2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

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# Characterizing Manure and Litter Properties and Their Carbon Dioxide Production in an Aviary Laying-Hen Housing System

**Yang Zhao[1], Ph.D.** **Deling Zhao[1,2], Ph.D.** **Wei Wang, MSc.** **Hongwei Xin[1], Ph.D.**

**Post-Doc** **Associate Professor** **Assistant Scientist** **Professor, Director**

[1] Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA, USA

[2] Department of Mechanical Engineering, Nanjing Institute of Industry Technology, Nanjing, China

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**Abstract.** *Contribution of carbon dioxide ($CO_2$) production from manure or litter can be significant relative to animal metabolic $CO_2$ production in housing systems with less frequent excretion removal. Such $CO_2$ contribution should be accounted for in order to improve the accuracy of estimating building ventilation rate (VR) and animal bioenergetics based on $CO_2$ mass balance. The objective of this study was to investigate the thermal conditions (temperature and relative humidity, or RH), production, moisture content (MC), and $CO_2$ production of laying-hen manure on collection belts and on litter in an aviary house. Hens spent about 15.25 h day$^{-1}$ in the aviary colony where their manure was deposited on the belts, and the remaining 8.75 h day$^{-1}$ on the litter floor where manure was deposited on belt or litter. Manure belts were operated 1/3 of their length each day.*

*Results show that temperature and RH were, respectively, 1.8 ± 9.3˚C (mean ± standard deviation) and 79 ± 14% for ambient air, 18.5 ± 1.7˚C and 76 ± 16% for air near manure on belt, and 19.8 ± 1.5˚C and 80 ± 17% for air near the litter. The overall daily manure production was 35.8 ± 1.4 g hen$^{-1}$ day$^{-1}$ on dry basis, with 90.9% deposited on manure belt and 9.1% on litter floor. MC of manure on belt was 66.4 ± 5.8%, which was significantly higher than 14.6 ± 2.4% for the litter. The combined moisture production from manure on belt and litter was estimated to be 22.6 g day$^{-1}$ hen$^{-1}$. The $CO_2$ production from as-is manure was 0.10 ± 0.06 ml s$^{-1}$ kg$^{-1}$ (or 0.32 ± 0. 20 ml s$^{-1}$ kg$^{-1}$ on dry basis), whereas $CO_2$ production from as-is litter was much lower, 0.02 ± 0.02 ml s$^{-1}$ kg$^{-1}$ (or 0.03 ± 0.02 ml s$^{-1}$ kg$^{-1}$ on dry basis). Without litter removal, $CO_2$ production from manure and litter could amount to as high as 8.1% of the hen's respiration $CO_2$ at 60 week of age. This potentially significant contribution should be considered when estimating VR or animal bioenergetics using $CO_2$ mass balance method in aviary housing systems.*

**Keywords.** Manure/litter management, whole-house animal calorimetry, $CO_2$ balance

## Introduction

Aviary laying-hen housing system has been increasingly used for niche-market of egg supply in the United States, and it may become more popular if the U.S. Congress passes the proposed legislation for the U.S. egg producers to transit from conventional cages to an alternative enriched colony housing system in future (18) years (Greene. J. L. and Cowan, 2013). This system features lower stocking density and enrichment elements such as perches, nest boxes and scratching areas to accommodate natural behaviors of the hens.

Manure is the source of gaseous pollutants and adds water vapor inside hen houses. The release of gases and water vapor depends on surrounding thermal conditions (temperature and relative humidity, or RH) and manure properties, e.g. moisture content (MC). Much research has been carried out to identify the above-mentioned factors and the related gas and water vapor emissions from manure in conventional cage housing systems (Chepete et al., 2004; Chepete et al., 2011; Li et al., 2008; Yang et al., 2000), where the manure was either regularly removed (manure-belt system) or stored in the low level of the house (high-rise system). In a typical aviary house in US, manure may deposit on collection belts below each colony tier and on floor (forming a layer of litter). The belt manure is scrapped off on a regular basis, while the floor litter is normally not removed until the end of the entire laying cycle (e.g., after 60 weeks of production), though some producers dispose of the litter one or two times within the laying cycle to control indoor air quality. The discrepancy between belt manure and litter handling leads to difference in manure properties, which may in turn affect its contribution to indoor aerial environment. However, information is merger concerning the manure or litter properties in US aviary hen housing systems.

Besides assessing environmental footprint, measurement of carbon dioxide ($CO_2$) in livestock houses has been used for a variety of auxiliary purposes. As a tracer gas, $CO_2$ is used to estimate house ventilation rate (VR) based on mass balance principle, providing a simple and relative accurate solution in VR determination for both naturally and mechanically ventilated houses (Li et al., 2005; Mosquera et al., 2012). The quantity of $CO_2$ production is also used to calculate the animals bioenergetics (i.e., metabolic rate or total heat production, and respiratory quotient (Hayes et al., 2013). In a livestock house without supplemental heating, $CO_2$ is produced from animal respiration and manure/litter biodegradation. Some previous studies neglected the contribution of $CO_2$ from manure and litter when calculating building VR or animal biogenetics (Van't Klooster and Heitlager, 1994). This maneuver is acceptable for houses with frequent manure and litter removal, whereas it might be not appropriate for housing systems where these excretes are stored for long periods (Jeppsson, 2000, 2002). Pedersen et al. (2008) recommended to consider an 8.3% constant contribution of $CO_2$ production from manure and litter in layer houses, and 8.1 – 8.3% in broiler houses, when the excretion storage period was less than 3 weeks. However, manure or litter can be stored indoors over much longer periods, e.g. over 1 year in aviary laying-hen housing system (Zhao et al., 2013a), and their $CO_2$ contribution would vary with the manure and litter accumulation. In order to accurately apply the $CO_2$ based methods, temporal profiles of $CO_2$ production from manure and litter in aviary hen housing system need to be investigated under practical situations throughout the production cycle.

The objectives of this study were to 1) examine the surrounding air temperature and RH, production, MC of belt manure and floor litter in an aviary hen housing system, and 2) determine $CO_2$ production from belt manure and floor litter over the hen's production cycle.

