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Assessing particulate matter (PM_{10}) emissions from outdoor runs in laying hen houses by integrating wind tunnel and lab-scale measurements

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Abstract

Laying hen houses are a known source of fine particulate matter (PM), but no information is available on the contribution of outdoor runs to the overall emissions. This study aims to investigate some of the main factors driving PM emissions from outdoor runs. A wind tunnel device was built to assess the effect of hen density (HD, hens m^{-2}) on PM emissions from outdoor runs. Moreover, a laboratory trial, using a soil resuspension chamber, was conducted to describe the influence of soil moisture on the emissions. The gathered information was then used to estimate PM_{10} emissions over a 1-year period. PM emissions increased exponentially with increasing HD and decreased exponentially with increasing soil water content. The average PM_{10} emissions from hen activities at the study farm, estimated using meteorological data from year 2019, were of 8.9 mg hen^{-1} d^{-1}. This emission is much lower than those reported by previous studies for indoor hens rearing.

KEYWORDS: particulate matter; emissions; laying hens; area source; wind tunnel

HIGHLIGHTS

- A new method to assess PM emissions from outdoor runs in hen houses was developed;
- PM_{10} emissions for hen activity in outdoor runs were estimated;
- An exponential increase of PM_{10} emission was observed with increasing hen density;
- The effect of soil moisture on soil derived PM_{10} emission was assessed.

1. Introduction

High environmental concentrations of particulate matter (PM) are regarded as a cause of concern for human health (Pope, 2007). Livestock activities are long known to play an important role in PM concentration raises both in indoor and outdoor environments (Cambra-López, Aarnink, Zhao, Calvet, & Torres, 2010; EEA, 2016). In fact, both the coarser (PM_{10}; particles with an aerodynamic diameter <10 μm) and finer ($PM_{2.5}$; particles with an aerodynamic diameter <2.5 μm) fractions of PM are held responsible for negative health effects in farmers and local residents surrounding livestock houses. Furthermore, high dust concentrations affect indoor air quality and health and welfare of animals (Borlée et al., 2017; María Cambra-López et al., 2010). Several studies have addressed the issue of PM emissions from poultry houses, quantifying the emission fluxes (Hayes, Curran, & Dodd, 2006; Roumeliotis & Van Heyst, 2008; Yao et al., 2018) and proposing mitigation measures (M. Cambra-López, Winkel, Harn, Ogink, & Aarnink, 2009; R. W. Melse, P. Hofschreuder, & N. W. M. Ogink, 2012; Winkel et al., 2016). Most of these studies focused on emissions coming from poultry houses, while very little information is available on the contribution of the outdoor runs on the overall emissions. This is partially due to the fact that assessing emissions from area sources in open space environments presents some difficulties, especially in case the sources are not homogeneous (Dumortier, Aubinet, Lebeau, Naiken, & Heinesch, 2019). The main methodologies that have been used to address this kind of sources in similar applications, such as cattle feedlots, are micrometeorological techniques and wind tunnel methods (Misselbrook, Nicholson, Chambers, & Johnson, 2005). Micrometeorological techniques such as the integrated flux method (Denmead, 1983) and dispersion models (Bonifacio et al., 2012; Flesch, Wilson, Harper, Crenna, & Sharpe, 2004) have proven to be very effective in back calculating emission fluxes from open field emission sources. These systems, however, despite their large range of application, have the common disadvantage of being unsuited to estimate emissions from sources, such as the outdoor runs, which are in proximity of multiple other sources of the same pollutant (e.g. barn, manure storage facilities etc.), due to cross interference. Wind tunnels are enclosure systems which have been widely used to assess PM and gaseous emissions from soil or other ground level area sources (Dinuccio, Gioelli, Balsari, & Dorno, 2012; Gao et al., 2020; Kabelitz et al., 2020) and allow to monitor the emissions, gathering data under standardized wind speed conditions. Aarnink, Hol, & Beurskens (2006) used a ventilated chamber technique to assess ammonia (NH_3) emissions from outdoor runs in laying hen houses, but did not address PM emissions. The main constraint regarding the use of a classical wind tunnel method to assess emissions from outdoor runs is linked with the hens behavior. In fact, hens often engage in dust bathing behavior, which was recognized as a form of personal hygiene and also as a social behavior which has beneficial effects on animal welfare (Abrahamsson, Tauson, & Appleby, 1996; van Liere, Kooijman, & Wiepkema, 1990; Vestergaard, Skadhauge, & Lawson, 1997). When hens dustbathe in outdoor runs soil, they can cause soil (re)suspension in the air leading to PM emissions. Therefore, in order for a wind tunnel to effectively assess outdoor runs PM emissions, it should allow to assess the emission deriving from dustbathing and other hen activities.

The main aim of this work is to develop a multi-step methodology to assess outdoor runs emissions of PM and identify the role of hens behavior and soil moisture as main drivers of the emission. A wind tunnel prototype was designed to allow the hens to enter it willingly and dustbathe inside of it, in order to assess the effect of hen density (HD, hens m^{-2}) on the emissions. Moreover, the emission potential of the outdoor run soil was assessed, using a Soil Resuspension Chamber (SRC) method to assess the effect of soil humidity on PM release. The gathered information, combined with daily meteorological data and evapotranspiration (ET) modelling, was utilized to assess PM emissions over a 1-year period.

The gathered results will allow to acquire a better understanding of poultry generated PM emissions by addressing some of the main factors driving PM formation from free range areas in poultry houses. Moreover, it will provide a new perspective on hens behavior, addressing its influence on PM emissions.

