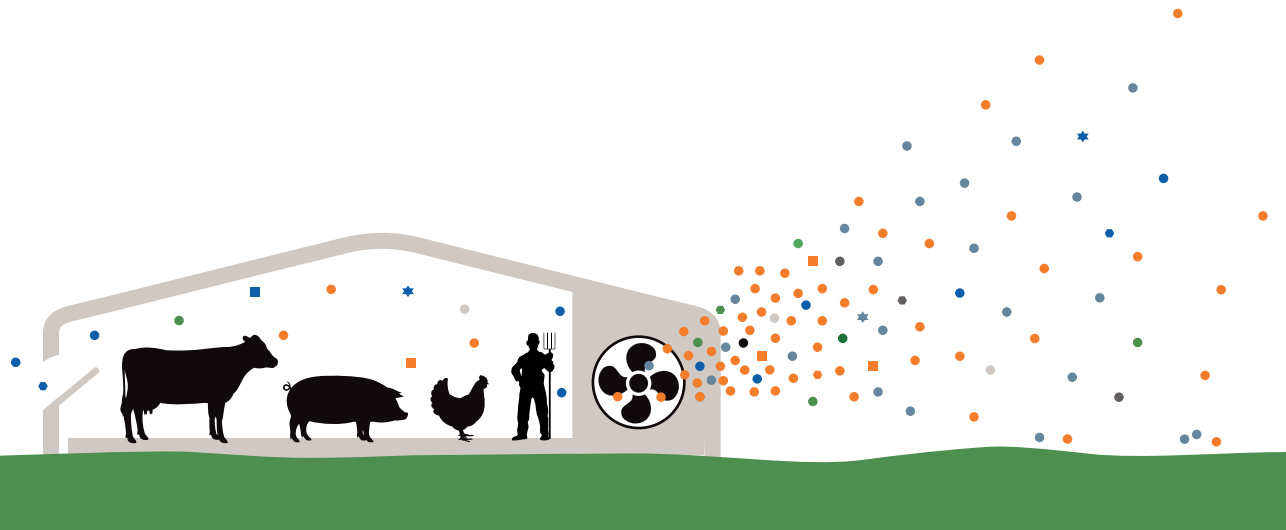
Particulate matter emission from livestock houses: measurement methods, emission levels and abatement systems

Albert Winkel



Particulate matter emission from livestock houses: measurement methods, emission levels and abatement systems

Albert Winkel

Thesis committee

Promotor

Prof. Dr Peter W.G. Groot Koerkamp

Professor of Farm Technology

Wageningen University

Co-promotors

Dr Nico W.M. Ogink

Senior scientist

Wageningen UR Livestock Research

Dr André J.A. Aarnink

Senior scientist

Wageningen UR Livestock Research

Other members

Prof. Dr Maarten C. Krol, Wageningen University

Prof. Dr Hongwei Xin, Iowa State University, Ames, USA

Prof. Dr Wolfgang Büscher, Bonn University, Germany

Prof. Dr Dick J.J. Heederik, Utrecht University, the Netherlands

This research was conducted under the auspices of the Graduate School of Wageningen Institute of Animal Sciences (WIAS).

Particulate matter emission from livestock houses: measurement methods, emission levels and abatement systems

Albert Winkel

Thesis

submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus
Prof. Dr A.P.J. Mol,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Friday 21 October 2016
at 11 a.m. in the Aula.

Albert Winkel
Particulate matter emission from livestock houses: measurement methods, emission levels and abatement systems, 279 pages.

PhD thesis, Wageningen University, Wageningen, NL (2016)
With references, with summary in English
ISBN: 978-94-6332-084-9
DOI: http://dx.doi.org/10.18174/390454

Contents

Chapter 1

General introduction

This first chapter serves four purposes. First, it provides a knowledge basis to the reader to facilitate the reading of the following chapters. Second, it defines the central problem the work in this thesis dealt with. Third, it identifies what it aimed to contribute to that problem. And finally, it familiarizes the reader with the content and structure of the thesis.

INTRODUCTION INTO THE TOPIC

In many parts of the world important food products such as meat, eggs, and milk are produced by animals kept in buildings. The way animals are housed in livestock farming has changed considerably over the last decades. Animal houses have become highly specialized for specific animal types and have grown in size and number of animal places. Nowadays, they contain many mechanical and computerized systems, such as feeding systems, milking systems, egg collection systems, and ventilation systems. These developments have replaced heavy duty hand work, increased labor productivity, increased the performance of the animals, and allowed farmers to maintain sufficient income from their farm at narrow financial margins.

Early in the emerging of modern-day animal houses, it was identified that their indoor environment is extremely dusty. Koon et al. (1963), for instance, already studied the origin and composition of poultry dust in 1963, more than half a century ago, and stated in the first line of their paper that '*dust is a major problem in poultry environmental control*'.

What is dust or particulate matter? The term 'dust' is often used in popular language, whereas this thesis uses the term *particulate matter* (PM). The latter term is used to refer to 'fine solid or liquid particles suspended in a gaseous medium' and is synonymous to the term *aerosol*. The term *dust* more specifically refers to solid particles (not liquid, and not necessarily fine) released from mechanical processes (Cambra-López et al. 2010). Besides these three terms (dust, particulate matter, aerosol), there are many terms used in the field of aerosol science. For clarity, Table 1 provides an overview of twenty commonly used terms, and their particle size range, definition, and applicable standards.

The 'solid and liquid particles suspended in air' are small: their diameter is usually expressed in micrometers (μm; i.e., one thousandth of a millimeter). PM is classified according to either the main region of deposition in the respiratory tract (terms used in the field of occupational health) or the sampling cut-off size (terms used in the field of atmospheric science). In the latter classification, abbreviations in the form PM_{xx} are used where PM stands for particulate matter and 'xx' denotes the upper size limit of the particles in μm (Table 1).

Table 1
Overview of terms, particle size ranges (fractions) and definitions, and applicable standards (Winkel et al., 2014a).

Term	Fraction (PM_{xx})	Definition	Standard	Reference; First author (year)
Dust	Not a fraction	'*Solid particles (settled or airborne) formed by mechanical fracture of a parental material, which can sediment under gravity forces, with diameters up to 500 or 1000 µm*'	-	Cambra-López (2010)
Particulate matter (= aerosol)	Not a fraction	Fine solid or liquid particles suspended in a gaseous medium	-	Cambra-López (2010)
Total airborne particles	Not a fraction	Theoretical term in ISO 7708 to refer to '*all particles surrounded by air in a given volume of air*'	ISO 7708	ISO (1995)
Suspended particulate matter (SPM)	Not a fraction	Theoretical term used in 40 CFR 50, EN 12341, and EN 14907: '*notion of all particles surrounded by air in a given, undisturbed volume of air*'	EN 12341 EN 14907	CEN (1998) CEN (2005)
Total dust	Undefined	Term for airborne particles that can be collected using 37-mm filter cassettes	NIOSH method 0500	NIOSH (1994)
Total suspended particles (TSP)	~PM_{35}	Archaic US-EPA term for ambient PM: particles up to 25–50 µm, depending on wind speed and direction	40 CFR 50, appendix B	US-EPA (2014)
Inhalable dust (= inspirable dust)	~PM_{100}	'*Mass fraction of total airborne particles which is inhaled through the nose and mouth*'	ISO 7708 EN 481	ISO (1995) CEN (1993)
Extrathoracic fraction	~$PM_{100–10}$	'*Mass fraction of inhaled particles that fail to penetrate beyond the larynx*'	ISO 7708 EN 481	ISO (1995) CEN (1993)
Thoracic fraction	~PM_{10}	'*Mass fraction of total airborne particles which penetrate beyond the larynx*'	ISO 7708 EN 481	ISO (1995) CEN (1993)
Fine dust (or: PM_{10})	PM_{10}	'*Particulate matter which passes through a size-selective inlet with a 50% efficiency cut-off at 10 µm aerodynamic diameter*' *)	EN 12341	CEN (1998)
Tracheobronchial fraction	~$PM_{10–4}$	'*Mass fraction of inhaled particles which penetrate beyond the larynx, but which fail to penetrate to the unciliated airways*'	ISO 7708 EN 481	ISO (1995)
Coarse fraction	$PM_{10–2.5}$	Particles bigger than 2.5 µm and smaller than 10 µm diameter (PM_{10} minus $PM_{2.5}$)	-	US-EPA (2004) Cambra-López (2010)
'Healthy adult' respirable fraction	~PM_4	'*Mass fraction of inhaled particles which penetrate to the unciliated airways*'	ISO 7708	ISO (1995)
'High risk' respirable fraction	~$PM_{2.5}$			
$PM_{2.5}$ (or 'fine fraction', next to 'coarse')	$PM_{2.5}$	'*Particulate matter which passes through a size-selective inlet with a 50% efficiency cut-off at 2.5 µm aerodynamic diameter*'	EN 14907	CEN (2005)
Submicron particles	PM_1	Particles smaller than 1 µm in diameter	-	Cambra-López (2010)
Nanoparticles (= ultrafine particles)	$PM_{0.1}$	Particles between 0.001 µm (1 nm) and 0.1 µm (100 nm)	-	-

*) The *aerodynamic diameter* of an irregular particle is equal to the diameter of a sphere with a density of 1 g cm^{-3} that has the same terminal falling velocity as the irregular particle.

Microscopic images of airborne particles in animal houses show that they are far from perfectly round, smooth and homogenous spheres (Cambra-Lopez et al., 2011; Nannen et al., 2004). Instead, they can be described as ovals, pyramids or cones, cubes, cylinders or rods, fibers, flakes, and so on. They can also be aggregates of multiple particles and have small spaces

of air inside. Their surface layer can be smooth, rough, layered, or cracked. Therefore, it is often not meaningful to describe the size of a particle in terms of its radius (r) or diameter (d, or $2r$).

More commonly, the diameter of airborne particles larger than 0.5 μm are presented as *aerodynamic diameter*. The aerodynamic diameter of an irregular particle is equal to the diameter of a sphere with a density of 1 g cm^{-3} that has the same terminal falling velocity as the irregular particle. Airborne particles can be sampled based on their aerodynamic behavior by sucking air through an impactor or cyclone which selectively remove particles larger than a certain aerodynamic diameter (cutpoint) from the air flow. The particles smaller than the cutpoint of the pre-separator, remain airborne in the sample air flow for determination of their mass (e.g., by collecting particles on filters that are weighed before and after loading). Another way of defining the diameter of a particle is by instruments that direct single particles through a light-scattering chamber. In this chamber, a beam of light is directed to the particle. The amount of scattered light, as determined by a sensor, is a measure for the size of the particle. When the instrument is calibrated with aerosols from latex spheres with a known diameter, the reading of the irregular particle can be expressed as *optical latex-equivalent diameter*. Such instruments measure particle numbers and size and calculate the mass concentration of particles in the sample air by assuming them to be spheres with a certain density.

Where do airborne particles inside animal houses come from? Table 2 shows the results of eight studies into this matter. The main sources of PM in poultry houses are the droppings of laying hens and broilers (i.e., manure and uric acid) and feathers, bedding material, and feed. In pig houses, skin flakes and hair are important additional sources. In dairy cattle kept in cubicle houses, wood shavings, straw, and silage are important sources, next to manure and concentrate feed. Fig. 1 shows that these sources are subject to three important processes: evaporation of water (e.g., through the heat produced by the animals and ventilation air exchange), disintegration into smaller particles (e.g., by scouring, trampling, or chewing) and aerosolization into the air (e.g., by running or wing flapping of the animals).

THE PROBLEM

Due to its organic nature, PM inside animal houses contains high levels of endotoxins (i.e., pro-inflammatory compounds from the outer membrane of Gram-negative bacteria) and micro-organisms (Seedorf et al., 1998; Winkel et al., 2014b). Farmers are chronically exposed to these components during work (Fig. 1) which is associated with respiratory problems such as Organic Dust Toxic Syndrome (ODTS; characterized by reversible flu-like symptoms), Chronic

Obstructive Pulmonary Disease (COPD), asthma (i.e., recurrent episodes of inflammation and obstruction of the lower airways), accelerated lung function decline, and general complaints, such as wheezing and coughing (Eduard et al., 2004, 2009; Omland, 2002; Seiffert et al., 2003).

Table 2
Overview of studies into sources of particulate matter in animal houses (adapted from Winkel et al., 2014b).

First author (year)	Loc.	Animal species	PM fraction	Sources and contributions identified
Poultry				
Koon (1963)	USA	Layers, cage	Total dust	Skin flakes, feed, feathers
Feddes (1992)	CAN	Turkeys	PM_5	70% manure, 28% uric acid
			$PM_{10–5}$	70% manure, 20% uric acid, 4% feed, 1% feathers, 1% skin
			$>PM_{10}$	43% manure, 29% skin, 12% feathers, 6% feed, 2% uric acid
Aarnink (1999)	NL	Broilers	Total dust	Feathers (>10%), uric acid (>10%), feed (<3%), micro-organisms (<3%), manure (<1%)
Aarnink (2011) ; Cambra-López (2011)	NL	Turkeys	$PM_{2.5}$	39% feathers, 35% manure, 26% bedding
			$PM_{10–2.5}$	52% manure, 25% feathers, 23% bedding
		Broilers	$PM_{2.5}$	72% manure, 21% feathers, 6% bedding, 1% ambient PM
			$PM_{10–2.5}$	96% manure, 4% feathers
		Layers, floor	$PM_{2.5}$	54% manure, 23% feed, 17% feathers, 6% ambient PM
			$PM_{10–2.5}$	86% manure, 15% feathers
		Layers, aviary	$PM_{2.5}$	64% manure, 36% feathers
			$PM_{10–2.5}$	70% manure, 30% feathers
Pigs				
Curtis (1975)	USA	Fattening pigs and sows	Total dust	Conclusion: barn PM contains more N than the feed; PM most likely originates from feed, manure, skin, hair
Donham (1986)	USA	Sows, piglets and fattening pigs	Total dust	Manure (bacteria, epithelial cells, undigested feed; main source), feed (starch, grains), skin flakes, hair, fungi, seed and grain parts, insects, mineral ash
Heber (1988)	USA	Fattening pigs	Total dust	Feed (starch, grain; main source), skin flakes
Aarnink (1999)	NL	Piglets	Total dust	Feed (>10%), skin flakes (>10%), manure (1–3%), crystalline PM from urine (1–3%), no micro-organisms
Aarnink (2003)	NL	Fattening pigs, 40% slatted floor	Inh. dust	Comparable contributions of manure, feed en skin
		Fattening pigs, 40% slatted floor, some bedding	Inh. dust	Comparable contributions of manure, skin and straw; little contribution of feed
		Fattening pigs, solid floor with straw; outdoor run	Inh. dust	Comparable contributions of skin and straw; little contributions of manure; smallest contribution of feed
Aarnink (2011) en Cambra-López (2011)	NL	Piglets	$PM_{2.5}$	95% manure, 5% skin, <1% feed, 0% ambient PM
			$PM_{10–2.5}$	92% manure, 8% skin, 0% feed, 0% ambient PM
		Fattening pigs	$PM_{2.5}$	93% manure, 6% skin, <1% feed, <1% ambient PM
			$PM_{10–2.5}$	69% skin, 30% manure, 1% feed, 0% ambient PM
		Sows	$PM_{2.5}$	79% skin, 17% manure, 4% feed, <1% ambient PM
			$PM_{10–2.5}$	71% skin, 29% manure, 0% feed, 0% ambient PM
Cattle				
Aarnink (2011) ; Cambra-López (2011)	NL	Dairy cows	$PM_{2.5}$	37% straw, 29% manure, 23% silage, 8% bedding, 3% ambient PM, 0% concentrate feed
			$PM_{10–2.5}$	27% wood shavings, 22% straw, 21% manure, 17% silage, 12% concentrate feed, 1% ambient PM

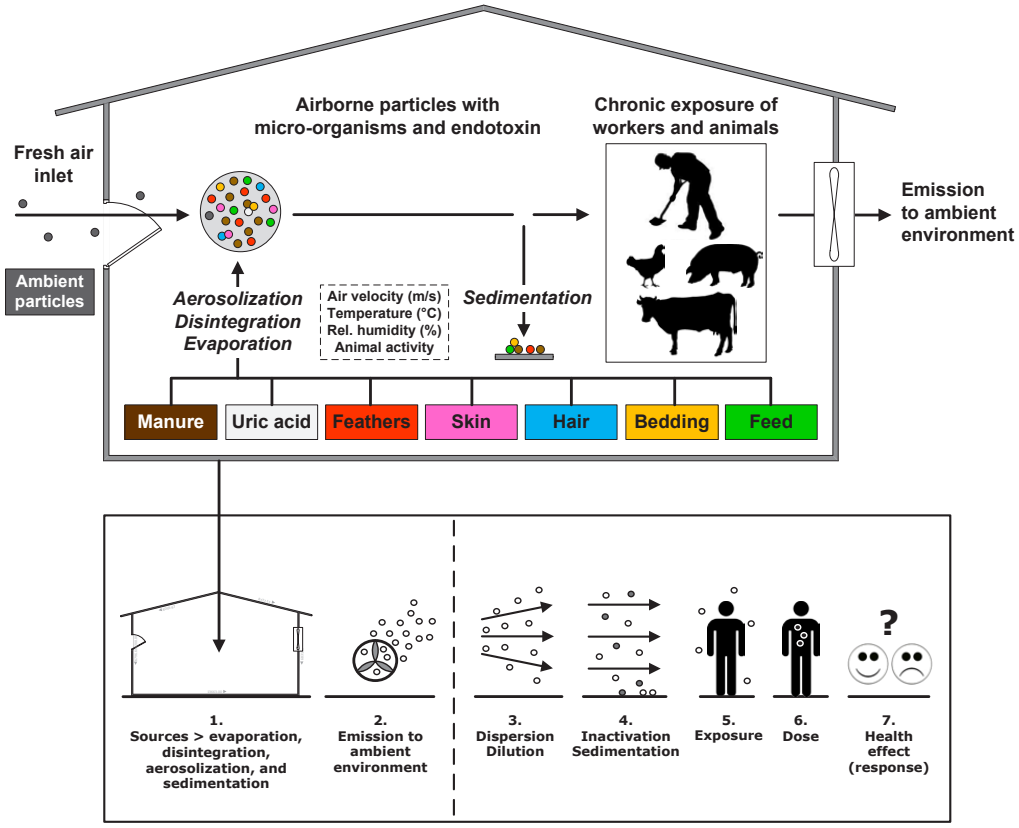


Fig. 1
Infographic that summarizes the central problem of this thesis: inside (upper picture) and outside (lower picture) the animal house.

Next to the farmers, animals are chronically exposed as well (Fig. 1). Adverse effects of PM exposure in animals are not always established in scientific studies. This could be caused by the fact that farming animals live relatively short (i.e., the exposure duration is limited) or are able to maintain resilient to a single stressor in the absence of other co-challenges. Studies on PM exposure in pigs report effects in terms of more cases of atrophic rhinitis, pneumonia, and pleuritis, decreased feed intake, and decreased growth (Hamilton et al., 1999; Murphy and Cargill, 2004; Wathes et al., 2004). Studies in chickens report effects in terms of lesions throughout the trachea and air sacks, reduced growth, and increased mortality (Anderson et al., 1968; Guarino et al., 1999; Al Homidan et al., 2003).

Table 3
Overview of studies which determined particulate matter concentrations downwind of livestock farms (adapted from Winkel et al., 2014b). Inside and downwind concentrations that exceed upwind concentrations are presented in bold.

First author (year)	Loc.	Farm characteristics	Sampling duration	PM fraction	PM concentration (µg m^{-3})	
					Upwind	Inside and downwind
Poultry						
Schmidt (1996)	Germ.	Two laying hen farms and two broiler farms	30 min	Total dust	n.g.	Inside: **80–2750** At 3 m: circa **30–1200** At 10 m: **<400** At 50 and 100 m: <4
Seedorf (1998)	Germ.	Fattening duck house, roof outlet; 2146 animals	18.5 h	Total dust	114	Inside: **1900** At 25 m: **123**
Visser (2006)	USA	Farm with 7 broiler houses; tunnel ventilation; 193,900 animals; age: 24–35 d	24–48 h	$PM_{2.5}$	24.0 [a]	Inside: **58.6** ** At 30 m: **24.1** [n.s.] At 91 m: **24.9** [n.s.] At 152 m: 23.1 [n.s.]
Worley (2013)	USA	Farm with 3 broiler houses; tunnel ventilation; 94,000 animals, age: 29–56 d	22 h	$PM_{2.5}$	Circa 31 [a]	Inside: **71.7** * At 30 m: **45.1** * At 61 m: **36.3** [n.s.] At 91 m: circa **34** [n.s.] At 152 m: circa **32** [n.s.]
Li (2010)	USA	Farm with 4 broiler houses; tunnel ventilation; 86,000 animals; age: 42–49 d	4 h	Total dust	290 [a]	At 4.6 m: **3848** At 31–61 m: **978**
Li (2012)	USA	Farm with 9 laying hen houses	24 h	$PM_{2.5}$	10.7 [a] 10.4 [a]	At 91 m: **+0.61** * At 153 m: **+0.38** *
				PM_{10}	22.3 [a] 18.0 [a]	At 91 m: **+4.98** * At 153 m: **+3.40** *
Pigs						
Hartung (1998)	Germ.	Pig house; 1000 animals, fully slatted floor; liquid feeding	24 h	Total dust	37	Inside: **600** At 50 m: **80** At 115 m: 37
Martin (2008)	USA	Farm with 3 houses (‘deep pit’); nat. ventilation; 3750 animals	23 h	PM_{10}	37.9 [a]	Between houses: **+25.1** At 39 m: **+15.8** At 15–50 m: **+5.8**
Thorne (2009)	USA	Farm with 3 open houses with littered floor; 600 animals	4 h	Inh. dust	circa 50 [b]	Inside: circa **1050** ** At 30 m: circa **500** ** At 160 m: circa **300** [ns]
		Farm with 1 house (‘deep pit’); 1200 animals	4 h	Inh. dust	circa 100 [b]	Inside: circa **1100** ** At 30 m: circa **120** [ns] At 160 m: circa **130** [ns]

[a] Arithmetic mean; [b] Geometric mean or median.
[ns] Not significant ($P \leq 0.05$), * significant ($P \leq 0.05$), or ** highly significant ($P \leq 0.01$); difference from upwind concentration.
n.d.: not determined.

Since animal houses are ventilated, large amounts of PM are emitted into the atmosphere as well (Fig. 1; step 2 in the lower picture). Locally, plumes of particles can be found outside ventilation exhausts which spread out in detectable concentrations downwind of livestock farms (Table 3). Concentrations generally decrease rapidly with distance from the exhaust, because particles are diluted with cleaner air, sediment to the ground or impact to vegetation or other objects (Fig. 1; step 3 in the lower picture). Furthermore, part of the micro-organisms present in

PM becomes inactivated through factors as UV-radiation, temperature, and humidity (Zhao et al., 2014). Eventually, neighboring residents of livestock farms may be exposed to elevated levels of livestock-related PM (Table 3).

