75–0.85 for *Aspergillus* spp.; 0.86–0.90 for *Staphylococcus* spp.; 0.92–0.95 for *Salmonella* spp.; 0.95 for *E. coli*; 0.93–0.97 for *Clostridium* spp.; and 0.98 for *Campylobacter* spp. These growth limiting A_W values depend on other factors including acidity, temperature, oxygen, nutrient availability and presence of inhibitors (Tapia et al., 2007). It has previously been recommended that the A_W of poultry litter should be kept below 0.84–0.91 to restrict the growth of *Salmonella* and other microbiota (Chinivasagam et al., 2012; Eriksson De Rezende et al., 2001; Hayes et al., 2000; Payne et al., 2007).

Carr et al. (1994) reported that new bedding material (sawdust) had higher A_W than litter and this was associated with the presence of *Salmonella*. Similarly, Chinivasagam et al. (2012) reported that litter being used for a first grow-out (when fresh bedding was used at the start) had higher A_W and *Salmonella* levels than litter that had already been used in a previous grow-out (re-used litter). In addition to restricting the growth of microbiota, maintaining low A_W in poultry litter should, in general, reduce bacterial odour production (Macklin et al., 2006).

A_W growth limits for selected microbiota were compared against the A_W isotherms for fresh pine shavings and day 52 litter that were measured in our study (Fig. 4). We speculate that lower A_W observed later in the grow-out may be beneficial for reducing growth of some microbial organisms (especially those with higher A_W limits), and that it may be less necessary to maintain very low litter moisture content at the end of a grow-out, compared to the start of the grow-out, in order to have the same A_W and respective microbial growth restriction. Further testing under field conditions is required to confirm this.

4. Conclusions

Water activity (A_W) is an important thermodynamic property of materials but has not received a great amount of attention with regard to poultry litter. In this study, we have shown that the relationship between litter moisture content and A_W changes during a meat chicken grow-out using standard exponential regression analysis and through application of the Henderson model. In general, A_W is greatest with fresh bedding materials and decreases during the grow-out with the addition of excreta and natural breakdown of the organic materials.

Poultry excreta and litter naturally contain microbiota. Whilst most of these organisms are ubiquitous and essential in some aspects of poultry production, for example in the chickens' gastrointestinal tract, once in the litter they contribute to odour production and increase risks to flock health, worker health and food safety. We speculate that maintaining low A_W (e.g. less than 0.85–0.91 A_W) in the poultry litter through active litter moisture management shall:

- reduce microbial risks to flock health, worker health and food safety;
- reduce microbial odour production and the potential for nuisance odour impacts;

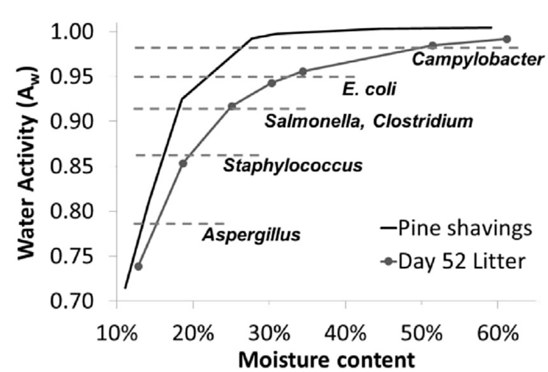

Fig. 4. Minimum water activity limits for growth of selected microbiota including Campylobacter, *E. coli*, *Salmonella*, *Clostridium*, *Staphylococcus* and *Aspergillus* (Fontana, 2007); Taoukis and Richardson, 2007) compared to water activity for fresh pine shavings and poultry litter collected on Day 52 of a grow-out.

- assist in the transfer of water from excreta, which initially has high A_w (0.96–0.99 A_w), into the litter, thus reducing the A_w of excreta and the survival of gut-sourced bacteria in the litter; and
- reduce litter particle cohesion and prevent caking thus maintaining friable and free-flowing litter.

High A_w in fresh bedding materials provides a major challenge early in the grow-out with respect to microbial control. We suggest that using litter from the previous grow-out as bedding material at the start of a grow-out (i.e. litter reuse) may provide some benefit from a A_w perspective, although other factors, such as ammonia, need to be considered.

Meat chickens raised on litter floors interact with their own waste products and therefore litter conditions need to be carefully managed to control the risks associated with this contact. A_w is an important measure of litter properties, and is closely related to microbial activity, physical properties and in-shed relative humidity/litter moisture management. Greater focus should therefore be placed on measuring A_w in addition to moisture content. In the absence of measuring A_w, the methods proposed in this paper to estimate A_w from moisture content should be considered.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2016.02.036.

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