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Article

Agricultural Emissions Measurements from Five English Farms

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Abstract

Emissions to air from agriculture include ammonia (NH3), particulate matter (PM), and bioaerosols. A main source of NH3 is livestock manures. Estimates of UK NH3 emissions show that around 82% of agricultural emissions are from livestock manures. Particulate matter emissions occur directly from farming activities, and from reaction of NH3 with acidic pollutants to form fine particles (PM2.5, i.e., particles with diameter of 2.5 μm or less). Air pollution emissions from most industrial and domestic sectors in the UK are declining, but those from agriculture are not and are attracting public health attention.The study reported here formed part of larger project that sought to provide evidence for the link between agricultural air pollution mitigation interventions and human health outcomes. The objective of this study was to provide evidence to support the use of emissions data, largely from other peer-reviewed reports, to model pollutant dispersion. The evidence is in the form of emissions data from livestock buildings (pigs, poultry and dairy). The measurements do not attempt to represent UK agriculture, but provide data that are additional to published data, for validation of emission factors chosen to estimate dispersion and exposure. Measurements were taken at five farms in the UK: two pig, two poultry, and one dairy farm, with measurement periods distributed over one year to align with production practices. The primary objective was to measure the emissions of ammonia from these activities. Los Gatos laser-based cavity ring down and Gasmet Fourier Transform infrared (FTIR) analysers enabled the continuous measurement of gaseous component concentrations. TSI Bluesky analysers were used to measure house internal particulate PM concentrations. Volume flowrates were determined from fan performance data or using surrogate measurements such as carbon dioxide concentration. Data were processed to produce ammonia emission values. The emission values presented in the results of this study are highly variable, as would be expected because of differences in design of the housing, feeding strategies, environmental factors (such as temperature, humidity), and how the manure is managed. Values are presented showing that, for pigs and poultry, emission values are similar to published values. For dairy, the values presented in the results of this study are lower than published values. The values presented are aligned with published values for pigs and poultry, giving confidence that the published values are applicable for modelling dispersion and exposure. For dairy farm emissions, the values measured in this study are lower than the published values, but with high uncertainty, suggesting that peer reviewed emission factors are appropriate for the modelling study rather than the values presented here.The main limitations of this study relate to the difficulty in sampling air to gain representative measurements of concentration; and the determination of the ventilation rates of buildings. This project was funded by the National Institute for Health and Care Research (NIHR) AIM-HEALTH programme.

Keywords: ammonia; particulate matter; agriculture; emissions; air pollution; livestock

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Background

Important emissions from agriculture, which affect air quality, are ammonia (NH_3), particulate matter (PM), volatile organic compounds (VOCs), oxides of nitrogen (NOx), hydrogen sulphide (H_2S), odours, and bioaerosols. The main sources of NH_3 are livestock manures exposed to the atmosphere in livestock housing, in storage, during and following application to land, and from manures deposited to pasture during grazing. Ammonia is also emitted following application to land of some manufactured fertilisers, and from crop residues and silage. Estimates of NH_3 emissions at a UK level show that around 82% of agricultural emissions are from livestock manures, with over half from cattle farming. Poultry and pig farming also make important contributions to the emissions total. Particulate matter emissions from agriculture occur directly from farming activities, and from reaction of NH_3 with acidic pollutants to form fine particles ($PM_{2.5}$, i.e., particles with diameter of 2.5 µm or less). Direct emissions of PM_{10} (i.e., particles with diameter of 10 µm or less) are predominantly from poultry and pig farming, with a smaller contribution from arable farming. Emissions of PM from livestock buildings are influenced by the type of bedding, factors that influence animal activity (e.g., age), feeding systems, manure management systems, and building design [1].