For some areas in the Netherlands, it was estimated that animal houses raise ambient concentrations of PM_{10} by several micrograms per cubic meter (Velders et al., 2008). On a national scale, PM_{10} emissions from animal houses make up approximately 17% of the total primary PM_{10} emission (CBS, 2009). Studies on urban aerosols show associations between PM_{10} concentration and respiratory and cardiovascular disease (Brunekreef and Holgate, 2002; Brunekreef and Forsberg, 2005; Pope and Dockery, 2006). For livestock PM, health effects of ambient exposure (Fig. 1; step 5 through 7) are less well studied. Recent studies suggest both protective effects (e.g., a lower prevalence of asthma) and adverse effects (e.g., a higher prevalence of pneumonia) (e.g., Heederik et al., 2012).

Fig. 1 illustrates that the problem of this thesis lies at three main levels: PM exposure of the farmer, PM exposure of the animals, and PM exposure of the residents living in the vicinity of livestock farms. The primary focus of this thesis is on the cause of the latter problem, namely: on *emissions of PM from livestock farms*.

RESEARCH NEEDS WITH REGARD TO THE PROBLEM

To protect the health of its residents, maximum PM limit values for ambient air were set by the European Union (European Directives 1996/62/EC, 1999/30/EC, and 2008/50/EC). As from January 2005, the daily average limit for PM_{10} is set at 50 μg m^{-3} with 35 exceedances allowed per year. The annual average limits are set at 40 μg m^{-3} for PM_{10} and 25 μg m^{-3} for $PM_{2.5}$. Atmospheric modelling of PM concentrations in the Netherlands indicate that the daily average PM_{10} limit of 50 μg m^{-3} is exceeded more often than the allowed 35 days per year in the vicinity of (amongst others) a few hundred animal houses in the Netherlands (Beijk et al. 2010; Van Zanten et al., 2012). There is, however, uncertainty about the actual PM emission rates of animal houses, used in the aforementioned modelling. The latest extensive field survey on emissions of airborne PM from animal houses in Europe goes back to a study in the nineties of the previous century carried out by Takai et al. (1998). In their work, the inhalable and respirable PM fractions, often used in occupational exposure measurements (Table 1), were determined, equivalent to PM_{100} and PM_4 respectively. To date, there is a need for data on the PM_{10} and $PM_{2.5}$ fractions applied in atmospheric air quality and related legislation.

Furthermore, there is an urgent need for effective measures that enable animal farmers to mitigate these emissions. Such measures may reduce the generation of PM or its uptake in the air, remove PM when it has already become airborne inside the animal house, or remove PM from the air at the ventilation exhausts (so-called *end of pipe* systems).

Finally, it is essential to have PM samplers available that are able to measure the high concentrations in animal house environments, so that emission rates can actually be quantified and PM removal performances of abatement measures can be assessed. Before the work described in this thesis started, such a sampler was developed at Wageningen UR (Hofschreuder et al., 2008), based on the European reference samplers for PM_{10} (CEN, 1998) and $PM_{2.5}$ (CEN, 2005). This sampler has been used throughout this thesis. There are, however, alternative samplers with various working principles available on the market and employed by other institutes. Very little is known about the accuracy and comparability of these alternative samplers that are usually designed to sample in ambient air at much lower PM concentrations.

OBJECTIVES AND OUTLINE OF THIS THESIS

In view of the problem and research needs described above, the work described in this thesis had three main objectives.

The first objective was to increase our understanding and knowledge of concentrations and emission rates of particulate matter in commonly applied animal housing types. This objective is worked out in chapter 2. This chapter describes a national emission survey that covered 13 housing systems for poultry, pigs, and dairy cattle, and included 36 farm locations. The results from this chapter can be used to develop abatement solutions, to adopt emission factors in legislation, to estimate national emissions, ambient PM concentrations and exceedances, to facilitate policy making, and to allow environmental permit granting to farmers.

The second objective was to develop, test, and validate technologies to mitigate PM concentrations and emissions such that these systems will become available for use in poultry farms, and ultimately contribute to cleaner outdoor air. This thesis specifically focused on systems for poultry farms as these have the highest emission levels. The systems should be effective in terms of their reduction as validated on commercial farms, affordable for farmers, and practically implementable within common housing systems and farming practices. This objective is worked out in chapters 3 through 7. Chapters 3 and 4 describe two experiments that investigated the effects of spraying rapeseed oil onto the litter of poultry houses on PM concentrations and emissions, but also on the birds. These studies were done inside small-scaled

experimental broiler houses (chapter 3) and in small-scaled experimental aviary houses for laying hens (chapter 4). The results from these two chapters were intended to facilitate the effective and safe use of oil spraying systems inside commercial poultry farms. On the basis of chapters 3 and 4, chapter 5 describes a field evaluation of four systems that mitigate PM emissions by reducing indoor concentrations in commercial poultry farms, namely: a *fixed oil spraying system*, an *autonomously driving oil spraying vehicle*, a *negative air ionization system*, and a *positive air ionization system*. Chapter 6 describes another field evaluation. This evaluation comprised two 'end of pipe' systems to remove PM from the exhaust air of poultry farms, namely: a *dry filter wall* and an *electrostatic precipitator*. Chapter 7 describes an emission survey carried out at a total of 16 commercial poultry farms with an 'end of pipe' manure drying tunnel. This chapter aimed to elucidate the PM abatement potential and possible additional emissions of ammonia and odor of these tunnels. Furthermore, this chapter aimed to elucidate the perspective of two strategies to reduce any additional emissions from the manure drying tunnels. The results from chapters 5 through 7, carried out at commercial farms, can be used to adopt accurate PM removal figures in legislation.

Finally, the third objective was to determine the applicability (in terms of acceptable accuracy and comparability) of alternative PM_{10} measurement methods – i.e., alternative to the sampler developed by Hofschreuder et al. (2008) and used in chapters 2 through 7. Such alternative samplers could then be applied in future for determination of PM_{10} emission rates of animal houses. This objective has been worked out in chapter 8 as an equivalence study between the European reference sampler for PM_{10} (described in EN 12341) and four different candidate measurement methods (the 'cyclone sampler' developed by Hofschreuder et al. (2008), a beta-ray attenuation sampler, and two light-scattering devices) in four different environments (a fattening pig house, a laying hen house, a broiler house, and an office room). The results from this chapter can be used to harmonize PM_{10} measurement methods across institutes and to further increase the availability of samplers for the measurement of PM_{10} in animal production.

REFERENCES

Aarnink, A.J.A., Cambra-López, M., Lai, T.L.H., Ogink, N.W.M., 2011. Deeltjesgrootteverdeling en bronnen van stof in stallen [Size distribution and sources of particulate matter in animal houses]. Wageningen University and Research Centre, Livestock Research, Lelystad, the Netherlands.

Aarnink, A.J.A., Roelofs, P.F.M.M., Ellen, H.H., Gunnink, H., 1999. Dust sources in animal houses. International Symposium on Dust Control in Animal Production Facilities. Danish Institute of Animal Science Aarhus, Denmark, pp. 34-40.

Aarnink, A.J.A., Stockhofe-Zurwieden, N., 2003. Pig house dust damage. Pig progress 19, 17-19.

Beijk, R., Wesseling, J., Mooibroek, D., Du Pon, B., Groot Wassink, H., Verbeek., C., 2010. Monitoringsrapportage NSL 2010 [State of affairs of the National Air Quality Cooperation Programme 2010; in Dutch, with English summary]. Report 680712002. National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands.

Brunekreef, B., Forsberg, B., 2005. Epidemiological evidence of effects of coarse airborne particles on health. *Eur. Resp. J.* 26:309–318.

Brunekreef, B., Holgate, S.T., 2002. Air pollution and health. *Lancet* 360:1233–1242.

Cambra-López, M., Aarnink, A.J.A., Zhao, Y., Calvet, S., Torres, A.G., 2010. Airborne particulate matter from livestock production systems: A review of an air pollution problem. *Environ. Pollut.* 158:1–17.

Cambra-López, M., Hermosilla, T., Lai, H.T.L., Aarnink, A.J.A., Ogink, N.W.M., 2011. Particulate matter emitted from poultry and pig houses: Source identification and quantification. *Trans. ASABE* 54: 629−642.

CBS, PBL, WUR, 2009. Emissies van fijn stof, vluchtige organische stoffen en koolmonoxide 1990-2009 (Emissions of fine dust, volatile organic compounds and carbon monoxide 1990-2009). Centraal Bureau voor de Statistiek, Planbureau voor de Leefomgeving, Wageningen University and Research Centre. Available at: http://www.compendiumvoordeleefomgeving.nl. Accessed 1 June.

CEN, 1993. EN 481:1993. Workplace atmospheres - Size fraction definitions for measurement of airborne particles. Comité Européen de Normalisation (CEN; European Committee for Standardization), Brussels, Belgium.

CEN, 1998. EN 12341:1998. Air quality - Determination of the PM 10 fraction of suspended particulate matter - Reference method and field test procedure to demonstrate reference equivalence of measurement methods. Comité Européen de Normalisation (CEN; European Committee for Standardization), Brussels, Belgium.

CEN, 2005. EN 14907:2005. Ambient air quality - Standard gravimetric measurement method for the determination of the PM2.5 mass fraction of suspended particulate matter. Comité Européen de Normalisation (CEN; European Committee for Standardization), Brussels, Belgium.

Curtis, S.E., Drummond, J.G., Grunloh, D.J., Lynch, P.B., Jensen, A.H., 1975. Relative and qualitative aspects of aerial bacteria and dust in swine houses. *J. Anim. Sci.* 41:1512−1520.

Donham, K.J., Popendorf, W., Palmgren, U., Larsson, L., 1986. Characterization of dusts collected from swine confinement buildings. *Am. J. Ind. Med.* 10:294−297.

Eduard, W., Douwes, J., Omenaas, E., Heederik, D., 2004. Do farming exposures cause or prevent asthma? Results from a study of adult Norwegian farmers. *Thorax* 59:381−386.

Eduard, W., Pearce, N., Douwes, J., 2009. Chronic bronchitis, COPD, and lung function in farmers: The role of biological agents. *Chest* 136:716−725.

Feddes, J.J.R., Cook, H., J., Z.M., 1992. Characterization of airborne dust particles in turkey housing. *Can. Agric. Eng.* 34: 273−280.

Hamilton, T.D.C., Roe, J.M., Hayes, C.M., Jones, P., Pearson, G.R., Webster, A.J.F., 1999. Contributory and exacerbating roles of gaseous ammonia and organic dust in the etiology of atrophic rhinitis. *Clin. Diagn. Lab. Immunol.*6:199–203.

Hartung, J., Seedorf, J., Trickl, T., Gronauer, H., 1998. Emission and distribution of particulates from a piggery with a central air exhaust. *Dtsch. Tierarztl. Wochenschr.* 105:244–245.

Heber, A.J., Stroik, M., Faubion, J.M., Willard, L.H., 1988. Size distribution and identification of aerial dust particles in swine finishing buidlings. *Trans ASAE* 31:882−887.

Heederik, D.J.J., Opstal-van Winden, A.J.W., Smit, L.A.M., Wouters, I.M., Hooiveld, M., IJzermans, C.J., van der Sman-de Beer, F., Spreeuwenberg, P.P.M., de Bruin, A., van Rotterdam, B., 2011. Mogelijke effecten van intensieve-veehouderij op de gezondheid van omwonenden: onderzoek naar potentiële blootstelling en gezondheidsproblemen. Institute for Risk Assessment Sciences (IRAS), Universiteit Utrecht; Nederlands instituut voor onderzoek van de gezondheidszorg (NIVEL); Rijksinstituut voor Volksgezondheid en Milieu (RIVM), Utrecht, the Netherlands.

Hofschreuder, P., Yang, Z., Aarnink, A.J.A., Ogink, N.W.M., 2008. Measurement protocol for emissions of fine dust from animal houses: considerations, draft protocol and validation. Report 134, Animal Sciences Group, Wageningen University and Research Centre, Lelystad, the Netherlands.

ISO, 1995. ISO 7708. Air Quality – Particle size fraction definitions for health related sampling. International Organization for Standardization, Genève, Switzerland.

Koon, J., Howes, J.R., Grub, W., Rollo, C.A., 1963. Poultry dust: origin and composition. *Agric. Eng.* 44:608−609.

Li, Q., Wang, L., Oviedo-Rondón, E., Parnell, C.B., 2010. Effect of ozonation on particulate matter in broiler houses. *Poult. Sci.* 89:2052–2062.

Li, Q.F., Wang-Li, L., Walker, J.T., Shah, S.B., Bloomfield, P., Jayanty, R.K.M., 2012. Particulate matter in the vicinity of an egg production facility: Concentrations, statistical distributions, and upwind and downwind comparison. *Trans. ASABE* 55:1965–1973.

Martin, R.S., Silva, P.J., Moore, K., Erupe, M., Doshi, V.S., 2008. Particle composition and size distributions in and around a deep-pit swine operation, Ames, IA. *J. Atmos. Chem.* 59:135–150.

Murphy, T., Cargill, C., 2004. The effects of indoor air pollutants on the health and production of growing pigs. *Anim. Sci. Rev.* 25:35N–44N.

Nannen, C., Schmitt-Pauksztat, G., Büscher, W., 2005. Mikroskopische Untersuchung von Staubpartikeln in Mastschweinestallen: Unterschiede zwischen Flüssig- und Trockenfütterung. *Landtechnik* 60:218–219.

NIOSH, 1994. Method 500: particulates not otherwise regulated (total dust or total aerosol mass). National Institute for Occupational Safety and Health (NIOSH). Available from: http://www.cdc.gov/niosh/docs/2003-154/pdfs/0500.pdf, NIOSH Manual of Analytical Methods (NMAM), 4th ed. U.S. Government Printing Office, Washington DC, USA.

Nannen, C., Schmitt-Pauksztat, G., Büscher, W., 2005. Mikroskopische Untersuchung von Staubpartikeln in Mastschweinestallen: Unterschiede zwischen Flüssig- und Trockenfütterung. Landtechnik 60, 218-219.

Omland, Ø., 2002. Exposure and respiratory health in farming in temperate zones - A review of the literature. *Ann. Agric. Environ. Med.* 9:119–136.

Pope, C.A., Dockery, D.W., 2006. Health effects of fine particulate air pollution: Lines that connect. *J. Air Waste Manag. Assoc.* 56:709–742.

Schmidt, R., Hoy, S., 1996. Investigations on dust emission from chicken and layer houses. *Berl. Munch. Tierarztl. Wochenschr.* 109:95–100.

Seedorf, J., Hartung, J., Schröder, M., Linkert, K.H., Phillips, V.R., Holden, M.R., Sneath, R.W., Short, J.L., White, R.P., Pedersen, S., Takai, H., Johnsen, J.O., Metz, J.H.M., Groot Koerkamp, P.W.G., Uenk, G.H., Wathes, C.M., 1998. Concentrations and emissions of airborne endotoxins and microorganisms in livestock buildings in Northern Europe. *J. Agric. Eng. Res.* 70:97–109.

Seedorf, J., Schröder, M., Hartung, J., 1998. Emissions and immisions of bio-aerosols from a duck fattening unit. *Zentralbl. Hyg. Umweltmed.* 201:387–403.

Seifert, S.A., Von Essen, S., Jacobitz, K., Crouch, R., Lintner, C.P., 2003. Organic dust toxic syndrome: A review. *Clinical Toxicol.* 41:185–193.

Takai, H., Pedersen, S., Johnsen, J.O., Metz, J.H.M., Groot Koerkamp, P.W.G., Uenk, G.H., Phillips, V.R., Holden, M.R., Sneath, R.W., Short, J.L., White, R.P., Hartung, J., Seedorf, J., Schröder, M., Linkert, K.H., Wathes, C.M., 1998. Concentrations and emissions of airborne dust in livestock buildings in Northern Europe. *J. Agric. Eng. Res.* 70:59–77.

Thorne, P.S., Ansley, A.C., Perry, S.S., 2009. Concentrations of bioaerosols, odors, and hydrogen sulfide inside and downwind from two types of swine livestock operations. *J. Occup. Environ. Hyg.* 6:211–220.

US-EPA, 2004. Air quality criteria for particulate matter - Volume I of II. United States Environmental Protection Agency, Research Triangle Park, Durham NC, USA.

US-EPA, 2014. Reference method for the determination of suspended particulate matter in the atmosphere (high-volume method), Electronic Code of Federal Regulations (CFR), Title 40 (Protection of Environment), Part 50 (National primary and secondary ambient air quality standards), Appendix B. Retrieved Februari 11, 2014, from: http://www.ecfr.gov.

Van Zanten, M.C., Van Alphen, A., Wesseling, J., Mooibroek, D., Nguyen, P.L., Groot Wassink, H., Verbeek, C., 2012. Monitoringsrapportage NSL 2012 [State of affairs of the National Air Quality Cooperation Programme 2012, in Dutch with English summary]. Report 680712004. National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands.

Velders, G.J.M., Aben, J.M.M., Blom, W.F., Van Dam, J.D., Elzenga, H.E., Geilenkirchen, G.P., Hammingh, P., Hoen, A., Jimmink, B.A., Koelemeijer, R.B.A., Matthijsen, J., Peek, C.J., Schilderman, C.B.W., van der Sluis, O.C., de Vries, W.J., 2008. Concentratiekaarten voor grootschalige luchtverontreiniging in Nederland, rapport 2008 [Large-scale air quality concentrations maps in the Netherlands, report 2008]. Milieu- en Natuurplanbureau, Bilthoven, the Netherlands.

Visser, M.C., Fairchild, B., Czarick, M., Lacy, M., Worley, J., Thompson, S., Kastner, J., Ritz, C., Naeher, L.P., 2006. Fine particle measurements inside and outside tunnel-ventilated broiler houses. *J. Appl. Poult. Res.* 15:394–405.

Wathes, C.M., Demmers, T.G.M., Teer, N., White, R.P., Taylor, L.L., Bland, V., Jones, P., Armstrong, D., Gresham, A.C.J., Hartung, J., Chennells, D.J., Done, S.H., 2004. Production responses of weaned pigs after chronic exposure to airborne dust and ammonia. *Anim. Sci.* 78:87–97.

Winkel, A., Demeyer, P., Feilberg, A., Jørgensen, M., Puterflam, J., Engel, P., 2014a. Measurement of particulate matter: recommendations for the VERA test protocol on air cleaning technologies. Report 797 (produced under an ICT-AGRI project by: Wageningen University and Research Centre, Aarhus University, Danish Pig Research Centre, Institute for Agricultural and Fisheries Research (ILVO), the Technical Institute for Poultry Research (ITAVI), and the VERA Secretariat), Wageningen UR Livestock Research, Wageningen, the Netherlands.

Winkel, A., Wouters, I.M., Aarnink, A.J.A., Heederik, D.J.J., Ogink, N.W.M., 2014b. Emissies van endotoxinen uit de veehouderij: een literatuurstudie voor ontwikkeling van een toetsingskader [Emissions of endotoxins from animal production: a literature survey for development of an assessment framework; in Dutch, with English

summary]. Report 773, Institute for Risk Assessment Sciences, Utrecht University and Wageningen UR Livestock Research, Wageningen, the Netherlands.

Worley, J.W., Naeher, L.P., Czarick, M., Fairchild, B.D., Ritz, C.W., Irvin-Barnwell, E., 2013. Monitoring of fine particulates downwind of broiler houses-A field study. *J. Appl. Poult. Res.* 22:351–360.

Zhao, Y., Aarnink, A.J.A., De Jong, M.C.M., Groot Koerkamp, P.W.G., 2014. Airborne microorganisms from livestock production systems and their relation to dust. Crit. Rev. Environ. Sci. Techn. 44:1071–1128.

Chapter 2

Emissions of particulate matter from animal houses in the Netherlands

A. Winkel [a], J. Mosquera [a], P.W.G. Groot Koerkamp [a,b], N.W.M. Ogink [a], and A.J.A. Aarnink [a]

[a] Wageningen UR Livestock Research, Wageningen, the Netherlands
[b] Farm Technology Group, Wageningen University, Wageningen, the Netherlands

Atmospheric Environment (2015) 111:202–212

Available online at: http://dx.doi.org/10.1016/j.atmosenv.2015.03.047

ABSTRACT

In the Netherlands, emissions from animal houses represent a major source of ambient particulate matter (PM). The objective of the present paper was to provide accurate and up to date concentrations and emission rates of PM_{10} and $PM_{2.5}$ for commonly used animal housing systems, under representative inside and outside climate conditions and ventilation rates. We set up a national survey which covered 13 housing systems for poultry, pigs, and dairy cattle, and included 36 farms. In total, 202 24-h measurements were carried out, which included concentrations of inhalable PM, PM_{10}, $PM_{2.5}$, and CO_2, ventilation rate, temperature, and relative humidity. On an animal basis, geometric mean emission rates of PM_{10} ranged from 2.2 to 12.0 mg h^{-1} in poultry and from 7.3 to 22.5 mg h^{-1} in pigs. The mean PM_{10} emission rate in dairy cattle was 8.5 mg h^{-1}. Geometric mean emission rates of $PM_{2.5}$ ranged from 0.11 to 2.41 mg h^{-1} in poultry and from 0.21 to 1.56 mg h^{-1} in pigs. The mean $PM_{2.5}$ emission rate in dairy cattle was 1.65 mg h^{-1}. Emissions are also reported per Livestock Unit and Heat Production Unit. PM emission rates increased exponentially with increasing age in broilers and turkeys and increased linearly with increasing age in weaners and fatteners. In laying hens, broiler breeders, sows, and dairy cattle, emission levels were variable throughout the year.