2. Materials and methods

2.1. Wind tunnel design

Wind tunnels used for PM and gaseous emission assessments have a wide variety of shapes, but they usually share some common elements. They are built in sturdy material, such as plastic or stainless steel, they have a main chamber, which has the purpose of enclosing the studied area source, and they are provided with input and output pipes. The wind speed inside the tunnel (WS_{tunnel}, m s^{-1}) is generated using a ventilator and normally set to a value that matches the average outdoor wind speed (Dinuccio et al., 2012). The pollutant concentrations (mg m^{-3}) are normally monitored through sampling ports placed on the inlet and outlet pipe. The emission rate (ER, mg m^{-2} hr^{-1}) is then calculated as follows:

$$ER = \frac{(C_{out} - C_{in})\, WT_{flow}}{A}$$

Where C_{out} (mg m^{-3}) is the outlet concentration, C_{in} is the background concentration (mg m^{-3}), WTflow is the total airflow passing through the tunnel (m^3 hr^{-1}), and A is the enclosed area (m^2).

The wind tunnel design proposed for assessing emissions from outdoor runs in poultry follows the same concept as described above, but it was modified to allow the assessment of emissions caused by dustbathing hens. To do so the inlet pipe was removed and the front of the tunnel was left open in order to allow the hens to walk in. The main chamber of the tunnel was built using a solid metal framework and wrapping a transparent plastic foil around it. This solution was adopted to allow sunlight to enter the tunnel, since the hen's behavior is affected by light. The funnel structure connecting the main chamber to the pipe was constituted by an iron wire framework covered by the same plastic foil covering the tunnel. Moreover, a metal grid was placed in between the main chamber and the funnel structure to prevent the hens from entering the funnel structure or the pipe. A ventilator with a 35 cm diameter was used (VOSTERMANS, Multifan IP 55 KLF). The overall design of the wind tunnel is illustrated in Figure 1.

The final design choices were forced by the necessity of allowing hens to dustbathe inside the wind tunnel. Similar designs were previously adopted by Balsari et al. (2006), for assessing ammonia emissions after manure spreading and by Roney et al. (2006) for fugitive dust emissions from soil. While similar in the overall design, the wind tunnel adopted by those two authors relied on different solutions for measuring the outlet concentration. To validate the wind tunnel design for emission assessment and to define a suitable concentration sampling strategy, a laboratory test was carried out using a tracer gas to test the tunnel capture efficiency. The wind tunnel flow and internal wind speed were also characterized under laboratory conditions.

2.2. Wind tunnel flow, internal wind speed and expected environmental wind speed

The flow of the tunnel was assessed by measuring, using a hotwire anemometer (Testo, 435), the wind speed (m s^{-1}) at the inlet of the ventilator pipe in 5 different positions and multiplying it by the section area of the pipe (116.2 cm^2).

The tunnel wind speed was set in order to match the external wind speed in the poultry farm area. The average external wind speed at 0.2 m meters from ground level was estimated, using the mean wind speed data retrieved from KNMI Deelen weather station (KNMI, 2020), according to the following formula:

$$ExpWS_{(0.2\,m)} = WS_{(10\,m)} \frac{\ln(0.2/z_0)}{\ln(10/z_0)}$$

Where $ExpWS_{(0.2\,m)}$ is the external mean wind speed at 0.2 m height from ground level, $WS_{(10\,m)}$ is the mean wind speed (average of hourly wind speed data for year 2020; 4.1 m s^{-1}) at 10 m from ground level (measured at Deelen station), and z_0 is the roughness length (set to 0.01). The equation used is explained in detail by Stull (2012).

The wind speed inside the tunnel was assessed by using the same hotwire anemometer, attached on a tripod (at 0.2m from the ground) and placed in 8 different positions inside the tunnel. The fan rotational speed was regulated using an external regulator (Stienen, SPM-6).

2.3. *Assessment of Wind Tunnel capture efficiency*

The capture efficiency of the WT was tested through a tracer gas experiment, using pure ammonia as tracer (the setup is shown in Figure 1). Ammonia was released from a cylinder and emitted inside the tunnel from a 30 cm long line source, constituted by a dead-end Teflon tube (4 mm ø), which had holes (performed with a 3 mm ø drill) every 10 cm. The line source was placed perpendicularly to the WT flow at 20 cm from the WT entrance. The NH_3 flow was regulated using a mass flow controller (Bronkhorst, EL-FLOW®), which was set at three flow levels F1, F2 and F3. The mass flow regulator was calibrated for the regulation of atmospheric airflow, therefore the amount of NH_3 emitted with the three flow settings (F1, F2 and F3) utilized had to be assessed in a further laboratory experiment. A scheme of the experimental layout is shown in Figure 2. The assessment consisted in fluxing the ammonia into an acid bottle, capped with an impinger, which contained 0.5 molar HNO_3 acid. A flow meter was connected to the outlet of the impinger to check whether all ammonia was captured by the acid solution. A safety outlet tubing was placed at 2 m height to prevent exposure for the operator. The experiment was repeated twice for each flow level and the fluxing time was 4 minutes per sample. The collected acid samples were then analysed for the NH_4-N content ($C_{N\text{-}NH4}$, mg L^{-1}). During the experiment the formation of a negative pressure inside the acid bottle was observed, especially at low pressure from the ammonia tank. This caused a pressure deficit, affecting the flow passing through the system. This issue was due to the height difference among the system outlet (2 m height) and the impinger (at ground level). To solve this imbalance, a correction factor (cf) was calculated by measuring, using a flow meter, the incoming and the outcoming flow to the impinger. This later assessment was performed using water in place of the acid and pressured air instead of ammonia, for safety reasons.

The amount of ammonia captured with the impinger method (I_{NH3}, mg) at the three flow levels was then assessed according to the following formula:

$$I_{NH3} = C_{N-NH4}\, L\, \frac{NH_{3Mmass}}{N_{Mmass}}\, cf$$

Where L is the amount of acid solution in the impinger bottle (L), NH_{3Mmass} and N_{Mmass} are the molar masses of NH_3 and N (g/mol) respectively and *cf* was found to be 1.3 (± 0.21), 1.09 (± 0.18) and 1.04 (± 0.17) for F1, F2 and F3 respectively.

