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Ji-Qin Ni

Marisa Erasmus

Deana R. Jones

Dana L.M. Campbell

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Effectiveness and characteristics of a new technology to reduce ammonia, carbon dioxide, and particulate matter pollution in poultry production with artificial turf floor

Ji-Qin Ni [a,*], Marisa Erasmus [b], Deana R. Jones [c], Dana L.M. Campbell [d]

[a] Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN 47907, USA
[b] Department of Animal Sciences, Purdue University, West Lafayette, IN 47907, USA
[c] US National Poultry Research Center, USDA-ARS, Athens, GA 30605, USA
[d] Commonwealth Scientific & Industrial Research Organisation (CSIRO), Armidale, NSW 2350, Australia

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ABSTRACT

Ammonia (NH_3), carbon dioxide (CO_2), and particulate matter (PM) are three major aerial pollutants that threaten the health of workers and animals in poultry production. An experiment was conducted in four laying hen rooms, with 735 to 740 hens per room, to study a new technology using artificial turf (AstroTurf®) floor for mitigation of the three pollutants. Air was sampled at three locations in each room to measure ammonia and carbon dioxide concentrations with an Innova 1412 multi-gas monitor for 83 days. Particulate matter was measured at one location at bird height in each room using a Dylos DC1700 Air Quality Monitor for 35 days. Ventilation rates in all rooms were monitored with RM Young anemometers. Compared with two wood shavings rooms, the two artificial turf rooms significantly (p<0.01) reduced concentrations of ammonia by 51.0%, carbon dioxide by 13.5%, small particles by 77.5%, and large particles by 83.6%. They also significantly (p<0.01) reduced ammonia and carbon dioxide emission rates by 38.4% and 8.3%, respectively. The artificial turf rooms' lower ammonia concentrations and emissions were a result of lower manure pH. The artificial turf rooms also retained more nitrogen in manure. Lower carbon dioxide concentrations and emissions were partially attributed to less carbon dioxide released from manure. Lower PM concentrations were related to reduced PM sources on floor surfaces. Artificial turf rooms had smaller in-room ammonia and carbon dioxide concentration gradients. Artificial turf is a promising new technology to improve indoor air quality in and reduce pollutant emissions from poultry production.

1. Introduction

Animals require appropriate environmental conditions to survive and grow. Poor air quality has been recognized to affect livestock and poultry health for nine decades since it was first reported in the 1930s (Ni et al., 2021). Air pollution in confined animal feeding operations can adversely impact on workers' health, including causing chronic bronchitis, respiratory airways obstruction, and asthma-like symptoms (Guillam et al., 2007) and increase workers' sick days (Banhazi and Pisaniello, 2018). Pollutants can also threaten animals' safety, health, productivity, and behavior (Ni et al., 2021).

* Corresponding author.
E-mail address: jiqin@purdue.edu (J.-Q. Ni).

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Laying hen houses generate a considerable amount of air pollutants, including ammonia (NH_3), carbon dioxide (CO_2), and particulate matter (PM). Compared with swine, dairy, and broiler buildings, concentrations of ammonia and particulate matter (PM) in laying hen houses are usually at higher levels (Hu et al., 2021; Ni et al., 2021). Additionally, non-cage houses generally have poorer air quality, associated with ammonia and PM, than cage houses (Xin et al., 2011).

More than 20 mitigation technologies have been developed and reported to improve air quality in animal feeding operations based on biochemical, chemical, managerial, microbiological, physical, and physiological working principles (Ni, 2015); however, their applications have been met with varying degrees of success (Zhao et al., 2022). Technically effective, economically feasible, and user-friendly technologies are still urgently needed to mitigate air pollutants in animal agriculture.

Indoor air pollutant concentrations in poultry houses are affected by many factors, e.g., bird density, bird age, feed, house structure, house maintenance, temperature, humidity, ventilation, indoor lighting, and floor types and bedding materials. Different floors and beddings and their effects on air quality in poultry production have only been reported in a few publications. Long rye straw and softwood shavings were compared in two turkey barns by Slobodzian-Ksenicz and Kuczynski (2002). Chopped and un-chopped straw, and microbial amendment of litter were studied in broiler production by Đukić Stojčić, et al. (2016). Knežević et al. (2021) investigated chopped wheat straw, wood shavings, peat, wheat straw pellets, and softwood pellets in broiler chambers. However, none of the three studies discovered effects of these litter types on ammonia concentrations or emissions.

The impact of litter types on ammonia was reported by Atapattu et al. (2008), who found that ammonia release from refused tea litter was significantly lower than sawdust and paddy husk in broiler cages. In another study with six different bedding types for laying hens, magnitudes of ammonia release were ranked from high to low as gravel, wood shavings, clay pellets, peat, chopped straw, and chopped paper (Gustafsson and von Wachenfelt, 2005). Carbon dioxide was only studied by Knežević et al. (2021), but no effects by the litter types was shown. Moreover, no study on the impact of litter types on PM in poultry production was found.

Artificial turf is a surface of synthetic fibers made to look like natural grass. It is most often used in arenas for sports. The potential of artificial turf as a floor substrate in a cage-free aviary system has been investigated to determine effects on hen behavior, production, and welfare (Campbell et al., 2017; Regmi et al., 2018) as well as egg and environmental microbiology (Garcia et al., 2022). However, no reports on artificial turf and air pollution in poultry housing have been found in the available literature. The objective of this paper was to study the impacts and characteristics of an artificial turf (AstroTurf®) floor, in comparison with typical wood shavings, on ammonia, carbon dioxide, and PM concentrations in four laying hen rooms under controlled experimental conditions.

2. Materials and methods

2.1. Experimental design

2.1.1. The study

The work reported in this paper was part of a larger study examining the influence of floor and bedding on laying hen behavior and welfare, and on air quality. The study was experimentally conducted at Purdue University's Animal Sciences Research and Education Center (ASREC), West Lafayette, Indiana. All procedures were approved by the Purdue University Animal Care and Use Committee (protocol # 1901001848). Partial results of this paper were presented in a conference (Zhao et al., 2022). The findings about the effects of artificial turf on laying hen behavior and welfare will be published elsewhere.

2.1.2. Experimental rooms

Four identical aviary system rooms in an ASREC experimental poultry facility were used in the study. Each room was divided into 4 sections, 2 large (6.1 m × 2.0 m) and 2 small (4.9 m × 2.0 m) (Fig. 1). The sections were separated by metal wire gates and wire mesh. Within each room, of which the height was 3.05 m from the concrete floor to the ceiling, there were two identical tiers of 18 cages per tier. The cage had an area of 0.74 m (W) × 1.21 m (L), and its height was 0.46 m at the back and 0.58 m at the front. No doors were designed for the cages. A manure belt was installed underneath the cage areas in each room.

2.1.3. Room floors

Each room included two 1.22 m wide open floor areas next to the walls and two 0.76 m wide closed floor areas underneath the cages. Birds had access to both types of areas in the respective section. The open areas in each room were covered with either an artificial turf (AstroTurf®) or a layer of 5–7 cm thick wood shavings at the start of the study (Fig. 2). The artificial turf was not changed, and the wood shavings were not top-dressed during the entire study.

The AstroTurf® product had a dimension of 91.4 cm (W) × 152.4 cm (L) × 2.0 cm (total H). Its pile height was 1.8 cm. It had a grass green color, upright blade profile, grass blade density of 5.0 cm^{-2}, perforation of 45%, and weight of 2.0 kg m^{-2}. Its crimp texture (pile height after/before crimp) was 80%.