NOMENCLATURE

BRB	Broilers Breeders
BRO	Broilers
C	The overall mean emission rate in Eq. 2, i.e., a constant
CBM	CO_2 balance method
CO_2	Carbon dioxide
$[CO_2]_{exhaust}$	Concentration of carbon dioxide in the exhaust air (ppm)
$[CO_2]_{inlet}$	Concentration of carbon dioxide in the inlet air (ppm)
ΔCO_2	Difference between the exhaust and inlet carbon dioxide concentration (ppm)
DCH	Dairy cattle in Cubicle Housing
$\underline{\varepsilon}_j \sim N(0, \sigma^2_j)$	Random effect of animal house j in Eq. 2; σ^2_j: pooled variance between houses
$\underline{\varepsilon}_{ij} \sim N(0, \sigma^2_{ij})$	Residual error term in Eq. 2, with σ^2_{ij} being the pooled variance within houses
Fco_2	Factor for conversion of total heat production to the volumetric CO_2 production by the animal and its manure ($m^3\ h^{-1}\ kW^{-1}$)
FTH	Fattening pigs in Traditional Housing
FLD	Fattening pigs in Low NH_3-emission housing and Dry feed
FLL	Fattening pigs in Low NH_3-emission housing and Liquid feed
GC	Gas chromatography
HPU	Heat Production Unit: a quantity of animals producing 1 kW of total heat
Inhalable PM	The inhalable fraction of particulate matter as defined by ISO 7708 and EN 481
KNMI	Royal Netherlands Meteorological Institute, Bilthoven, the Netherlands
LAH	Laying hens in Aviary Housing
LFH	Laying hens in Floor Housing
$Log(\underline{Y}_{ijk})$	Response variable in Eq. 2, i.e., the natural logarithm of the PM emission rate of measurement i, in animal house j of housing system k
LU	Livestock Unit, i.e., 500 kg of live weight
$n_{animals}$	The number of animals present in a house
NAQM	National Air Quality Monitoring network in the Netherlands
PAS	Infrared photoacoustic spectroscopy (INNOVA 1312 device)
PM	Particulate matter
$PM_{emission}$	Emission rate of particulate matter ($mg\ h^{-1}$)
$[PM]_{exhaust}$	Concentration of particulate matter in the exhaust air ($mg\ m^{-3}$)
$[PM]_{inlet}$	Concentration of particulate matter in the inlet air ($mg\ m^{-3}$)
PM_{10}	Particulate matter which passes through a size-selective inlet with a 50% efficiency cut-off at 10 µm aerodynamic diameter (EN 12341)
$PM_{2.5}$	Particulate matter which passes through a size-selective inlet with a 50% efficiency cut-off at 2.5 µm aerodynamic diameter (EN 14907)
SD	Standard deviation
SD_{BH}	Standard deviation between farm locations of the same housing system
SE	Standard error
SIH	Sows in Individual Housing
SGH	Sows in Group Housing
S_k	Fixed effect of housing system k in Eq. 2
TUR	Turkeys
Q	Ventilation rate ($m^3\ h^{-1}$)
WFS	Weaners on Fully Slatted floors
WPS	Weaners on Partially Slatted floors
Φ_{total}	Total heat production by the animal (Watt)

INTRODUCTION

In recent decades, animal production in the Netherlands and many other European countries has evolved from small-scale mixed farms to large-scale, specialized facilities. Considering that the Netherlands is a small country (approximately 41,500 km^2), it has a large number of residents (approximately 16.8 million; 405 residents per km^2) as well as a large animal production sector. This sector consists of about 3.9 million head of cattle in 32,000 farms, 12 million pigs in 6500 farms, 45 million broilers in 640 farms, and 34 million laying hens in 1100 farms (PPE-PVE, 2012). The air inside animal houses usually contains high levels of particulate matter (PM) (Takai et al., 1998). Mechanical and natural ventilation systems are used in these houses to remove the heat, moisture, and carbon dioxide produced by the animals. As a result, large quantities of PM are released into the atmosphere. Consequently, livestock PM emissions may adversely affect the health of the general population (Brunekreef and Holgate, 2002; Pope and Dockery, 2006), although very little is known about the specific impacts of ambient livestock PM on the health of people in farming areas (Heederik et al., 2011). To protect the health of its residents, the European Union has set maximum PM limit values for ambient air (European Directives 1996/62/EC, 1999/30/EC, and 2008/50/EC). As from 1 January 2005, the daily average limit for PM_{10} (PM with aerodynamic diameters smaller than 10 μm) was set at 50 μg m^{-3} with 35 exceedances allowed per year. The annual average limit for PM_{10} was set at 40 μg m^{-3}. The annual average limit for PM with aerodynamic diameters smaller than 2.5 μm ($PM_{2.5}$) was set at 25 μg m^{-3}, to be met by 2015. Currently, the PM_{10} limit is exceeded in some regions in the Netherlands and a substantial part of these exceedances occur in close proximity to animal houses (Van Zanten et al., 2012).

Data on PM emissions from animal housing systems are needed to estimate national emission rates (kTon $year^{-1}$), ambient PM concentrations, and exceedances, to facilitate policy making, to adopt emission factors in legislation, to allow environmental permit granting to farmers, and to effectively develop abatement solutions. The most comprehensive study yielding such data for Northern-Europe is a field survey carried out in 329 animal houses in England, the Netherlands, Denmark, and Germany, from September 1993 to November 1995 (Wathes et al., 1998). In this project, the inhalable and respirable fractions were measured (described in ISO 7708 (ISO, 1995) and EN 481 (CEN, 1993)). These are occupational health fractions corresponding with ~PM_{100} and ~PM_4 respectively. In the current situation however, data is required on the PM_{10} and $PM_{2.5}$ fractions defined in EN 12341 (CEN, 1998) and EN 14907 (CEN, 2005) respectively, which are generally used in the field of atmospheric air quality (Cambra-López et al., 2010). Furthermore,

changes in housing systems and management practices since the 1990s (such as non-cage layer systems or dairy houses with open side walls) may have altered concentrations and emissions. Therefore, there is a need for accurate, up to date, and housing system specific data on emissions of PM_{10} and $PM_{2.5}$ in the Netherlands.

The objective of the present paper was to determine concentrations and emissions of PM (PM_{10} and $PM_{2.5}$) under representative inside and outside climate conditions and ventilation rates in animal houses in the Netherlands. To be able to make a comparison with the Northern-European survey (Takai et al., 1998), inhalable PM concentrations and emissions were determined in some housing systems as well.

METHODOLOGY

Outline of the survey

Within this study the measurement protocol for particulate matter of Ogink et al. (2011) was followed. This protocol describes the measurement method and measurement strategy for establishing PM emission factors of animal housing systems. In summary, 4 animal houses (located at 4 different farms) of the same housing system must be measured to take variation between houses into account (e.g., due to differences in animal breed or feeding). Variation within houses (e.g., due to seasonal changes or increasing animal mass) is taken into account by conducting 6 measurements per house over a certain time period. For animal houses with a stable emission pattern over the production cycle (egg-laying poultry, sows, and dairy cows) measurements must be spread over the year (one measurement per 2-month period). For growing animals measurements must be spread over the production cycle. Broilers have an exponential increase in PM emission (Aarnink et al., 2011) and for turkeys a similar exponential increase was expected. To increase the accuracy of the yearly emission rate for these animal categories more measurements were performed in the second phase of the growing period than in the first phase. Variations within a day (e.g., due to light regime or temperature fluctuations) were taken into account by conducting measurements over 24-h periods. This meant that establishing an emission factor for one housing system required (4 houses × 6 =) 24 measurements. For efficient use of the available budget within this project however, the number of farm locations was reduced to 2 for those housing systems that were assumed to have a small impact on a national scale, because of their relatively small number (Table 1).

The survey covered 13 housing systems and was carried out at 36 different farm locations throughout the Netherlands. In Table 1 a short description is provided of the layout of the housing systems and their acronyms (which are further used in this paper). For a more extended description of the housing systems see Supplementary information 1. At each house, 6 measurements were scheduled (except for DCH: 5). In total, this project yielded 202 successful 24-h measurements (96 in poultry, 86 in pigs, and 20 in dairy cattle) performed between August 2007 and November 2009.

Table 1
Acronyms and main characteristics of the 13 housing systems in this study (h = house or houses).

Housing system: acronym and main characteristics	Nr. of houses
LFH: laying hens in floor housing; ⅓ litter area (wood shavings, alfalfa), ⅔ elevated slatted floor above manure pit, forced drying of manure (1 h), laying nests, chain feeders and lines with nipple or round drinkers	4
LAH: laying hens in aviary housing; litter floor (wood shavings, sand), aviary systems with manure belts (forced drying: 3 h), laying nests, feeders and nipple drinkers, outdoor run (1 h)	4
BRB: broiler breeders in floor housing; ⅓ litter area (wood shavings), ⅔ elevated slatted floor with manure pit, laying nests, male feed pans, female chain feeders	2
BRO: broilers on full litter (wood shavings), lines with feed pans, lines with nipple drinkers and drip cups, hot-air blowers	4
TUR: male turkeys on full litter (wood shavings, straw), lines with feed pans, water troughs or round drinkers, hot-air blowers	2
SIH: sows in individual housing; rooms with feed alley and rows of confined gestation stalls, individual feed trough (dry feed) and drinking nipple, solid floor with slats, manure pit	2
SGH: sows in group housing; similar to SIH but free access to gestation stalls and slatted aisles	2
WFS: weaners in rooms with feed alley and pens with fully slatted floor, manure pit, dry feed	2
WPS: weaners; housing similar to WFS, but partially slatted floor (50%)	2
FTH: fattening pigs in traditional housing; compartments with feed alley and trad. pens, partially slatted floor (43–53%), manure pit, dry feed	4
FLD: fattening pigs; compartments with feed alley and pens with partially slatted floor (40%), pit with slanted walls and vacuum system for manure removal (low NH_3 emission), dry feed	2
FLL: fattening pigs; housing similar to FLD, but with liquid feed	2
DCH: dairy cattle in traditional cubicle housing; cubicles in 2–4 rows, walking aisles with fully slatted concrete floors, automatic slurry scraper (2 h), slurry pit underneath slatted floor, drive through feed alley with feed fences, automatic concentrate feeders, water troughs, fan coolers (2 h)	4

Measurements

Sampling positions

Concentrations of aerial pollutants and environmental variables were determined at the air inlet and exhaust points. Samplers for the ingoing air were positioned outside and upwind from the building, within 2 m from an inlet opening. Here, we determined concentrations of PM_{10}, $PM_{2.5}$, and CO_2, and temperature and relative humidity. We did not determine background

concentrations of inhalable PM. Samplers for the exhaust air were placed inside the building, near emission points. For buildings with roof ventilators, samplers were mounted at a vertical distance of 0.1 m under the ventilation shaft and at a horizontal distance of 0.5 m from the ventilation shaft. For buildings with end wall ventilators, samplers were placed in front of these walls at a horizontal distance of approximately 2–3 m. In all cases, air flow rate near inside air samplers was <2 m s^{-1} to avoid non-isokinetic sampling conditions. For the naturally roof ventilated dairy houses, sampling positions were within 1.5 m under the roof ridge opening at three positions equally distributed along the length of the opening (length of the houses: 25 to 56 m). Inside pig and poultry houses, concentrations of PM and CO_2 were determined in duplicate. For dairy houses, singular concentration measurements were done at the aforementioned three positions. In all houses, the inside temperature and relative humidity were determined at the emission point. All measurements described in this paper were carried out in 24-h sampling periods from noon to noon.

Measurement of inhalable PM

The inhalable fraction defined by ISO 7708 (ISO, 1995) and EN 481 (CEN, 1993) was sampled using air pumps and IOM samplers (SKC Inc., Pennsylvania, USA; 50%-cut point at 100 μm) at an air flow rate of 2 L min^{-1}. Concentrations were determined in 19 different houses representing 6 of the 13 housing systems: 4 for LAF, 4 for BRO, 2 for SIH, 1 for WPS, 4 for FTR, and 4 for DCH (see Table 1 for acronyms of housing systems). Those housing systems were measured that have also been measured in the Northern-European survey (Takai et al., 1998).

Measurement of PM_{10} and $PM_{2.5}$

Concentrations of PM_{10} and $PM_{2.5}$ were determined by gravimetric filtration, using cyclone samplers (model URG-2000-30ENB for PM_{10} and URG-2000-30EG for $PM_{2.5}$; URG Corp., Chapel Hill NC, USA) and stationary sampling pumps (Tecora, model Charlie HV; Ravebo B.V., Brielle, the Netherlands) at a flow rate of 16.7 L min^{-1}. After pre-separation inside the cyclone, PM of the desired size fraction was collected on a glass fiber filter (type GF-3, Ø 47 mm, Macherey-Nagel, Düren, Germany). Filters were weighed before and after loading at standard conditions (20 ± 1°C and 50 ± 5% relative humidity) as described in EN 12341 (CEN, 1998) and EN 14907 (CEN, 2005), using a precise balance (AT261 DeltaRange, Mettler, Greifensee, Switzerland; resolution: 10 μg). Each filter was weighed four times during two consecutive days. PM concentrations were calculated as the mass of collected PM divided by the

volume of air drawn through the filter. For PM_{10}, concentrations were calibrated to the EN 12341 reference sampler by the equations published by Zhao et al. (2009): $y = 1.09x$ (when $x \leq 223$ µg m^{-3}) and $y = 0.83x + 57.5$ (when $x > 223$ µg m^{-3}), where x is the cyclone concentration and y the calibrated concentration. PM_{10} and $PM_{2.5}$ concentrations were determined in all houses in this project.

To determine daily patterns in PM_{10} concentrations, continuous measurements of PM_{10} were carried out using a light-scattering device (DustTrak Aerosol Monitor, model 8520, TSI Inc., Shoreview, USA; air flow rate: 1.7 L min^{-1}). PM_{10} concentrations were determined per second and minute-averaged values were logged in the memory of the device. Due to limited availability of devices, data was obtained from 159 out of a total of 202 conducted measurements at all 36 houses. These DustTrak measurements were done inside the buildings only.

Measurement of environmental variables

Temperature (ºC) and relative humidity (%) inside and outside animal houses were measured with combined sensors (Rotronic Instrument Corp., Hauppauge NY, USA). Hourly mean values were stored in a data-logging system (Campbell Scientific Inc., Logan UT, USA; types: CR10, CR10X, CR23, and CR23X). In addition, meteorological data of the nearest whether station for each animal house were obtained from the Royal Netherlands Meteorological Institute (KNMI).

Measurement of carbon dioxide

For determination of the ventilation rate by the CO_2 balance method, concentrations of CO_2 were determined by gas chromatography (GC) and/or by infrared photoacoustic spectroscopy (PAS). For GC measurements, 24-h total air samples were taken using the 'lung principle' (vessels with 40 L Nalophan air sampling bags connected to electrical air pumps; Thomas Industries Inc., Wabasha MN, USA; model 607CD32; critical capillary: 0.02 L min^{-1}). The pump sucked air from the vessel which caused the sampling bag to be filled with air taken from the sampling position. Singular samples taken from the air inlet and exhaust points were taken to the lab and analyzed by GC (Interscience/Carlo Erba Instruments Inc., Breda, the Netherlands, GC 8000 Top; column Molsieve 5A; detector: HWD). Depending on availability of the equipment, as a back-up, we measured CO_2 concentration continuously at the farms by PAS as well (INNOVA 1312, LumaSense Technologies, Ballerup, Denmark). This device was only used at the exhaust point.

Data preparation and analysis

Estimation of ventilation rate

In 11 of the 16 pig houses, the ventilation rate was determined by calibrated fan-wheel anemometers with the same diameter as the ventilation shaft (these included 55 out of 86 pig house measurements). The rotational frequency of the fan wheel (pulses per minute) was stored in a data logging system. Calibration curves were used to calculate ventilation rates from these pulses. For 31 pig house measurements such data could not be obtained. In the latter measurements, and in all poultry and dairy houses, ventilation rate was determined indirectly by the CO_2 balance method (CBM), which uses the CO_2 produced inside the animal house as a tracer gas. In most poultry houses, multiple fans of varying diameters were present, making the use of fan-wheel anemometers impractical, and in naturally ventilated dairy houses their use is impossible. For the description of CBM to calculate the ventilation rate see Supplementary information 2.

Calculation of PM emission rates

PM emission rates ($PM_{emission}$; mg h^{-1}) were calculated for each measurement using Eq. 1:

$$PM_{emission} = Q \times ([PM]_{exhaust} - [PM]_{inlet}) \quad (1)$$

where Q is the ventilation rate (m^3 h^{-1}), $[PM]_{exhaust}$ is the concentration of inhalable PM, PM_{10} or $PM_{2.5}$ in the exhaust air (mg m^{-3}), and $[PM]_{inlet}$ the concentration of PM_{10} or $PM_{2.5}$ (mg m^{-3}) in the inlet air. For inhalable PM, no correction was made for PM in the inlet air, similar as in the Northern-European survey (Takai et al., 1998). Emission rates were expressed in three different units of production: per animal present during the measurement (mg h^{-1} $animal^{-1}$), per Livestock Unit (i.e., 500 kg live weight; mg h^{-1} LU^{-1}), and per heat production unit (i.e., a quantity of animals producing 1 kW of total heat; mg h^{-1} HPU^{-1}). Emission data were expressed per hour, while they were determined per day, to make them easy to compare with data from literature. Emission rates were not corrected for empty periods (e.g., cleaning days between production cycles). For DCH, the animals were kept inside during measurements (no pasture grazing).

Statistical analysis

PM emission rates of poultry and pig houses were analyzed using the REML directive of GenStat (VSN, 2013) by a mixed model, described by Eq. 2:

$$\text{Log}(\underline{Y}_{ijk}) = C + S_k + \underline{\varepsilon}_j + \underline{\varepsilon}_{ij} \quad (2)$$

where $\text{Log}(Y_{ijk})$ is the response variable (i.e., the natural logarithm of the PM emission rate of measurement i, in animal house j of housing system k), C is the overall mean emission rate (i.e., a constant), S_k is a fixed effect of housing system k (13 housing systems; Table 1), $\underline{\varepsilon}_j \sim N(0, \sigma^2_j)$ is a random effect of animal house j (36 houses; 2 or 4 per housing system; with σ^2_j being the pooled variance between animal houses), and $\underline{\varepsilon}_{ij} \sim N(0, \sigma^2_{ij})$ is the residual error term (with σ^2_{ij} being the pooled variance of measurements within houses). PM emission rates were analyzed at log-scale because these emissions were positively skewed and the variance in the dataset was proportional to absolute levels. We used deviance tests to determine whether including autocorrelation (i.e., correlation between measurements in time within a house) in the model variance structure improved the model output, but autocorrelation was not significant, and was therefore omitted from the final model (Eq. 2). The model was run for 9 emission variables, i.e., each combination of the PM fractions (inhalable PM, PM_{10}, and $PM_{2.5}$) and units of production (animal, LU, and HPU). Model-predicted mean emission rates on the natural log-scale were computed for each housing system, which were back-transformed to yield a geometric mean emission rate at the original scale.

RESULTS AND DISCUSSION

For the climate conditions during the measurements we refer to Supplementary information 3. These data show that outdoor climate conditions during the measurement days closely resembled long-term trends in the Netherlands.

Ventilation rate

Table 2 shows the ventilation rates of the housing systems, the recorded body weights of the animals, and the inside CO_2 concentrations. The overall mean (SD) inlet CO_2 concentration in our dataset was 478 (60) ppm. This is higher than the background concentration in open fields without animal houses. This relatively high inlet CO_2 concentration is most probably caused by

CO_2 emission from other animal houses on the same farm or from recirculated CO_2 from the same house. Because we also corrected for the inlet PM concentrations (except inhalable PM), and these were also raised at the inlet as can be seen from Fig. 1, the emission calculation is not affected by this high inlet CO_2 concentration. According to Seedorf et al. (1998), the difference between the inlet and exhaust concentration (ΔCO_2) should be greater than 250 ppm for an accurate estimation of the ventilation rate based on CO_2. This condition was met in 97% of the measurements: 95 out of 96 measurements in poultry, all 31 measurements in pigs (excluding 55 measurements where fan-wheel anemometry was used), and 16 out of 20 measurements in dairy cattle. The overall mean (range) ΔCO_2 in our dataset was 1054 (137–2792) ppm.

Table 2
Ventilation rates, CO_2-concentrations, and body weights (based on 24-h mean values).

Housing system	Ventilation rate ($m^3\ h^{-1}\ animal^{-1}$)		Ventilation rate ($m^3\ h^{-1}\ LU^{-1}$)		CO_2, inside (ppm)		Body weight (kg)	
	Mean	Min–Max	Mean	Min–Max	Mean	Min–Max	Mean	Min–Max
LFH	3.5	1.1–9.0	949	306–2432	1327	741–2456	1.8	1.5–2.0
LAH	3.0	0.8–6.3	826	233–1727	1484	844–3060	1.8	1.5–1.9
BRB	4.1	1.2–8.9	641	166–1754	1762	775–3290	3.4	2.5–3.8
BRO	2.1	0.1–9.6	797	367–2225	2177	917–3230	1.1	0.1–2.4
TUR	12.2	6.9–22.1	681	350–1130	1430	963–2000	10.6	4.1–19.5
SIH	63.5	23.8–137	140	53.6–299	1836	865–2980	227	220–240
SGH	50.8	22.2–75.9	132	61.6–190	1719	1150–2980	190	180–200
WFS	9.0	3.2–16.1	338	135–706	1629	896–2830	13.7	9.8–21.0
WPS	10.2	6.2–19.7	306	175–529	2429	1420–4070	17.7	10.0–23.8
FTH	28.0	6.6–49.3	236	71.3–483	2038	1080–3370	66.0	21.0–109
FLD	26.7	9.7–46.0	227	122–365	2001	1360–2640	63.5	29.0–102
FLL	25.0	9.6–36.8	185	120–338	2196	1510–3460	71.7	40.0–120
DCH	862	196–2111	698	158–1688	819	553–1880	617	603–625

In this study, we calculated the volumetric CO_2 production at the house level by the values given by Pedersen et al. (2008), which are composed of the metabolic CO_2-production by the animal multiplied by a factor 1.1 for the contributions of manure and litter, provided that the manure is removed frequently (i.e., every three weeks) and the litter is not of the deep-litter type (i.e., <0.5 m). Recent studies in broilers where manure was replaced by fresh bedding material between growth cycles, showed that the contribution of the litter to the total CO_2-production increased exponentially from negligible levels during the first 4 weeks to values between 8 and 20% at the end of the growth cycle (Calvet et al., 2011; Calvet et al., 2012). In a high-rise cage house, Liang et al. (2005) measured the CO_2-production from manure that had accumulated for 6 months and found that it contributed 5 to 9% to the total CO_2-production. These empirically found contributions agree reasonably well with the additional 10% incorporated in the values recommended by Pedersen et al. (2008). Ni et al. (1999) studied the CO_2 release from slurry pits

in a mechanically ventilated fattening pig room with partially slatted floors during a 135-day period and found a mean CO_2-production from manure of 42.1 g h^{-1} per m^2 of pit surface, which would yield contributions of the manure to the total CO_2-production in excess of 10%.