During the capture efficiency test, the ammonia concentration at the outlet and inlet of the tunnel (mg m^{-3} was measured using electrochemical sensors (Polytron® 8100 EC, Dräger). The outlet concentration was measured in three different sampling points (S1, S2 and S3, as shown in Figure 1). The concentration measurements lasted 15 minutes for each of the NH_3 flows and sampling point combinations, for a total of 135 minutes. The observed concentrations were then averaged over three minutes time intervals and used to calculate the total amount of ammonia captured by the WT system (WT_{NH3}, mg), according to the following formula:

$$WT_{NH3} = (C_{out} - C_{in})\, WT_{flow}\, T$$

Where C_{out} (mg m^{-3}) is the outlet concentration measured in S1, S2 and S3, C_{in} is the background ammonia concentration (mg m^{-3}), WT_{flow} is the wind tunnel flow (m^{-3} s^{-1}) and T is the time (s) of the experiment. It was assumed that the PM particles are transported by the air flow in a similar way as NH_3, as previously done by other authors (Maffia, Dinuccio, Amon, & Balsari, 2020; Pattey & Qiu, 2012), and that the capture efficiency remains the same.

2.4. *Field measurement protocol for wind tunnel trials*

Field measurements were performed in a free range laying hen house sited in the Netherlands (52°05'58.6"N 5°34'38.2"E), in an area characterized by sandy soils. The farm is provided with a large outdoor area and the hens are allowed out from 10 am till sunset. The wind tunnel equipment was placed at 6 m from the barn, inside of the area where, according to Niekerk et al. (2016), most of the hens stand when outside. The measurements where performed, on sunny days, twice a week for 1 month and a short period was needed for the hens to adapt to the tunnel and start entering inside. Each measurement event lasted 3-4 hours and the hens where left free to enter the tunnel at will. Concentration measurements were performed using optical particle counters (DustTrak II, TSI) for PM_{10} measuring both at the inlet and the outlet (position S3) of the tunnel. The measuring frequency was of one measurement every 10 seconds. The two instruments were compared before the experiment, by measuring for 6 h in the same spot, and gave consistent results.

The first measurement was made with a 0.95 $m^3 s^{-1}$ WT_{flow}, which generates a wind speed inside the tunnel more similar to the actual wind conditions in the region. Then, since it was observed that the hens preferred to enter the tunnel under slightly lower wind speed conditions, WT_{flow} was set at 0.73 $m^3 s^{-1}$. Being that this work aims mainly to assess PM emissions deriving from hens activity and that those emissions are predominantly caused by mechanical resuspension of soil, it was assumed that having a slightly lower wind speed as compared to the natural one is acceptable. The ERs were calculated with the same method used for the wind tunnel efficiency assessment, described in section 2.3, expressing the emissions as mg $m^{-2} hr^{-1}$.

A video camera (HERO 7 Silver, GoPro) was placed inside the tunnel to observe hens activity and count the number of hens inside the tunnel. This was necessary to relate the obtained ERs to the hen density (HD, hens $m^{-2}hr^{-1}$), which was calculated as follows:

$$HD = \frac{N_{hens}}{A}$$

Where N_{hens} is the number of hens present inside the tunnel and A is the enclosed area (m^2).

When the hen density was over 3.2 hens m^{-2} (5 hens inside the tunnel at the same time), the density was considered simply as >3.2 hens m^{-2}, since, due to fouling of the tunnel, it was impossible to distinguish the exact number of hens.

The ERs were then averaged over the HD, in order to obtain a dataset with an average ER for each HD category (0.6, 1.3, 1.9, 2.6, 3.2, >3.2 hens m^{-2}) for each measurement event. Each HD category correspond to an exact number of hens inside the tunnel (1, 2, 3, 4, 5 and >5 hens).

The soil moisture content on each measuring day was assessed by collecting a soil sample inside the tunnel, before and after the measurement, and assessing soil humidity with a gravimetric method by drying in a hoven at 105°C for 24 h.

2.5. Soil resuspension chamber experiment to determine soil moisture effect

A soil resuspension chamber (SRC), which has been fully described in a previous paper (Padoan, Maffia, Balsari, Ajmone-Marsan, & Dinuccio, 2021), was used to resuspend the outdoor run soil. The chamber was composed of a rotating drum, with a 25 L capacity, and a rotation frequency of 26 revolutions per minute, powered by an electric engine with 0,75 kW of power and an electric potential of 220 V. During the trials, the drum was closed by a flange, on which were nested four flexible PVC tubes

(0.4 m long with 8 mm diameter), provided with a series of small holes (diameter 0.3 mm), allowing clean air inside the rotating drum. The air was sucked from the drum through an aspiration pipe, which pulled the emitted dust towards a deposition chamber. A vane pump (5; VTE3, Rietschle) was used to draw the air from the deposition chamber and induced an air flow of 30 L min^{-1} through the system. The re-suspended particulate matter was sampled, through a sampling port, using both an optical PM monitor (Grimm 11-D, Grimm Aerosol Technik), to assess particle quantity. A scheme of the system is provided in Figure 3.

Soil samples (three replicas per each soil humidity level) were resuspended by placing a soil aliquot inside the SRC rotating drum for 15 min. The experiments were conducted using soil samples of 5 g. The emission potential (EP, mg kg^{-1}) was defined at four different moisture contents (calculated as 0, 15, 30 and 40%, by weight, of the soil field capacity). Soil EP (mg kg^{-1}) was calculated as follows:

$$EP = \frac{C}{1000} * \frac{Q * t}{S}$$

Where C is the particle concentration (µg m^{-3}) measured with the Grimm PM monitor, Q is the SRC airflow (m^{3} min^{-1}), calculated as the sum of the pump and the flow of the Grimm internal pump (1.2 L min^{-1}), S is the soil sample mass (kg), and t the considered time-span (min).

A detailed description of the sampling systems and intervals is provided in Padoan et al. (2021) Soil emission potentials were calculated in terms of PM_{10}, PM_4 and $PM_{2.5}$.