Air pollution emissions from most industrial and domestic sectors in the UK are declining, but those from agriculture are not and are attracting public health attention [2]. Ammonia from agriculture is a precursor to $PM_{2.5}$ which has negative impacts for human health, for example, through causing respiratory illness. Some research on the relationship between agriculture and human health has been researched in the past, including a rapid evidence assessment of agricultural interventions to improve ambient air quality, commissioned by Public Health England (PHE) in 2019 [3]. This study aimed to assess the evidence for effective and cost-effective interventions, and to identify actions that will significantly reduce harm from air pollution. Agriculture interventions included changes in livestock house design or management (e.g., yard design, exhaust air scrubbing or strategic tree planting), changes in diet or feeding regime and changes to manure storage and application. The PHE study did not identify substantial information on the effects of agricultural interventions on health, equality or economic outcomes. It is possible that this is because the evidence found was primarily made up of studies reporting emissions data for alternative farm practices, or effects of farm practices on air quality. As a result, the evidence assessment was not able to conclude which agricultural interventions have an impact on public health outcomes.

The study undertaken and reported here sought to provide evidence for the link between agricultural air pollution mitigation interventions and human health outcomes. It forms part of larger project with a mixed methods design incorporating both qualitative and quantitative methods. Building evidence to show the impact on human health outcomes can show the benefits of interventions that have already been implemented, and can support, or not, the case for further interventions.

The study reported here focuses on the measurement of emissions from dairy, poultry and pig buildings in the UK, with varying farm practices and interventions to reduce the impacts of air pollution.

This work provided evidence to support the use of emissions data, largely from other peer-reviewed reports, to model pollutant dispersion and to estimate changes in population exposure to $PM_{2.5}$, O_3 (Ozone) and bioaerosols associated with future implementation of interventions. The measurements do not attempt to represent UK agriculture, but rather provide data that is additional to published data, for validation of emission factors chosen to estimate dispersion and concentrations in other locations.

Aim and Objectives

The study reported in this paper formed part of a larger project with the objective to investigate whether interventions designed to reduce emissions from livestock farms are effective and cost-effective in minimising the adverse health impacts of outdoor air pollution from agricultural sources.

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For the work reported here, the objective was to provide evidence to support the use of emissions data, largely from other peer-reviewed reports to model pollutant dispersion. The evidence provided by this study is in the form of emissions data from livestock buildings (dairy, pigs and poultry).

Methods

The methods for this study involved emission measurements of the exhaust air from livestock buildings, i.e., measuring the air pollutants that were being released into the environment. For the pigs and poultry buildings which were mechanically ventilated, this involved taking measurements from the fan duct exit points. For dairy, the building was open sided, so measurements were taken from exit points around the building. These measurements observed concentrations of ammonia, particulate matter, carbon dioxide and water vapour.

Following this, emission calculations were done to calculate the concentration and mass emission rates of emissions.

Farm Types

Measurements were taken at five farms in England: two pig farms, two poultry farms, and one dairy farm.

Farm 1

Farm 1 was a pig farm with five grower and seven finisher houses with housing design interventions to reduce the air quality impacts associated with pigs. This included mechanically ventilated systems using vented exhausts, with roof fans which were activated using an internal temperature threshold. The floors were slatted to allow waste to be directed away from the animals into under floor storage, rather than remain on the surface and lead to ammonia emissions. The slurry from the under floor storage was removed from below the slatted floors at the end of each cycle, taking typically up to one hour.

Two buildings were identified as being suitable to take air quality measurements as they contained pigs of different stages of growth. Both buildings were ventilated by fans:

- Growers – 1,100 pigs weighing between 15kg to 45kg, from ages 5 days to 3-4 weeks, and divided into 28 pens.
- Finishers – 1,100 pigs weighing between 45kg and 110kg. The growers were moved to the finishers house at roughly 4 weeks of age and remained there up to 16 weeks of age. The house was divided up into six areas, ventilated by two fans each, one of which was monitored.

Emission measurements of ammonia, carbon dioxide, water vapour and methane were taken by analyser enclosures inside the buildings. These were positioned inside the main building, but not inside the livestock enclosure to ensure the equipment did not pose a risk to, or was damaged by, the pigs. To minimise sample length, the analysers were positioned as close to the selected fan as possible.

In the emission calculations which followed, the ventilation rates that were applied were based on fan design criteria to achieve suitable environments.