In our study, deep litter systems were not included. The issue of CO_2-production from sources other than the animal's metabolism could however be a source of uncertainty mainly for BRO and TUR (where propane was burned in hot air blowers during the initial phase of the growth cycle), LAH (where manure accumulated underneath elevated slatted floors during laying cycles of 14 months), the pig houses (where the frequency of slurry pit emptying varied from monthly to annually, depending on the farm management), and DCH (where slurry pits were partially emptied for slurry spreading several times between February and September). To gain insight into the reliability of the CO_2 balance method (CBM), we recently compared ventilation rates obtained with the CBM in broilers, weaners, fattening pigs, and sows with values obtained from simultaneous measurements by fan-wheel anemometry (Mosquera et al., 2012). This comparison was done by linear regression analysis (with the ventilation rate from fan-wheel anemometry as the independent variable) and was partially based on the dataset presented here. The values from the CBM were consistent with those obtained with fan-wheel anemometers, indicated by zero intercepts, regression coefficients not significantly different from one (between 0.91 and 0.98), and coefficients of determination between 0.69 and 0.99. Other studies too have shown that, when input variables are accurately determined, CBM values on a 24-h basis are generally reliable for housing systems without prolonged manure storage, deep litter, and natural ventilation (Blanes and Pedersen, 2005; Hinz and Linke, 1998; Li et al., 2005; Xin et al., 2009). For naturally ventilated houses (i.e., DCH in this survey) ventilation rates determined by the CBM are surrounded by a higher degree of uncertainty (Calvet et al., 2013).

The ventilation capacities of the animal houses given in Supplementary information 1 and the measured ventilation rates listed in Table 2 can be compared with the guidelines of the Dutch expert committees on poultry house ventilation (WUR, 2010) and pig house ventilation (WUR, 2006). On a 500 kg liveweight (LU) basis, these recommendations are (minimum–maximum): 350–2000 m^3 h^{-1} for LFH, LAH, BRO, and TUR, 250–1800 m^3 h^{-1} for BRB, 34–480 m^3 h^{-1} for SIH and SGH, 133–667 m^3 h^{-1} for WFS and WPS, and 87–435 m^3 h^{-1} for FTH, FLD, and FLL. On a 500 kg liveweight basis, the installed ventilation capacities match the aforementioned maxima. For 3 out of 4 broiler houses, and for 3 out of 8 houses for fattening pigs however, the ventilation capacity was insufficient to realize the recommended maximum. The measured ventilation rates (Table 2; m^3 h^{-1} LU^{-1}) match the ventilation guidelines well. Only in BRB, ventilation rate in winter clearly dropped below the recommended minimum of 250 m^3 h^{-1} LU^{-1}.

In Supplementary information 4 scatter plots are presented of the ventilation rate against the day number in the growing period (for growing animals) or against the outside temperature or wind speed (for non-growing animals).

Outside PM concentrations

The mean (maximum) outside PM_{10} concentration measured near the house inlets was 52 (187) µg m^{-3} for poultry farms, 27 (119) µg m^{-3} for pig farms, and 28 (81) µg m^{-3} for dairy farms. The mean (maximum) outside $PM_{2.5}$ concentration was 15 (46) µg m^{-3} for poultry farms, 14 (60) µg m^{-3} for pig farms, and 11 (20) µg m^{-3} for dairy farms.

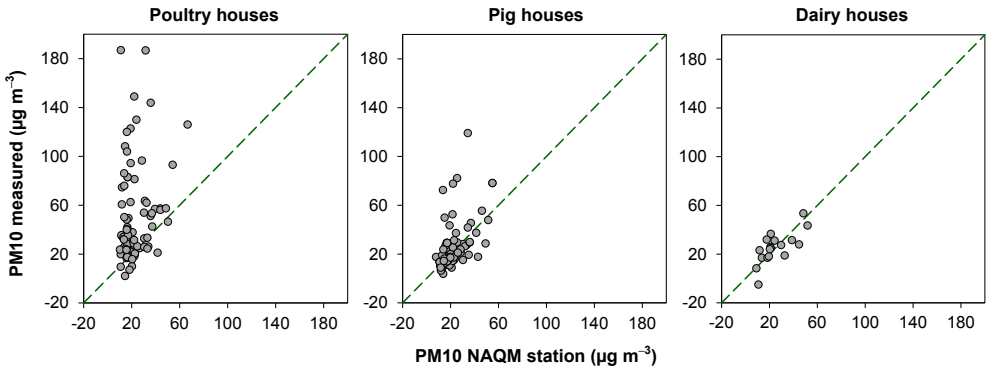


Fig. 1
Measured PM_{10} concentrations outside poultry houses, pig houses, and dairy houses, against the PM_{10} concentrations of the nearest National Air Quality Monitoring (NAQM) station for that day (based on 24-h mean values). Green dashed lines: $y = x$.

In Fig. 1 the PM_{10} concentrations measured near the house inlets are plotted against those from the nearest rural National Air Quality Monitoring (NAQM) station for the same 24-h period (the stations were within 5 to 35 km from the farms). This figure shows that concentrations outside poultry and pig farms tended to be either comparable to or higher than the ambient concentration in that region and on that day, but never substantially lower. Inlet PM samplers were positioned away from the exhausts, upwind of the buildings, and away from other possible PM sources. It is possible however, that a change in wind direction caused part of the PM emitted to be recirculated, or that the houses were incidentally in the plume of other nearby PM sources. In either case, PM emission rates were corrected for background concentrations (Eq. 1). In general, the data in Fig. 1 support the recent finding that ambient PM concentrations may be

elevated in proximity to poultry and pig houses in the Netherlands (Heederik et al., 2011). At dairy farms, PM_{10} concentrations measured near the house inlets were generally low and reasonably similar to those from the nearest NAQM station.

Inside PM concentrations

Table 3 shows descriptive statistics of the inside concentrations of Inhalable PM, PM_{10}, and $PM_{2.5}$. Mean PM concentrations were clearly highest in poultry houses, followed by pig houses, and lowest in dairy houses, for each of the three PM fractions. In the Northern-European survey (Takai et al., 1998), mean inhalable PM concentrations inside animal houses in the Netherlands were 8780 µg m^{-3} for layers in percheries, 10,360 µg m^{-3} for broilers on litter, 1200 µg m^{-3} for sows on slats, 3740 µg m^{-3} for weaners on slats, 2610 µg m^{-3} for fatteners on slats, and 140–220 µg m^{-3} for dairy in cubicles.

Table 3
Concentrations of particulate matter in the exhaust air of the housing systems (based on 24-h mean values).

Housing	Inhalable PM (µg m^{-3})			PM_{10} (µg m^{-3})			$PM_{2.5}$ (µg m^{-3})		
system	*n*	Mean	Min–Max	*n*	Mean	Min–Max	*n*	Mean	Min–Max
LFH	19	8175	3633–14,307	23	3143	1216–7315	23	175	41.2–423
LAH				22	3362	1198–10,951	22	217	54.3–866
BRB				12	1703	913–2737	12	120	45.2–205
BRO	18	4392	998–7882	24	1931	486–3784	24	137	28.4–495
TUR				11	1280	483–2515	10	351	54.4–947
SIH	8	1245	726–1969	11	485	187–826	10	53.5	21.9–101
SGH				10	415	267–599	10	37.8	19.2–52.8
WFS				11	1091	419–1836	11	51.1	19.2–98.4
WPS	5	3616	2913–4674	10	988	534–1274	10	39.7	16.0–81.4
FTH	20	2203	614–4623	23	662	229–1334	23	47.8	10.8–113
FLD	2	3282	2402–4161	10	963	543–1458	10	52.7	32.6–65.5
FLL				10	714	198–1247	10	41.5	14.8–63.0
DCH	19	295	68–580	20	40.0	14.0–95.0	20	13.8	3.9–24.9

The concentrations of inhalable PM found in the present study (Table 3), are reasonably consistent with these data from the 1990s. Only for broilers, the mean concentration in the present study was 58% lower. This can be explained by the fact that the measurements in the present study were spread more evenly over the growing cycle in comparison to the Northern-European survey, where measurements were mainly done in the second half of the growth cycle (P.W.G. Groot-Koerkamp, pers. comm.), when PM concentrations are higher (Supplementary information 5). The PM_{10} and $PM_{2.5}$ concentrations found here are roughly in accordance with the concentrations from other emission studies, as summarized in Supplementary information 6.

Inside DCH, PM_{10} concentrations (mean: 40 µg m^{-3}) were only slightly higher than ambient levels (mean: 28 µg m^{-3}). Similar data have recently been reported by Schrade et al. (2014), who found a mean (maximum) PM_{10} concentration of 26 (~70) µg m^{-3} inside Swiss dairy houses, only slightly above the mean background level of 17 µg m^{-3}.

On the basis of the DustTrak measurements, Fig. 2 provides diurnal patterns of the relative inside PM_{10} concentration. In LFH, LAH, and BRB, a sharp drop in the PM_{10} concentration was found in the evening when the lights went off (around 20:00), followed by a sharp rise in the early morning when the lights were turned on again (around 04:00). In BRO and TUR, distinct patterns were found marked by high concentrations during light periods and low concentrations during dark periods. Since lighting schemes differed between houses, and also over the course of a growing cycle within a house (which lead to diffuse trends when combined in one figure), Fig. 2 shows one typical measurement for BRO and TUR each. In pigs, diurnal patterns were clearly flatter, showing low concentrations during the night and two peaks during daytime, roughly between 05:00 and 10:00, and between 15:00 and 19:00. In DCH, the concentration profile was below average (i.e., below 100%) and rather flat during the night, but elevated and spiked during the day. For all housing systems, elevated concentrations were probably caused by the activity of the animals (e.g., due to lights being switched on, feed being delivered, milking, etcetera). The direct relationship between animal activity and PM concentration has been well demonstrated (Calvet et al., 2009; Costa et al., 2009; Joo et al., 2013).

In Supplementary information 5, scatter plots are given of the PM_{10} concentration against the day number in the growing period (for growing animals) or against the ventilation rate (for non-growing animals).

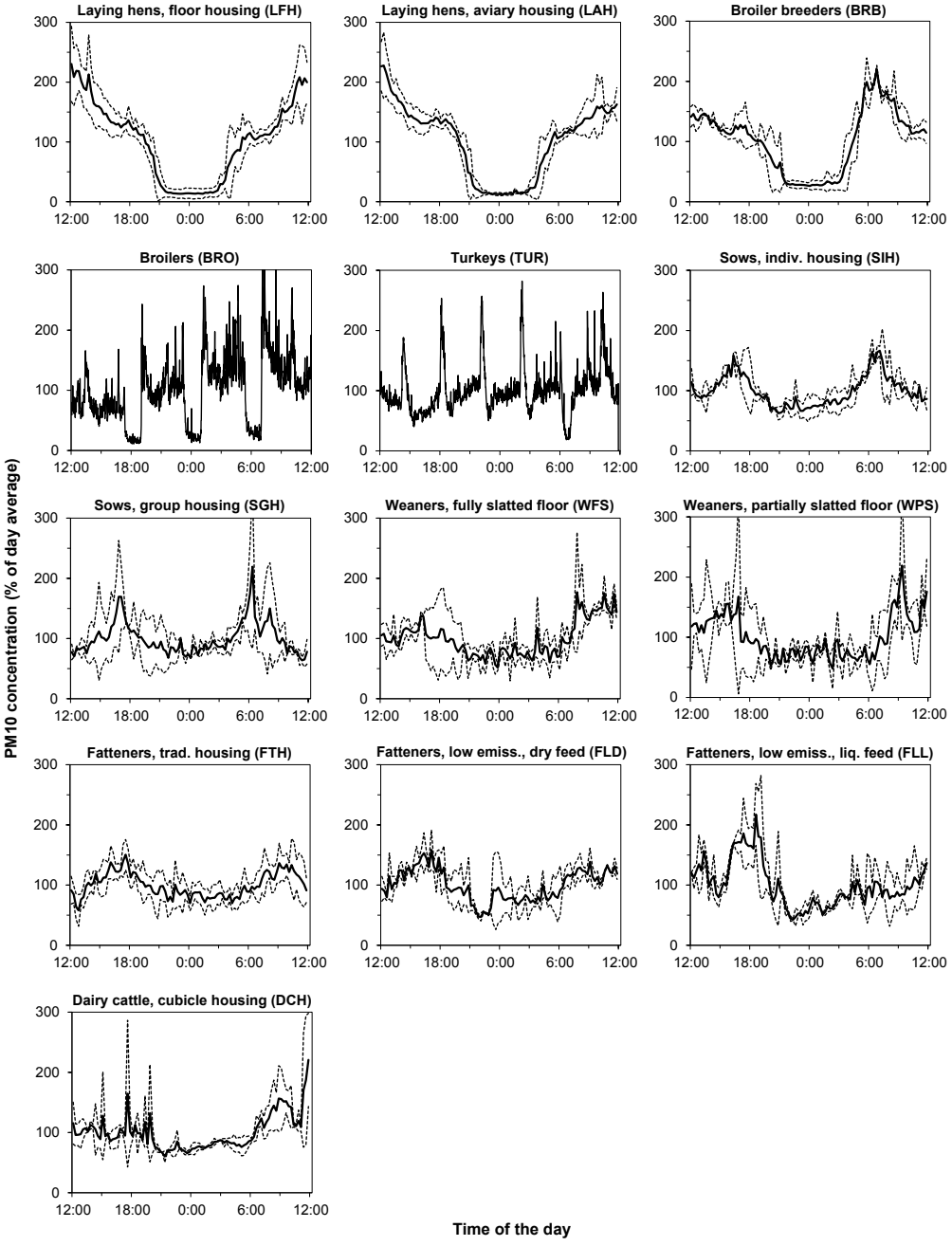


Fig. 2
Diurnal patterns of the relative PM_{10} concentration in 13 housing systems. One typical 24-h measurement is presented for broilers and turkeys. For the other 11 housing systems, bold lines represent overall means and dotted lines the mean ± one standard deviation between houses.

PM emission rates

In Table 4 the emission rates of inhalable PM, PM_{10}, and $PM_{2.5}$ (each on an animal basis) are shown. First, arithmetic mean emission rates are presented on the original (measured; mg h^{-1}) scale, together with the SD between house averages. Second, the model-predicted means are given, together with their standard error, based on the natural log-transformations of the original data (Eq. 2). Finally, back-transformed values of these predictions are given, which then represent geometric mean emission rates on the original scale. As noted by other authors, measured PM emission rates were positively skewed and the variance in the dataset was proportional to absolute levels (Joo et al., 2013; Takai et al., 1998), but after transformation a normal distribution was obtained. Due to the positive skewness, the back-transformed (geometric) means generally provided lower but more valid estimates of central tendency than the arithmetic means (Table 4).

A highly significant effect was found for the housing system term ($P < 0.001$). On a LU and HPU basis, as presented in Supplementary information 7, PM emission rates were clearly higher for poultry than for pigs and dairy. This is also remarkably reflected by the finding that, on an animal basis, the PM_{10} emission rate of one laying hen is of the same order of magnitude as the emission rate of one weaner or one dairy cow. Presumably, the presence of dusty litter (i.e., bedding material and dry, friable manure) in all poultry housing systems investigated contributed to this.

For DCH, no model-predicted mean emission rate is shown for PM_{10} and $PM_{2.5}$, because 3 out of 20 emission rates for PM_{10} were slightly negative (Fig. 4), as well as 6 out of 20 emission rates for $PM_{2.5}$, which hindered the use of a natural log-transformation. As noted earlier, the concentration inside DCH was on average only 12 μg m^{-3} higher than outside. At such low concentration differences, random sampling errors can result in slightly negative emissions. Despite that these negative emissions have actually been zero or very small, setting these values to zero would introduce a systematic bias for the lowest values only, since similar errors are present in both negative and positive values in the dataset. Therefore, all values remained in the dataset for the calculation of the arithmetic mean emission rate of DCH (Table 4).

PM emission rates increased exponentially with increasing age in broilers and turkeys and increased linearly with increasing age in weaners and fatteners (Fig. 3). In non-growing animals (laying hens, broiler breeders, sows, and dairy cattle), emission levels were variable throughout the year (Fig. 4).

Table 4
Arithmetic mean and standard deviation between houses (SD_{BH}) of original-scaled PM emission rates, model-estimated mean emission rates on the natural log-scale (SE: standard error), and back-transformed mean emission rates (i.e., geometric means on the original scale), expressed per animal. For data presented per Livestock Unit (LU), and per Heat Production Unit (HPU) see Supplementary information 7.

Housing system	Nr. of houses	*n*	Emission rate[a] (mg h^{-1} $animal^{-1}$)		
			Mean (SD_{BH}); original-scaled data	Log-transformed mean (SE)	Back-transf. mean
Inh. PM[b]					
LFH	4	19	28.3 (15.3)	3.05 (0.20)	21.2
BRO	4	18	8.47 (2.65)	1.58 (0.20)	4.87
SIH	2	8	77.1 (7.41)	4.26 (0.30)	70.7
WPS	1	5	34.2 (–)	3.44 (0.39)	31.2
FTH	4	20	53.0 (27.5)	3.73 (0.19)	41.7
FLD	1	2	96.8 (–)	4.56 (0.59)	95.9
DCH	4	19	265 (32.2)	5.28 (0.20)	197
PM_{10}					
LFH	4	23	10.6 (4.09)	2.16 (0.18)	8.67
LAH	4	22	7.91 (1.73)	1.96 (0.19)	7.08
BRB	2	12	5.81 (0.11)	1.54 (0.26)	4.66
BRO	4	24	4.13 (2.14)	0.81 (0.18)	2.24
TUR	2	11	15.1 (4.51)	2.49 (0.26)	12.0
SIH	2	11	22.2 (1.48)	3.05 (0.26)	21.1
SGH	2	10	19.8 (9.48)	2.90 (0.27)	18.2
WFS	2	11	7.60 (1.38)	1.99 (0.26)	7.29
WPS	2	10	9.47 (0.36)	2.20 (0.27)	8.98
FTH	4	23	16.4 (7.89)	2.66 (0.18)	14.3
FLD	2	10	23.8 (4.99)	3.11 (0.27)	22.5
FLL	2	10	17.5 (2.02)	2.69 (0.27)	14.7
DCH	4	20	8.53 (2.83)	n.d.	n.d.
$PM_{2.5}$					
LFH	4	23	0.57 (0.24)	–0.94 (0.23)	0.39
LAH	4	22	0.46 (0.11)	–0.94 (0.24)	0.39
BRB	2	12	0.43 (0.02)	–1.33 (0.33)	0.27
BRO	4	24	0.31 (0.19)	–2.24 (0.23)	0.11
TUR	2	10	3.86 (0.27)	0.88 (0.35)	2.41
SIH	2	10	1.69 (0.66)	0.44 (0.35)	1.56
SGH	2	10	1.41 (0.61)	0.28 (0.35)	1.32
WFS	2	11	0.26 (0.11)	–1.50 (0.34)	0.22
WPS	2	10	0.24 (0.05)	–1.54 (0.35)	0.21
FTH	4	23	0.83 (0.48)	–0.41 (0.23)	0.67
FLD	2	10	1.02 (0.13)	–0.04 (0.35)	0.96
FLL	2	10	0.77 (0.21)	–0.57 (0.35)	0.56
DCH	4	20	1.65 (0.62)	n.d.	n.d.

[a] Hourly values were calculated by dividing the 24-h determined data by 24.
[b] Not corrected for inlet concentration.
n.d.: not determined.

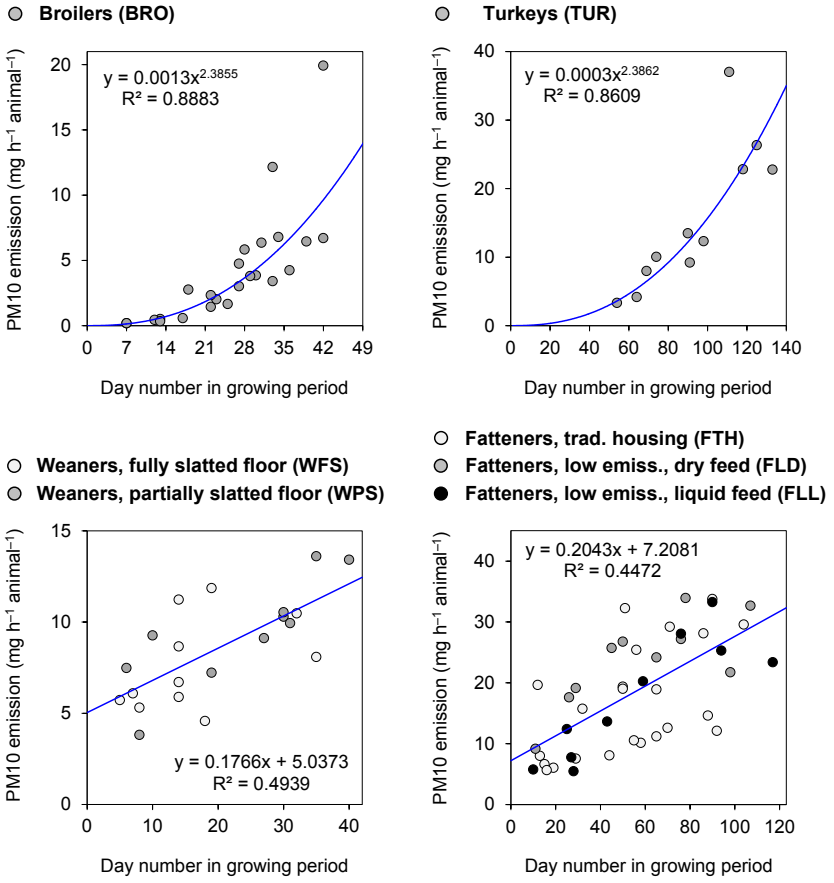


Fig. 3
Scatter plots of PM_{10} emission rates for housing systems with growing animals (based on 24-h mean values).

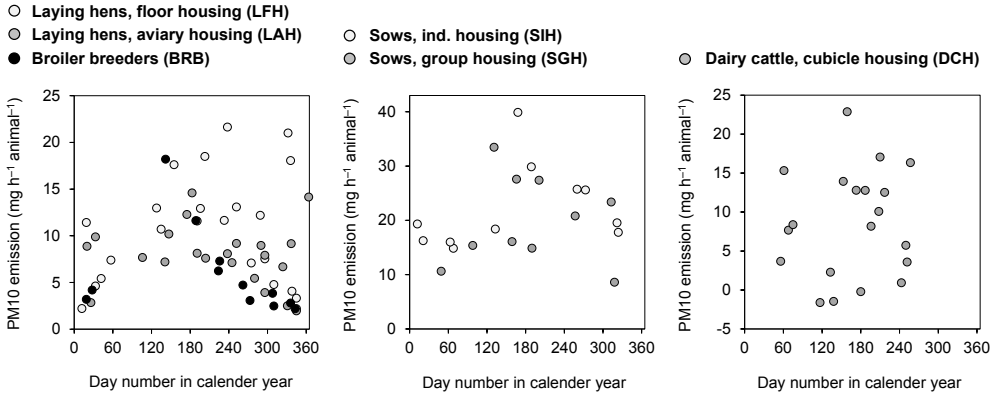


Fig. 4. Scatter plots of PM_{10} emission rates for housing systems with non-growing animals (based on 24-h mean values).