2.6. Soil humidity estimation and PM_{10} emission estimation over one year period

Soil humidity was assessed on the base of weather data, applying a water balance approach. The soil water balance was calculated by applying the Hargreaves–Samani equation (HS, Hargreaves & Samani, 1985) to calculate the potential evapotranspiration (ET0). The HS method was chosen since it is, among the simplified ET estimation methods, the one that finds better agreement with the Penman-Monteith recommended method from FAO 56 (Allen, Pereira, Smith, Raes, & Wright, 2005). The HS equation applied for this study is as follow:

$$ET0 = K_{HS}K_T(T_a + 17.78)(T_{max} - T_{min})^{0.5}R_a$$

Where K_{HS} and K_T are dimensionless coefficients, T_a is the average daily temperature (°C), T_{max} is the maximum daily temperature (°C), T_{min} is the minimum daily temperature and R_a is the extra-terrestrial radiation (mm day^{-1}).

T_a, T_{max}, T_{min} and R_a where derived from nearby KNMI weather stations located in Deelen (2019 dastaset).

The actual evapotranspiration ETc was then derived by multiplying ET0 by the coefficient Kc (which was set to 1.1 for bare soil conditions). The soil water content (WC, mm) was then calculated, considering a soil depth of 15 cm, as follows:

$$WC = WC_i + Rain - (ETc * k_s) - LW$$

Where Rain is the daily rainfall (mm), k_s is the stress coefficient (derived as in Allen et al., 2005), LW is the leaching water (mm) and WC_i is the soil water content at the start of the day (WC the first day of the series was set to FC, since it was after a heavy rain event). LW was calculated as the difference among WC_i, net of the ET flux, and soil Field capacity.

The 15 cm depth of soil considered was selected observing the average depth of ridges caused by hens activity in the outdoor run area. Soil physical characteristics and field capacity were experimentally assessed. Fifteen subsamples of soil were taken by applying a X sampling scheme (Colombo & Miano, 2015). The topsoil subsamples were collected to a depth of 15 cm, which was considered the depth interested by hens dustbathing activities. Field capacity was determined for each soil according to the official method proposed by MiPAF (1997) and soil texture was defined according to the Soil Science Division Staff (2017) guidelines.

Finally, the daily emissions (Ed, mg m^{-2} d^{-1}) were calculated by integrating soil emission potential (as affected by humidity) and outdoor run emission level, according to the following equation:

$$E_d = \frac{EP_d \, ER_{HD}}{EP_{WT}} \, H$$

Where, EP_d (mg kg^{-1}) is the emission potential related to the soil moisture conditions of the day, ER_{HD} is the emission rate (mg m^{-2} hr^{-1}) calculated on the base of the HD expected on the specific day, EP_{WT} (mg kg^{-1}) is the emission potential related to the moisture conditions occurred during the wind tunnel trials and H is the number of hours in which hens are allowed outside.

The HD expected on each specific day was estimated on basis of literature information. The few studies available on this topic reported very different data regarding the number of hens (% on total flock consistence), ranging from around 10 to 40% (Gebhardt-Henrich, Toscano, & Fröhlich, 2014; Hegelund, Sørensen, Kjaer, & Kristensen, 2005; Hirt & Zeltner, 2000). This large variability is due to several aspects that influence hens behavior and their usage of outdoor spaces. The main influencing parameters are the flock size (Gebhardt-Henrich et al., 2014), the environmental conditions (Pettersson, Freire, & Nicol, 2016) and the presence of sheltering structures in the outdoor run (E. Zeltner & Hirt, 2003; Esther Zeltner & Hirt, 2008). Moreover, most of free ranging hens (60-95%) tend to graze in the first 20 m from the outdoor run, causing complete destruction of the canopy in that area (Fürmetz, Keppler, Knierim, Deerberg, & Heß, 2005). The farm in which this study was performed had a large flock size (24,000 hens) and an outdoor area of 9.6 ha. On basis of this information, it was considered that only 20% of laying hens are found outside at one moment and 80% of those are found in the over grazed area at short distance from the house. This area, presented in Figure 4, was measure to be equal to 6,263 m^2. Therefore, the emission from the overgrazed area of the outdoor run was assessed considering an average HD of 0.6 hens m^{-2}. The number of hours in which the hens were let outside (7 h in winter and 11 h in summer) was also considered when assessing the daily emission.

2.7. Statistical analysis

Statistical analyses were performed to test the fluxes of NH_3 observed during the wind tunnel efficiency estimation trial, with the 3 concentration sampling position (S1, S2, S3), as compared to the actual amount of ammonia released from the ammonia vessel determined with the impinger method (I_{NH3}). A two-way ANOVA procedure, performed using the R statistical software (R core team, 2019), followed by a Bonferroni post-hoc test, was used. Observed differences were considered significant for $P<0.05$. A linear regression was applied to investigate the relation between the natural logarithm of PM_{10} ER and HD and that between EP and soil water content.

3. Results

3.1. Wind tunnel flow and wind speed charts

The first flow rate tested was of 0.95± 0.01 m^{-3} s^{-1}, leading to a wind speed of 1.8±0.03, which matches the expected wind speed of the area ($ExpWS_{(0.2\ m)}$ = 1.8 m s^{-1}). Since the hens were reluctant to enter the tunnel at this high windspeed, a lower flow rate of 0.73 ± 0.01 m^{-3} s^{-1} was used, leading to an average wind speed inside the tunnel of 1.5 ± 0.11 m s^{-1}. The average wind speed inside the tunnel was measured at 8 positions, at 0.20 m height, and resulted in higher values in the central row and slightly lower values in the side rows (Figure 5). At the tunnel inlet the wind speed was less evenly distributed than in the central and back portion of the tunnel.

3.2. Assessment of WT capture efficiency

The ammonia concentration observed during the wind tunnel validation test, as measured in S1, S2 and S3, with F1, F2 and F3 NH_3 flows are summarized in Figure 6. The observed concentration varied slightly among the three sampling points. It was also highlighted that the standard deviation of the results obtained from measurements in S3 is lower than those of S1 and S2, allowing for a steadier signal.