## Materials and Methods

### Aviary house and hens

The experiment was carried out in an aviary house on a commercial farm in the Midwest USA. The house measured 150.8 m long, 21.4 m wide and 3.0 m high, with 20 exhaust fans installed on one sidewall (fig. 1). Fresh air entered the attic through the continuous eave inlet then into the room through three rows of ceiling box inlets. At the onset of the flock, 50,000 Hy-Line CV22 hens at 17 weeks of age were introduced into the house on August 30, 2012. The aviary house had six colony rows. The inner four rows were two-by-two paired, with each pair sharing a double-wide litter area (6 m wide). The two side rows used single-wide litter area (3 m wide). In each of the three compartments attached to the sidewall of the aviary house, there were one blower and one heater installed to recirculate the room air for manure drying and provide supplemental heat, as needed. For each row, two cage-row-length manure belts were installed underneath the wire floor in the aviary colonies. The upper manure belt was 1.2 m wide and the lower one was 1.5 m wide. The aviary colonies were equipped with nipple drinkers, feed troughs, nest boxes and perches. The resource allowances are listed in Table 1; and the schematic drawing is shown in Figure 2.

**Table 1. Resource allowance of the aviary housing system**

| *Parameter* | *Value* |
|---|---|
| Wire mesh floor space | 620 $cm^2$ / hen |
| Litter floor space | 510 $cm^2$ / hen |
| Nest space | 80 $cm^2$ / hen |
| Perch space | 13 cm / hen |
| Feed trough space | 7 cm / hen |
| Nipple drinker | 8.6 hens / drinker |

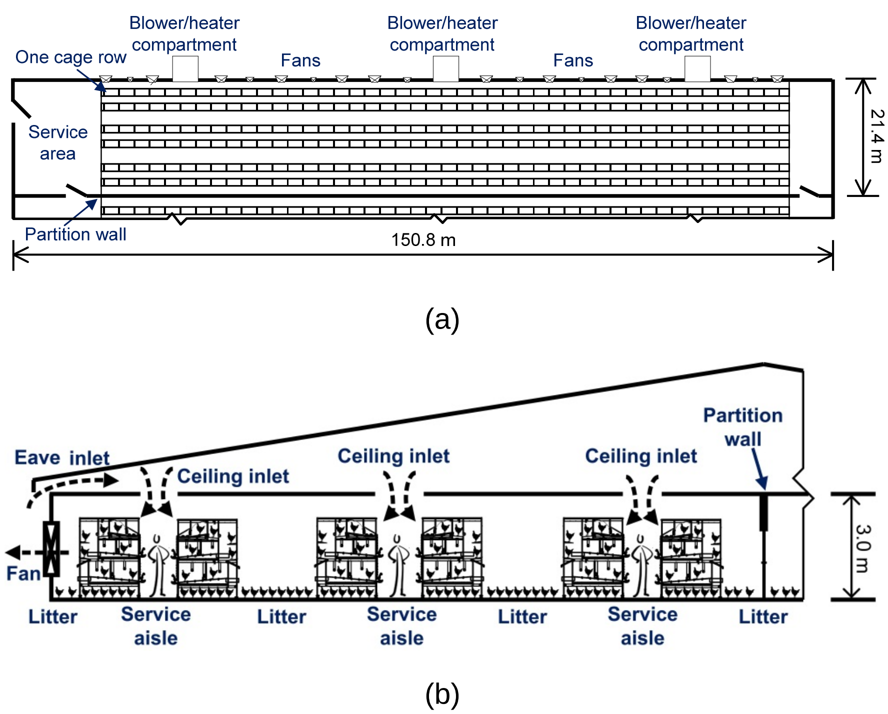


**Figure 1. Schematic layout (a) and cross-section (b) views of the aviary laying-hen house.**

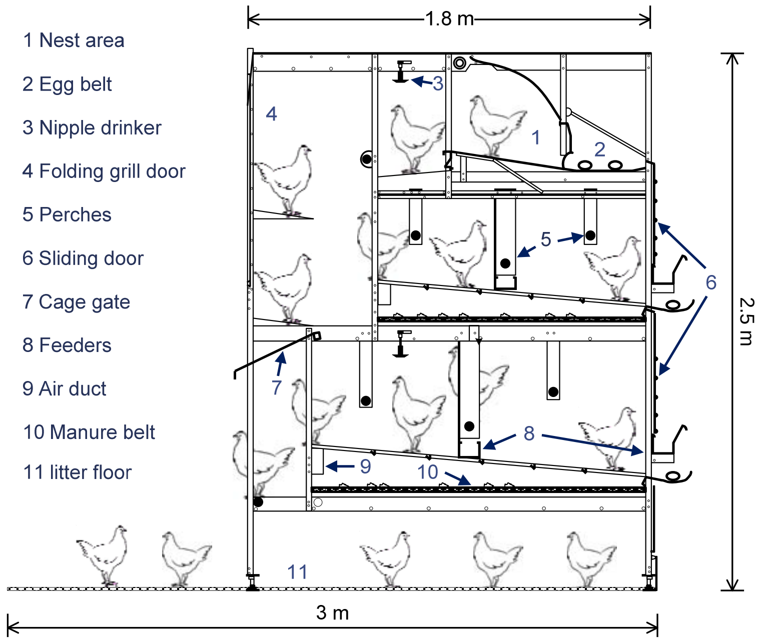


**Figure 2. Schematic drawing of the aviary cage with litter area (side row).**

## Management

Hens were reared in the colonies to become acclimated to the system for the first five weeks after introduced to the aviary house. Starting from 22 weeks of age, they were given 8.75-hr litter access everyday (13:00 – 21:45). Feed and water was provided *ad libitum*.

Manure belt was operated at 6:00h for 10 min every morning, so that manure at the end 1/3 section was scraped off the belt and removed out of the house. This manure handling strategy yielded manure at three different ages on the belt, i.e., 0-1 day old at the beginning 1/3 section, 0-2 days old at the middle 1/3 section, and 0-3 days old at the end 1/3 section. The manure on the belt was continuously dried by the room air that was recirculated and distributed by the blowers through air ducts (fig. 3) between the wire floor and manure belt. Litter on the floor was removed once on March 6, 2013 when hens were at 43 weeks of age.

**Figure 3. Air distribution duct for drying belt manure.**

Three 73.25 kW gas heaters (Guardian Forced Air Heater, Model AD250, L.B. White Co., Onalaska, WI, USA) were turned on if temperature in the hen house was below 18°C and off when temperature of the blower/heater compartment reached 47°C (a safety control).

The light was on a 16L: 8D schedule. In the morning, lights came on gradually, starting at 5:00h and reaching the maximum level at 6:00h; in the evening, the lights were dimmed down, starting at 8:45h and completely off at 9:45h to simulate sunrise and sunset. In the meantime when the lights were dimmed down, rope lights attached to the colonies were turned on to call the hens back to the colonies.