As explained earlier, measurements in broilers and turkeys focused on the middle and last phase of the growth cycle, which may distort the emission estimates in Table 4. Furthermore, measurements in turkeys were only carried out in two grow-out houses where male birds were kept from approximately 5 to 20 weeks of age, but not in the rearing house. An indication of the mean PM_{10} emission rate over the full growing period can be estimated by fitting the emission curve for TUR in Fig. 3 to days 1 to 140, and dividing the sum of these fitted values by 140. This approach yields a mean PM_{10} emission rate of 11.8 mg h^{-1} $bird^{-1}$ and a mean $PM_{2.5}$ emission rate of 0.20 mg h^{-1} $bird^{-1}$ (estimated from $y = 0.00002x^{2.8032}$; $R^2 = 0.83$) for a full 140-day cycle. In BRO, the same approach for a 42-day growing period yields a mean PM_{10} emission rate of 2.98 mg h^{-1} $bird^{-1}$ and a mean $PM_{2.5}$ emission rate of 3.33 mg h^{-1} $bird^{-1}$ (estimated from $y = 0.0000003x^{3.5877}$; $R^2 = 0.87$).

In the Northern-European survey (Takai et al., 1998), model-predicted (geometric) mean inhalable PM emission rates for animal houses in the Netherlands (on a LU basis) were 4340 mg h^{-1} for layers in percheries, 4984 mg h^{-1} for broilers on litter, 151 mg h^{-1} for sows on slats, 1309 mg h^{-1} for weaners on slats, 418 mg h^{-1} for fatteners on slats, and 216 mg h^{-1} for dairy in cubicles. The mean emission rate for BRO in the present study is about 50% lower, possibly, as mentioned earlier, because measurements were spread more evenly over the growing cycle in the present work as compared to Takai et al. (1998). Furthermore, the mean emission rate of dairy cattle (DCH) in the present study is about 26% lower, whereas the mean emission rates for layers (LFH), sows (SIH) and fatteners (FTH) are within a 15% difference. It should be noted that in this study and in the study of Takai et al. (1998) no correction was made for the inlet inhalable PM concentrations. Preliminary results from an ongoing study show that in the outside air inhalable PM concentrations are rather similar to PM_{10} concentrations, because of sedimentation of the heavy particles. When we compare mean inlet concentrations of PM_{10} with mean exhaust concentrations of inhalable PM and when we assume inhalable PM concentration to be similar as PM_{10} concentration at the inlet, an overestimation is made of the emission of inhalable PM of 0.7% in poultry, 1.8% in pigs, and 12.2% in dairy cattle. So, in dairy cattle there is some overestimation of inhalable PM emission, but in poultry and pigs the error is small.

Prior to this study, a first set of tentative PM_{10} emission factors was estimated from the inhalable PM emission rates reported by Takai et al. (1998), assuming a general conversion factor of 0.45 (Chardon and Van der Hoek, 2002; Van der Hoek, 2007). In the present dataset, mean (SD) concentration ratios between PM_{10} (corrected for background concentration) and inhalable PM, were 0.40 (0.15) for LFH, 0.44 (0.12) for BRO, 0.32 (0.06) for SIH, 0.31 (0.10) for WPS, 0.32 (0.08) for FTH, and 0.06 (0.04) for DCH. In retrospect, concentration ratios are

all lower than the general conversion factor of 0.45, and varied clearly between poultry, pigs, and dairy cattle. Consequently, the tentative emission factors in legislation have been replaced by measured emission factors that were generally lower.

In Supplementary information 6, a summary of results from earlier PM_{10} and $PM_{2.5}$ emission studies is provided for housing systems comparable to those studied in this work. This summary shows that emission figures for $PM_{2.5}$ are scarcer than for PM_{10}, and that the present work in 36 animal houses represents a substantial contribution to the current state of knowledge. Despite that differences between studies may arise from differences in sampling instruments, sampling strategies, meteorological conditions, and so on, in general, Table 4 and Supplementary information 6 show typical and consistently ranged values for each housing system.

In this work, a 'multi-site approach' was used which recognizes that quantifying livestock PM emissions comprises systematic effects of housing systems, random effects of houses within each housing system, and a random error term representing variation in time within houses. To increase our understanding of relevant sources of variation, and ultimately improve the accuracy of sampling strategies, variation between and within houses for each housing system could be described by the variance between houses (i.e., σ^2_j in Eq. 2) and the variance within houses (i.e., σ^2_{ij} in Eq. 2). Expressed as coefficient of variation (i.e., relative standard deviation, calculated as the square root of the variance on the natural-log scale), the pooled variation between houses for PM_{10} emission rate in our dataset (pig and poultry houses) was 23%, and the pooled variation within houses was 68%. For $PM_{2.5}$, these values were 26% and 93% respectively. Ideally, variances should be reliably estimated for each housing system. For this, however, the number of houses per housing system in our dataset (2 or 4) was insufficient. The outside temperature (Supplementary information 4) and the moment in the growing period (Fig. 3) are promising candidates to serve as covariates. In the present study however, we refrained from the use of covariates, because their effect, i.e., their slope, cannot be expected to be the same for different housing systems, and the present data are not informative enough to account for interaction between covariates and housing systems. In view of the aforementioned considerations, the analysis and emission estimates in Table 4 and Supplementary information 7 are presented with some reservation, even though the dataset presented here is presumably one of the largest in its kind. Nevertheless, we believe that the estimates give a useful, albeit first indication of the PM_{10} and $PM_{2.5}$ emissions from livestock production in the Netherlands.

CONCLUSIONS

In this study, we investigated climate conditions, ventilation rates, and concentrations and emissions of particulate matter (primarily PM_{10} and $PM_{2.5}$, next to inhalable PM) in 36 farm locations, which covered 13 main housing systems for poultry, pigs, and dairy cattle in the Netherlands. Our main results and conclusions are:

- The temperature and relative humidity measured outside the animal houses were consistent with long-term meteorological trends in the Netherlands. In pig and poultry houses, mean inside temperatures ranged from 19.9 to 26.7 °C and mean inside relative humidities ranged from 53.8 to 71.6%. In the open and uninsulated dairy houses, temperature ranged from 7.3 to 26.9 °C, whereas the relative humidity ranged from 50.7 to 95.2%. These results show that emissions of PM were determined at representative climate conditions.
- On an animal basis, mean ventilation rates ranged from 2.1 to 12.2 $m^3\ h^{-1}$ in poultry and from 9.0 to 63.5 $m^3\ h^{-1}$ in pigs. The mean ventilation rate in dairy cattle was 862 $m^3\ h^{-1}$. The mean inside concentrations of CO_2 ranged from 1327 to 2177 ppm in poultry and from 1629 to 2429 ppm in pigs. In dairy cattle, the mean inside concentration of CO_2 was 819 ppm. Ventilation rate increased with increasing outside temperature and with the age of growing animals. The ventilation capacity of mechanically ventilated buildings and the measured ventilation rates were generally in agreement with Dutch ventilation guidelines, which shows that concentrations and emissions of PM have been determined at representative ventilation rates.
- Mean inside concentrations of PM_{10} ranged from 1280 to 3362 µg m^{-3} in poultry, from 415 to 1091 µg m^{-3} in pigs. The mean inside concentration of PM_{10} in dairy cattle was 40.0 µg m^{-3}. Mean inside concentrations of $PM_{2.5}$ ranged from 120 to 351 µg m^{-3} in poultry and from 37.8 to 53.5 µg m^{-3} in pigs. The mean inside concentration of $PM_{2.5}$ in dairy cattle was 13.8 µg m^{-3}. For growing animals, inside PM concentration increased linearly with increasing age. For non-growing animals, PM concentration decreased with increasing ventilation rate. Outside poultry and pig houses, PM_{10} concentrations were often higher than those obtained from the nearest National Air Quality Monitoring station, whereas outside dairy cattle houses, these concentrations were similar.
- On an animal basis, geometric mean emission rates of PM_{10} ranged from 2.2 to 12.0 mg h^{-1} in poultry and from 7.3 to 22.5 mg h^{-1} in pigs. The mean PM_{10} emission rate in dairy cattle was 8.5 mg h^{-1}. Geometric mean emission rates of $PM_{2.5}$ ranged from 0.11 to 2.41 mg h^{-1} in

poultry and from 0.21 to 1.56 mg h^{-1} in pigs. The mean $PM_{2.5}$ emission rate in dairy cattle was 1.65 mg h^{-1}. PM emission rates increased exponentially with increasing age in broilers and turkeys and increased linearly with increasing age in weaners and fatteners. In laying hens, broiler breeders, sows, and dairy cattle, emission levels were variable throughout the year. The emission rates found here and in literature show typical and consistently ranged values for each housing system.

ACKNOWLEDGMENTS

This study was commissioned by the Dutch Ministry of Economic affairs, Agriculture and Innovation, and the Dutch Ministry of Infrastructure and Environment. We thank the farmers for their participation in this project. We acknowledge Mr. Freerk Dousma, Mr. Alfred Gerrits, Mr. Theo van Hattum, Mrs. Annemieke Hol, Mr. Jos Huis in't Veld, Ms. Renske Kwikkel, Mr. Guus Nijeboer and Mr. Johan Ploegaert for carrying out the field measurements, Mr. Eef Lovink for maintenance and calibrations, Mr. Jean Slangen and Mr. Geert Kupers for carrying out the lab analyses, and Mr. Johan van Riel, Mr. Bas Engel, and Mr. Pieter Vereijken for fruitful discussions on the statistical procedures.

REFERENCES

Aarnink, A.J.A., van Harn, J., van Hattum, T.G., Zhao, Y., Ogink, N.W.M., 2011. Dust reduction in broiler houses by spraying rapeseed oil. *Trans. ASABE* 54:1479–1489.

Blanes, V., Pedersen, S., 2005. Ventilation flow in pig houses measured and calculated by carbon dioxide, moisture and heat balance equations. *Biosyst. Eng.* 92:483–493.

Brunekreef, B., Holgate, S.T., 2002. Air pollution and health. Lancet 360, 1233–1242.

Calvet, S., Estelles, F., Cambra-Lopez, M., Torres, A.G., van den Weghe, H.F.A., 2011. The influence of broiler activity, growth rate, and litter on carbon dioxide balances for the determination of ventilation flow rates in broiler production. *Poult. Sci.* 90:2449–2458.

Calvet, S., Gates, R.S., Zhang, G., Estellés, F., Ogink, N.W.M., Pedersen, S., Berckmans, D., 2013. Measuring gas emissions from livestock buildings: A review on uncertainty analysis and error sources. *Biosyst. Eng.* 116:221–231.

Calvet, S., van den Weghe, H., Kosch, R., Estellés, F., 2009. The influence of the lighting program on broiler activity and dust production. *Poult. Sci.* 88:2504–2511.

Calvet, S.F.E., Cambra-López, M., Torres, A.G., 2012. Measuring ventilation using carbon dioxide balances: Evolution of CO 2 production from litter in two broiler cycles. In: 9th International Livestock Environment Symposium 2012, ILES 2012, Valencia, Spain, pp. 123–128.

Cambra-López, M., Aarnink, A.J.A., Zhao, Y., Calvet, S., Torres, A.G., 2010. Airborne particulate matter from livestock production systems: A review of an air pollution problem. *Environ. Pollut.* 158:1–17.

CEN, 1993. EN 481:1993. Workplace atmospheres - Size fraction definitions for measurement of airborne particles. European Committee for Standardization (CEN), Brussels, Belgium.

CEN, 1998. EN 12341:1998. Air quality - Determination of the PM 10 fraction of suspended particulate matter - Reference method and field test procedure to demonstrate reference equivalence of measurement methods. European Committee for Standardization (CEN), Brussels, Belgium.

CEN, 2005. EN 14907:2005. Ambient air quality - Standard gravimetric measurement method for the determination of the PM2.5 mass fraction of suspended particulate matter. European Committee for Standardization (CEN), Brussels, Belgium.

Chardon, W.J., Van der Hoek, K.W., 2002. Berekeningsmethode voor de emissie van fijn stof vanuit de landbouw [Calculation method for emission of fine dust from agriculture; in Dutch]. Report 682, Alterra, Wageningen, the Netherlands.

Costa, A., Borgonovo, F., Leroy, T., Berckmans, D., Guarino, M., 2009. Dust concentration variation in relation to animal activity in a pig barn. *Biosyst. Eng.* 104:118–124.

Heederik, D.J.J., Opstal-van Winden, A.J.W., Smit, L.A.M., Wouters, I.M., Hooiveld, M., IJzermans, C.J., van der Sman-de Beer, F., Spreeuwenberg, P.P.M., de Bruin, A., van Rotterdam, B., 2011. Mogelijke effecten van intensieve-veehouderij op de gezondheid van omwonenden: onderzoek naar potentiële blootstelling en gezondheidsproblemen. Institute for Risk Assessment Sciences (IRAS), Universiteit Utrecht, Utrecht, the Netherlands.

Hinz, T., Linke, S., 1998. A comprehensive experimental study of aerial pollutants in and emissions from livestock buildings. Part 2: Results. *J. Agric. Eng. Res.* 70:119–129.

ISO, 1995. ISO 7708. Air Quality – Particle size fraction definitions for health related sampling. International Organization for Standardization (ISO), Genève, Switzerland.

Joo, H.S., Ndegwa, P.M., Heber, A.J., Ni, J.Q., Bogan, B.W., Ramirez-Dorronsoro, J.C., Cortus, E.L., 2013. Particulate matter dynamics in naturally ventilated freestall dairy barns. *Atmos. Environ.* 69:182–190.

Li, H., Xin, H., Liang, Y., Gates, R.S., Wheeler, E.F., Heber, A.J., 2005. Comparison of direct vs. indirect ventilation rate determinations in layer barns using manure belts. *Trans. ASABE* 48:367–372.

Liang, Y., Xin, H., Wheeler, E.F., Gates, R.S., Li, H., Zajaczkowski, J.S., Topper, P.A., Casey, K.D., Behrends, B.R., Burnham, D.J., Zajaczkowski, F.J., 2005. Ammonia emissions from U.S. laying hen houses in Iowa and Pennsylvania. *Trans. ASAE* 48:1927–1941.

Mosquera, J., Groenestein, C.M., Ogink, N.W.M., Aarnink, A.J.A., 2012. Evaluation of the CO2 mass balance method to calculate ventilation rates from mechanically ventilated livestock buildings. In: 9th International Livestock Environment Symposium (ILES IX), Valencia, Spain.

Ni, J.Q., Vinckier, C., Hendriks, J., Coenegrachts, J., 1999. Production of carbon dioxide in a fattening pig house under field conditions. II. Release from the manure. *Atmos. Environ.* 33:3697–3703.

Ogink, N.W.M., Hofschreuder, P., Aarnink, A.J.A., 2011. Protocol for the measurement of fine dust emissions from housings in animal production 2010 [in Dutch]. Report 492, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Pedersen, S., Blanes-Vidal, V., Joergensen, H., Chwalibog, A., Haeussermann, A., Heetkamp, M.J.W., Aarnink, A.J.A., 2008. Carbon dioxide production in animal houses: a literature review. Manuscript BC 08 008, Agricultural Engineering International: *CIGR Ejournal* X.

Pope, C.A., Dockery, D.W., 2006. Health effects of fine particulate air pollution: Lines that connect. *J. Air Waste Manag. Assoc.* 56:709–742.

PPE-PVE, 2012. Livestock, meat and eggs in the Netherlands: keyfacts 2011 (edition 2012). Dutch Product Board for Poultry and Eggs (PVE) and the Dutch Product Board for Livestock and Meat (PVV), Zoetermeer, the Netherlands.

Schrade, S., Keck, M., Zeyer, K., Emmenegger, L., 2014. PM10 emission measurements in six Swiss dairy cubicle housing systems with natural ventilation and an outdoor exercise area. In: International Conference of Agricultural Engineering (AgEng), Zurich, Switzerland.

Seedorf, J., Hartung, J., Schroder, M., Linkert, K.H., Pedersen, S., Takai, H., Johnsen, J.O., Metz, J.H.M., Koerkamp, P., Uenk, G.H., Phillips, V.R., Holden, M.R., Sneath, R.W., Short, J.L., White, R.P., Wathes, C.M., 1998. A survey of ventilation rates in livestock buildings in Northern Europe. *J. Agric. Eng. Res.* 70:39–47.

Takai, H., Pedersen, S., Johnsen, J.O., Metz, J.H.M., Groot Koerkamp, P.W.G., Uenk, G.H., Phillips, V.R., Holden, M.R., Sneath, R.W., Short, J.L., White, R.P., Hartung, J., Seedorf, J., Schröder, M., Linkert, K.H., Wathes, C.M., 1998. Concentrations and emissions of airborne dust in livestock buildings in Northern Europe. *J. Agric. Eng. Res.* 70:59–77.

Van der Hoek, K.W., 2007. Particulate matter emissions from animal production in the Netherlands. In: DustConf 2007 - How to improve air quality, Maastricht, the Netherlands.

Van Zanten, M.C., Van Alphen, A., Wesseling, J., Mooibroek, D., Nguyen, P.L., Groot Wassink, H., Verbeek, C., 2012. State of affairs of the national air quality cooperation programme 2012 [in Dutch, with English summary]. National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands.

VSN, 2013. GenStat reference manual (release 16). Ver. 16.2.0.11713, VSN-Int., Ltd, Hemel Hempstead, UK.

Wathes, C.M., Phillips, V.R., Holden, M.R., Sneath, R.W., Short, J.L., White, R.P., Hartung, J., Seedorf, J., Schröder, M., Linkert, K.H., Pedersen, S., Takai, H., Johnsen, J.O., Groot Koerkamp, P.W.G., Uenk, G.H., Metz, J.H.M., Hinz, T., Caspary, V., Linke, S., 1998. Emissions of aerial pollutants in livestock buildings in Northern Europe: Overview of a multinational project. *J. Agric. Eng. Res.* 70:3–9.

WUR, 2006. Leaflet normen klimaatinstellingen [Leaflet on standards for climate settings; in Dutch]. Wageningen UR Livestock Research, Secretariaat Klimaatplatform Pluimveehouderij, Sterksel, the Netherlands.

WUR, 2010. Leaflet maximale ventilatie in pluimveestallen [Leaflet on maximum ventilation rates in poultry houses; in Dutch]. Wageningen UR Livestock Research, Secretariaat Klimaatplatform Pluimveehouderij, Lelystad, the Netherlands.

Xin, H., Li, H., Burns, R.T., Gates, R.S., Overhults, D.G., Earnest, J.W., 2009. Use of CO 2 concentration difference or CO 2 balance to assess ventilation rate of broiler houses. *Trans. ASABE* 52:1353–1361.

Zhao, Y., Aarnink, A.J.A., Hofschreuder, P., Groot Koerkamp, P.W.G., 2009. Evaluation of an impaction and a cyclone pre-separator for sampling high PM10 and PM2.5 concentrations in livestock houses. *J. Aerosol Sci.* 40:868–878.

SUPPLEMENTARY INFORMATION 1: main characteristics and acronyms of the 13 housing systems in this study (h. = house or houses)

Housing system: acronyms and main characteristics	Nr. of houses	Air inlet and outlet, max. ventilation rate	Animals	Production cycle
LFH: laying hens in floor housing; ⅓ litter area (wood shavings, alfalfa), ⅔ elevated slatted floor above manure pit, forced drying of manure (1 h.), laying nests, chain feeders and lines with nipple or round drinkers	4	Side wall inlets End wall fans (2 h.) Roof fans (2 h.) 6.7–10.9 m^3 h^{-1} $bird^{-1}$	7–9 per m^2 4,300–17,500 per house	55–59 wk laying, 14–24 d empty
LAH: laying hens in aviary housing; litter floor (wood shavings, sand), aviary systems with manure belts (forced drying: 3 h.), laying nests, feeders and nipple drinkers, outdoor run (1 h.)	4	Side wall inlets End wall fans 6.5–8.7 m^3 h^{-1} $bird^{-1}$	14–18 per m^2, 10,900–36,900 per house	55–60 wk laying, 7–14 d empty
BRB: broiler breeders in floor housing; ⅓ litter area (wood shavings), ⅔ elevated slatted floor with manure pit, laying nests, male feed pans, female chain feeders	2	Side wall inlets End wall fans 15.3–19.5 m^3 h^{-1} $bird^{-1}$	7–8 per m^2, 8,121–10,253 per house, 9–10% males	40 wk laying, 3–4 wk empty
BRO: broilers on full litter (wood shavings), lines with feed pans, lines with nipple drinkers and drip cups, hot-air blowers	4	Side wall inlets End wall fans 6.2–9.4 m^3 h^{-1} $bird^{-1}$	22–24 per m^2 19,000–52,000 per house	42–49 d growing, 7 d empty
TUR: male turkeys on full litter (wood shavings, straw), lines with feed pans, water troughs or round drinkers, hot-air blowers	2	Side wall inlets End wall fans 99–109 m^3 h^{-1} $bird^{-1}$	3.0–3.4 per m^2 4,500–5,000 per house	16–17 wk growing, 10–14 d empty
SIH: sows in individual housing; rooms with feed alley and rows of confined gestation stalls, individual feed trough (dry feed) and drinking nipple, solid floor with slats, manure pit	2	Ceiling (baffle) inlet Ceiling fans 188–222 m^3 h^{-1} pig^{-1}	32–135 gestation stalls per room, 1.3 m^2 sow^{-1}	Continuous housing of pregnant gilts and sows
SGH: sows in group housing; similar to SIH but free access to gestation stalls and slatted aisles	2	Ceiling (baffle) inlet Ceiling fans 154–234 m^3 h^{-1} pig^{-1}	39–44 gestation stalls per room, 2.1–2.5 m^2 sow^{-1}	Idem
WFS: weaners in rooms with feed alley and pens with fully slatted floor, manure pit, dry feed	2	Ceiling or door inlet Ceiling fans 34–59 m^3 h^{-1} pig^{-1}	75–130 pigs in 1–4 pens, 0.3 m^2 pig^{-1}	6 wk growing (6 to 25 kg), 2–3 d empty
WPS: weaners; housing similar to WFS, but partially slatted floor (50%)	2	Ceiling inlet Ceiling fans 35 m^3 h^{-1} pig^{-1}	80 pigs in 4–8 pens per room, 0.3 m^2 pig^{-1}	Idem
FTH: fattening pigs in traditional housing; compartments with feed alley and trad. pens, partially slatted floor (43–53%), manure pit, dry feed	4	Ceiling or door inlet Ceiling fans 67–109 m^3 h^{-1} pig^{-1}	55–120 pigs in 6–8 pens, 0.7–0.8 m^2 pig^{-1}	120 d growing (25 to 118 kg), 3–4 d empty
FLD: fattening pigs; compartments with feed alley and pens with partially slatted floor (40%), pit with slanted walls and vacuum system for manure removal (low NH_3 emission), dry feed	2	Floor (feed alley) inlet Ceiling fans 59–104 m^3 h^{-1} pig^{-1}	132–144 pigs in 12 pens per room, 0.8–1.0 m^2 pig^{-1}	Idem
FLL: fattening pigs; housing similar to FLD, but with liquid feed	2	Floor (feed alley) inlet Ceiling fans 80–104 m^3 h^{-1} pig^{-1}	144–156 pigs in 12 pens, 0.75–1.0 m^2 pig^{-1}	Idem
DCH: dairy cattle in traditional cubicle housing; cubicles in 2–4 rows, walking aisles with fully slatted concrete floors, automatic slurry scraper (2 h.), slurry pit underneath slatted floor, drive through feed alley with feed fences, automatic concentrate feeders, water troughs, fan coolers (2 h.)	4	Natural: side wall inlet (eave openings or fully open with windbreak mesh/chicken wire and flexible wind curtains), outlet through ridge opening	50–170 cubicles per house, slatted aisles: 2.6–3.7 m^2 cow^{-1}	305–400 d lactation, 60 d dry period; pasture grazing (daytime) from April to October (3 h.)