Table 1 shows the results of the ANOVA comparing the amount of ammonia emitted from the cylinder (I_{NH3}), assessed with the impinger method, and the amount detected with the wind tunnel, WT_{NH3}, in the three sampling positions. The WT_{NH3} observed in S2 and S3 does not differ significantly from I_{NH3} with all the flux levels tested. The S1 assessment is instead significantly lower than expected at maximum NH_3 flow level.

3.3. Results of wind tunnel assessments

The average PM_{10} ER calculated as a result of the field trials was equal to 100.2 ± 26.4 mg m^{-2} hr^{-1}.

The linear regression analysis showed that HD had a significant ($P<0.05$) effect on the logarithm of PM_{10} emissions, showing a linear correlation (Figure 7). This means that the increase of HD causes an exponential increase of the ERs. It is possible to identify a function that allows to estimate the ER on basis of HD, as follows:

$$ER = e^{(0.94\,HD + 2.14)}$$

Where the intercept value (2.14) accounts for the effect of wind erosion and the slope value (0.94) accounts for the effect of HD. The linear model shows a good fit (R^2 = 0.76). In general, PM_{10} emissions ranged from 10.5 ± 2.1 mg m^{-2} hr^{-1} (with HD = 0 hens m^{-2}) to 170.7 ± 47.1 mg m^{-2} hr^{-1} (with HD = 3.2 hens m^{-2}).

Soil humidity was found to be equal to 0.84 ± 0.14 % (on mass) and remained almost constant throughout the experiment, due to the presence of the tunnel, which prevented the precipitations to reach the enclosed soil.

3.4. Effect of soil moisture on PM emission potential

The emission potentials curves for outdoor run soil, as well as the soil textural components, are presented in Figure 8. It can be observed that the EP decreases exponentially with the increase of soil water content. The regression curves were able to describe the EP trend with good fit and the overall results are similar to those presented by previous authors who adopted similar methods to study the effect of soil moisture on soils' EP (Carvacho, Ashbaugh, Brown, & Flocchini, 2004; Funk, Reuter, Hoffmann, Engel, & Öttl, 2008; Madden, Southard, & Mitchell, 2009, 2010). It was also observed that of the soil emitted as PM_{10} 56% and 17% is in the PM_4 and $PM_{2.5}$ ranges respectively. The soil texture in the study farm was Sandy (92% sand, 5% silt and 2% clay).

3.5. Estimated PM emissions from overgrazed area of outdoor runs

The information gathered on the effect of HD and soil moisture on PM_{10} emissions, coupled with meteorological data, allowed to provide a first estimation of daily PM_{10} emissions from the overgrazed areas of outdoor runs. The estimated E_d were averaged on a monthly basis and are presented, together with monthly rainfall (mm) and ET fluxes (mm), in Figure 9. The average gravimetric soil water content was maximum in January (14%) and rapidly decreased in April, reaching its minimum value in July (7%), then it rose again from September. PM emissions were highly seasonal, with higher emissions occurring in the central months of the year. The total PM_{10} emissions over 2019, as estimated with the simplified procedure described in paragraph 2.6, were of 12.5 g m^{-2} yr^{-1} (this estimation is referred only to the overgrazed area of the outdoor run, 6263 m^2).

4. Discussion

4.1. Wind tunnel validation: internal wind speed and capture efficiency

The results showed a slightly uneven distribution of the wind speed inside the tunnel. This is due to the friction effect of the tunnel walls and to the turbulence created by the funnel structure leading to the outlet pipe. The variations observed are consistent with those observed by Balsari et al. (2006, 2007), who adopted a similar wind tunnel design. The average wind speed inside the tunnel, of approx. 1.5 m s^{-1}, is only slightly lower than the expected WS at that height (1.8 m s^{-1}), calculated on basis of the 10 m average annual wind speed of the location where the measurements were done (approx. 4.1 m s^{-1}; KNMI, 2020). It was preferred to set a slightly lower wind speed since it was observed that the hens were more comfortable with this lower flow rate than with higher ones. Moreover, the hens normally gather around obstacles and trees, which act as repairs against the wind. In fact, the surface roughness effect, as well as the presence of natural obstacles, drastically reduce the wind speed at ground level (Stull, 2012).

Observing the results of the wind tunnel validation test (Table 1) it appears that both S2 and S3 sampling solutions are suitable for measurement and show a good agreement with the impinger method assessment. The WT_{NH3} observed in S2 and S3, in fact, did not differ significantly from I_{NH3} with all the flux levels tested. At S1, however, NH_3 concentrations were significantly lower than expected from I_{NH3} at maximum NH_3 flow level.

Nonetheless, the S3 sampling point appears to perform more consistently and provide data with lower standard variation (as highlighted in Figure 6). Moreover, the S2 sampling solution is not suitable for PM measurements, since the DustTrak instrument is not designed for isokinetic sampling and, therefore, is not suited for measurement inside a pipe with a strong airflow. It was noticed that the average values derived from the measurements in S3 were slightly higher than the expected ones (I_{NH3}, as shown in Table 1), but the difference was not statistically significant. In conclusion, the S3 sampling point performed better than S1 and S2 and was identified as the best option to determine the emissions.

4.2. *Influence of hen density and soil moisture on particulate matter emissions*

The first field assessments allowed to estimate PM_{10} emissions from hens outdoor activities, which were found to be equal to 100.2 ± 26.4 mg m^{-2} hr^{-1}. It has been also shown that dust emissions were affected by the density of hens in the outdoor runs. In fact, when HD increased PM_{10} emissions increased exponentially. The obtained ELs must be referred to the particular soil humidity conditions monitored during the experiment, which were extremely dry. Since, as highlighted by Funk et al. (2008), dry soil conditions lead to high PM emissions, the ERs calculated in these first field assessments should be considered as emission potentials, indicating the maximum amount of PM_{10} that can be derived from the outdoor runs in critical environmental conditions.