**Measurement**

To cover the seasonal effect, production of $CO_2$ from belt manure and floor litter was measured once every month from Oct. 16, 2012 to Apr. 27, 2013. On each sampling day, measurements were taken at 9:00 h, 13:00 h, 19:00 h and 2:00 h (the next day). At each sampling moment, $CO_2$ production from 0-1 day old belt manure, 0-3 day old belt manure and litter were measured in triplicate. The 0-1 day old manure was collected using six plastic trays, which were paired and placed on the (upper and lower) manure belts of three randomly-selected colony rows immediately after manure scrapping in the morning. The 0-3 day old manure was collected at the end 1/3 belt section.

**Figure 4. A static flux bucket used for measuring $CO_2$ production from manure and litter.**

Three identical static flux buckets (diameter = 29.8 cm, height = 26.7 cm) were used to measure the $CO_2$ production (fig. 4). While measuring, a bucket was placed upside-down and covered the manure or litter concerned for $CO_2$ production. The gaps between bucket and floor were sealed with manure or litter. The $CO_2$ concentration in the bucket was determined using an infrared transmitter (GMP222, Vaisala, Helsinki, Finland) for 10 min, and data were recorded by a data logger (HOBO, Onset Computer Corp., Bourne, MA) every 15 s. A stirring fan was continuously running to uniform the air in the bucket. The covered manure and litter were weighed after measurement to derive $CO_2$ production normalized by mass. Since the produced $CO_2$ could be diluted in the bucket due to leakage that was likely exacerbating toward the end of the measurement, only $CO_2$ concentrations measured for the first few minutes when the concentration change was linear ($R^2$ > 0.95) were used to calculate the production rate using Equation 1.

$$P = \frac{C_e - C_s}{t \times 10^3} \times V/M \qquad (1)$$

where $P$ is $CO_2$ production rate, ml $s^{-1}$ $kg^{-1}$; $C_s$, $C_e$ are bucket $CO_2$ concentrations at the start and near the end of the linear change of $CO_2$ concentration, ppm; $t$ is duration corresponding to the linear change of $CO_2$ concentration in the bucket, s; $V$ is bucket volume, $m^3$; and $M$ is mass of manure or litter covered in the bucket, g.

Manure collected on the trays and litter covered in the bucket were weighted five times (9:00h, 13:00h, 19:00h, 2:00h, and 6:00h) on a sampling day. Knowing the tray size, bucket dimension, the area of the manure belt and litter floor, and the number of hens housed, the belt manure and floor litter production on per hen basis could be estimated.

After the 10-min measurement, the covered manure (or litter) sample was mixed and stirred. About 100 g of the stirred sample was packed in double layer plastic bags and sent to lab for MC measurement. In addition, MC of 0-2 day old manure was also measured.

Temperatures of the manure belt and litter floor were measured using a portable infrared thermometer (model RAYST2PU, Raytek, Santa Cruz, CA). The air temperature and RH surrounding the manure and litter were continuously measured using T/RH sensors (HOBO, Onset Computer Corporation, Bourne, MA). Feed and water consumptions were recorded on the sampling days.

**Data processing**

Manure and litter production was presented on either as-is or dry basis. The $CO_2$ production from 0-2 day old manure was not measured; instead the average $CO_2$ production rate of 0-1 day old and 0-3 day old manure was used to estimate the overall $CO_2$ production from manure. All statistical analyses were performed with Statistical Analysis Systems (SAS, version 9.2, Cary, NC, USA) using the ANOVA procedure.

## Results and Discussion

### Temperature and relative humidity (RH)

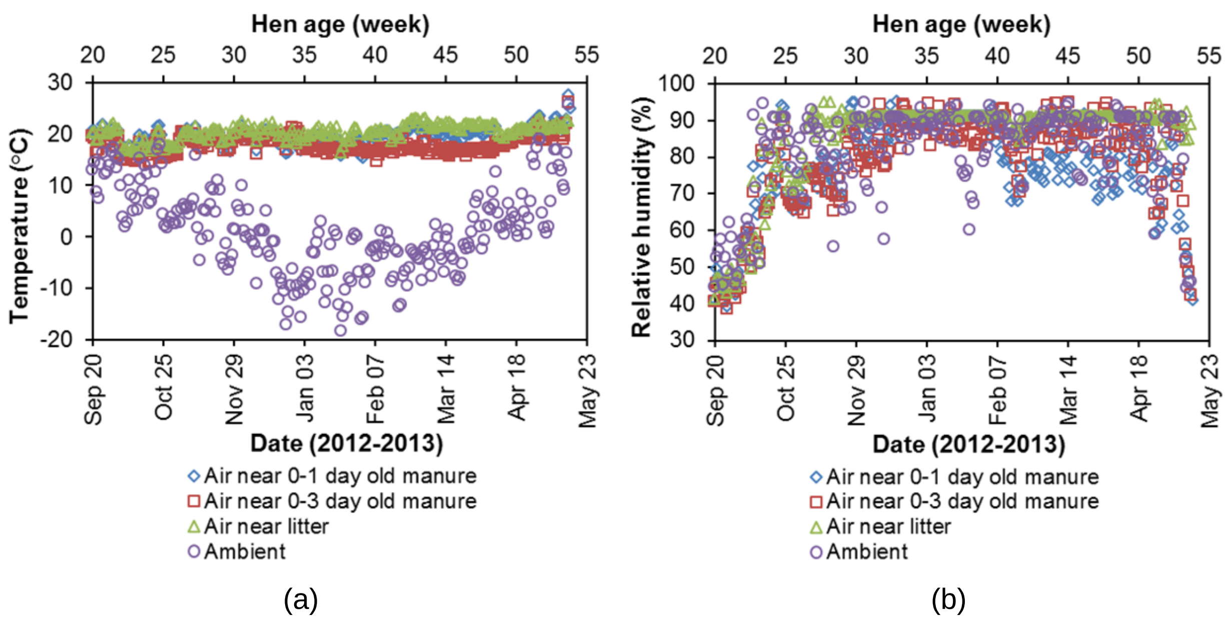


**Figure 5. Daily mean temperature (a) and relative humidity (RH, b) of ambient air and air near manure and litter.**

Daily mean temperature and RH of ambient air and air surrounding manure and litter are shown in Figure 5. During the experiment period, the ambient temperature and RH were 1.8 ± 9.3°C and 73.6 ± 13.9%, respectively. The air temperatures near 0-1 day old and 0-3 day old manure were 18.9 ± 1.6°C and 18.0 ± 1.7°C, respectively. Air temperature near litter, 19.8 ± 1.5°C, tended to be higher than those near manure, probably due to the higher sensible heat production by hens during litter access. Significant increase of indoor RH in winter time was noticed. The RH of air near 0-1 day old manure, 0-3 day old manure and litter was 77 ± 16%, 75 ± 15% and 80 ± 17%, respectively.