False floors were installed in the open floor area. They consisted of metal beams for the AstroTurf® in the artificial turf rooms and plywood boards for making similar spatial dimensions in the wood shavings rooms. Wood shavings were

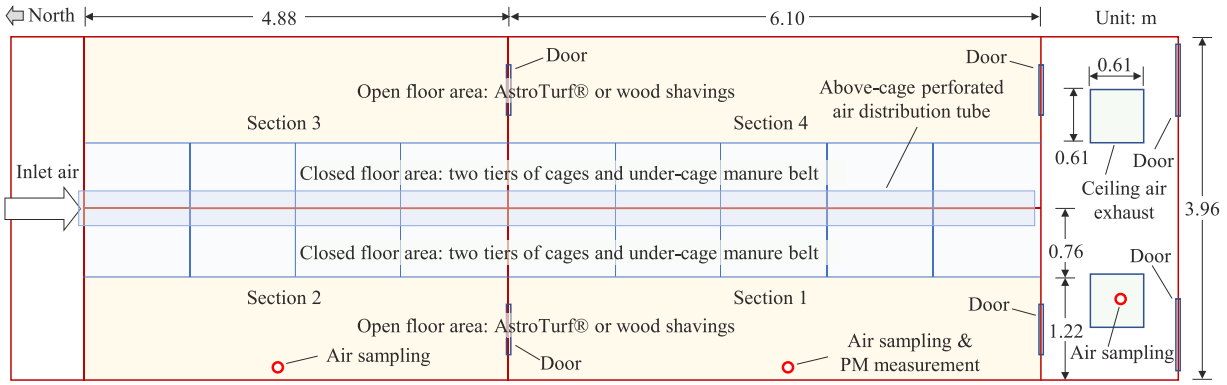

Fig. 1. Floor plan of the experimental room.

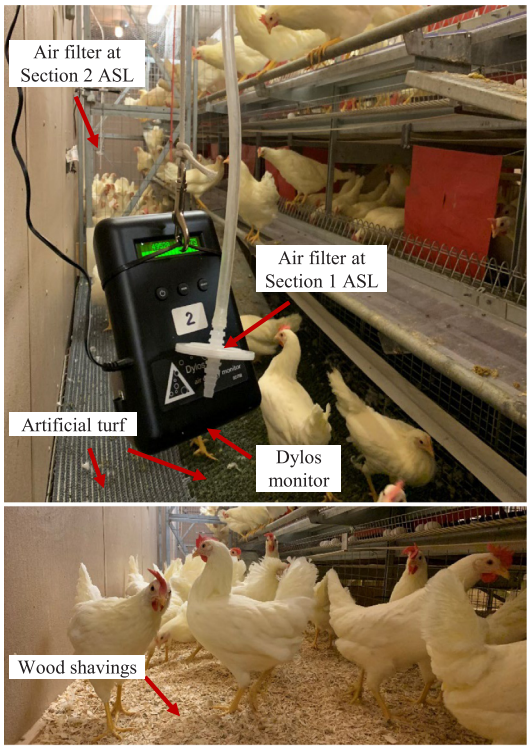

Fig. 2. The artificial turf treatment and air sampling locations (ASLs) (top) and the wood shavings treatment (bottom). Photos taken at the beginning of the study.

placed on top of the plywood false floors. A manure scraper underneath the false floor was installed to collect the manure that fell through the artificial floor weekly.

The closed floor area for the artificial turf rooms was 0.23 m high from the concrete floor at the back and 0.36 m high at the front to the side wall. For the wood shavings rooms, that height was 0.36 m at both the back and front.

2.1.4. Animals and room management

Commercial white laying hens (Novogen White) between 16 and 17 weeks of age were randomly selected and placed into the two artificial turf rooms (A1 and A2) on February 17 and the wood shavings rooms (W-1 and W-2) on February 19, 2020, with 735–740 birds per room (Table 1). They were depopulated from July 6 to 7, 2020. The entire experiment in the four rooms lasted for 141 days.

Birds were fed standard diets, and water was provided via nipple drinkers *ad libitum*. Lighting and temperature were managed according to industry guidelines (Novogen, 2022). Hen manure below the housing system dropped onto the

Table 1
Treatment and management of the artificial turf rooms (A-1 and A-2) and wood shavings rooms (W-1 and W-2).

	A-1	A-2	W-1	W-2
Floor or bedding	Artificial turf	Artificial turf	Wood shavings	Wood shavings
Height or thickness (cm)	2	2	5–7	5–7
Date room filled	Feb. 17	Feb. 17	Feb. 19	Feb. 19
Initial bird (n)	735	737	736	740
Date depopulated	July 7	July 7	July 6	July 6

manure belt and was scraped once a week. The building staff scooped up the manure at the back of the room and took it out of the building.

Fresh air was supplied into the room from the north end wall. Air was distributed in the room via a 0.45 m diameter perforated plastic tube, which was installed along the length of the room above the housing system (Fig. 1). Two 0.61 m $\times$ 0.61 m = 0.372 m^2 openings in the ceiling at the south side of each room served as room air exhausts. Two single-speed air exhaust fans, one of 0.46 m and another of 0.61 m diameters, provided ventilation for each room. The fans in each room were controlled automatically with a Honeywell NEMA 4X controller (Honeywell, Golden Valley, MN, USA) based on room temperatures and control settings.

2.2. Room environment monitoring

2.2.1. Ventilation measurement

Ventilation rate in each room was continuously measured at the two air exhaust openings in the ceiling (Fig. 1) with two freely rotating impeller anemometers (Model 27106T, RM Young, Traverse City, MI, USA), one at each opening. The anemometer's measurement range is 0–35 m s^{-1} with a threshold of 0.4 m s^{-1} (Anon., 1988). The center of the anemometers was set at 0.15 m to one side and 0.18 m to another side of the opening to measure the mean wind speed of the opening.

The anemometers continuously measured the speeds of air flowing through the openings. The airflow rate (in m^3 per min) was calculated by multiplying the opening area (0.372 m^2) with the airflow speed (in m min^{-1}) [Eq. (1)]. The airflow speed was calculated using Eqs. (2) and (3) based on the anemometer manufacturer's specifications (Anon., 1988).

$$Q = 0.372\ m^2 \cdot W \tag{1}$$

where Q is airflow rate, m^3 min^{-1}; W is airflow speed, m min^{-1}.

$$W = PT \cdot A = 0.300 \cdot A \tag{2}$$

where PT is pitch of the impeller and is 0.300 m $revolution^{-1}$; A is anemometer rotational speed, RPM.

$$A = K \cdot V \tag{3}$$

where K is coefficient related to the tacho-generator in the anemometer, RPM VDC^{-1}; V is output of the anemometer, VDC.

The coefficient K was obtained by calibrating the anemometer using a Selectable Speed Anemometer Drive (Model 18802, RM Young) and a Fluke Model 189 Multimeter (Fluke Co., Everett, WA, USA), which has a 0.025% basic DC accuracy and a 50,000-count resolution.

2.2.2. Temperature and relative humidity measurements

Air temperature in each room was continuously monitored with a Type-T thermocouple installed at the ceiling air exhaust, next to an air sampling probe. Relative humidity in the room air was measured in the sampling air with a relative humidity and temperature probe (Model HMP50Y Humitter, Vaisala, Helsinki, Finland) that was built into the multiple air sampling system, which is described in Section 2.2.4.