Farm 2

Farm 2 was a pig farm with farrowers (sows who had either already given birth to piglets or were expected to soon), growers and finishers. The buildings had roof fans and side inlet vents/flaps providing the ventilation when required. The buildings had slatted floors, allowing waste to be directed away from the buildings and into underfloor storage. Growers and finisher buildings had misting nozzles positioned below the side inlet vents, within the barn. The height of the roof in the farrower building was significantly lower than the other buildings. The ventilation rates used for emission calculations were based on design criteria to achieve suitable environments.

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Three buildings were identified as being suitable to take air quality measurements as they contained pigs of different stages of growth:

- Farrowers – 480 pigs. The building had two sections, one section was selected for taking measurements, the specific location chosen was close to a fan. The analyser enclosure was positioned outside the building close to the selected fan to minimise the sample line length. The sample line was positioned through a side vent of the building allowing air sampling just prior to the fan inlet. The thermocouple measuring the house temperature was in the same position as the sample line.
- Growers – 1,100 pigs. As with farrowers, the measurements were taken close to a fan. The analyser enclosure was positioned outside the building in a position close to the selected fan to minimise sample line length. The end of the sample line was positioned through a hole in the side of the vent duct, allowing air sampling as it enters the fan. The thermocouple measuring the house temperature was in the same position as the sample line.
- Finishers – 1,400 pigs. There were 14 finisher enclosures and a central walkway. There were three identical fans positioned centrally in the building roof ridge and a fan was selected for the measurement location. The analyser enclosure was positioned outside the building close to the selected fan to minimise sample line length. The end of the sample line was positioned through a hole in the side of the vent duct, allowing air sampling as it enters the fan. The thermocouple measuring the house temperature was in the same position as the sample line.

Farm 3

Farm 3 was a broiler farm raising birds for meat from day old chicks in a cycle typically from 1 to 39 days of age.

The farm consists of three buildings of similar dimensions, one of which was selected to undertake emissions measurements. The selected building had concrete floors, onto which bedding (sawdust) was placed initially and topped up during the cycle (deep litter method). The litter was retained for the complete period of the cycle. This approach relies on the ventilation, heating and water strategy to ensure that the litter stays dry.

Roof fans (20 of 820 mm diameter) and side inlet vents/flaps provided the ventilation. Ventilation was controlled using internal temperature, external temperature, stocking rates and fan characteristics. Fans were positioned centrally along the roof ridge and could move 18,000 m^3 of air per hour per fan. Additional fans at one end of the building were used when the ambient temperature was high but were not in use during these measurements

Typically, 50000-51000 birds are place in each house at the start of each cycle

A sample line was installed into fan number eight duct to enable the emission concentration to be measured. The analyser enclosure used to house the Los Gatos analyser measuring NH_3 and H_2O was placed outside the building close to the selected fan to minimise sample line length

Farm 4

Farm 4 was a broiler farm raising birds from egg to 32-44 days of age. Eggs were placed in the building at 2.5 to 3 days prior hatching, the typical stocking density was 38 kg m^{-2} typically equivalent to 47000 birds at the start of each cycle.

The selected building had roof fans and side vents/flaps to provide ventilation. Fans were distributed evenly along the length of the roof line. There were multiple production stages which determined the differing criteria for fan operation:

- 0 to 3.5 days: eggs were placed in the building, and the building was heated with no ventilation until hatching.
- 3.5 to 14 days: extraction fans, wall vents and heat exchangers were used to control the atmosphere within the house. The building was heated and operated under a slight positive pressure with air emitted from the building via vents in the side walls.

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- 14 to 39 days: there were six stages of fan ventilation, with four fans operating during stage one and four additional fans introduced at the start of each subsequent stage, to a total of 24 fans. The roof vents to provided ventilation by extracting air from the building and using the side vents to allow air ingress. Fans were activated by a temperature threshold within the house.

The house was used to rear approximately 48,000 to 50,000 birds including 10,000 cockerels which were removed around day 30, and the remaining birds were removed at the end of the cycle.

The analyser enclosure was positioned outside the building close to the selected roof fan to minimise sample line length.