The mean temperatures of manure belt covered with 0-1 day old manure and 0-3 day old manure were 20.4 ± 1.7°C and 19.5 ± 1.3°C, while the litter floor temperature was 20.0 ± 1.0°C (fig. 6).

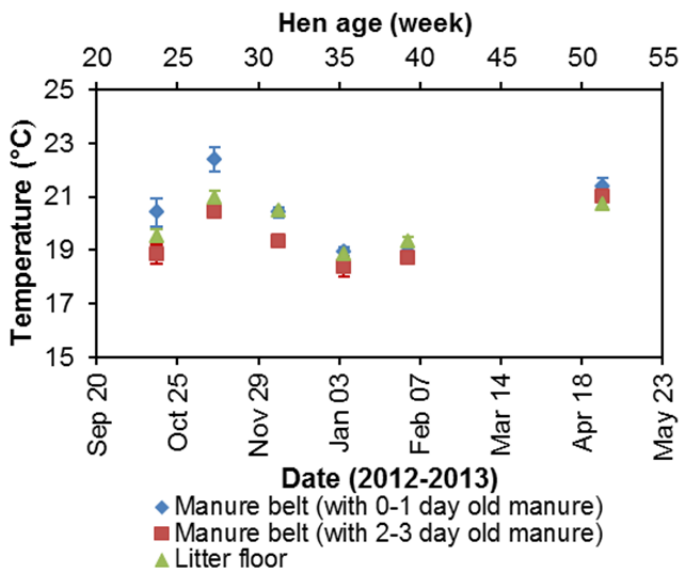


**Figure 6. Mean temperature on manure belt and litter floor on experimental days. Each datum point is the mean of 15 values. Vertical bars represent standard error (SE).**

## Manure and litter production

### *Production of belt manure*

The daily manure production on belt is shown in Figure 7. The wet (as-is) manure production was 102.9 ± 5.0 g $hen^{-1}$ $day^{-1}$, equivalent to a dry manure production of 32.6 ± 1.3 g $hen^{-1}$ $day^{-1}$ during the experimental period. The manure production was quite consistent among days. Due to malfunction of manure belt system, manure data in March 2013 was not collected.

Figure 8 shows the within-the-day belt manure production profile. Manure accumulated on the belt significantly faster between 6:00 h and 13:00 h as compared to the rest of the day (13:00 h to 6:00 h). Specifically, the wet manure production was 7.9 ± 0.5 g $hen^{-1}$ $hr^{-1}$ during 6:00 h – 13:00 h *vs.* 2.6 ± 0.6 g $hen^{-1}$ $hr^{-1}$ during 13:00 h – 6:00 h (or 2.2 ± 0.2 vs. 1.0 ± 0.1 g $hen^{-1}$ $hr^{-1}$ g $hen^{-1}$ $hr^{-1}$, expressed on dry matter basis). The slower manure accumulation on belt during 13:00 h – 6 h was because some manure was produced on litter floor when most of the hens were away from the colonies during 13:00 h – 22:00 h and less manure production at night. The within-the-day manure production could be delineated with linear regression equations, as follows.

Within-day wet belt manure production:

$$y = 7.90x \qquad \text{(6:00h – 13:00h, } R^2 = 0.99) \qquad (2)$$

$$y = 2.59x + 37.40 \quad \text{(13:00h – 6:00h next day, } R^2 = 0.99\text{)} \tag{3}$$

Within-day dry belt manure production:

$$y = 2.16x \quad \text{(6:00h – 13:00h, } R^2 = 0.99\text{)} \tag{4}$$

$$y = 1.03x + 8.66 \quad \text{(13:00h – 6:00h next day, } R^2 = 0.99\text{)} \tag{5}$$

where y is the belt manure production in g $hen^{-1}$, and x is number of hours post belt scrapping (belt was scrapped at 6:00h in this case).

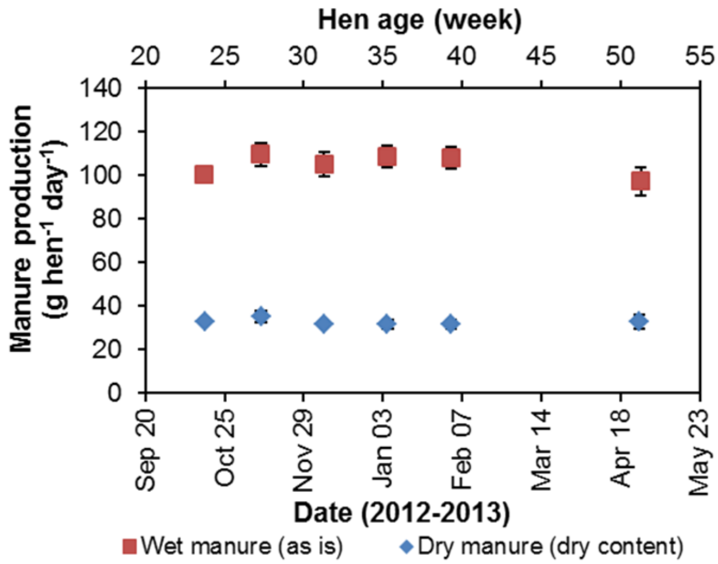


**Figure 7. Daily belt manure production of CV 22 laying hens (on a 15.25h colony: 8.75h litter-floor schedule) in an aviary housing system. Each datum point is the mean of three values. Vertical bars represent standard error (SE).**

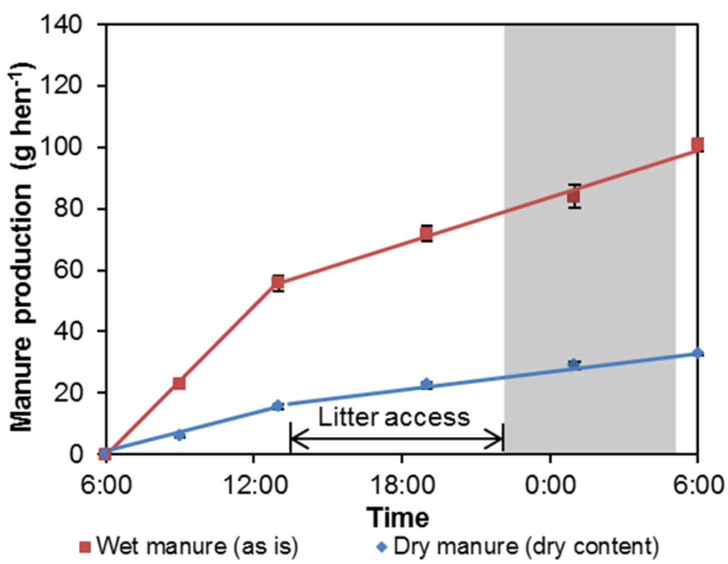


**Figure 8. Within-the-day belt manure production of CV 22 laying hens on a 15.25h colony: 8.75h litter-floor schedule. Each datum point is the mean of 18 values. Vertical bars represent standard error (SE). Shaded area indicates the dark period, non-shaded area indicates the light period. Litter floor access was from 13:00 till 21:45 h.**