4.3. *Influence of soil moisture on particulate matter emission potential*

The exponential decrease of soil emission potential with increasing soil water content, observed during SRC experiment is in agreement with previous findings (Carvacho et al., 2004; Madden et al., 2009, 2010; Padoan et al., 2021). Moreover, previous researches showed that soil texture is a crucial factor in influencing EP and hydrological properties of soil. According to these findings, the very high sand % of the soil analyzed in this study, could have led to a lower maximum EP level in dry soil condition. Nonetheless, a more compact soil usually has more capacity to retain water and a higher field capacity, being less prone to the dryer conditions that are necessary for PM_{10} to be emitted.

4.4. Estimation of PM emissions over a 1-year period

The estimated PM_{10} emission fluxes were highly seasonal, with most of PM losses occurring during the central months of the year. This is attributable to the higher temperatures and lower precipitation, which promote dry soil condition and favor PM formation. The estimated emissions for overgrazed outdoor run areas were of 12.5 g m^{-2} yr^{-1}. These emissions, if divided for the total number of hens reared in the farm, are equal to 8.9 mg hen^{-1} d^{-1}. Cambra-López et al. (2009) reported, in their assessment of PM_{10} emissions from indoor poultry houses, emissions up to 146.9 mg hen^{-1} d^{-1}. Therefore, PM_{10} emitted from outdoor spaces appears to be lower than that deriving from the indoor areas of the farm. Nonetheless, since the hens are using only a small portion of the outdoor area, their activity causes significant degradation of soil, with formation of furrows where hens gather to dustbathe. The concentration of many hens on little space can lead to other environmental issues linked with the concentration of nutrients on small areas (Menzi, Katz, Fahrni, Neftel, & Frick, 1998). Therefore, measures to favor the usage of a bigger portion of outdoor runs by hens should be implemented.

More studies should be performed to provide precise assessments of the usage of outdoor spaces by hens and identify the main factors influencing it, since current information is insufficient. The parametrization of average HD through the year is, in fact, the main drawback of the estimation technique used for assessing emissions.

Moreover, since PM emissions from soil are also strongly affected by wind speed conditions (Avecilla, Panebianco, & Buschiazzo, 2017)

, improvements should be made also in the parametrization of this factor, through further wind tunnel experiments.

5. Conclusions

A wind tunnel method to assess the effect of hen density on PM emission from outdoor runs in free range laying hens houses was successfully developed. The methodology allowed to measure PM emissions levels from hens activity and to study the influence of hens behavior on the emissions. HD influences PM_{10} emissions, causing them to increase exponentially when a higher number of animals are present per surface area unit ($ER = e^{(0.94\ HD+2.14)}$). The emission fluxes deriving from the outdoor runs under dry soil conditions, ranged from 10.5 ± 2.1 mg m^{-2} hr^{-1} (with HD = 0.0 hens m^{-2}) to 170.7 ± 47.1 mg m^{-2} hr^{-1} (with HD = 3.2 hens m^{-2}).

A laboratory experiment allowed to assess the effect of soil moisture on the emissions, deriving emission potential (EP, mg kg^{-1}) curves, showing an exponential decrease of EP with increasing soil moisture. This information allowed to scale the emission levels assessed with the wind tunnel, according to soil water content, estimated with a soil water balance procedure and averaged on a daily basis. An estimation of PM_{10} emission occurring from the overgrazed areas of outdoor runs was provided and resulted equal to 12.5 g m^{-2} yr^{-1}. These emissions, if divided for the total number of hens reared in the farm, are equal to 8.9 mg hen^{-1} d^{-1}, while EF for indoor poultry farms in literature are up to 146.9 mg hen^{-1} d^{-1}. Therefore, PM_{10} emitted from outdoor spaces is less of a concern than in-house emissions. Nonetheless, by using only a small portion of the outdoor area, hens activity can cause significant degradation of soil, with formation of furrows where hens gather to dustbathe. Therefore, new solutions should be implemented to face this issue and to favor the spreading of hens on larger surfaces.

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List of tables

Table 1. Mean values and the 95% confidence intervals (CL) of ammonia emissions detected with the Impinger (I_{NH3}) and wind tunnel (S1, S2, S3) methodologies, at three different NH_3 flow regulation levels (F1, F2 and F3). N = number of observations.

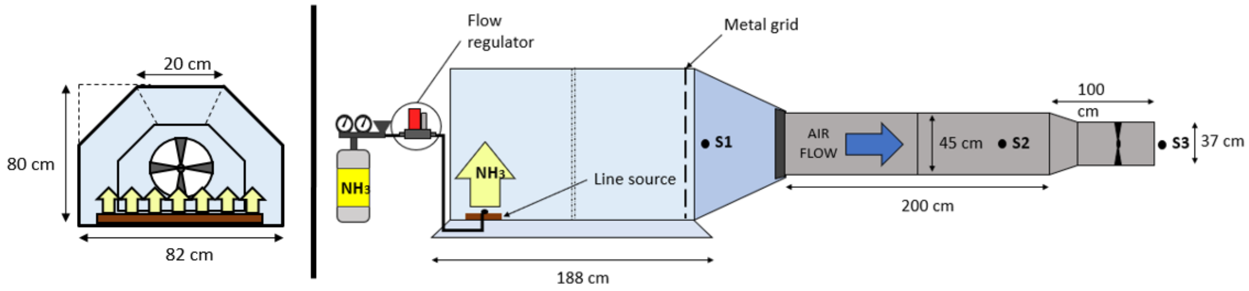
Table 1.

Sampling method	NH_3 regulation	N	NH_3 flux (mg)[a]		Lower CL	Upper CL
S3	F3	30	1672	a	1499	1844
I_{NH3}			1559	a	1386	1731
S2			1492	ab	1319	1664
S1			1271	b	1099	1444
S3	F2	30	1106	a	933	1279
I_{NH3}			993	a	820	1165
S2			926	ab	753	1098
S1			706	b	533	878
S3	F1	30	645	a	472	817
I_{NH3}			532	a	359	704
S2			465	ab	292	637
S1			244	b	72	417

a. Means in column followed by a different letter differ significantly ($P<0.05$)

List of figures

Figure 1.