Farm 5

Farm 5 was a dairy farm housing just over 350 cows with an integrated milking facility. The buildings used natural ventilation via openings on all four walls. The buildings sampled were the main living area housing cows, where time was spent feeding, sleeping and other daily activities. This area did not include the milking area. Animals spend most of the time in the housing area when in the building, only moving to the milking area when needed. The floors were of concrete, scraped every three hours by automatic scrapers. The slurry was stored in an open lagoon.

The analyser enclosure was positioned outside the building, but as close as possible to the building and the selected sampling locations. The sample lines were uninsulated and positioned through the slatted sides of the building. The ends of the sample lines were attached to fixed structures in the building. The thermocouple measuring the house temperature was in the same position as the sample line. Two TSI Bluesky PM monitors were installed close to the roof on support girders above the main living area.

Measurements

Overview

The measurements taken from the farms using analysers are listed in Table 1. This included air pollutants and other parameters such as temperature and building ventilation.

The methodology of the measurement was selected by its suitability for positioning within livestock housing and the robustness of results that could be achieved. For ammonia, two methodologies were used to enable a wide range of concentrations to be measured. The Los Gatos method uses laser absorption spectroscopy to provide frequent measurements of ammonia down to ppb (parts per billion) precision. The Gasment Fourier-transform infrared spectroscopy (FTIR) method uses infrared light to measure ammonia down to ppm (parts per million) precision. FTIR also measures components such as carbon dioxide which can be used to determine building ventilation rates.

The limits of detection (LOD) for these instruments are also shown in Table 1.

Table 1. Substances and parameters measured. LOD = limit of detection.

Substance	Methodology 1	LOD	Methodology 2	LOD
Ammonia (NH_3)	Los Gatos	0.3 ppb	Gasmet FTIR	0.13ppm
Moisture (H_2O)	Los Gatos	50ppm	Gasmet FTIR	100ppm
Carbon Dioxide (CO_2)	Gasmet FTIR	20ppm		
Methane (CH_4)	Gasmet FTIR	0.5ppm		
Particulate Material (PM)	Bluesky			

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Substance	Methodology 1	LOD	Methodology 2	LOD
Ambient PM and Endotoxin	Mini Vol samplers			
Temperature	K-type Thermocouple		Site installed thermocouples	
Building Ventilation (ventilated housing, pigs/poultry)	Fan vent velocity		Fan design characteristics with internal building temperature	
Building Ventilation (open-sided housing, dairy)	Gasmet FTIR measuring CO_2	20ppm		

Locations of Measurements

During the initial site visits to the farms, buildings were observed to identify the most suitable locations for the measurement equipment. This involved identifying where the equipment would be safely positioned, but at the same time, capture the emissions from the livestock.

Real-time direct reading measurements of gases were collected from building emission points such as fan duct exit points in the ventilated houses, and for particulate matter (PM), from inside livestock buildings. Where possible, ammonia, PM and endotoxin sampling was also undertaken in the ambient environment at upwind and downwind positions relative to the building.

Sampling Periods

Sampling periods and the seasons in which they occurred are given in Table 2.

The variations in the test periods results from operational practices on the farms

- Full growth cycles were monitored for boiler farms, the length of which are determined by the required end weight. This results in variable lengths of cycle.
- Pig farm test periods were determined
  - Period of access made available
  - Period of animals present in housing at the time of measurements

Table 2. Measurement periods.

Farm	Measurement period (days)	Season (months)
Farm 1: housed pigs	36	March - April 2022
	27	June – September 2023
Farm 2: housed pigs	27	June – September 2023
	37	September – October 2023
	20	October – November 2023
	28	November – December 2023
Farm 3: broilers	31	July – August 2022
	36	November – December 2022
	26	May – June 2023
	31	September – October 2023

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	37	November – December 2023
Farm 4: broilers	21	October – November 2023
	26	November – December 2023
Farm 5: dairy cows	12	November- December 2023

Gases

Measurement of the gaseous components which included: ammonia, (NH_3), methane (CH_4), carbon dioxide (CO_2) and water vapor (H_2O) were made using a sampling system that representatively collected and transported the sampled gas stream to an analyser; and an analyser.