Area-weighted manure accumulation on upper and lower manure belts is shown in Figure 9. More manure accumulated on the lower belts than on the upper ones, namely, 2302 ± 464 vs. 1936 ± 396 g $m^{-2}$ $day^{-1}$ on as-is basis (P = 0.02) or 744 ± 165 vs. 625 ± 139 g $m^{-2}$ $day^{-1}$ on dry basis (P = 0.01). Currently, identical air distribution ducts that delivered similar amount of air were used for both lower and upper belts to dry the manure for minimizing $NH_3$ volatilization. The discrepancy of manure accumulation reported in this study suggested more air should be delivered to the lower belt in order to achieve similar drying effect for both upper and lower belts.

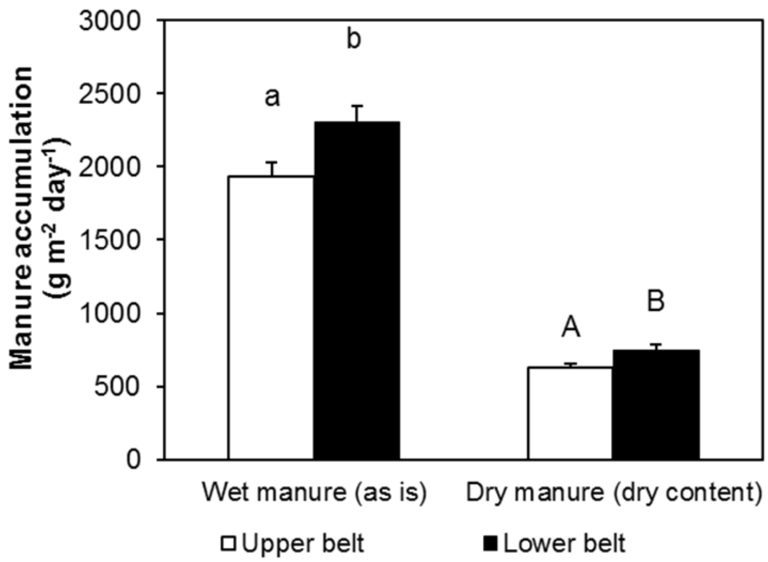


**Figure 9. Area-weighted manure accumulation on upper and lower belts in the aviary colonies. Each datum point is a mean of 18 measurements. Vertical bars represent standard error (SE). [a,b; A,B] means with different letters in each manure category are significantly different ($P < 0.05$).**

*Manure production on litter floor*

Figure 10 shows the production rate of manure deposited on litter floor. With a period of 8.75h daily litter access, the wet litter (as is) production rate was 3.6 – 4.2 g $hen^{-1}$ $day^{-1}$ (or 3.0 – 3.7 g $hen^{-1}$ $day^{-1}$ if expressed on dry basis). The cumulative litter production was linearly related with the number of litter-access days (eqs. 6 and 7). It should be noted that the cumulative curves in Figure 10 are the total litter production since the first litter-floor access day, and not necessarily reflect the actual amount of litter in the aviary house. The actual amount of litter in the house was less since Mar 6, 2013 due to the litter removal on that day.

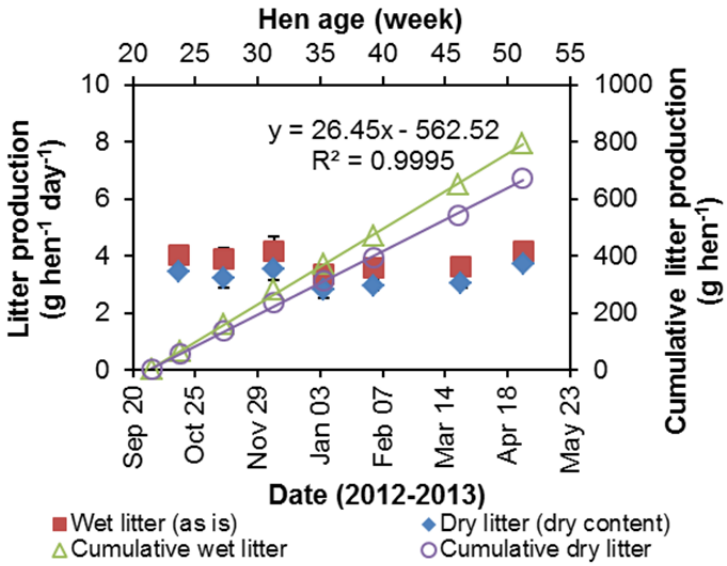


**Figure 10. Litter manure production on a 15.25 h cage:8:75h litter-floor schedule. Each datum is a mean of 15 measurements. Vertical bars represent standard error (SE).**

For wet litter: $y = 3.82x$ ($R^2$ = 0.99) (6)

For dry litter: $y = 3.22x$ ($R^2$ = 0.99) (7)

Where, *y* is the litter production in g $hen^{-1}$, and *x* is the number of litter-access days.

*Overall manure production (on belt and on litter floor)*

Figure 11 shows the daily overall manure production, including deposition both on belt and on litter. The overall dry-basis manure production was 35.8 ± 1.4 g $hen^{-1}$ $day^{-1}$. Yang et al. (2000) reported a much lower dry-basis manure production of 17 g $hen^{-1}$ $day^{-1}$ (assuming 1.6 kg hen body weight) in high-rise housing systems. The discrepancy stemmed from the fact that the values reported previously were for high-rise houses where manure was stored in the lower level for one year or longer (Lorimor and Xin, 1999), during which some losses took place (e.g. nitrogen loss due to $NH_3$ volatilization); in addition, feed intake of the hens in their study was about 20% less than that in the current study. Majority of the manure (90.9 ± 0.9%) was deposited on the manure belts, while manure deposited on litter only accounted for 9.1 ± 0.9% of the total manure production. A larger portion of manure, 22.5%, was deposited on litter floor had been reported by Groot Koerkamp et al. (1995). In their study, the hens were given full day litter access as compared to 8.75 h litter access in our study.