20 cm
80 cm
82 cm
Flow regulator
Metal grid
NH_3
NH_3
Line source
S1
AIR FLOW
45 cm
S2
100 cm
S3
37 cm
200 cm
188 cm

Figure 2.

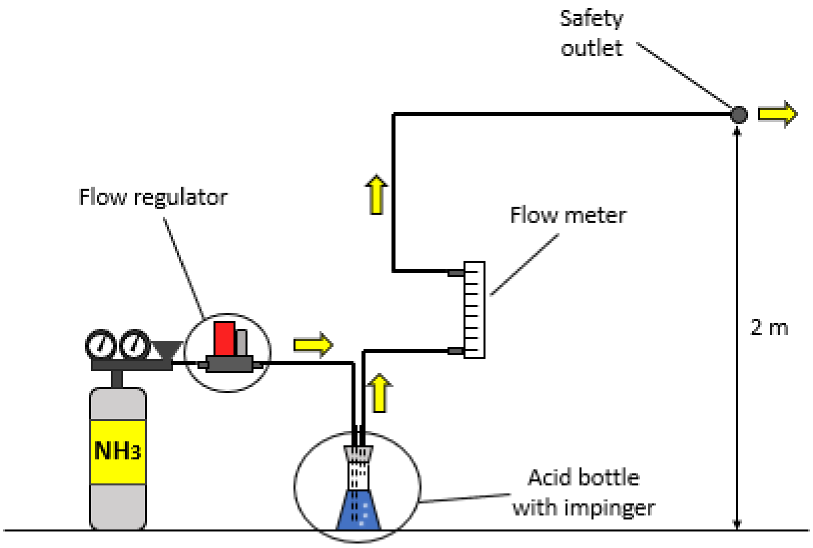

Safety outlet
Flow regulator
Flow meter
2 m
NH3
Acid bottle with impinger

Figure 3.

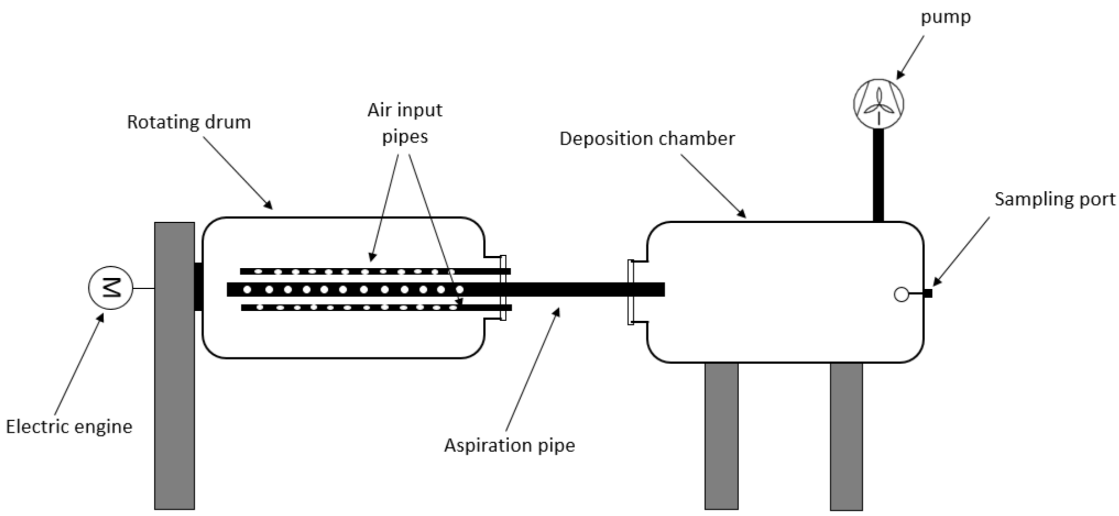
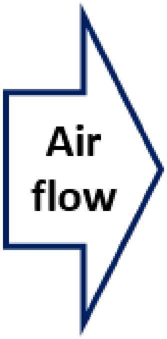

pump
Rotating drum
Air input
pipes
Deposition chamber
Sampling port
M
Electric engine
Aspiration pipe

Figure 4.

Figure 5.

Wind speed = 1.5 ± 0.11 $m\ s^{-1}$



1.0	1.5	1.4	1.4
2.3	2.0	1.7	1.6
0.9	1.4	1.3	1.2

Figure 6.

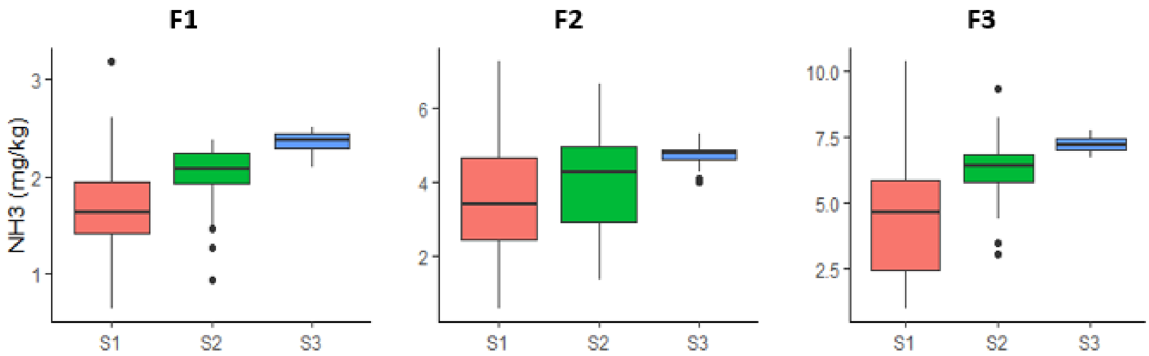


Figure 7.