SUPPLEMENTARY INFORMATION 2: estimation of ventilation rate from the CO_2 balance method (CBM)

For the CBM, we first estimated the total heat production of one animal (Φ_{total}; kW) based on input variables such as the animal's body weight, the energy content and consumption of feed, and production figures, applying the equations given by the CIGR (CIGR, 2002) in chapter two. For each measurement, farmers were asked to provide us with these input variables as accurate as possible, based on latest milk and egg production records, automatic poultry weighing system data, manual weighings of pigs, feed intake, energy content of feed, etcetera. For dairy cattle, we estimated a weighted mean animal weight representative for a measurement at a farm location, based on the number of pregnant heifers and lactating/dry cows present in the house, and by assuming their weights to be 500 and 625 kg respectively (cows were of the Holstein-Friesian breed). The calculated heat production was converted to a volumetric CO_2 production at the house level (i.e., by the animal and its manure) by the factors for various animal categories published in Table 6 of the review paper by Pedersen et al. (2008) (Fco_2; in: m^3 CO_2 h^{-1} kW^{-1}) and multiplied by the number of animals ($n_{animals}$) present in the house. Finally, the 24-h mean ventilation rate (Q; m^3 h^{-1}) was calculated using Eq. 1:

$$Q = \frac{\Phi_{total} \times Fco_2 \times n_{animals}}{([CO_2]_{exhaust} - [CO_2]_{inlet}) \times 10^{-6}} \quad (1)$$

where $[CO_2]_{exhaust}$ is the CO_2-concentration measured in the exhaust air, and $[CO_2]_{inlet}$ the CO_2 concentration measured in the inlet air (ppm). If available, we used the GC concentrations (132 of 147 measurements), in the other 35 cases we used the PAS concentration. Since Q was estimated on a 24-h basis, the diurnal variation in animal activity was not taken into account.

References

CIGR, 2002. 4th Report of Working Group on Climatization of animal houses. Heat and moisture production at animal and house levels (eds. Pedersen, S. and K. Sällvik). International Commission of Agricultural Engineering (CIGR), Section II.

Pedersen, S., Blanes-Vidal, V., Joergensen, H., Chwalibog, A., Haeussermann, A., Heetkamp, M.J.W., Aarnink, A.J.A., 2008. Carbon dioxide production in animal houses: a literature review. Manuscript BC 08 008, Agricultural Engineering International: *CIGR Ejournal* X.

SUPPLEMENTARY INFORMATION 3: climate conditions

The climate conditions inside and outside the houses are listed in Table 1. The means of the outside temperature and relative humidity were centered around the long term averages of the Netherlands (10.2 °C for ambient temperature and 80.4% for relative humidity; 1981–2010), which is the result of spreading the measurements over the year within each house. The overall mean (standard deviation, SD) outside temperature in this study was 11.2 (6.0) °C, and the overall mean (SD) outside relative humidity 81.0% (11.2%). In Fig. 1, the 24-h mean values of outside temperature and relative humidity are shown for all 202 measurements, together with the long-term average trends of these variables. From this figure, it is clear that the climate conditions in our dataset closely resembled these long-term trends.

Table 1 shows that the mean temperatures are higher, and that the mean relative humidities are lower, inside poultry and pig houses as compared to outside. Also, the ranges in temperature and relative humidity within the housing systems are narrower inside poultry and pig houses as compared to outside, as a result of the insulation and the ventilation systems in these buildings. Based on 24-h values, the inside temperature (Table 1) was generally above the Lower Critical Temperature as summarized for various animal types by Seedorf et al. (1998).

In the houses for egg-laying poultry (LFH, LAH, and BRB) the animals represented the only inside heat source. The temperature inside these houses was controlled by adjustment of the ventilation rate whereas the insulation of the building reduced external heat load by solar radiation in Summer and reduced heat loss in Winter. In BRO and TUR, additional heating was applied by hot-air blowers, and in weaners and fatteners by pen floor heating systems or heating of inlet air in the central corridor of the building. The dairy houses in this study all had partially open side walls with windbreak mesh or chicken wire, manually controlled and flexible wind curtains, a roof ridge opening and uninsulated corrugated roofs. In these naturally ventilated buildings, the inside climate very much resembled the outdoor environment (Table 1), as found earlier by Seedorf et al. (1998) as well. The outside temperature for DCH is higher than the long-term average, because measurements in this housing system were carried out from February to September, and during the relatively warm summer of 2009.

The mean climate conditions (Table 1) were generally very similar to those reported for layers in percheries, broilers on litter, sows on slats, weaners on slats, and dairy cows in cubicles reported by Seedorf et al. (1998) from the survey in Northern-Europe in the 1990s. Only for fattening pigs (FTH, FLD, and FLL) mean temperature in the present study is about 4°C higher, and relative humidity is about 9 percentage points lower, compared to fatteners on slats of that

study. In the Netherlands, the advised CO_2 concentration limit in pig houses was raised in the last decade from 2000 to 3000 ppm, causing a general decrease in ventilation levels and an increase in temperature, which might explain this difference.

Table 1
Temperature and relative humidity, inside and outside the animal houses (based on 24-h mean values).

Housing system	Temperature, inside (°C)		Relative humidity, inside (%)		Temperature, outside (°C)		Relative humidity, outside (%)	
	Mean	Min–Max	Mean	Min–Max	Mean	Min–Max	Mean	Min–Max
LFH	20.2	16.1–25.3	65.0	51.8–75.5	11.1	2.0–21.2	82.2	53.8–99.8
LAH	21.0	16.6–25.6	63.7	51.4–92.9	9.6	-3.3–21.8	82.6	60.5–96.5
BRB	21.5	20.2–22.3	68.3	48.8–90.4	10.2	-0.4–17.8	85.3	51.6–98.9
BRO	24.1	17.4–29.5	66.7	50.5–86.4	10.4	2.3–19.5	82.2	54.5–96.4
TUR	19.9	15.6–23.6	71.6	64.1–86.3	10.7	1.5–19.7	81.4	68.0–99.9
SIH	21.3	18.1–24.0	59.6	43.3–74.3	10.0	3.5–18.7	80.7	45.1–93.5
SGH	22.7	19.4–26.1	64.7	48.7–84.0	11.5	1.3–17.7	81.4	60.5–94.5
WFS	26.7	25.0–29.5	53.8	41.2–69.1	13.5	6.4–23.0	77.5	65.5–92.5
WPS	26.0	24.2–28.5	54.9	41.9–64.8	8.4	-0.6–18.8	84.9	74.4–93.4
FTH	25.1	20.1–28.0	57.9	41.0–73.8	12.0	-0.5–19.8	81.5	64.0–92.9
FLD	25.2	23.2–27.9	53.9	44.0–78.0	12.0	6.2–21.6	77.4	52.9–93.3
FLL	25.1	22.3–26.7	57.2	45.1–71.4	9.3	-0.7–18.7	80.6	64.5–97.5
DCH	17.5	7.3–26.9	74.3	50.7–95.2	15.0	5.7–22.5	74.8	48.6–98.6

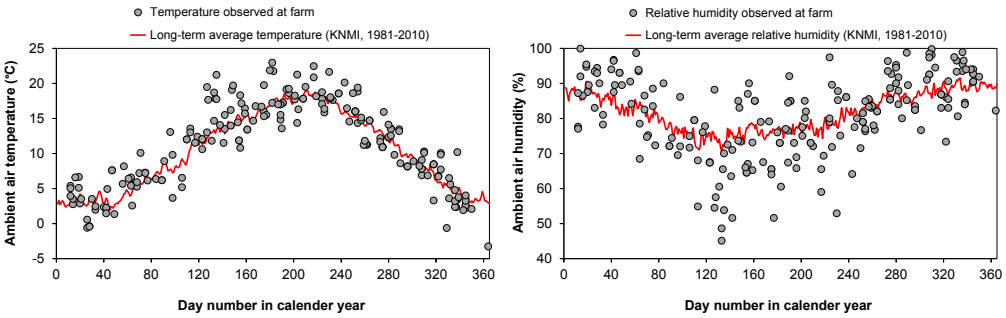


Fig. 1
Outside temperature and relative humidity during this study (based on 24-h mean values).

References

Seedorf, J., Hartung, J., Schroder, M., Linkert, K.H., Pedersen, S., Takai, H., Johnsen, J.O., Metz, J.H.M., Koerkamp, P., Uenk, G.H., Phillips, V.R., Holden, M.R., Sneath, R.W., Short, J.L., White, R.P., Wathes, C.M., 1998. A survey of ventilation rates in livestock buildings in Northern Europe. *J. Agric. Eng. Res.* 70:39–47.

SUPPLEMENTARY INFORMATION 4: ventilation rate

In Fig. 1 and Fig. 2, scatter plots are presented of the ventilation rates against the day number in the growing period (for growing animals; Fig. 1) or against the outside temperature (for non-growing animals; Fig. 2). Data points were obtained from multiple farms, and from multiple production cycles and seasons within each farm, which contributes to the heterogeneity of the plots. Nevertheless, the scatter plots indicate that ventilation rate increased exponentially with the age of BRO, increased linearly with the age of fattening pigs, increased exponentially with outside temperature in egg-laying poultry, increased linearly with outside temperature in sows, and increased with wind speed in DCH. For fattening pigs, ventilation rate clearly increased with increasing outside temperature as well (scatter plot not given), which showed that the ventilation rate depends on both the animal mass in the house, and the outside temperature.

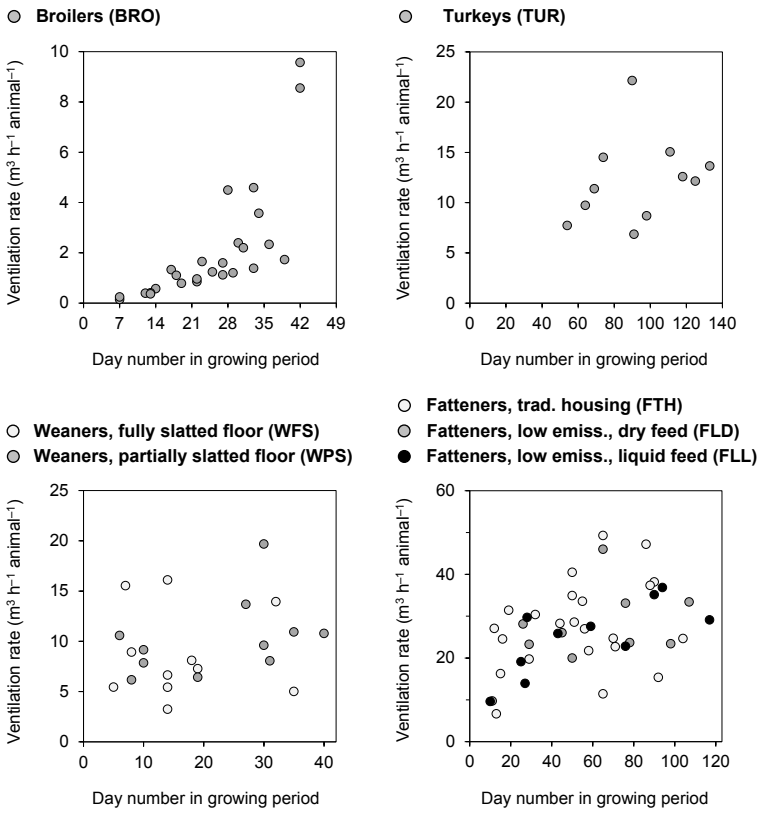


Fig. 1
Scatter plots of ventilation rates for housing systems with growing animals.

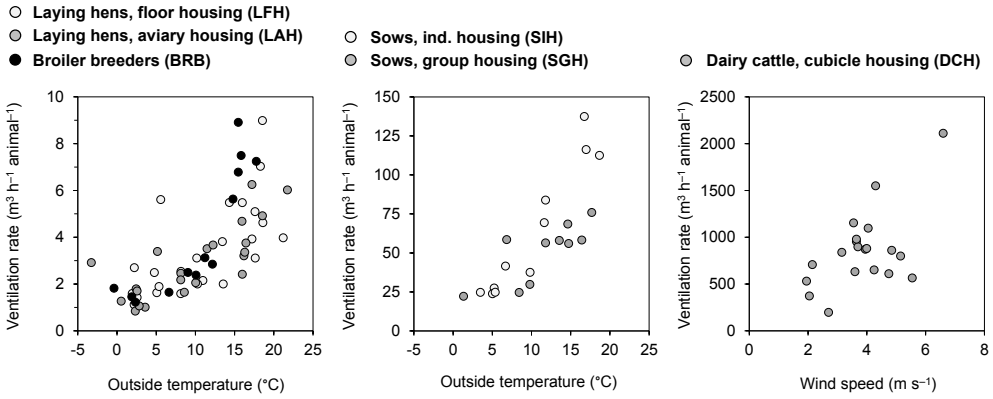


Fig. 2
Scatter plots of ventilation rates for housing systems with non-growing animals.

SUPPLEMENTARY INFORMATION 5: inside PM concentrations

In Fig. 1 and Fig. 2, scatter plots are given of the PM_{10} concentration against the day number in the growing period (for growing animals; Fig. 1) or against the ventilation rate (for non-growing animals; Fig. 2). These plots show that PM_{10} concentration increased linearly with increasing age in BRO, TUR, and fatteners (FTH, FLD, and FLL). When these animals grow, increasing amounts of feed are being delivered, more manure and skin debris is produced, and more force can be exerted on these PM sources, resulting in an increasing rate of disintegration and aerosolization. In egg-laying poultry (LFH, LAH, and BRB), sows (SIH and SGH) and DCH, PM_{10} concentration decreased with increasing ventilation rate, which presumably represents PM dilution due to the greater air exchange rate.

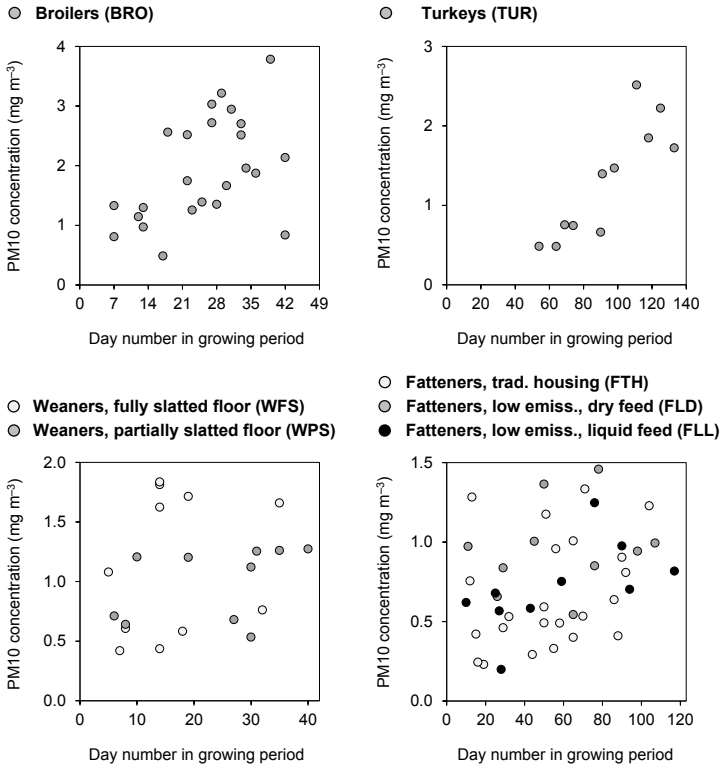


Fig. 1. Scatter plots of the PM_{10} concentration for housing systems with growing animals.

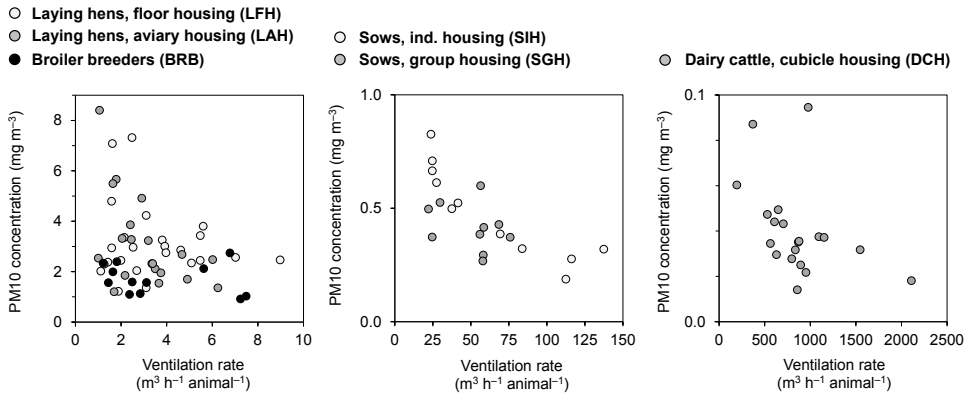


Fig. 2. Scatter plots of the PM_{10} concentration for housing systems with non-growing animals.

SUPPLEMENTARY INFORMATION 6: overview of publications reporting livestock PM_{10} and $PM_{2.5}$ emission rates [a] (all recalculated to mg h^{-1})

Animal type [b]	Country [c]	Concentration [µg m^{-3}]; mean [d] and (range)	Emission rate [mg h^{-1}]; mean [d] and (range)		Source; first author (year)
			Per animal	Per LU	
PM_{10}					
Layers, floor (2)	UK	-	5.79	-	Demmers (2010)
Layers, aviary (1)	IT	215	1.23	-	Costa (2012)
Layers, aviary (1)	IT	-	5.27	1700 (513–3229)	Valli (2012)
Layers, aviary (2)	USA	2300	4.58	1229	Hayes (2013)
Broilers, floor (4)	USA	-	1.10	536	Lacey (2003)
Broilers, floor (1)	CA	690	0.56	-	Roumeliotis (2007)
Broilers, floor (1)	DE	(10–5000)	1.97 (0.22–5.6)	-	Calvet (2009)
Broilers, floor (2)	UK	2990	1.32	-	Demmers (2010)
Broilers, floor (1)	AU	365	-	981	Modini (2010)
Broilers, floor (1)	CA	-	-	246	Roumeliotis (2010)
Broilers, floor (2)	USA	930 (110–4768)	1.88 (max. 7.1)	1358 (max. 13,291)	Lin (2012)
Turkeys, floor (1)	USA	720	-	727 (135–2133)	Schmidt (2002)
Turkeys, floor (1)	USA	-	(2.71–25.6)	(558–1200)	Li (2008)
Sows, slats (1)	IT	310 (<10–10,600)	-	29.2 (<1–750)	Haeussermann (2008)
Sows, slats (1)	IT	-	-	51.3	Costa (2009)
Weaners, slats (2)	IT	255 (<10–16,500)	-	64.4 (<1–1008)	Haeussermann (2008)
Weaners, slats (1)	IT	-	-	83.3	Costa (2009)
Fatteners, slats (1)	USA	935	-	126 (72–242)	Schmidt (2002)
Fatteners, slats (2)	USA	471 (135–1001)	-	120 (49–192)	Koziel (2004)
Fatteners, slats (2)	IT, DE	600 (20–5610)	-	167 (22–1242)	Haeussermann (2008)
Fatteners, slats (1)	IT	-	-	108	Costa (2009)
Fatteners, slats (6)	BE	719 (328–1746)	11.4	85.7 [e]	Van Ransbeeck (2013)
Dairy, cubicles (1)	USA	60	-	33 (5–83)	Schmidt (2002)
Dairy, cubicles (2)	USA	106 (22–240)	560	-	Joo (2013)
Dairy, cubicles (6)	CH	(<10–69)	-	(0.83–87.5)	Schrade (2014)
$PM_{2.5}$					
Layers, floor (2)	UK	-	1.52	-	Demmers (2010)
Layers, aviary (2)	USA	250	0.33	87.5	Hayes (2013)
Broilers, floor (1)	CA	190	0.12	-	Roumeliotis (2007)
Broilers, floor (2)	UK	655	0.21	-	Demmers (2010)
Broilers, floor (1)	AU	79	-	216	Modini (2010)
Broilers, floor (1)	CA	-	-	58.3	Roumeliotis (2010)
Broilers, floor (2)	USA	-	0.22 (max. 0.49)	70.8 (max. 129)	Lin (2012)
Fatteners, slats (6)	BE	38 (15.2–105)	0.89	6.7 [e]	Van Ransbeeck (2013)
Dairy, cubicles (2)	USA	19 (4–44)	117	-	Joo (2013)

[a] For animal housing layouts comparable to those studied here in this work (Table 1), i.e., no cage housing for layers, deep-litter systems, sow farrowing rooms, mechanically ventilated dairy houses, or cattle feedlots.
[b] Number of houses in parenthesis.
[c] ISO 3166-1 country code.
[d] Arithmetic mean.
[e] Our calculations, based on a mean live weight of 66.5 kg (weights given in article).

References

Calvet, S., van den Weghe, H., Kosch, R., Estellés, F., 2009. The influence of the lighting program on broiler activity and dust production. *Poult. Sci.* 88:2504–2511.

Costa, A., Ferrari, S., Guarino, M., 2012. Yearly emission factors of ammonia and particulate matter from three laying-hen housing systems. *Anim. Prod. Sci.* 52:1089–1098.

Costa, A., Guarino, M., 2009. Definition of yearly emission factor of dust and greenhouse gases through continuous measurements in swine husbandry. *Atmos. Environ.* 43:1548–1556.

Demmers, T.G.M., Saponja, A., Thomas, R., Phillips, G.J., McDonald, A.G., Stagg, S., Bowry, A., Nemitz, E., 2010. Dust and ammonia emissions from UK poultry houses. In: XVII-th World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR), Québec City, Canada.

Haeussermann, A., Costa, A., Aerts, J.M., Hartung, E., Jungbluth, T., Guarino, M., Berckmans, D., 2008. Development of a dynamic model to predict PM10 emissions from swine houses. *J. Environ. Qual.* 37:557–564.

Hayes, M.D., Xin, H., Li, H., Shepherd, T.A., Zhao, Y., Stinn, J.P., 2013. Ammonia, greenhouse gas, and particulate matter emissions of aviary layer houses in the Midwestern U.S. *Trans. ASABE* 56:1921–1932.