2.2.3. Lighting and door status monitoring

Lighting in each room was monitored with a custom-made lighting sensor that contained a low-cost Photosensitive Sensor Module for Arduino (ASIN: B01N1FKS4L, Amazon.com). The light sensor was installed on the south wall in the room between the two room doors (Fig. 1). The sensor output was a voltage, corresponding to light intensity. The lighting sensors continuously monitored the relative light intensity in the room. They sensed lighting on and off, and the light from the building hallway when the room doors were open.

The status of open or close of the two doors at the south end of each room was continuously monitored with two normally open magnetic reed switches for quality control of the experiment. The reed sensor part of the switch was mounted on the door frame, and the magnet part of the switch was mounted on the door.

2.2.4. Air sampling and gas concentration measurement

Air was sampled from 13 air sampling locations (ASLs), three in each room for indoor air (12 in total for 4 rooms), plus one in the building hallway to the south of the rooms. One of the three in-room ASLs was close to the west side ceiling air exhaust opening to sample room exhaust air. Two other ASLs were at the middle length of Sections 1 and 2 (Fig. 1), respectively, on the west wall, about 0.60 m from the floor (Fig. 2).

A custom-designed multi-location air sampling system (Ni et al., 2017) was used to regulate the sampling air streams and control the sampling location and timing. The sampling locations, sampling durations at each location, and sampling sequence were programmed in an on-site computer system (OSCS) and controlled automatically. Manually controlled sampling was only done during measurement instrument calibration. A vacuum pump in the system supplied air at about 5 L min^{-1} from only one ASL at any given time to the measurement instrument. The sampling duration at each ASL was programmed in AirDAC, which is custom-developed data acquisition and control software, for 10 min each for the 12 in-room ASLs and 20 min for the background air. The system sampled through all the programmed ASLs one after another. Thus, all the ASLs were sampled once in a 140-min cycle, and a little more than 10 sampling and measurement cycles were conducted daily.

Each ASL was connected to the sampling system with a single piece of 6.26 mm inside diameter PVC tubing, which has been validated as a reliable air sampling option for ammonia studies in animal feeding operations (Zhu et al., 2012). To prevent dust from entering the sampling system and the measurement instrument, two in-line 47 mm diameter 0.2 μm pore size dust filters were installed in each sampling tubing, one at the air inlet end of the tubing (Fig. 2) and another between the end of the tubing and the inlet of the sampling system.

Gas concentrations in sampling air streams were measured with a photoacoustic infrared multi-gas monitor (Innova, Model 1412, LumaSense Technologies, Ballerup, Denmark). The monitor measured five different gases, including ammonia and carbon dioxide that are reported in this paper, and moisture. The monitor was checked with certified ammonia and carbon dioxide gases periodically during the study to ensure measurement quality.

2.2.5. Particulate matter measurement

Particulate matter in the four rooms was measured with six new and relatively low-cost optical particle counters (Model DC 1700 Air Quality Monitors, Dylos Corporation, Riverside, CA, USA). One Dylos monitor was set up in each room at the same location of Section 1 ASL, side by side with the air sampling inlet filter (Fig. 2). The remaining two Dylos monitors were used as backups. The monitor has an internal data logger that can store measurement results at 1-min intervals for about 8 days. At the end of each measurement period, which lasted from 6 to 8 days, the Dylos monitors were collected from the rooms, and the logged data were downloaded to a computer for analysis.

The Dylos DC 1700 monitor had been used in many studies across different environmental conditions (e.g., Han et al., 2017), including a swine building (Jones et al., 2016) and broiler houses (Yasmeen et al., 2019). According to the User Manual, the monitor measures small particle and large particle concentrations. Small particles are all particles detected by the monitor down to its detection limit of 0.5 μm. Large particles are all particles detected above the large particle threshold of approximately 2.5 μm. The particles between 0.5 μm and 2.5 μm can be obtained by subtracting the large particle reading from the small particle reading.

2.3. Data acquisition, processing, and analysis

2.3.1. Real-time data acquisition

The OSCS was set up in the hallway in the building. It consisted of a personal computer, custom software AirDAC written in LabVIEW (National Instruments Co., Austin, TX, USA), and I/O hardware from National Instruments Co. All measurement instruments and sensors in this study were connected to the OSCS, except for the Dylos monitors. The AirDAC acquired sensor output signals at 1 Hz, converted the signals to engineering units, averaged them over 60-s intervals, recorded the means in data files, and pre-processed the data files daily.

2.3.2. Post-measurement data processing

Custom-developed software CAPECAB (Fibre Recovery Systems, Inc., Calgary, AB, Canada) was used for post-measurement data processing of the 1-min AirDAC data (Eisentraut et al., 2004; Cortus et al., 2010). The Dylos data that were downloaded to the computer were imported to the CAPECAB database and synchronized with the on-line measurement variables in AirDAC. This allowed the Dylos PM data to be analyzed side by side with all AirDAC data to obtain new insights into the factors affecting PM generation. The original concentration unit of particle per cubic foot in the Dylos was converted to particles per cm^3 (Vercellino et al., 2018).

Only the last 3 min of ammonia concentrations and the last 5 min of carbon dioxide concentrations in a 10- or 20-min sampling period at each ASL were validated. This was to allow the measurement system to reach equilibrium after switching from a different ASL (Ni et al., 2017). Concentrations of gases at the same sampling ASL during the 140-min between two adjacent sampling cycles were obtained by interpolation.

2.3.3. Gas emission calculation

Emission rates of ammonia and carbon dioxide from each room were calculated using CAPECAB with Eq. (4), which was discussed by Lim and Bogan (2009).

$$E = (C_{ex} - C_{in}) \cdot \frac{P_{ex} \cdot M}{R \cdot (273.15 + T_{ex})} \cdot Q_{ex} \quad (4)$$

where E is emission rate, mg min^{-1}; C_{ex} and C_{in} are pollutant concentrations in the room exhaust air and outdoor incoming air, respectively, ppm; P_{ex} is atmospheric pressure of the exhaust air, atm; M is gas molecular weight, 17.03 and 44.01 g mol^{-1} for ammonia and carbon dioxide, respectively; R is the Universal Gas Constant, 0.08206 L·atm mol^{-1} K^{-1}; T_{ex} is exhaust air temperature, °C; Q_{ex} is room ventilation rate, m^3 min^{-1}.

The measured ammonia and carbon dioxide concentrations in the ceiling air exhaust (Fig. 1) were used as gas concentrations in the room exhaust air C_{ex}. The P_{ex} was taken as 1 atm. The T_{ex} was measured at the ceiling air exhaust. The Q_{ex} was the measured room ventilation rates. However, because this study focused on indoor air quality, gas concentrations in the outdoor incoming air (Fig. 1) were not measured during the study. Therefore, typical outdoor concentrations of 0.5 ppm ammonia and 450 ppm carbon dioxide, which were measured with the same set of equipment at ASREC, were used as C_{in}. A daily emission rate was the sum of the calculated emission rates of all minutes during the day.

2.3.4. Post-measurement data analysis

Daily mean data were based on the "valid data day", which was defined as the day containing > 75% (18 h) of valid data during a 24 h period. All on-line daily mean data were calculated for 24 h from 00:00 to 23:59. However, a day's worth of data for a Dylos monitor was calculated for 24 h starting from the time the monitor was set up and started measurement, e.g., from 17:30 May 1 to 17:29 May 2.