Sampling System

To obtain a representative sample of the emission of NH_3, components were unreactive. Sample lines made from PTFE were used, insulated when the line passed through areas of different temperature to the sample point. Flow rate was maintained at the highest flow rate possible to minimise the possibility of reactions occurring in the sample. Filtration of particulate material used PTFE filters. The arrangement of these components was refined depending on the conditions of the environment being sampled.

Los Gatos (ABB) LGR-ICOS Economical Ammonia Analyzer (NH_3, H_2O).

The Los Gatos analyser utilised cavity enhanced absorption technique, which employed a high-finesse optical cavity as the measurement cell. This analyser is highly sensitive, with low drift characteristics. The analyser measures ammonia and moisture in the ppb and ppm ranges respectively.

Fourier Transformer Infrared Spectroscopy (FTIR).

This analyser enabled simultaneous measurement of ammonia (NH_3), methane (CH_4), carbon dioxide (CO_2) and water vapor (H_2O) by infrared absorption.

Particulate Matter (PM) and Endotoxins

The measurement of particulate matter was undertaken using two different approaches: continuous and discontinuous. Continuous measurement was by an optical particle counting technique, and Discontinuous $PM_{2.5}$ and PM_{10} measurements were made using extractive filtration methods, to quantify PM as well as endotoxin content used as a marker for bioaerosol concentrations around farms. The methods used are described in the following sections. Continuous measurement was undertaken inside the house and Discontinuous measurement was undertaken outside the buildings.

Continuous PM Measurement - TSI BlueSky

The BlueSky monitors were positioned inside the houses to monitor the internal PM concentration. These are laser-based, continuous, optical particle counters, which simultaneously monitored $PM_{1.0}$, $PM_{2.5}$, $PM_{4.0}$, and PM_{10} particulate concentrations, and temperature and humidity. The BlueSky monitors enabled a remote connection to review a unit's operation and collect data, subject to availability of a Wi-Fi connection.

To determine a mass concentration there are assumptions: all PM is spherical and has the same density. However, the particulate material at the farms monitored are likely to be of different shapes and densities to the control materials used to calibrate. Consequently, the measured data should be viewed with caution.

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Discontinuous Active PM and Endotoxin Sampling

Air metrics MiniVol™ TAS samplers (hereafter referred to as MiniVols) were used to measure PM_{10} and $PM_{2.5}$, with the filters being analysed for PM and endotoxin. During each visit, one sampler was set up to measure $PM_{2.5}$ and the other to measure PM_{10}. The TAS MiniVol sampler was developed to enable ambient air sampling for particulate material in remote locations. The units have a battery powered pump that can be set at specific flowrate, and sampled total particulate, PM_{10} and $PM_{2.5}$ on to a 47 mm quartz fibre filter. To enable PM_{10} and $PM_{2.5}$ measurement, impactors were installed into the sample head, providing specific aerodynamic sizing of particle material when sampled at a fixed rate of 5 l min^{-1}. The MiniVols were installed on a tripod located at breathing zone height and were placed in upwind / downwind locations. They were also located in an unobstructed area at least 30 cm from any obstacle to air flow. The MiniVols were set to run at 5 l/min for the period of each test. The volume sampled was determined by the flowrate and period of sampling. The mass of the PM sampled was determined gravimetrically.

Measurements of $PM_{2.5}$ and PM_{10} by filtration sampling was carried out simultaneously upwind and downwind of the main buildings and at the same locations, where practicable, as the ammonia measurements, to quantify PM as well as endotoxin content used as a marker for bioaerosol concentrations around farms. In addition, real-time direct reading measurements were collected in the same location, where practicable, as the ammonia measurements. These measurements, in conjunction with the box/reverse modelling approaches, would allow the project to estimate or confirm PM/bioaerosol emission factors available in the scientific literature.

Ventilation

Sampling from Forced Ventilation Buildings

Forced ventilation comprised ducted fans drawing air from the building and emitting it to the environment. These provide specific points of emission from the building in the form of ducts with a controlled and known velocity, where measurements were taken. The control of fans for ventilation enables precise control of the internal environment.