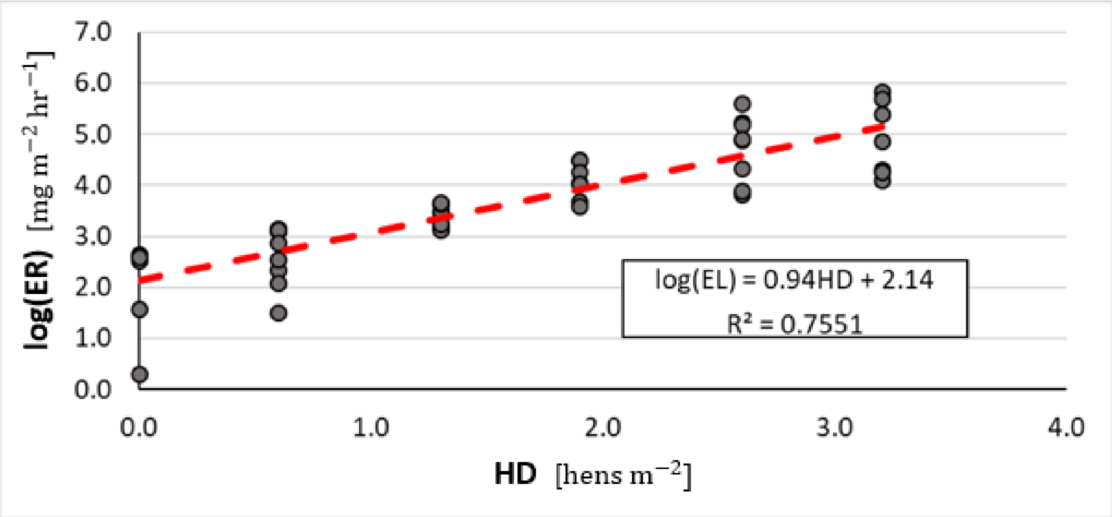
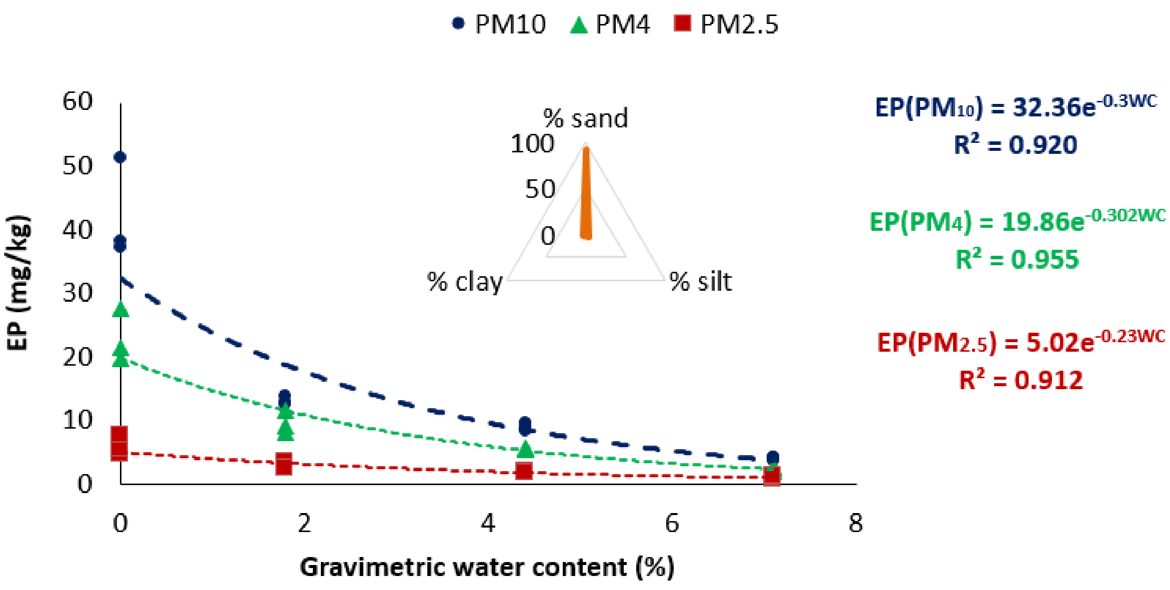
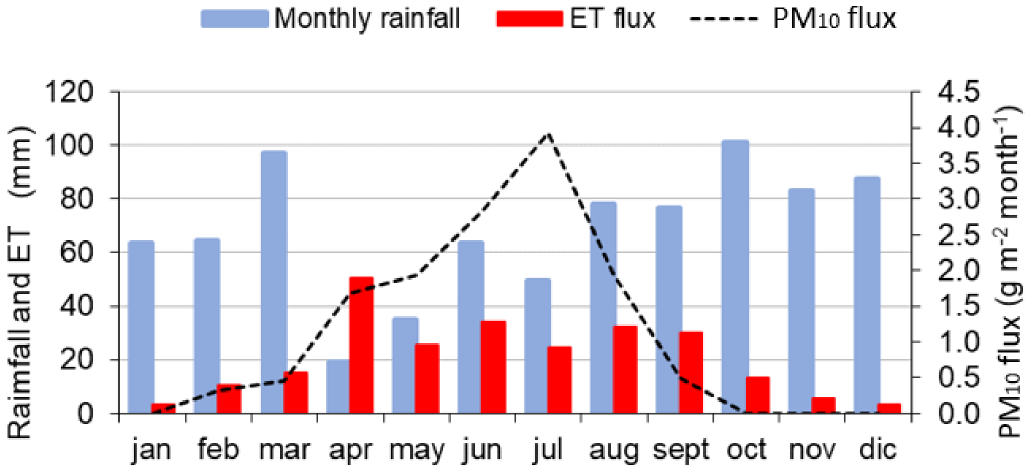

log(ER) [mg m⁻² hr⁻¹]
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
1.0
2.0
3.0
4.0
HD [hens m⁻²]
log(EL) = 0.94HD + 2.14
R² = 0.7551

Figure 8.



PM10 PM4 PM2.5
EP (mg/kg)
Gravimetric water content (%)
% sand
% clay
% silt
EP(PM10) = 32.36e-0.3WC
R² = 0.920
EP(PM4) = 19.86e-0.302WC
R² = 0.955
EP(PM2.5) = 5.02e-0.23WC
R² = 0.912

889 Figure 9.



890