Data statistics for all variables in each room were calculated for daily mean, average daily mean (ADM), standard deviation (Std), 95% confidence interval (c.i.), and correlation coefficient (r). Gas concentrations were calculated for each ASL and for an entire room, of which the concentrations were averages of the three ASLs in the room. Comparison of indoor environmental data among the four rooms were made by using statistical t-Tests with 2 tails and two-sample unequal variance (heteroscedastic) in Microsoft Excel. This method was applied to all the data, i.e., including on-line measurement data and Dylos downloaded data.

2.4. Manure sampling and analysis

Manure was sampled in the four rooms on July 9 shortly after all birds were depopulated. Rooms A-1 and A-2 had about 3 cm thick manure underneath the artificial turf on the sampling date. Eight subsamples in each room in the south and north sides were taken. Rooms W-1 and W-2 had about 5- to 6 cm thick manure on the floor. In W-1 and W-2, 20 and 24 subsamples, respectively, were taken equally distanced, half on the open areas and the other half underneath the cages.

The subsamples from the same room were taken in equal volumes. They were placed in a bucket and thoroughly mixed. A composite sample was taken from the bucket for each room and put into a zipped bag. Four composite samples for the four rooms were temporarily stored in a refrigerator within 2 h after they were taken. They were shipped in a cooler with ice packs to Midwest Laboratories Inc. (Omaha, NE, USA) for analysis, which was conducted on July 18.

3. Results and discussion

3.1. Room environmental conditions

3.1.1. Ventilation rate and valid measurement days

Room ventilation rates varied considerably from February to April because of low outdoor temperatures. This reduced the number of valid days in the study. Although the four rooms were controlled to maintain similar ventilation conditions, on-site observations and measurement data analysis indicated that the ventilation rates among the four rooms were statistically different ($p < 0.05$) before April 11. Moreover, at times of minimum ventilation or zero ventilation (both fans in a room were turned off), some air backflows from the ceiling exhaust openings to the rooms were recorded.

Data analysis revealed that ventilation became consistent without backflows at 08:15 and at 08:50 on March 24 for A-1 and A-2, respectively; at 08:05 on April 11 for W-1, and at 00:30 on April 13 for W-2. Room ventilation provides dilution of indoor aerial pollutants and is critical for indoor air quality assessment. To ensure the research quality, valid data dates were taken from April 13 to July 5 (a total of 83 days) for the online measurement and from April 28 to June 28 (a 2-month period) for the PM measurement.

During the 83 valid measurement days, 79 valid data days for ventilation rates were obtained (Fig. 3 and Table 2). The ADM room ventilation rates were 74.0, 88.9, 68.9, and 89.6 m^3 min^{-1} for A-1 to W-2, respectively. The difference in ventilation rates between A-1 and W-1 was not statistically significant ($p > 0.05$), and so was that between A-2 and W-2.

The room environmental control situation demonstrated that continuous and reliable monitoring of ventilation rates is very important for air quality studies. In winter with minimum ventilation, it was challenging to keep comparable ventilation rates and maintain statistically acceptable environmental conditions for scientific experiments.

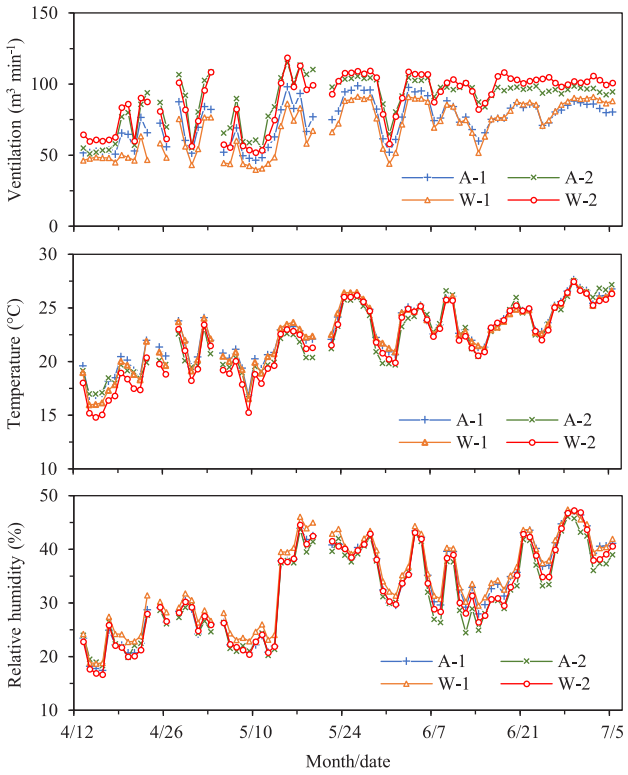

Fig. 3. Comparison of daily mean room ventilation rates (top), temperature (middle), and relative humidity (bottom) of the four rooms during 83 valid measurement days of the experiment.

3.1.2. Temperature and relative humidity

Daily mean room temperatures and relative humidity fluctuated from day to day, and with a general trend to increase from April 13 to the end of the study (Fig. 3). The ADM room temperatures ranged from 22.0 °C in W-2 to 22.7 °C in A-1. No statistical significance was found in room temperatures among the four rooms ($p > 0.05$, Table 2). The ADM relative humidity in the four rooms ranged from 32.6% in A-2 to 36.1% in W-1. Significant difference was only found between A-2 and W-1 ($p < 0.01$, Table 2).

3.2. Ammonia concentrations

3.2.1. Concentration comparison

Ammonia concentrations in the four rooms varied considerably. The ADM concentrations ranged from 5.8 ± 2.3 ppm (mean ± standard deviation) in A-2 to 15.5 ± 6.3 ppm in W-2 (Table 3). The minimum daily mean concentration was 2.6 ppm in A-2. The maximum daily mean concentration of 39.4 ppm in W-1 was more than 3 times as high as that in A-2. The maximum 10-min sample concentration was 80.5 ppm in W-1 at noon on June 29. The pungent odor of ammonia could be sensed by the researchers on some days while working in W-1 and W-2, confirming the higher concentrations in the rooms with wood shavings as bedding materials. Ammonia release from wood shavings was ranked the second highest among six different bedding materials in the study by Gustafsson and von Wachenfelt (2005).

Statistical tests showed significantly lower ammonia concentrations in A-1 and A-2 compared with those in W-1 and W-2 ($p < 0.01$, Table 3), but W-1 and W-2 ammonia concentrations had no difference ($p = 0.66$). The average of ADM in A-1 and A-2 was 7.5 ppm and that in W-1 and W-2 was 15.2 ppm. The artificial turf rooms reduced indoor ammonia concentrations by 51.0% ($p < 0.01$).

3.2.2. Temporal variations

One characteristic of the ammonia concentrations was the profound temporal variations. The daily mean concentrations exhibited a general and gradual increase from April 13 to July 5 (Fig. 4). This trend was more evident in W-1 and W-2 than in the other two rooms. Ammonia concentrations in all four rooms were strongly correlated with temperature variations in each room, and the r values ranged from 0.609 to 0.763. Ammonia concentrations were also moderately or strongly correlated with the ventilation rates (Table 3).

Table 2
Results of ventilation rates, temperatures (T), and relative humidity (RH) in the artificial turf rooms (A-1 and A-2) and wood shavings rooms (W-1 and W-2) from April 13 to July 5.