Sampling from Natural Draft Ventilated Buildings

Natural ventilation relies on the movement of ambient air and internal conditions to move air around the building and into and out of the building. To determine the emissions from naturally ventilated buildings ventilation rates were determined using the measurement of carbon dioxide (CO_2) inside and outside the building.

Temperature

Temperature was measured at the emission point and a measurement was made close to the enclosure where the monitoring system sampling took placed. This was undertaken using k-type thermocouples, the outputs from which were recorded directly by data loggers.

House temperature was used to control rates of ventilation in forced ventilated buildings. Consequently, this independent measurement enabled the operation of fans to be defined where system control data were not available.

Data Processing

Concentration Measurements

Emission concentrations were measured using a 5-minute averaging period for data from both Los Gatos and Gasmet FTIR analysers. For the Gasmet FTIR this allowed several scans to be combined enabling analysis of components at low concentrations. The raw data was in ppb and ppm for the Los Gatos and Gasmet respectively. These were converted into mg m^{-3} using the following equation

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$$concentration\ (mg\ m^{-3}) = concentration\ (ppm) * \frac{relative\ molecular\ mass\ (g)}{molar\ volume\ (dm^3)}$$

The data were averaged to provide hourly and daily averages and extrapolated to annual values.

Ventilation Rates

As a result of the variety of the ventilation systems installed and limited data availability in some cases, ventilation rates were determined in the following ways.

1. Measurement of fan performance – dimensions and velocity profiles of the fans were measured. The activation of the fans and the rates at which the fans were operating were measured by monitoring the current to each fan.
2. Use of information provided by the building ventilation control system.
3. Use of fan performance data and information provided by the farmer on the operation of the ventilation system.
4. Measurement of in-house and ambient concentration of carbon dioxide to determine the ventilation rate (V_r) using the carbon dioxide balance method[1]. This approach was used for the naturally ventilated building where no contained emission points were available.
5. Use design parameters to meet minimum ventilation air exchange criteria for animal house environments. [2]

Results

Pig Farm Ammonia Emissions

The results from the measurements made at the two pig farms are provided in Tables 3–5.

The finishers sampling location presented environmental conditions that influenced the operation of the analyser. Consequently, data for the finishers for period 1-3 inclusive have been eliminated as they are not representative.

Table 3. Pig farm one ammonia emissions. ND = no representative data.

			Ammonia Emission g NH_3/day/animal		
Period	Pig Type	No of animals	Average	Max	Min
Period 1	Growers	220	0.84	1.08	0.57
	Finishers	220	ND	ND	ND
Period 2	Growers	220	2.8	14.0	1.2
	Finishers	220	ND	ND	ND
Period 3	Growers	220	3.1	15.6	1.3
	Finishers	220	ND	ND	ND
Period 4	Growers	220	1.57	8.8	0.04
	Finishers	220	5.9	29.6	2.5
Period 5	Growers	220	13.8	77.51	0.3
	Finishers	220	23.8	118.5	10.0

[1] Assessing ventilation rate measurements in a mechanically ventilated layingbvhen facility E. Rosa , H. Arriaga, S. Calvet, and P. Merino, Neiker-Tecnalia, Conservation of Natural Resources, Bizkaia Technology Park, P. 812, 48160 Derio, Bizkaia, Spain; and Institute of Animal Science and Technology, Unviersitat Polit´ecnica de Valencia, 46022 Valencia, Spain

[2] Calculating the Right Air Exchange. Pig Improvement Company.

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The ventilation rates for farm two was based on fan inlet measurements. There was no data available on the periods of fan operation.

Table 4. Pig farm two ammonia emissions.

			Ammonia Emission g NH_3/day/animal		
Period	Type	No of animals	Average	Max	Min
1	Growers	150	0.9	4.6	0.3
1	Finishers	150	2.2	13.7	1.4
2	Growers	150	1.3	4.6	0.1
2	Finishers	150	3.6	14.4	1.5
3	Farrowers	16	0.2	1.0	0.1
3	Growers	150	1.2	2.8	0.4
3	Finishers	150	3.3	13.0	1.9
4	Farrowers	16	1.2	9.7	0.02
4	Growers	150	0.5	1.9	0.1
4	Finishers	150	2.8	9.0	1.6

During period one finishers there were days when the ventilation did not activate, consequently there was no emission on these days hence the lower emission. These resulted from periods of temperature did not attain sufficient temperature to activate the fans.