Joo, H.S., Ndegwa, P.M., Heber, A.J., Ni, J.Q., Bogan, B.W., Ramirez-Dorronsoro, J.C., Cortus, E.L., 2013. Particulate matter dynamics in naturally ventilated freestall dairy barns. *Atmos. Environ.* 69:182–190.

Koziel, J.A., Baek, B.H., Bush, K.J., Balota, A., Bayley, C.L., Sweeten, J.M., 2004. Emissions of particulate matter from swine finish barns in Texas. In: Proceedings of the AgEng 2004 "Engineering the Future" Conference, Leuven, Belgium.

Lacey, R.E., Redwine, J.S., Parnell Jr, C.B., 2003. Particulate matter and ammonia emission factors for tunnel-ventilated broiler production houses in the southern U.S. *Trans. ASABE* 46:1203–1214.

Li, H., Xin, H., Burns, R.T., Hoff, S.J., Harmon, J.D., Jacobson, L.D., Noll, S.L., 2008. Effects of bird activity, ventilation rate and humidity on concentration and emission rate of a turkey barn. In: 8th International Livestock Environment Symposium, ILES VIII, Iguassu Falls, Brasil, pp. 111–116.

Lin, X.J., Cortus, E.L., Zhang, R., Jiang, S., Heber, A.J., 2012. Air emissions from broiler houses in California. *Trans. ASABE* 55:1895–1908.

Modini, R.L., Agranovski, V., Meyer, N.K., Gallagher, E., Dunlop, M., Ristovski, Z.D., 2010. Dust emissions from a tunnel-ventilated broiler poultry shed with fresh and partially reused litter. *Anim. Prod. Sci.* 50:552–556.

Roumeliotis, T.S., Dixon, B.J., Van Heyst, B.J., 2010. Characterization of gaseous pollutant and particulate matter emission rates from a commercial broiler operation part II: Correlated emission rates. *Atmos. Environ.* 44:3778–3786.

Roumeliotis, T.S., Van Heyst, B.J., 2007. Size fractionated particulate matter emissions from a broiler house in Southern Ontario, Canada. *Sci. Total Environ.* 383:174–182.

Schmidt, D.R., Jacobson, L.D., Janni, K.A., 2002. Continuous monitoring of ammonia, hydrogen sulfide and dust emissions from swine, dairy and poultry barns. In: ASAE Annual International Meeting, ASAE Meeting Paper No. 024060, American Society of Agricultural Engineers (ASAE), Chicago, USA.

Schrade, S., Keck, M., Zeyer, K., Emmenegger, L., 2014. PM10 emission measurements in six Swiss dairy cubicle housing systems with natural ventilation and an outdoor exercise area. In: International Conference of Agricultural Engineering (AgEng), European Society of Agricultural Engineers, Zurich, Switzerland.

Valli, L., Moscatelli, G., Labartino, N., 2012. Ammonia and particulate matter emissions from an alternative housing system for laying hens. In: Emissions of Gas and Dust from Livestock (EmiLi 2012), Saint-Malo, France, pp. 103–106.

Van Ransbeeck, N., Van Langenhove, H., Demeyer, P., 2013. Indoor concentrations and emissions factors of particulate matter, ammonia and greenhouse gases for pig fattening facilities. *Biosyst. Eng.* 116:518–528.

SUPPLEMENTARY INFORMATION 7: Arithmetic mean and standard deviation between houses (SD_{BH}) of original-scaled PM emission rates, model-estimated mean emission rates on the natural log-scale (SE: standard error), and back-transformed mean emission rates (i.e., geometric means on the original scale), each expressed per Livestock Unit (LU), and per Heat Production Unit (HPU)

Housing system	Nr. of houses	*n*	Emission rate					
			mg h^{-1} LU^{-1}			mg h^{-1} HPU^{-1}		
			Mean (SD_{BH}); original-scaled data	Log-transformed mean (SE)	Back-transf. mean	Mean (SD_{BH}); original-scaled data	Log-transformed mean (SE)	Back-transf. mean
Inh. PM								
LFH	4	19	7634 (4268)	8.66 (0.19)	5739	2326 (1285)	7.47 (0.19)	1746
BRO	4	18	3058 (726)	7.84 (0.19)	2540	613 (158)	6.16 (0.20)	473
SIH	2	8	170 (15)	5.05 (0.28)	156	246 (21.8)	5.42 (0.29)	225
WPS	1	5	899 (–)	6.73 (0.36)	835	418 (–)	5.94 (0.38)	379
FTH	4	20	437 (219)	5.91 (0.18)	367	264 (136)	5.39 (0.19)	219
FLD	1	2	863 (–)	6.76 (0.50)	863	480 (–)	6.17 (0.52)	479
DCH	4	19	215 (28)	5.07 (0.19)	159	200 (34.0)	4.99 (0.19)	146
PM_{10}								
LFH	4	23	2858 (1134)	7.76 (0.17)	2343	872 (342)	6.57 (0.17)	713
LAH	4	22	2216 (499)	7.59 (0.17)	1978	666 (148)	6.39 (0.17)	595
BRB	2	12	913 (9.80)	6.51 (0.23)	671	345 (7.37)	5.55 (0.24)	257
BRO	4	24	1439 (621)	7.08 (0.16)	1190	289 (132)	5.40 (0.17)	221
TUR	2	11	658 (124)	6.44 (0.23)	627	230 (50.5)	5.37 (0.25)	214
SIH	2	11	48.9 (2.26)	3.84 (0.23)	46.7	70.6 (3.73)	4.21 (0.25)	67.3
SGH	2	10	51.3 (21.2)	3.87 (0.24)	48.1	70.2 (30.5)	4.18 (0.25)	65.4
WFS	2	11	278 (60.4)	5.60 (0.23)	272	164 (38.1)	5.07 (0.25)	159
WPS	2	10	268 (22.4)	5.56 (0.24)	260	130 (12.4)	4.80 (0.25)	122
FTH	4	23	130 (57.0)	4.77 (0.16)	118	82.1 (39.2)	4.29 (0.17)	73.3
FLD	2	10	199 (39.4)	5.26 (0.24)	192	120 (22.5)	4.76 (0.25)	117
FLL	2	10	117 (18.1)	4.71 (0.24)	111	84.9 (10.2)	4.31 (0.25)	74.7
DCH	4	20	6.91 (2.20)	n.d.	n.d.	6.39 (2.07)	n.d.	n.d.
$PM_{2.5}$								
LFH	4	23	154 (67.3)	4.66 (0.22)	105	47.0 (20.4)	3.46 (0.23)	31.9
LAH	4	22	128 (35.0)	4.69 (0.23)	108	38.4 (10.2)	3.48 (0.23)	32.6
BRB	2	12	68.6 (3.74)	3.64 (0.31)	38.2	25.8 (1.13)	2.68 (0.32)	14.6
BRO	4	24	96.7 (48.6)	4.09 (0.22)	59.7	20.1 (10.8)	2.39 (0.23)	10.9
TUR	2	10	156 (17.1)	4.87 (0.33)	130	55.5 (5.46)	3.79 (0.33)	44.1
SIH	2	10	4.06 (1.36)	1.23 (0.33)	3.43	5.37 (2.01)	1.60 (0.33)	4.95
SGH	2	10	3.67 (1.34)	1.25 (0.33)	3.48	5.01 (1.95)	1.55 (0.33)	4.73
WFS	2	11	9.39 (4.48)	2.12 (0.32)	8.31	5.50 (2.71)	1.58 (0.33)	4.85
WPS	2	10	6.73 (1.16)	1.82 (0.33)	6.19	3.28 (0.53)	1.06 (0.33)	2.89
FTH	4	23	6.45 (3.45)	1.70 (0.22)	5.48	4.12 (2.36)	1.23 (0.23)	3.41
FLD	2	10	8.62 (1.19)	2.11 (0.33)	8.22	5.15 (0.61)	1.61 (0.33)	4.98
FLL	2	10	5.01 (1.09)	1.45 (0.33)	4.25	3.67 (1.00)	1.05 (0.33)	2.87
DCH	4	20	1.33 (0.49)	n.d.	n.d.	1.23 (0.49)	n.d.	n.d.

n.d.: not determined.

Chapter 3

Abatement of particulate matter emission from experimental broiler housings using an optimized oil spraying method

A. Winkel [a], M. Cambra-López [b], P.W.G. Groot Koerkamp [a,c], N.W.M. Ogink [a], and A.J.A. Aarnink [a]

[a] Wageningen UR Livestock Research, Wageningen, the Netherlands
[b] Institute of Animal Science and Technology,Universidad Polytéchnica de Valencia, Valencia, Spain
[c] Farm Technology Group, Wageningen University, Wageningen, the Netherlands

Transactions of the ASABE (2014) 57:1853–1864

Reprinted with permission from the American Society of Agricultural and Biological Engineers
Available online at: https://dx.doi.org/10.13031/trans.57.10870

ABSTRACT

In this follow-up study, we investigated effects of two rapeseed oil application rates (8 or 16 mL m^{-2} d^{-1}) in combination with two spraying frequencies (daily or every other day) in four oil treatments: 8 mL m^{-2} $(24\ h)^{-1}$, 16 mL m^{-2} $(48\ h)^{-1}$, 16 mL m^{-2} $(24\ h)^{-1}$, and 32 mL m^{-2} $(48\ h)^{-1}$ during two growth cycles of broilers. Oil treatments were randomly assigned to four rooms, whereas two rooms served as control (0 mL m^{-2}). Oil spraying started on day 21. Prior to the second growth cycle, the spraying system was optimized to improve the distribution of oil and reduce the generation of small oil particles. We measured concentrations of PM_{10}, $PM_{2.5}$, ammonia, and odor, and ventilation rate. Furthermore, we recorded bird performance and birds' exterior quality. PM_{10} emission was significantly reduced by 59% at 8 mL m^{-2} d^{-1} and by 64% at 16 mL m^{-2} d^{-1}. For $PM_{2.5}$, these values were 81% and 74% respectively. In the two 'every other day' treatments, PM_{10} emission was 44% higher on days after spraying than on spraying days. No significant effect of oil spraying was found on ammonia emission, odor emission, bird performance, and birds' exterior quality. The latter confirms that at an application rate of 16 mL m^{-2} d^{-1} the incidence of foot-pad lesions is not increased. It is recommended to validate the effects of oil spraying inside full-scale commercial broiler houses at a daily application of 16 mL m^{-2} or less.

INTRODUCTION

In many parts of the world, broiler chickens are reared inside mechanically ventilated buildings which house up to tens of thousands of birds on litter floors. The presence of litter (i.e., manure and bedding material), together with the feathers of the broilers, give rise to high concentrations of airborne particulate matter (PM) (Cambra-López et al., 2011; Winkel et al., 2015). The abundance of PM in the air of poultry houses is associated with an increased risk of respiratory diseases in poultry farmers (Omland, 2002; Radon et al., 2001). In broilers, exposure to airborne PM may devitalize the respiratory mucosa, damage bronchi, lungs and air sacs, facilitate the invasion of micro-organisms and affect body weight gain and mortality (Al Homidan et al., 2003; Madelin and Wathes, 1989). By their exhaust emissions, broiler houses may raise PM concentration in the ambient environment and thereby adversely affect respiratory and cardiovascular health of the general population (Brunekreef and Holgate, 2002). In the Netherlands, intensive livestock farming has been identified as the third largest source of particles with aerodynamic diameters smaller than 10 µm (PM_{10}), responsible for approximately 17% of the primary PM_{10} emitted nationally (RIVM, 2014). Limit concentrations for the ambient environment have been laid down by the European Union in EU directive 2008/50/EC (EU, 2008) for PM_{10} and for particles with aerodynamic diameters smaller than 2.5 µm ($PM_{2.5}$). Mitigation options for the most relevant PM sources are urgently needed to be able to comply to these limits and protect the population. Therefore, a research program was initiated with the aim to develop PM mitigation options for the poultry industry which were selected based on their efficacy and economic feasibility (Ogink and Aarnink, 2011).

One of these options is spraying vegetable oil to prevent particles on surfaces (e.g., litter floors) to become airborne. Effects of spraying oil, or oil-water mixtures, have been studied in pig houses (Takai, 2007), but in broiler houses only few studies have been carried out (Drost et al., 1999; Griffin and Vardaman, 1970; McGovern et al., 1999, 2000). The latter studies investigated the perspective of oil spraying to improve indoor air quality and the performance and health of the broilers. None of these studies however focused on the abatement of PM emission to the ambient environment.

In a first study (Aarnink et al., 2011) we used an oil spraying system installed inside four rooms of an experimental broiler house to investigate dose-response effects of spraying rapeseed oil (6 to 24 mL m^{-2} d^{-1}; daily spraying) on the reduction of PM and ammonia emission, on workers' exposure to PM, and on the performance and exterior quality of the broilers. That study showed that PM_{10} concentration and emission decreased with increasing oil application rate,

whereas no effect was found on ammonia emission and bird performance. The system however, produced small oil particles (<10 µm; aerodynamic diameter) during spraying and the application of 24 mL m^{-2} d^{-1} significantly increased the incidence and severity of foot-pad lesions as compared to the control treatment (0 mL m^{-2}). Based on this study it was advised not to exceed a maximum application rate of 16 mL m^{-2} d^{-1}.

In the present paper, we report a follow-up study from Aarnink et al. (2011) carried out in the same broiler house. The objective of this study was to further increase our understanding of the effects of oil application rate and application frequency on particulate and gaseous emissions, bird performance and birds' exterior quality. More explicitly, the main research questions within this study were:

- What is the effect of spraying oil daily versus a double dose every other day?
- What is the effect of oil spraying on odor emission?
- What is the effect of system optimizations on the generation of small oil particles?
- What is the effect of application rates of 16 mL m^{-2} d^{-1} or less on the exterior quality of the broilers?

MATERIAL AND METHODS

Experimental design

We investigated the effect of two oil application rates (8 or 16 mL m^{-2} d^{-1}) in combination with two spraying frequencies (daily or every other day) resulting in four oil treatments: 8 mL m^{-2} $(24\ h)^{-1}$, 16 mL m^{-2} $(48\ h)^{-1}$, 16 mL m^{-2} $(24\ h)^{-1}$, and 32 mL m^{-2} $(48\ h)^{-1}$. Oil treatments were randomly assigned to four broiler rooms, whereas two rooms served as control (0 mL m^{-2}). The experiment lasted for two consecutive growth cycles. In both cycles, oil spraying started on day 21.

Housing and animals

The study was conducted inside the broiler house at 'Het Spelderholt' experimental station in Lelystad, the Netherlands. Each room measured 8.32 × 16.06 m (133.6 m^2) and contained four feeding lines with seven feeders and eight drinking lines with 180 drinking nipples in total. The rooms were heated by a central heating system with radiators on the side walls underneath the air

inlets. In each room 2,675 one-day-old Ross 308 broilers (Probroed en Sloot, Groenlo, the Netherlands) were placed. The broilers were delivered at 35 days of age, at approximately 2.0 to 2.1 kg live weight. Broilers had ad libitum access to feed and drinking water. They were vaccinated against infectious bronchitis (IB), Gumboro, and New Castle Disease (NCD). The broilers received a pre-starter diet (crumb feed) during the first ten days, followed by a starter diet (granules and 15% wheat; days 11 to 28) and a finisher diet (granules and 30% wheat; days 29 to 35) (Superreeks diet, ForFarmers, Lochem, the Netherlands). During the first two days the rooms were continuously lit. During the rest of the growth cycle an intermittent light scheme was given of 8 h light and 4 h dark (07:45 to 15:45 (light); 15:45 to 19:45 (dark); 19:45 to 03:45 (light); 03:45 to 07:45 (dark)). Light intensity was the same for all rooms (20 lux). Between growth cycles litter was removed and feeders and drinking lines were pre-treated with a cleaning agent (PRO-REIN, CID LINES, Ieper, Belgium; 26 kg in 400 L water). After 30 min of soaking time, rooms were cleaned with a high-pressure cleaner using tap water. One day before the broilers were introduced, 1 kg m-2 of fresh wood shavings was spread in the rooms as bedding material. All rooms were heated to 33 °C 3 days before the broilers were placed in the rooms. The target temperatures at the different ages were: 33 °C at day 1, 28 °C at day 7, 25 °C at day 14, 22 °C at day 21, and 20 °C at day 35 (the temperatures between these days were linearly interpolated). Each room had 12 air inlets in the side walls and three exhaust fans in the roof (0.6 m dia., capacity: 7000 m^3 h^{-1} each, variable speed; Fancom B.V., Panningen, the Netherlands): one fan operated continuously and the other two operated when needed. Minimum ventilation was controlled at 1 m^3 h^{-1} per kg live weight. Based on the inside temperature, the ventilation rate was increased automatically by the climate computer (type: FSU.4; Fancom B.V., Panningen, the Netherlands). The maximum ventilation rate in the room was 21,000 m^3 h^{-1} or 7.9 m^3 h^{-1} $bird^{-1}$.

Oil spraying system

During the first growth cycle, the same oil spraying system was used as in Aarnink et al. (2011). This system consisted of full cone nozzles (type SU26B-SSBR, Spraying Systems, Ridderkerk, the Netherlands) installed on oil tubes (Fig. 1). Two oil tubes (PVC Kiwa tube, 32 mm dia.) were suspended across the room in parallel at a height of approximately 2.5 m. Four nozzles were placed on each tube, pointing in opposite directions. Each tube with nozzles had to

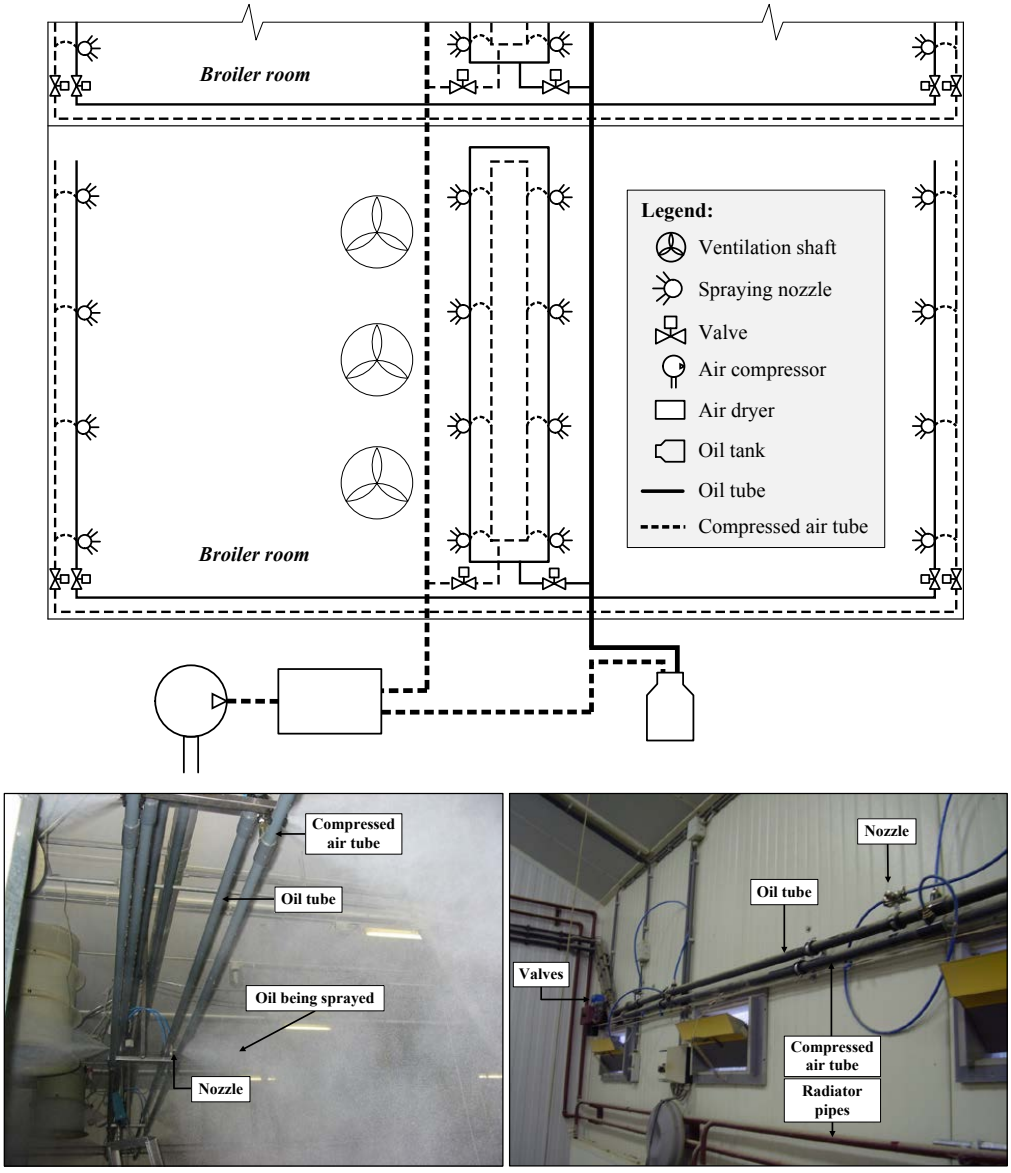


Fig. 1
Schematic plan view (top) and photographs of the oil spraying system during spraying (bottom left) and of the extra side wall nozzles spraying towards the centre of the room (bottom right).

cover half the area of the room (8 × 8 m). Oil was sprayed by injecting oil and air into the nozzles at the same time, both at a pressure of 3.5 bar. Compressed air was delivered through two tubes underneath the oil tubes (PVC Kiwa tube, 32 mm dia.). Air and oil pressure was delivered by a compressor (type CV 40, 3.0 kW, 400 VAC, 50 Hz) with an air dryer (model DE

101, 230 VAC, 0.36 kW, max. 16 bar, min. 5 °C, max. 43 °C; Airpress, Euro series, V.R.B. Friesland bv, Leeuwarden, the Netherlands). Oil and air delivery to the nozzles was controlled by valves (BE 024AS, 24 VAC, 50 Hz, 10 W, Danfoss, Hasselager, Denmark). The valves were opened for a certain time depending on how much oil needed to be sprayed in the room. The spraying was automatically controlled by a control unit (Moeller Easy 821-DC-TC, F-Central software, Fancom, Panningen, The Netherlands). The oil was delivered from a high-pressure tank (24 L, model N24, Mondeo, Montecchio Maggiore, Italy). Pure, cold-pressed, and refined rapeseed oil (density: 0.91 g mL^{-1}) was used, suitable to be used as bio-fuel for vehicles.

To achieve a more uniform distribution of oil over the litter floor, the oil spraying system was expanded prior to the second growth cycle, with two additional oil tubes per room, mounted on the side walls (Fig. 1). Both additional oil tubes contained four nozzles, thereby increasing the number of nozzles per room from eight to sixteen, and decreasing the litter floor area per oil tube from half of the room to a quarter of the room. The side wall nozzles sprayed towards the center of the room. To minimize the formation of small oil particles, oil pressure and air pressure were decreased in the second growth cycle from 3.5 to 3.0 bar. At these configurations, the volume median diameter of the oil particles was 44 µm and 49 µm respectively (Aarnink and Van Hattum, 2009).