	A-1	A-2	W-1	W-2
Ventilation (79 valid data days)				
Daily mean range (m^3 min^{-1})	46.5–98.8	51.1–114.8	39.9–91.2	51.9–118.6
ADM ± Std. (m^3 min^{-1})	74.0 ± 14.9	88.9 ± 17.1	68.9 ± 17.3	89.6 ± 18.5
ADM ± 95% c.i. (m^3 min^{-1})	74.0 ± 3.3^{a,b}	88.9 ± 3.8^{a,c}	68.9 ± 3.8^{c,d}	89.6 ± 4.1^{b,d}
2-room ADM ± 95% c.i. (m^3 min^{-1})	81.5 ± 2.8		79.3 ± 3.2	
T (79 valid data days)				
Min–Max (°C)	16.8–27.6	16.6–27.5	16.0–27.5	14.8–27.5
ADM ± Std. (°C)	22.7 ± 2.7	22.2 ± 2.9	22.5 ± 2.8	22.0 ± 3.2
ADM ± 95% c.i. (°C)	22.7 ± 0.6	22.2 ± 0.6	22.5 ± 0.6	22.0 ± 0.7
2-room ADM ± 95% c.i. (°C)	22.4 ± 0.4		22.3 ± 0.5	
RH (74 valid data days)				
Min–Max (%)	19.0–47.0	19.7– 46.0	20.9–48.0	18.4–47.8
ADM ± Std. (%)	33.9 ± 7.7	32.6 ± 7.6	36.1 ± 7.3	34 ± 7.8
ADM ± 95% c.i. (%)	33.9 ± 1.8	32.6 ± 1.7^{a}	36.1 ± 1.7^{a}	34 ± 1.8
2-room ADM ± 95% c.i. (%)	33.2 ± 1.2		35.1 ± 1.2	

Note: Differences among the rooms within the same row of ADM ± 95% confidence interval (c.i.) that are statistically significant ($p < 0.01$) are marked with the same superscript letters.

Table 3
Results of ammonia and carbon dioxide concentrations in the artificial turf rooms (A-1 and A-2) and wood shavings rooms (W-1 and W-2) from April 13 to July 5 (74 valid data days).

	A-1	A-2	W-1	W-2
Ammonia				
Daily mean range (ppm)	2.8–21.8	2.6–12.1	3.7–39.4	6.8–32.1
ADM ± Std (ppm)	9.1 ± 4.8	5.8 ± 2.3	14.9 ± 9.5	15.5 ± 6.3
ADM ±95% c.i. (ppm)	9.1 ± 1.1^{a,b}	5.8 ± 0.5^{a,c,d}	14.9 ± 2.2^{a,c}	15.5 ± 1.4^{b,d}
2-room ADM ± 95% c.i. (ppm)	7.5 ± 0.7^{a}		15.2 ± 1.3^{a}	
r of conc. & vent.	0.489	0.358	0.638	0.532
r of conc. & *T*	0.722	0.609	0.691	0.763
Carbon dioxide				
Daily mean range (ppm)	680–1042	637–1044	758–1319	722–1088
ADM ± Std (ppm)	837 ± 105	751 ± 114	995 ± 147	840 ± 98
ADM ± 95% c.i. (ppm)	837 ± 24^{a}	751 ± 26^{a,b,c}	995 ± 34^{a,b}	840 ± 22^{b,c}
2-room ADM ± 95% c.i. (ppm)	794 ± 19^{a}		917 ± 24^{a}	
r of conc. & vent.	−0.943	−0.942	−0.957	−0.927
r of conc. & *T*	−0.841	−0.780	−0.834	−0.755

Note: Differences of ADM ± 95% confidence interval (c.i.) among the rooms that are statistically significant ($p < 0.01$) are marked with the same superscript letter; r = correlation coefficient.

The reason for this characteristic could be related to the mechanism of ammonia release from manure, in which temperature and airflow speed over the manure surface have positive impacts on the release of ammonia (Ni, 1998). Another reason for this trend could be the increasing amount of manure accumulated on the floor, although manure on the under-cage manure belts was removed periodically. Considering the higher room ventilation rates from late May to early July (Fig. 3), the study showed that more ammonia was released in and emitted from the rooms during warmer months.

3.2.3. Spatial variations

Another characteristic of changes in ammonia concentrations was the spatial variations among the three ASLs, i.e., in-room north (Section 2) and south (Section 1), and ceiling ventilation air exhaust (Fig. 1). Moreover, this characteristic was different among the four rooms.

In A-1, concentrations at the ceiling exhaust ASL were lower than the two cage-level ASLs (∼0.60 m above the floor) before May 19. However, this changed later and the concentrations in the room north ASL became lower than the other two ASLs (Fig. 5). Because the rooms' air flowed from the north to the south of the rooms, more fresh air was expected in the north side of the room, resulting in more pollutant dilution and lower ammonia concentrations.

In A-2, which had the lowest ammonia concentrations among the four rooms, the daily mean concentrations at the three ASLs showed smaller variations than in A-1. The ADM concentrations were slightly lower at the north (5.7 ± 2.1 ppm) than at the south (6.2 ± 2.4 ppm) of the room. Compared with A-1, although the concentration patterns had some similarities, the daily mean values were lower in A-2 after May 17. Nevertheless, the reasons for the lower ammonia concentrations and more uniform concentration distribution in A-2 were unclear.

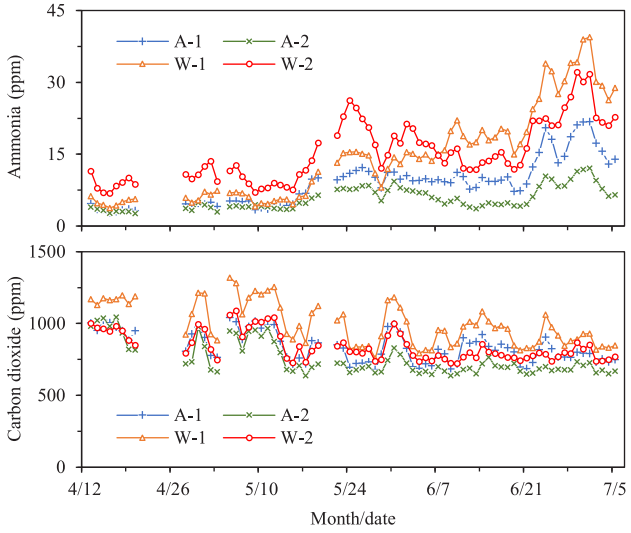

Fig. 4. Comparison of daily mean concentrations of ammonia (top) and carbon dioxide (bottom) in the four rooms.