The maximum concentrations of ammonia were measured at the times prior to fans commenced operating or when fans were not in operation.

Table 5 gives a comparison of annual ammonia emissions for the pig farms monitored.

Table 5. Pig Farm Annual Emission comparison.

	No of Animals	Ammonia Emission (kg NH_3/year/animal)
Farm One Growers	220	1.15
Farm One Finishers	220	2.14
Farm Two Farrowers	16	1.7
Farm Two Growers	150	2.1
Farm Two Finishers	150	1.6

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Poultry Farm Ammonia Emissions

Tables 6–8 provide the ammonia emission data measured at the poultry farms.

Table 6. Poultry farm three ammonia emissions.

		Ammonia Emission (g NH_3/day/animal)		
Period	No of Birds	Average	Max	Min
Period 1 August 2022	47074	0.038	0.047	0.018
Period 2 Nov Dec 2022	47176	0.030	0.05	0.02
Period 4 22 May 2023	47176	0.08	0.09	0.06
Period 5 June 2023	45350	0.07	0.1	0.02
Period 6 November 2023	45359	0.0025	0.035	0.002

Table 7. Poultry farm four ammonia emissions.

		Ammonia Emission (g NH_3/day/animal)		
Period	No of birds	Average	Max	Min
Period 1 25 Nov 21 Dec 2023	36024	0.05	0.12	0.03

The ventilation rates for farm four were determined using design criteria for minimum air exchanges, to achieve suitable environments for the housed animals. However, this will provide an over estimation of the emissions, as there are no control parameters available. These would have provided information relating to the periods of fan operation therefore the actual total volumes and masses emitted.

Table 8 provides the annual emission for the poultry farms monitored.

Table 8. Poultry Farm Annual Emission comparison.

	Ammonia Emission (kg NH_3/year/animal)		
	Average	Max	Min
Farm Three	0.025	0.035	0.02

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Farm Four	0.018	0.041	0.01

Dairy Farm Ammonia Emissions

Dairy farm ammonia emissions are presented in Table 9.

Table 9. Dairy farm ammonia emissions.

Period	No of animals	Ammonia Emission (g/NH_3/day/animal)		
		Average	Max	Min
1 August – September	185	0.15	0.3	0.02
2 November	185	1.06	1.84	0.6

PM Emissions

The data were highly variable, with large ranges, indicating high uncertainty. There were no clear trends. Some data are presented as Supplementary Information.

Discussion

The emission values presented in this report have been compared against emission factors published by the UK Environment Agency and the European Environment Agency. These emission factors are presented in Table 10.

Table 10. Emission factors for ammonia, from this study, from the UK Environment Agency, and from the European Environment Agency. AAP = annual average population.

Production system	Emission factors (kg a^{-1} AAP^{-1} NH_3)		
	This study	UK Environment Agency[1]	European Environment Agency[2]
Farm 1: housed pigs, slatted floor Growers	1.15	2.813	3.7
Farm 1: housed pigs, slatted floor Finishers	2.14	2.813	3.7
Farm 2: housed pigs, slatted floor Farrowers	1.7	No data	No Data
Farm 2: housed pigs, slatted floor Growers	2.1	2.813	3.7
Farm 2: housed pigs, slatted floor Finishers	1.6	2.813	3.7
Farm 3: broiler chickens	0.025	0.024	0.13
Farm 4: broiler chickens	0.018	0.024	0.13
Farm 5: housed dairy cows, natural ventilation	0.4	No data	16.1

[1] https://www.gov.uk/guidance/ammonia-emission-factors-for-pig-and-poultry-screening-modelling-and-reporting Last accessed 14 March 2023. [2] https://www.eea.europa.eu/en/analysis/publications/emep-eea-guidebook-2023 Last accessed 14 March 2023.

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The emission values presented in the results of this study are, for pigs and poultry, similar to the published values in Table 10. The values in Table 10 mainly fall within the ranges presented in Tables 3, 4, 6 and 7. For dairy, the values presented in the results of this study are lower than the published values in Table 10.