Daily feed and water consumptions were 113 ± 4 g $hen^{-1}$ $day^{-1}$ and 227 ± 9 g $hen^{-1}$ $day^{-1}$, respectively. The dry-basis manure production was, therefore, 31.8 ± 1.1% of the daily (as-is) feed intake.

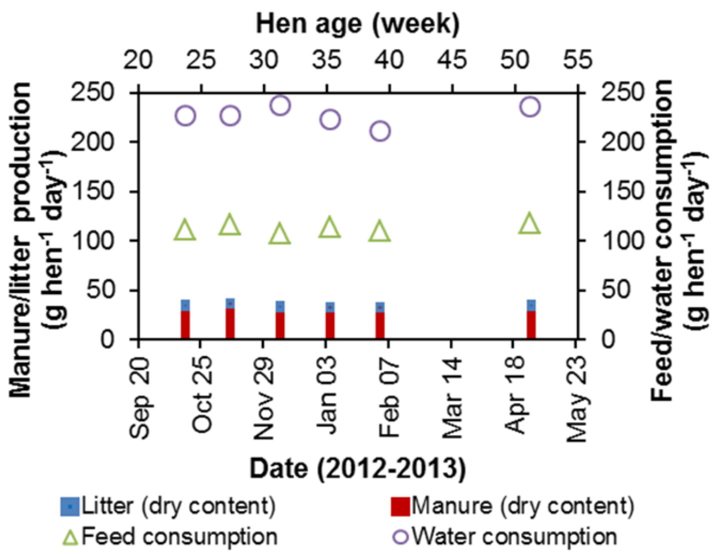


**Figure 11. Production of belt manure and floor litter (on dry content basis) on a 15.25 h colony: 8:75h litter-floor schedule, and the feed and water consumption. Each datum point for manure production is the mean of three values; datum for litter is the mean of 15 values.**

### Moisture content (MC)

Daily mean MC values of belt manure and litter are shown in Figure 12. In general, MC of belt manure was between 55% and 75%. MC of the manure with different age significantly differed ($P = 0.03$), with MC of fresh manure (or 0-1 day old) being the highest (69.6 ± 4.5%), followed by 0-2 day old manure (66.0 ± 4.8%) and 0-3 day old manure (63.5 ± 6.2%). The heaters were not operated on the sampling days, thus the MC of belt manure reported in this study was the result of drying with non-heated room air. Litter had much lower MC, 14.6 ± 2.4%, as compared to the manure ($P < 0.01$).

Moisture production (MP) from animals and their manure is used to design minimum ventilation rate under cold weather conditions (Zhao et al., 2013b). Hen-level MP has been extensively investigated, while the MP from manure could vary between housing systems, depending on the manure management schemes. In a lab-scale experiment, Chepete et al. (2004) reported that the mean MP from manure was 19.4 g day$^{-1}$ hen$^{-1}$, accounting for 12.1% of the total MP, for 21 – 64 week old hens. With the MC data and manure and litter production data reported in this study, we estimated the overall MP from belt manure (14.9 g day$^{-1}$ hen$^{-1}$) and litter (7.7 g day$^{-1}$ hen$^{-1}$) was 22.6 g h$^{-1}$ hen$^{-1}$ (Table 2) which is slightly higher than the value previously reported. The discrepancy is possibly because the belt manure in this study was continuously dried with room air, thus expediting the water evaporation from manure. In addition, manure deposited on litter floor continuously contributed to MP.

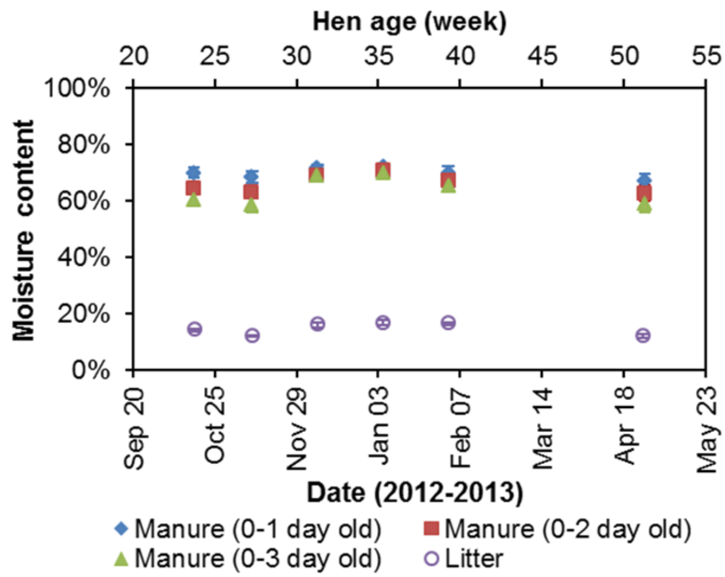


**Figure 12. Daily mean moisture content of the manure and litter. Each datum is the mean of 15 values. Vertical bars represent standard error (SE).**

Variations in MC of manure and litter within sampling days are shown in Figure 13. The MC of manure at all ages decreased from 9:00h till 1:00h the next day, and then slightly increased at 6:00h the next day. The decrease stemmed from evaporation, while the later increase was due to the accumulation of fresh manure after lights on. The MC of litter tended to be higher at 19:00h, probably because of the manure deposition during litter access.

Moisture contents of manure on upper and lower belts are shown in Figure 14. The MC of the 0-1 day old manure deposited on upper and lower belts was similar. The elder manure on lower belts, due to the thicker layer of manure deposition (fig. 9), had significantly higher MC than that on the upper belts.

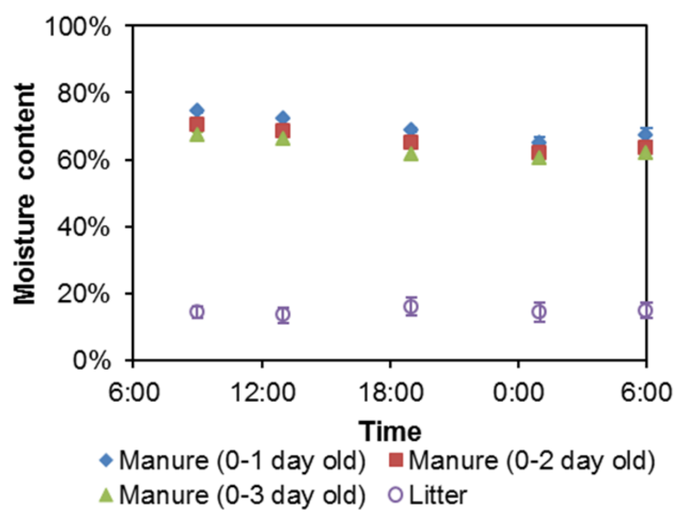


**Figure 13. Within-the-day moisture content of the manure and litter of the aviary laying-hen house. Each datum point is the mean of 18 values. Vertical bars represent standard error (SE).**