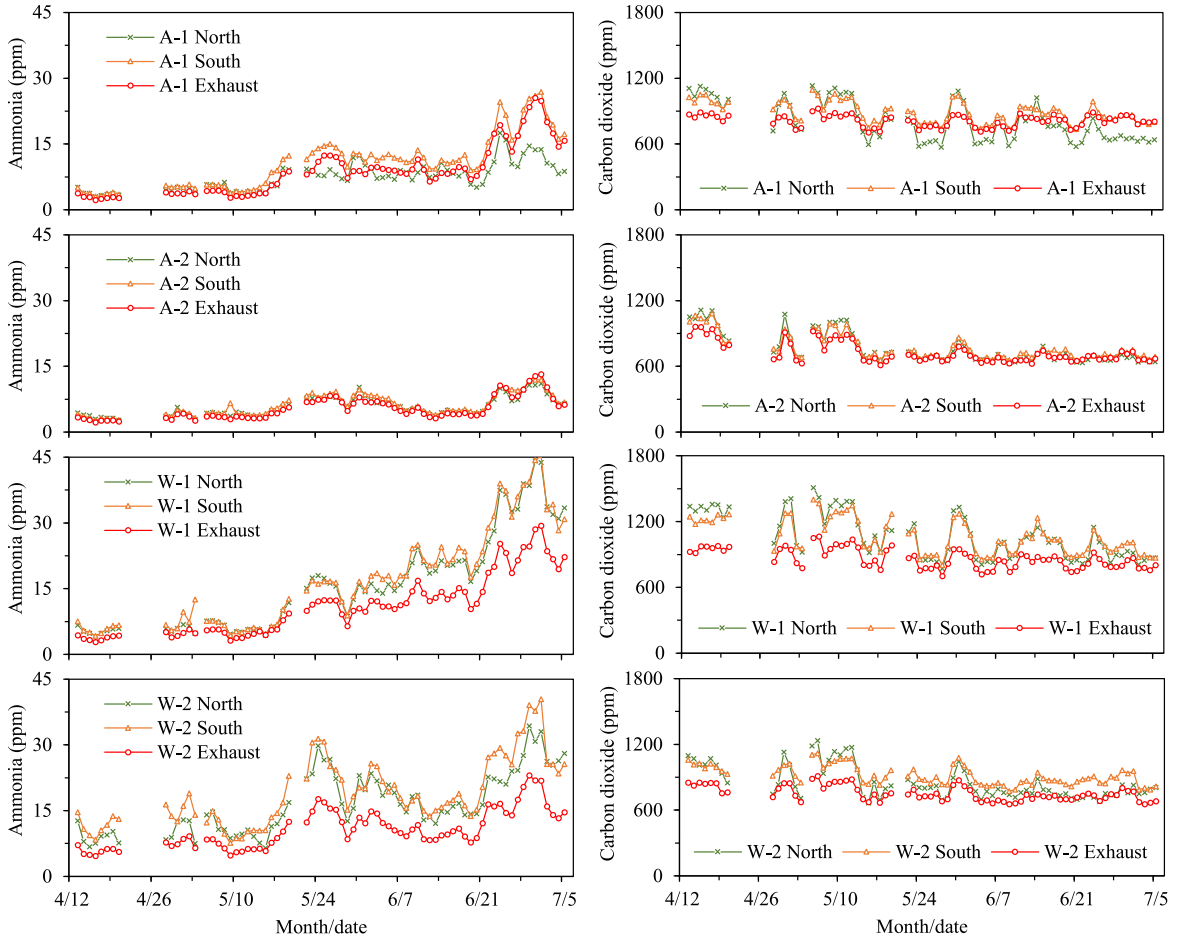

Fig. 5. Daily mean concentrations of ammonia (left four graphs) and carbon dioxide (right four graphs) at three sampling locations in the four rooms.

Rooms W-1 and W-2 demonstrated different characteristics of ammonia concentrations from the other two rooms. The ADM room ammonia concentrations (average of the concentrations of all three ASLs) between W-1 and W-2 were not statistically different ($p > 0.60$, Table 2). Evident variations among the three ASLs were found in both rooms. Compared with the north ASL, ammonia concentrations at the north ASL exhibited slightly lower concentrations (ADM 0.9 ppm lower in W-1 and ADM 2.3 ppm lower in W-2). This further confirmed that air flow direction from north to south in the rooms affected the distribution of ammonia concentrations and agreed with observations in commercial layer houses (Chai et al., 2010).

The ADM ammonia concentrations at the ceiling air exhausts were much lower than the other two ASLs throughout the study in W-1 and W-2. They were 5.5 ppm and 7.1 ppm lower in W-1 and W-2, respectively, compared with the average of the other two ASLs in the same room. These values were only 0.4 ppm for A-1 and 0.6 ppm for A-2. This phenomenon could be related to the ventilation design of the rooms and the different floors in the two pairs of rooms. Because the air inlets were in the north walls and the air exhausts were in the south side ceiling in the rooms, fresh air that could flow close to the manure on the floor, which was the major ammonia release source, was limited. This could result in an ammonia concentration gradient that was higher close to the floor and lower close to the ceiling. The fact that wood shavings rooms released more ammonia made this gradient larger.

3.3. Carbon dioxide concentrations

3.3.1. Concentration comparison

Carbon dioxide concentrations showed different characteristics compared with ammonia. The ADM carbon dioxide concentrations ranged from 751 ± 114 ppm in A-2 to 995 ± 147 ppm in W-1 (Table 3). The minimum and maximum daily mean concentrations were 637 ppm in A-2 and 1319 ppm in W-1, respectively. For carbon dioxide concentrations between the two treatments, A-1 was significantly lower than W-1 ($p < 0.01$) but had no difference with W-2 ($p = 0.85$), and A-2 was significantly lower than both W-1 and W-2 ($p < 0.01$). On average, the ADM carbon dioxide concentration in the two artificial turf rooms (794 ppm) was reduced by 13.5% ($p < 0.01$) compared with that in the two wood shavings rooms (917 ppm). This result was different from the report of Knežević et al. (2021), who did not find significant differences ($p > 0.05$) in carbon dioxide concentrations among six different litter types, which did not include artificial turf.

3.3.2. Temporal variations

Carbon dioxide concentrations in the four rooms had a general trend of decreasing from April to July, instead of increasing as ammonia concentrations did over this period (Fig. 4). Moreover, carbon dioxide concentrations were strongly and negatively correlated to both ventilation rates and room temperatures (Table 3). Ventilation rate demonstrated an effective dilution of carbon dioxide concentrations in this study.

3.3.3. Spatial variations

Similar to ammonia, the spatial distributions of carbon dioxide concentrations showed variations among the three ASLs. However, the four rooms demonstrated different characteristics. In A-1, carbon dioxide concentrations were the highest and lowest in the north ASL before and after May 10, respectively. In A-2, carbon dioxide concentrations in the north ASL did not differ from those of the other two ASLs ($p > 0.05$). Carbon dioxide concentrations at the air exhausts in both W-1 and W-2 were significantly lower than the other two ASLs ($p < 0.01$) (Fig. 5).

Carbon dioxide has a higher density (around 1.98 kg m^{-3}) than air (around 1.29 kg m^{-3}) and tends to remain close to the floor if no sufficient air mixing occurs in the rooms. The air flow profiles in these rooms, which might have affected the spatial ammonia concentration variations discussed in Section 3.2.3, could have also played a role in carbon dioxide spatial variations.

3.3.4. Sources of carbon dioxide

There are two major sources of carbon dioxide in poultry facilities, bird respiration and manure release (Liang et al., 2005). A laboratory study showed that carbon dioxide release from manure depended on manure characteristics and could be substantial. The maximum release was about 1.8 kg d^{-1} per m^2 manure surface area (Ni et al., 2010). In a study at two commercial layer houses for carbon dioxide from both bird respiration and manure release, the ratio of ammonia and carbon dioxide mass was 1:86 (Heber et al., 2005). The fact of significantly lower carbon dioxide concentrations at the ceiling air exhaust in W-1 and W-2 might also demonstrate that a large portion of carbon dioxide in these rooms were from manure release because no direct evidence and logical explanation were found that birds in the different rooms produced significantly different amounts of carbon dioxide by respiration.

3.4. Particulate matter concentrations

3.4.1. Concentration comparison

Five PM measurements were within the valid data period. Each measurement lasted from 141 to 193 h. The total valid PM measurement time was 836 h (Table 4). Statistical analysis results showed that the small particle daily mean (24 h mean) concentrations between A-1 and A-2 were not significantly different ($p = 0.83$, Table 5). However, A-1 and A-2

Table 4
Times of the measurement of particulate matter.