The results from this study show high variation in the emission values per animal, with, for example, a range across measurement periods from approximately 0.3 to 5 kg NH_3 per year per animal for growing pigs at Farm 1. Emissions are related to many factors including the design of the housing, feeding strategies, environmental factors (such as temperature, humidity), and how the manure is managed [4].

Measurements undertaken across the farms raised several challenges that impacted on the quality of the data collected. These include;

- Number of emission points – all farms monitored involved multiple points of emission. It was not possible to monitor at all, consequently assumptions were made for each site. These assumptions have an impact on how representative the data produced is.
- Volumetric flow – the flow from each fan was determined using physical and performance characteristics measured. However, this does not provide real time performance data at the time of the measurements. Performance of fans can change over time and the approach adopted does not account for any changes in fan performance.
- Ventilation – monitoring and quantifying the flow rates through fans is critical in the determination of the mass emissions and emission rates. Fans used for ventilation can be variable consequently results using a fixed flowrate will not fully represent the total emissions. Approaches to monitoring variable fan emissions should be included in monitoring undertaken at this type of facilities. The determination of the ventilation rate and the fan specific flow rates was the weak point of the measurements.

The farms monitored using mechanically driven fans all used temperature to control the operation of fans and hence the internal environment and the emissions. There are sensors available that can monitor other components such as carbon dioxide (CO_2). These could provide additional means to control ventilation and the internal environment. Consequently, this will impact on the emission and the generation of ammonia and other compounds resulting from breakdown of waste products and the animals present.

Poultry presents several challenges for measurement due to the presence of particulate material from litter and birds and the presence of moisture. It was not possible to put analysers in the houses, consequently analyser houses were positioned outside the buildings. Care was taken to ensure that sections of sample line outside the houses were insulated to maintain temperature and avoid loss of sample through condensation.

Measurements taken with the BlueSky monitors used optical particle counters. These devices are designed to operate in the ambient environment. However, the environments in animal houses can be different to the ambient environment, with higher PM concentration and humidity. Furthermore, the particulate material at the farms monitored are likely to be of different shapes and densities to the control materials used to calibrate.

Conclusions

The determination of the real-world ventilation rates has a significant impact on the emission rates from buildings. Each method of determination has different associated uncertainties. It is not possible to quantify the uncertainties associated with the determination of ventilation rates due to the limited data gathered during this project. For example, using the fan design parameters to determine ventilation rates is impacted by degrading performance of the fans, deposition on the fan blades, composition/deposition of internal atmosphere, pressure and temperature in the building and the ambient conditions.

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The representative measurement of ammonia from multiple points is challenging with limited analysers, adding to the associated measurement uncertainty. The limited number of measurements made means that it is not possible to develop a complete uncertainty budget for these measurements.

This study has provided evidence to support the use of emissions data from other peer-reviewed reports, to model pollutant dispersion. The values presented are aligned with published values (Table 10) for pigs and poultry, giving confidence that the published values are applicable for modelling dispersion and exposure. For dairy farm emissions, the values measured in this study are lower than the published values, but with high uncertainty, suggesting that peer reviewed emission factors are appropriate for the modelling study rather than the values presented here.

Supplementary Materials: The following supporting information can be downloaded at: Preprints.org.

Abbreviations

CH_4	Methane
CO_2	Carbon Dioxide
FTIR	Fourier-transform infrared spectroscopy
H_2O	Water Vapour
H_2S	Hydrogen Sulphide
NO_X	Oxides of Nitrogen
O_3	Ozone
PHE	Public health England
PM	Particulate Material
$PM_{1.0}$	Particulate material with aerodynamic diameter of 1μm
$PM_{2.5}$	Particulate material with aerodynamic diameter of 2.5μm
PM_4	Particulate material with aerodynamic diameter of 4.0μm
PM_{10}	Particulate material with aerodynamic diameter of 10μm
ppb	Parts per billion
ppm	Parts per million
PTFE	Teflon
μm	micron
NH_3	Ammonia
UK	United Kingdom
VOC	Volatile organic carbon

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