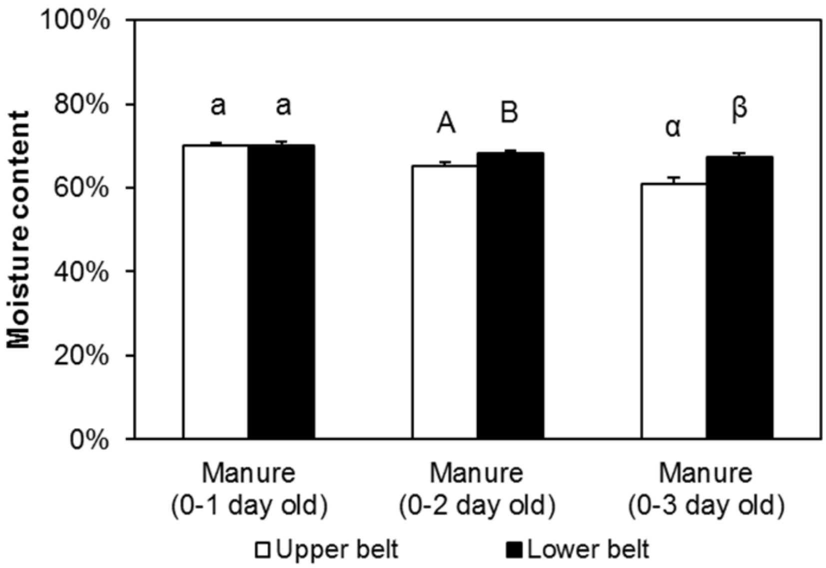


**Figure 14. Moisture content of the manure deposited on upper and lower belts in the aviary colonies. Each datum is a mean of 45 measurements. Vertical bars represent standard error (SE). [a; A,B; α,β] means with different letters in each manure category are significantly different ($P < 0.05$).**

## $CO_2$ production of the manure and litter

The $CO_2$ production rates for 0-1 day old manure, 0-3 day old manure and litter were, respectively, 0.32 ± 0.26 ml $s^{-1}$ $kg^{-1}$, 0.35 ± 0.13 ml $s^{-1}$ $kg^{-1}$, 0.03 ± 0.02 ml $s^{-1}$ $kg^{-1}$ on dry manure basis (or 0.09 ± 0.07 ml $s^{-1}$ $kg^{-1}$, 0.11 ± 0.04 ml $s^{-1}$ $kg^{-1}$, 0.02 ± 0.02 ml $s^{-1}$ $kg^{-1}$ on as-is basis, fig. 15). The $CO_2$ production rates were not significantly different between the two types of manure ($P = 0.44$ for dry-basis production rate, and $P = 0.13$ for wet-basis production rate). However, the $CO_2$ production rate from litter was significantly lower than that from manure ($P < 0.05$).

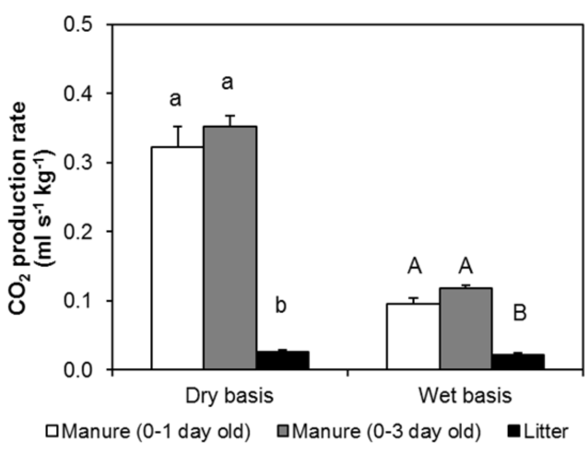


**Figure 15. Carbon dioxide ($CO_2$) production from manure and litter. Each datum is a mean of 72 measurements. Vertical bars represent standard error (SE). [a,b; A,B] means with different letters in each manure or litter MC category are significantly different ($P < 0.05$).**

Figure 16 shows the $CO_2$ production from manure and litter relative to that from hen respiration. Since hens had no litter access during 20-22 weeks of age, the additional $CO_2$ was solely from manure which constantly accounted for 3.4% of animal metabolism. This value was within the range that has been reported in other studies, i.e. 1.7 - 4.7% (Hayes et al., 2013; Ning, 2008; Zhao et al., 2013a). From 22 week onwards, $CO_2$ production from manure and litter gradually increased due to litter accumulation. Assuming $CO_2$ production rates from manure and litter (fig. 15), the relative $CO_2$ production could reach 8.1% at 60 week of age (blue curve in fig. 16). If the manure-litter-associated $CO_2$ was not included, ventilation rate based on only animal total heat production (THP)-derived $CO_2$ mass balance would be considerably underestimated. Deeming 5% as significant, consideration of the $CO_2$ contribution from manure and litter should begin as early as 35 weeks of hen age under the current management scheme (8.75 h litter access, 1/3 manure belt ran daily) in the aviary houses.

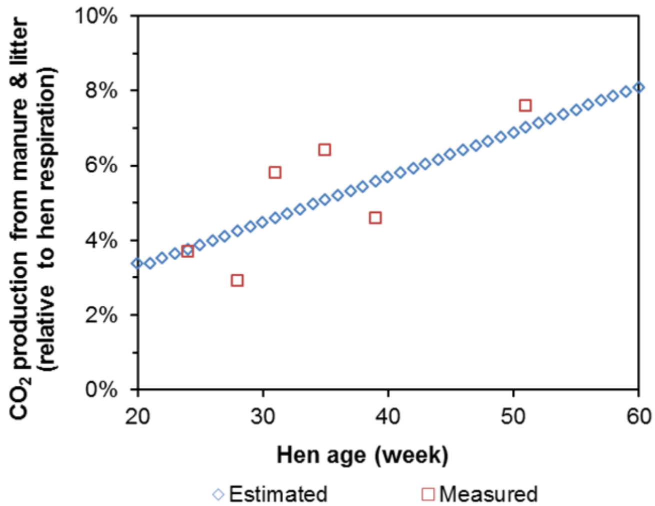


**Figure 16. Estimated and measured relative carbon dioxide ($CO_2$) production from manure and litter on a 15.25 h colony: 8:75h litter-floor schedule. $CO_2$ production from hen respiration is set to 0.46 ml $s^{-1}$ $hen^{-1}$ (assuming 7.1 W $kg^{-1}$ total heat production, 1.5 kg $hen^{-1}$ body weight, and 0.9 respiratory quotient)**

The summary of the data reported in this study was listed in Table 2.