Start date and time	End date and time	Duration (hour)
4/28/2020 18:00	5/4/2020 17:30	143
5/4/2020 19:40	5/10/2020 17:00	141
5/23/2020 18:00	5/30/2020 18:00	168
6/6/2020 18:00	6/14/2020 16:30	191
6/20/2020 16:30	6/28/2020 17:00	193

Table 5
Results of particle concentrations in the artificial turf rooms (A-1 and A-2) and wood shavings rooms (W-1 and W-2) from April 28 to June 27.

	A-1	A-2	W-1	W-2
Valid data days (d)	31	33	30	33
Small particles				
DM range (n cm^{-3})	11.2–25.2	9.4–28.4	42.7–155.4	31.9–91.4
ADM ± Std (n cm^{-3})	17.8 ± 3.3	18 ± 3.6	101.7 ± 25.9	59 ± 18.7
ADM ± 95% c.i. (n cm^{-3})	17.8 ± 1.1[a]	18 ± 1.2[b,c]	101.7 ± 9.3[a,b,c]	59 ± 6.4[a,b,c]
2-room ADM ± 95% c.i. (n cm^{-3})	17.9 ± 0.8[a]		79.3 ± 7.6[a]	
r with lighting	0.387	0.730	0.802	0.594
Large particles				
DM range (n cm^{-3})	4.6–12.4	4.5–13.8	21.3–108.9	16.9–63.9
ADM ± Std (n cm^{-3})	7.9 ± 1.9	9.1 ± 2.1	69.4 ± 26.1	35.9 ± 14.1
ADM ± 95% c.i. (n cm^{-3})	7.9 ± 0.7[a]	9.1 ± 0.7[b,c]	69.4 ± 9.3[a,b,c]	35.9 ± 4.8[a,b,c]
2-room ADM ± 95% c.i. (n cm^{-3})	8.5 ± 0.5[a]		51.8 ± 6.6[a]	
r with lighting	0.581	0.750	0.725	0.558

Note: Differences within the same row of ADM ± 95% confidence interval (c.i.) among the rooms that are statistically significant ($p < 0.01$) are marked with the same superscript letters; r = correlation coefficient.

had lower concentrations than W-1 and W-2 ($p < 0.01$). Moreover, the daily mean small particle concentrations between W-1 and W-2 were significantly different from each other ($p < 0.01$). Compared with the average concentrations of W-1 and W-2 (79.3 particles cm^{-3}), A-1 and A-2 (average of 17.9 particles cm^{-3}) demonstrated a significant reduction of 77.5% ($p < 0.01$).

The characteristics of large particle concentrations during the 35 day monitoring were similar to the small particles. Only the daily mean concentrations between A-1 and A-2 were insignificantly different ($p > 0.01$). The concentrations between other room pairs were all significantly different ($p < 0.01$). The artificial turf rooms (average of 8.5 particles cm^{-3}) had 83.6% reduction in large particle concentrations ($p < 0.01$) compared with the wood shaving rooms (51.8 particles cm^{-3}).

The differences in room PM concentrations between the two treatments could be attributed to the differences in room floor surfaces that the birds directly interacted with. The wood shavings floor was fully covered with litter from which PM could easily become airborne under activities of the birds (Fig. 2). Moreover, wood shavings themselves were a source of PM. Whereas the artificial turf floor surface was only covered with a little manure, therefore, greatly reduced PM generation sources in the rooms.

3.4.2. Temporal variations

The daily (24 h) mean particle concentrations in the artificial turf rooms were very different from the wood shavings rooms for both small particles and large particles (Fig. 6). The daily mean particle concentrations in A-1 and A-2 had a slight decrease from April 28 (day 1 in Fig. 6). A peak concentration occurred on the 29 day in A-1 when the room lighting and other monitoring variables did not show any anomalies. The reason for this peak could not be identified. Otherwise, the daily mean PM concentrations in the two artificial turf rooms were regular. The daily mean particle concentrations in W-1 and W-2 had more substantial decreases from April 28 to June 27 (from day 1 to day 35 in Fig. 6).

3.4.3. Room lighting and particulate matter concentrations

Particulate matter concentrations were greatly affected by bird activities, which in turn were affected by the room lighting schedule and daily room maintenance (Fig. 7). On a typical day, the PM particle concentrations immediately increased when the room light was turned on and caused suddenly agitated bird activities, which generated a surge of small and large particles.

Additional light from the hallway, when the room door(s) were opened, coupled with the daily maintenance by the staff, usually caused a minor peak of dust concentrations, although the light from the hallway only affected part of the room. At night when the light was turned off, the particle concentrations immediately decreased. These observed PM concentration characteristics were the same in all rooms with both floor treatments. They also agreed with the reported PM concentrations in commercial laying hen houses (Heber et al., 2006; Knight et al., 2019; Hong et al., 2021).

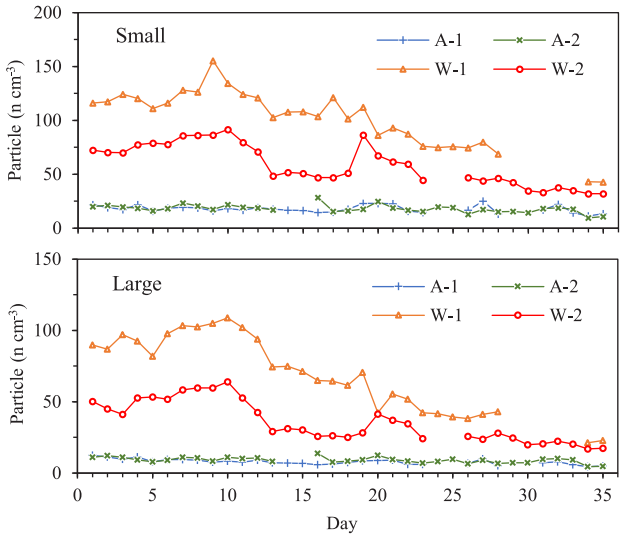

Fig. 6. Daily (24 h) mean small (top) and large (bottom) particle counts in the four rooms from April 28 (day 1) to June 27 (day 35).

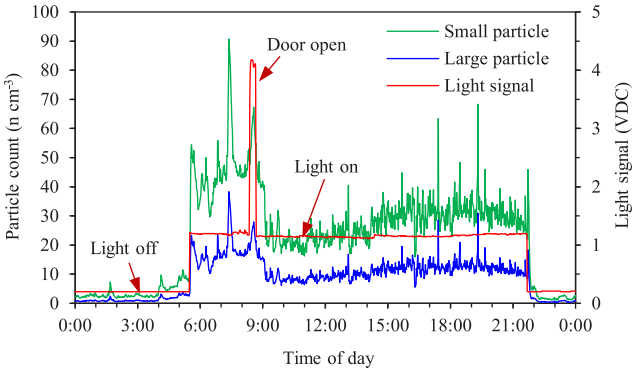

Fig. 7. Small and large particle counts during a typical day (June 7) in A-1.

3.5. Ammonia and carbon dioxide emissions

Results demonstrated that the ADM ammonia emissions from the two artificial turf rooms were both lower than the two wood shavings rooms (Table 6), although the emission rates between A-1 and W-1 were not statistically significant ($p > 0.07$). Comparison of ammonia emissions resulted in a 38.4% reduction ($p < 0.01$) from A-1 and A-2 (563 g d^{-1}) than W-1 and W-2 (914 g d^{-1}).

Carbon dioxide emissions from the two artificial turf rooms were both lower than the two wood shavings rooms (Table 6), although emissions from A-1 (66.9 kg d^{-1}) was not significantly lower than W-1 (69.4 kg d^{-1}, $p > 0.08$) and W-2 (67.5 kg d^{-1}, $p > 0.70$). Compared with the two control rooms (68.4 kg d^{-1}), the two artificial turf rooms (62.7 kg d^{-1}) reduced carbon dioxide emissions by 8.3% ($p < 0.01$).

Gas emission rate is the gas concentration difference between the inlet and the exhaust of room air multiplied by the room ventilation rate [Eq. (4)]. Because the four rooms received the same inlet air and their ventilation rates did not vary significantly (Table 2), the gas emission rate differences among the four rooms were mainly determined by the gas concentrations at the room exhausts. Therefore, the ammonia and carbon dioxide emission rates, like their concentrations, from the artificial turf rooms also showed significant reductions compared with those from the wood shavings rooms.

3.6. Manure characteristics and pollutant concentrations and emissions

3.6.1. Manure characteristics

Manure sample analysis results showed interesting manure characteristics between the two floor treatments (Table 7). These characteristics could be related to whether the manure was mixed with or without the wood shavings. The

Table 6
Ammonia and carbon dioxide emission rates from the artificial turf rooms (A-1 and A-2) and wood shavings rooms (W-1 and W-2) from April 13 to July 5 (74 valid data days).

	A-1	A-2	W-1	W-2
Ammonia				
ADM ± Std (g d^{-1})	668 ± 499	458 ± 269	839.4 ± 636	988 ± 514
ADM ± 95% c.i. (g d^{-1})	668 ± 114[a]	458 ± 61[b,c]	839 ± 145[b]	988 ± 117[a,c]
2-room ADM ± 95% c.i. (g d^{-1})	563 ± 67[a]		914 ± 94[a]	
Carbon dioxide				
ADM ± Std (kg d^{-1})	66.9 ± 9.4	58.6 ± 7.5	69.4 ± 7.9	67.5 ± 8.3
ADM ± 95% c.i. (kg d^{-1})	66.9 ± 2.2[a]	58.6 ± 1.7[a,b,c]	69.4 ± 1.8[b]	67.5 ± 1.9[c]
2-room ADM ± 95% c.i. (kg d^{-1})	62.7 ± 1.5[a]		68.4 ± 1.3[a]	

Note: Differences of ADM ± 95% confidence interval (c.i.) among the rooms that are statistically significant ($p < 0.01$) are marked with the same superscript letter.

Table 7
Characteristics of manure samples taken in the artificial turf rooms (A-1 and A-2) and wood shavings rooms (W-1 and W-2).

	A-1	A-2	W-1	W-2
TAN (%)	0.35	0.46	0.32	0.26
Organic nitrogen (%)	2.42	2.95	2.43	2.53
TKN (%)	2.77	3.41	2.75	2.79
Total solids (%)	72.7	76.2	78.1	80.4
pH	7.3	7.4	8.4	8.2

Note: TAN = Total ammonium nitrogen; TKN = Total Kjeldahl Nitrogen.

concentrations of total ammonium nitrogen (TAN), organic nitrogen, and Total Kjeldahl Nitrogen (TKN) were all higher in A-1 and A-2 than in W-1 and W-2, indicating that artificial turf floors preserved more nitrogen in the manure.

However, the total solids and the pH of the manure in A-1 and A-2 were both lower than in W-1 and W-2. These characteristics could have profound effects on aerial pollutants released from the manure and emitted from the rooms.

3.6.2. Manure and ammonia

Manure characteristics demonstrated correlations with room ammonia concentrations, which were the dynamic balance of ammonia released from manure and ammonia emitted via ventilation. The TAN is known to be directly proportional to the rate of ammonia release from manure (Sommer et al., 2006). However, the r of the ADM ammonia concentrations and the TAN concentrations in the four rooms was −0.93 and could not explain the higher ammonia with lower TAN concentrations in the wood shavings rooms (Table 6). Nevertheless, a very strong r of 0.91 between the ADM ammonia concentrations and the manure pH in the four rooms was found. Higher pH could result in higher ammonia release from manure.

The contradictory correlations of TAN and pH with the room ammonia concentrations could be explained with the different magnitudes of TAN's and pH's effects on ammonia release. The effect of TAN on ammonia release from manure is proportional. A one-fold increase in TAN tends to result in a one-fold increase in ammonia concentration in the aqueous phase (Sommer et al., 2006). However, it has long been known that pH influences ammonia release in a more profound way because it can increase ammonia in the aqueous phase with an approximately 10-fold per unit increase in pH up to pH 9 (Vlek and Stumpe, 1978).

The mean manure pH of W-1 and W-2 was 8.30, lower than pH 8.66 for wood shavings reported by Tasistro et al. (2007), but was 0.95 unit higher than the mean manure pH of 7.35 in A-1 and A-2. Therefore, there was an imbalance of the effects of manure TAN and pH on ammonia release in the four rooms. The positive effects of pH on ammonia release from manure and emission from the wood shavings rooms were much stronger than the negative effect of the TAN, making the ammonia concentrations and ammonia emissions significantly higher than in the artificial turf rooms, from which less nitrogen was lost. This finding was supported by the study of Munir et al. (2019), who reported that the pH of bedding had a direct link with ammonia generation.

3.6.3. Manure and carbon dioxide

The r of carbon dioxide concentrations and manure total solids and pH was 0.27 and 0.76, respectively (Table 6). Carbon dioxide release from manure has been related to manure total solids and pH. Wet manure could release more carbon dioxide than dry manure (Ni et al., 2010). However, the moderate and positive r of carbon dioxide and manure total solids did not provide strong support to the higher carbon dioxide in the wood shavings rooms. Carbon dioxide release from manure could raise the manure pH and accelerate ammonia release from manure (Ni et al., 2000). The possibility that more carbon dioxide was released from the wood shavings rooms (Section 3.3.4) also implied its positive impact on higher ammonia concentrations in these rooms. However, more studies are still needed to distinguish the two sources, from animal respiration and from manure release, of carbon dioxide in poultry rooms.

3.6.4. Manure and particulate matter

The r between manure solids and small and large particle concentrations were 0.64 and 0.62, respectively. Dust particles tend to be more easily released from drier manure and become air borne in the poultry houses. These strong r values can explain the higher dust concentrations in the wood shavings rooms.

4. Conclusions

The following conclusions were drawn from this study:

1. Artificial turf floor is a new promising technology for air pollution reduction in laying hen housing. Compared with the wood shavings rooms, the artificial turf rooms significantly reduced ($p < 0.01$) concentrations and emissions of ammonia and carbon dioxide, and concentrations of small particles and large particles.
2. Artificial turf rooms preserved more nitrogen and lowered manure pH. Lower pH was the main cause of reduced ammonia concentrations and emissions.
3. Artificial turf reduced PM concentrations by reducing the PM sources on the floor surface, with which the birds directly interacted.
4. Room airflow patterns affected distribution of ammonia and carbon dioxide concentrations and resulted in concentration gradients. Artificial turf rooms had smaller gas concentration gradients compared with the wood shavings rooms.
5. Continuous and reliable ventilation rate monitoring was critical for quality assurance and quality control in air pollution comparison studies.

CRediT authorship contribution statement

Ji-Qin Ni: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Funding acquisition. **Marisa Erasmus:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Deana R. Jones:** Conceptualization, Writing – review & editing, Funding acquisition. **Dana L.M. Campbell:** Conceptualization, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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