**Table 2. Summary of the monitored variables or hen responses in the aviary housing system that covered the period of 10/16/2012-4/27/2013 and hen age of 23-51 weeks.**

| | Unit | Mean ± SD | Max | Min |
|---|---|---|---|---|
| **Temperature** | | | | |
| Ambient | ºC | 1.8 ± 9.3 | 20.3 | -18.4 |
| Air near manure belt | ºC | 18.5 ± 1.7 | 23.0 | 14.5 |
| Air near litter | ºC | 19.8 ± 1.5 | 23.0 | 16.3 |
| Manure belt | ºC | 19.9 ± 1.6 | 16.9 | 25.4 |
| Litter floor | ºC | 7.9 ± 0.5 | 18.3 | 22.0 |
| **Relative humidity (RH)** | | | | |
| Ambient | % | 79 ± 14 | 95 | 45 |
| Air near manure belt | % | 76 ± 16 | 95 | 39 |
| Air near litter | % | 80 ± 17 | 95 | 41 |
| **Feed and water consumption** | | | | |
| Feed | g hen$^{-1}$ day$^{-1}$ | 113 ± 4 | 118 | 108 |
| Water | g hen$^{-1}$ day$^{-1}$ | 227 ± 9 | 237 | 212 |
| **Manure and litter production (wet basis)** | | | | |
| Manure on belt (6:00h – 1:00h) | g hen$^{-1}$ h$^{-1}$ | 7.9 ± 0.5 | 8.6 | 7.2 |
| Manure on belt (1:00h – 6:00h next day) | g hen$^{-1}$ h$^{-1}$ | 2.6 ± 0.6 | 3.1 | 1.5 |
| Litter | g hen$^{-1}$ day$^{-1}$ | 3.8 ± 0.3 | 4.2 | 3.4 |
| **Manure and litter production (dry basis)** | | | | |
| Manure on belt (6:00h – 1:00h) | g hen$^{-1}$ h$^{-1}$ | 2.2 ± 0.2 | 2.4 | 1.9 |
| Manure on belt (1:00h – 6:00h next day) | g hen$^{-1}$ h$^{-1}$ | 1.0 ± 0.1 | 1.1 | 0.7 |
| Litter | g hen$^{-1}$ day$^{-1}$ | 3.2 ± 0.3 | 3.7 | 2.8 |
| Overall | g hen$^{-1}$ day$^{-1}$ | 35.8 ± 1.4 | 38.2 | 34.4 |
| **Moisture content (MC)** | | | | |
| Manure on belt (0-1 day old) | % | 69.6 ± 4.5 | 75.8 | 59.2 |
| Manure on belt (0-2 day old) | % | 66.0 ± 4.8 | 73.3 | 54.8 |
| Manure on belt (0-3 day old) | % | 63.5 ± 6.2 | 73.6 | 50.3 |
| Litter | % | 14.6 ± 2.4 | 19.0 | 10.7 |
| **Moisture production (MP)** | | | | |
| Manure on belt | g day$^{-1}$ hen$^{-1}$ | 14.9 | - | - |
| Litter | g day$^{-1}$ hen$^{-1}$ | 7.7 | - | - |
| Overall | g day$^{-1}$ hen$^{-1}$ | 22.6 | | |
| **$CO_2$ production (wet basis)** | | | | |
| Manure on belt (0-1 day old) | ml s$^{-1}$ kg$^{-1}$ | 0.095 ± 0.075 | 0.396 | 0.042 |
| Manure on belt (0-3 day old) | ml s$^{-1}$ kg$^{-1}$ | 0.114 ± 0.038 | 0.195 | 0.060 |
| Litter | ml s$^{-1}$ kg$^{-1}$ | 0.022 ± 0.018 | 0.079 | 0.012 |
| **$CO_2$ production (dry basis)** | | | | |
| Manure on belt (0-1 day old) | ml s$^{-1}$ kg$^{-1}$ | 0.322 ± 0.259 | 1.366 | 0.173 |
| Manure on belt (0-3 day old) | ml s$^{-1}$ kg$^{-1}$ | 0.353 ± 0.134 | 0.672 | 0.191 |
| Litter | ml s$^{-1}$ kg$^{-1}$ | 0.026 ± 0.020 | 0.088 | 0.014 |

## Summary and Conclusions

This study investigated the production, surrounding temperature and RH, moisture content (MC) and $CO_2$ production of manure and litter in an aviary hen housing system, where the hens were given 8.75 h day$^{-1}$ litter access and 1/3 manure belt was operated every day. The following observations and conclusions were made.

- The temperature and RH were 1.8 ± 9.3˚C (mean ± standard deviation) and 79 ± 14% for ambient air, 18.5 ± 1.7˚C and 76 ± 16% for air surrounding belt manure, and 19.8 ± 1.5˚C and 80 ± 17% for air surrounding litter.

- The wet (as-is) manure production was 103 ± 5 g hen$^{-1}$ day$^{-1}$, equivalent to a dry manure production of 32.6 ± 1.3 g hen$^{-1}$ day$^{-1}$ during the experimental period. The litter production was 3.8 ± 0.3 g hen$^{-1}$ day$^{-1}$ (as is), or 3.2 ± 0.3 g hen$^{-1}$ day$^{-1}$ on dry basis.
- The MC was 69.6 ± 4.5% for the 0-1 day old manure, 66.0 ± 4.8% for the 1-2 day old manure, 63.5 ± 6.2% for the 2-3 day old manure. Manure on lower belts tended to be somewhat wetter than that on upper ones due to thicker manure accumulation. Litter has much lower MC (14.6 ± 2.4%) as compared to the manure.
- The moisture production (normalized to per hen basis) from manure and litter was estimated to be 22.6 g day$^{-1}$ hen$^{-1}$.
- The average $CO_2$ production from as-is manure was 0.10 ± 0.06 ml s$^{-1}$ kg$^{-1}$ (or 0.34 ± 0. 20 ml s$^{-1}$ kg$^{-1}$ on dry basis). The average $CO_2$ production from as-is litter was much lower, 0.02 ± 0.02 ml s$^{-1}$ kg$^{-1}$ (or 0.03 ± 0.02 ml s$^{-1}$ kg$^{-1}$ on dry basis).
- Contribution of $CO_2$ production from manure and litter to total $CO_2$ production in the hen house could be significant with litter/manure accumulation on the floor, and should be taken into consideration when estimating ventilation rate or animal bioenergetics involving $CO_2$ production in aviary housing systems.

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