Treatments

The oil spraying treatments were: 8 mL m^{-2} $(24\ h)^{-1}$, 16 mL m^{-2} $(48\ h)^{-1}$, 16 mL m^{-2} $(24\ h)^{-1}$, and 32 mL m^{-2} $(48\ h)^{-2}$. The relationship between spraying time and the amount of oil applied found in Aarnink et al. (2011) (0.4 mL m^{-2} s^{-1}) was used to determine spraying duration. Spraying times in the first growth cycle were 20 s for application of 8 mL m^{-2}, 40 s for application of 16 mL m^{-2}, and 80 s for application of 32 mL m^{-2}. In the second growth cycle, these spraying times were halved because twice the number of nozzles was used. No clear change in oil application rate was found due to the reduction of oil and air pressure from 3.5 to 3.0 bar. Previous work showed that PM concentrations and emissions strongly increased only after two to three weeks (Aarnink et al., 2011). Therefore, we started the oil spraying at day 21 of the growth cycle. On oil spraying days, oil was sprayed once, normally at 08:00. Only on the second day of each 24 h PM sampling period, oil was sprayed at 14:00, to protect the PM sampling equipment which sampled from noon to noon.

Measurements

An overview of measured variables is given in Table 1.

Table 1
Summary of measured variables.

Variable	Measurement method/instrument	Unit	Sampling duration	Time resolution	Frequency (days in growth cycle)
PM concentration					
PM_{10} and $PM_{2.5}$	Cyclone sampler	mg m^{-3}	24 h	24 h	16, 23, 30, 33
PM_{10} and $PM_{2.5}$ during oil spraying	Cyclone sampler	mg m^{-3}	2 h	2 h	25, 31 (2^{nd} cycle)
Personal PM_{10} exposure	DustTrak Aerosol Monitor	mg m^{-3}	7 min	1 min	25, 32, 33 (1^{st} cycle); 25, 32 (2^{nd} cycle)
Ammonia concentration	NH_3-converter, NO_x-monitor	mg m^{-3}	Continuous	-	-
Odor concentration	Dynamic olfactometry	OU_E m^{-3}	2 h	2 h	24, 31
Ventilation rate	Ventilation shaft anemometers	m^{-3} h^{-1}	Continuous	1 h	-
Environmental conditions					
Air temperature	Temperature sensor	°C	Continuous	1 h	-
Relative humidity	Relative humidity sensor	%	Continuous	1 h	-
Animal parameters					
Body weight	Weighing	g	-	-	0, 21, 34, 35
Feed consumption	Feed weighing system	kg d^{-1} $room^{-1}$	-	-	21, 35
Water consumption	Water meter	L d^{-1} $room^{-1}$	Continuous	1 day	Daily
Mortality	Visual inspection, counting	%	Continuous	1 day	Daily
Foot-pad lesions	Visual observation, scoring	Score	-	-	33
Exterior quality	Visual observation, scoring	Score	-	-	33
Rapeseed oil use	Weighing	kg d^{-1} $room^{-1}$	Continuous	1 day	Daily
Litter characteristics					
Dry matter content	Oven-drying, weighing	%	-	-	14, 28, 35
Manure cake formation	Visual observation	% of litter area	-	-	14, 28, 35
Room cleaning time	Visual observation	min	-	-	36

Particulate matter

Measurements of PM_{10} and $PM_{2.5}$ concentrations were done on four days spread over the growth cycle: on day 16, when oil spraying had not yet started, and during the oil spraying phase on days 23, 30, and 33; in both growth cycles. Duplicate PM samplers for sampling exhaust air were placed in each room near the shaft of the ventilator that was continuously running: 0.5 m

horizontally from the border of the exhaust opening and 0.1 m vertically below the exhaust opening. In the incoming air, single samples of PM_{10} and $PM_{2.5}$ were taken just outside the animal house. Sampling times were from noon to noon (24 h). These measurements were carried out to determine concentrations and emissions of PM.

PM_{10} and $PM_{2.5}$ concentrations were determined by gravimetric filtration, using sampling pumps (Tecora, model Charlie HV; Ravebo B.V., Brielle, the Netherlands) and cyclone samplers (URG, model URG-2000-30ENB for PM_{10} and URG-2000-30EG for $PM_{2.5}$; URG Corp., Chapel Hill, N.C.) at a sample flow rate of 16.7 L min^{-1}. Inside the cyclones, the aimed particle size was collected on a glass fiber filter (type GF-3, 47 mm dia., Macherey-Nagel, Düren, Germany). Unloaded and loaded filters were weighed with a precise balance (AT261 DeltaRange, Mettler, Greifensee, Switzerland; resolution: 10 µg) under standard conditions of 20 ± 1 °C and 50 ± 5% relative humidity (CEN, 1998, 2005). After 48 h of stabilization, filters were weighed four times spread over two consecutive days. The average value was recorded as the filter weight. The PM mass concentration was calculated by dividing the mass of collected PM by the volume of air drawn through the filter. PM_{10} concentrations were calibrated to the reference impaction sampler described in EN 12341 (CEN, 1998) using the equations reported by Zhao et al. (2009): $y = 1.09x$ (when $x \leq 223$ µg m^{-3}) and $y = 0.83x + 57.5$ (when $x > 223$ µg m^{-3}), where x is the concentration measured with the cyclone sampler and y is the calibrated concentration.

To assess the generation of small oil particles of the adapted oil spraying system during the second growth cycle, PM_{10} and $PM_{2.5}$ concentrations were additionally measured during the time around oil spraying on days 25 and 31. On these days, PM was sampled during 2 h (from 15 min before until 105 min after oil spraying) following the same procedures as described above.

Personal PM_{10} sampling

The exposure of stock handlers to PM_{10} was determined on days 25, 32, and 33 in the first growth cycle, and on days 25 and 32 in the second growth cycle, using a light-scattering device (DustTrak aerosol monitor, model 8520, TSI, Inc., Shoreview, Minn.). The DustTrak was attached to the stock handler's lapel, at a height of approximately 1.5 m, with the sampling inlet facing upward. Stock handlers wore respiratory masks to prevent directly breathing into the inlet. On a measuring day, the stock handler simulated daily animal care routine activities following a standard procedure for 7 min per room. Concentrations of PM_{10} (mg m^{-3}) close to the nose and mouth were measured each second and logged as one-minute means in the memory of the device.

Ammonia

Ammonia concentrations were measured semi-continuously by continuously sampling air from each room and by sequentially measuring concentrations in each room for 5 min with a NOx monitor (model ML8840, Monitor Labs, Englewood, Colo.). Aerial ammonia was first converted to NO at 775 °C by separate converters for each room. Exhaust air was sampled inside the shaft of the ventilator that was continuously running. The monitor was calibrated weekly with a gas of 40 ppm NO in nitrogen (N_2), and the flow rate was checked. Of each 5 min sampling period per room, only the data of the last minute were used and hourly mean ammonia concentrations were stored in a data logger.

Odor

Odor concentrations were measured on days 24 and 31 in both growth cycles. On these days, air samples were taken from 10:00 to 12:00 in each room using the 'lung principle' (vessels with 40 L Nalophan air sampling bags connected to electrical pumps; Thomas Industries Inc., Wabasha, Minn., model 607CD32; critical capillary: 0.5 L min^{-1}). The pump removed air from the vessel which caused the sampling bag to be filled with air taken from the room. The air samples were transported and stored according to EN 13725 (CEN, 2003) and odor concentrations (OU_E; European Odor Units) were determined by olfactometry within 30 h after sampling.

Ventilation rate, temperature, and humidity

The ventilation rate in all three ventilation shafts was measured with calibrated anemometers (ATM.56, Fancom, Panningen, the Netherlands) of the same diameter as the ventilation shafts. Hourly means were stored in a data logger. Temperature and relative humidity (RH) outside and in each room, near the ventilation shaft, were continuously measured with combined temperature/humidity sensors (HygroClip, Rotronic AG, Bassersdorf, Switzerland). The accuracy of these sensors was ±1.0 °C and ±2% RH. Hourly means were stored in a data logger.

Animal variables

All broilers were weighed on arrival at the broiler house (day 0) and before transport to the processing plant (day 35) by group weighing of birds in transportation crates. Furthermore, a sample of 100 broilers per room (50 males, 50 females) was weighed on days 21 (just before oil spraying started) and day 34. The amount of feed delivered to each room was recorded daily by the automatic feed weighing unit of the house and the amount of water was recorded by separate

water meters. Mortality numbers were recorded daily per room. Foot pad lesions and bird exterior quality were scored in samples of 100 broilers per room (50 males, 50 females) on day 33 of both growth cycles. Foot pad lesions were scored according to the protocol described by Berg (1998). Within this protocol, the foot-pads of the broilers are scored in three classes: class 0 = lesions absent or minor, class 1 = medium lesions, and class 2 = severe lesions. The final foot-pad score is calculated as follows: 100 × [(number of birds in class 0 × 0) + (number of birds in class 1 × 0.5) + (number of birds in class 2 × 2)] / total number of birds scored. Bird exterior quality was scored on breast dirtiness, breast irritations, scabby hips (thigh scratches), and hock burns in four classes (none, mild, medium, or severe) as described by Van Harn (2009).

Oil spraying

The amount of oil sprayed was measured daily by weighing the oil storage tank before and after spraying on a platform weighing unit (type FB 64EDE571205413; maximum capacity 64 kg, 0.4 × 0.3 m platform, Sartorius, Nieuwegein, the Netherlands). The time needed to clean the rooms was recorded at the end of both growth cycles.

Litter

On days 14, 28, and 35 of the growth cycle, litter samples were taken at six spots in each room (approx. 0.5 kg per room). The dry matter (DM) content of these samples was determined by weighing before and after oven-drying for 24 h at 105 °C. On the same days, the percentage of the litter floor being either friable or covered with solid manure cakes was scored by visual observation.

Data preparation and analysis

Calculation of emission rates

Emission rates of PM and ammonia were calculated using Eq. 1:

$$\text{Emission} = (C_{\text{exhaust}} - C_{\text{inlet}}) \times Q \quad (1)$$

where:

- Emission = emission rate (mg h^{-1} for PM_{10}, $PM_{2.5}$, and ammonia; OU_E s^{-1} for odor);
- $C_{exhaust}$ = exhaust air concentration (mg m^{-3} for PM_{10}, $PM_{2.5}$, and ammonia; OU_E m^{-3} for odor);

- C_{inlet} = inlet air concentration (mg m^{-3} for PM_{10}, $PM_{2.5}$, and ammonia; OU_E m^{-3} for odor);
- Q = ventilation rate (m^3 h^{-1} for PM_{10}, $PM_{2.5}$, and ammonia; m^3 s^{-1} for odor).

Estimation of airborne PM_{10} or $PM_{2.5}$ oil particles

Based on the PM_{10} and $PM_{2.5}$ concentration measurements during the time around oil spraying on days 25 and 31 in the second growth cycle, the proportion of oil applied measured as airborne particles in the PM_{10} and $PM_{2.5}$ fraction was estimated using Eq. 2:

$$PM_{oil} = \frac{\left[E_k - (1 - \eta_k) \times E_{control}\right] \times T \times \frac{1}{\rho}}{A} \times 100 \quad (2)$$

where:

- PM_{oil} = proportion of oil applied measured as airborne PM_{10} or $PM_{2.5}$ oil particles (%);
- E_k = emission of PM_{10} or $PM_{2.5}$ in treatment k during oil spraying (g h^{-1});
- η_k = relative reduction of PM_{10} or $PM_{2.5}$ in treatment k (0 to 1, based on the PM measurements outside spraying times);
- $E_{control}$ = emission of PM_{10} or $PM_{2.5}$ of control rooms during oil spraying (g h^{-1});
- T = sampling duration around oil spraying (h);
- ρ = density of rapeseed oil (0.91 g mL^{-1});
- A = application of oil (1069 mL $room^{-1}$ at 8 mL m^{-2}, 2138 mL $room^{-1}$ at 16 mL m^{-2}, and 4275 mL $room^{-1}$ at 32 mL m^{-2}).

In Eq. 2, the emission of PM from oil spraying rooms during spraying (E_k) is assumed to consist of oil particles and regular PM from litter and feathers. The amount of regular PM in E_k is estimated by $(1 - \eta_k) \times E_{control}$, whereas the amount of oil particles in E_k is determined by subtracting the amount of regular PM from E_k.

Statistical analysis

Reductions in emission rates of PM_{10} and $PM_{2.5}$ relative to the mean of control rooms were estimated and tested for significance with a longitudinal regression model which recognizes that repeated measurements over time were done within rooms. The treatments were split up in the model into effects of oil application rate (0, 8, or 16 mL m^{-2} d^{-1}) and effects of spraying frequency (daily or every other day). Interaction effects between oil application rate, spraying

frequency, growth cycle, and day in the growth cycle were not statistically significant and were therefore omitted from the final model, which is described by Eq. 3:

$$\mathrm{Log}(\underline{Y}_{ijklmn}) = \alpha_i + \beta_j + a \times \gamma_k + \theta_l + \underline{\varepsilon}_m + \underline{\varepsilon}_{mn} + \underline{\varepsilon}_{ijklmn} \quad (3)$$

where:

- $\log(\underline{Y}_{ijklmn})$ = response variable, i.e., the natural logarithm of the PM_{10} or $PM_{2.5}$ emission rate of oil application rate i and spraying frequency j, on relative moment k on day l of growth cycle m inside room n;
- α_i = effect of oil application rate i (0, 8, or 16 mL m^{-2} d^{-1});
- β_j = effect of spraying frequency j (daily or every other day);
- a = regression coefficient;
- γ_k = moment of the measurement in relation to the last oil spraying k (on the same day or on the day after);
- θ_l = effect of day l in the growth cycle (23, 30, and 33);
- $\underline{\varepsilon}_m \sim N(0,\sigma_m^2)$ = random growth cycle effect;
- $\underline{\varepsilon}_{mn} \sim N(0,\sigma_{mn}^2)$ = random room effect within growth cycles;
- $\underline{\varepsilon}_{ijklmn} \sim N(0;\sum\tau_j,\varphi_l^t)$ = random day effect correlated within rooms (autoregression), variance different between weeks.

The model described in Eq. 3 was also used to test significant differences between treatments and control for emission rates of ammonia and odor, with the only modification that treatments were not split into separate effects of oil application rate and spraying frequency. Bird performance data of days 0 to 21 (before oil spraying had started) and of days 0 to 35 were both analyzed by analysis of variance (ANOVA), with mean values per treatment and growth cycle as the experimental units, treatment as the explanatory factor, and growth cycle as block. Foot-pad lesions and exterior quality parameters were analyzed using the IR Class test because frequencies were not normally distributed over the categories. All analyses were done using the GenStat software (VSN, 2012), and probability values <0.05 were considered statistically significant.

RESULTS

Functioning of the oil spraying system

During this study, oil leakage from the nozzles was observed, and therefore we mounted a small bucket underneath each nozzles. Per 8 nozzles, the system applied on average 0.38 mL m^{-2} per second of spraying time. In the second growth cycle, when the system had two additional oil tubes along the side walls of each room, we visually observed that oil was distributed more uniformly over the litter floor in comparison to the configuration in the first growth cycle.

Ventilation rate, temperature, and humidity

Mean ventilation rate, indoor and outside temperature, and relative humidity in the different treatments and growth cycles are given as descriptive statistic in Table 2. Fig. 2 shows the patterns of the ventilation rate per treatment and growth cycle. From the overlapping lines in this figure, it is clear that ventilation rates were very similar between rooms. Ventilation rates increased with the age of the broilers and after the second week, ventilation rate was higher during the day than at night, resulting in a spiked and gradually increasing pattern. Mean ventilation rate was 1.94 m^3 h^{-1} $bird^{-1}$ in the first and 1.67 m^3 h^{-1} $bird^{-1}$ in the second growth cycle. Indoor temperature and relative humidity were similar between treatments (Table 2).

Table 2
Mean ventilation rate, indoor and outside temperature, and relative humidity in the different treatments and growth cycles.

Variable	Growth cycle	Outside	Control rooms (0 ml m^{-2})	8 mL m^{-2} d^{-1}		16 mL m^{-2} d^{-1}	
				8 mL m^{-2} (24 h)$^{-1}$	16 mL m^{-2} (48 h)$^{-1}$	16 mL m^{-2} (24 h)$^{-1}$	32 mL m^{-2} (48 h)$^{-1}$
Ventilation rate (m^3 h^{-1} $bird^{-1}$)	1	-	1.88	2.02	1.93	1.94	1.92
	2	-	1.65	1.73	1.69	1.62	1.67
Temperature (°C)	1	16.6	25.7	25.7	25.9	26.5	25.7
	2	16.1	25.2	24.9	25.1	25.2	25.0
Relative humidity (%)	1	75.6	59.4	59.4	57.7	58.4	59.3
	2	83.4	64.2	64.3	63.9	65.9	64.0

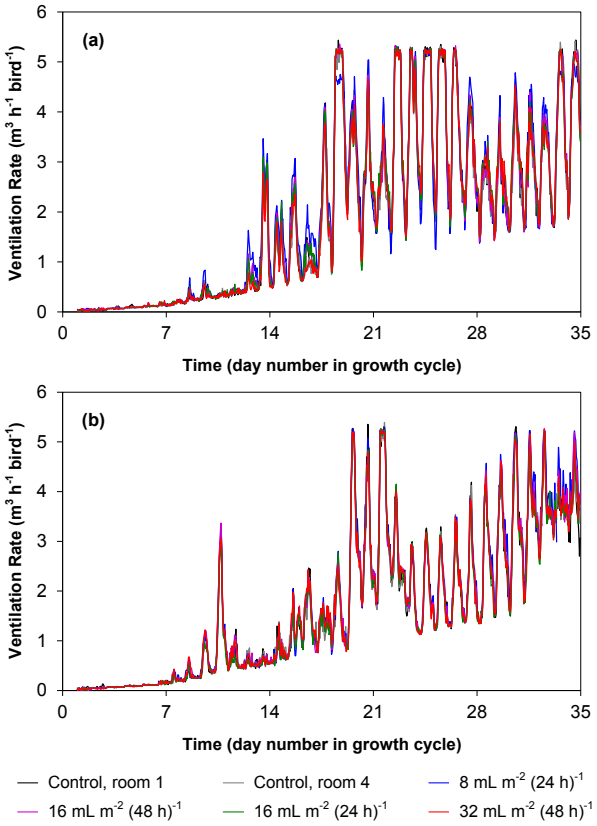


Fig. 2
Ventilation rates during the first (a) and second (b) growth cycle. Note that the treatment lines mostly overlap.

Particulate matter concentrations and emissions

Table 3 shows mean concentrations and emission rates of PM_{10} and $PM_{2.5}$ per growth cycle and treatment. The mean (standard deviation; SD) concentrations at the air inlet were 0.023 (0.015) mg m^{-3} for PM_{10} and 0.016 (0.007) mg m^{-3} for $PM_{2.5}$. On day 16 of the growth cycle, when oil spraying had not yet started, mean (SD) PM_{10} concentration was 0.739 (0.215) mg m^{-3} in the control rooms and 0.751 (0.150) mg m^{-3} in the oil treatment rooms and mean (SD) $PM_{2.5}$ concentration was 0.050 (0.037) mg m^{-3} in the control rooms and 0.053 (0.049) mg m^{-3} in the oil treatment rooms.

With regard to oil application rate (α_i in Eq. 3; 0, 8, or 16 mL m^{-2} d^{-1}), the statistical analysis showed that, relative to the control treatment, PM_{10} emission was significantly reduced by spraying oil at 8 or 16 mL m^{-2} d^{-1} (P = 0.006). The model-estimated reductions in PM_{10}

emission were 59% for 8 mL m^{-2} d^{-1} and 64% for 16 mL m^{-2} d^{-1}, but no significant difference was found between these two oil application rates. Relative to the control treatment, $PM_{2.5}$ emission was significantly reduced by oil spraying at 8 or 16 mL m^{-2} d^{-1} ($P < 0.001$). The model-estimated reductions in $PM_{2.5}$ emission were 81% for 8 mL m^{-2} d^{-1} and 74% for 16 mL m^{-2} d^{-1}, but no significant difference was found between these two oil application rates.

With regard to spraying frequency (β_j in Eq. 3; daily or every other day), the statistical analysis showed that neither the PM_{10} emission nor the PM2.5 emission differed significantly between the 'every other day' treatment and the ‘daily’ treatment.

With regard to the moment of the measurement in relation to the last oil spraying ($a \times \gamma_k$ in Eq. 3; on the same day or on the day after), the model-estimated PM_{10} emission on days after spraying was 44% higher than on spraying days, which was borderline significant ($P = 0.05$). For $PM_{2.5}$ emission however, no significant difference was found between days after spraying and spraying days.

Table 3
Descriptive statistics (number of data points, mean, and standard deviation in parenthesis) of PM_{10} and $PM_{2.5}$ concentrations and emission rates in the two growth cycles for days on which oil spraying had already started (days 23, 30, and 33).

Variable	Growth cycle	*n*	Control Rooms (0 ml m^{-2})	8 mL m^{-2} d^{-1}		16 mL m^{-2} d^{-1}	
				8 mL m^{-2} $(24\ h)^{-1}$	16 mL m^{-2} $(48\ h)^{-1}$	16 mL m^{-2} $(24\ h)^{-1}$	32 mL m^{-2} $(48\ h)^{-1}$
PM_{10} concentration	1	3	1.746 (0.797)	1.013 (0.639)	0.847 (0.241)	0.786 (0.399)	0.948 (0.449)
($mg\ m^{-3}$)	2	3	0.989 (0.248)	0.441 (0.070)	0.360 (0.086)	0.233 (0.033)	0.492 (0.320)
PM_{10} emission rate	1	3	5.982 (3.041)	3.427 (2.321)	2.871 (0.861)	2.666 (1.561)	3.314 (1.843)
($mg\ h^{-1}\ bird^{-1}$)	2	3	2.753 (0.737)	1.285 (0.317)	1.072 (0.495)	0.591 (0.121)	1.197 (0.349)
$PM_{2.5}$ concentration	1	3	0.094 (0.038)	0.042 (0.003)	0.049 (0.026)	0.029 (0.013)	0.040 (0.017)
($mg\ m^{-3}$)	2	3	0.058 (0.010)	0.019 (0.010)	0.017 (0.009)	0.019 (0.007)	0.028 (0.012)
$PM_{2.5}$ emission rate	1	3	0.248 (0.154)	0.070 (0.014)	0.082 (0.075)	0.033 (0.029)	0.066 (0.059)
($mg\ h^{-1}\ bird^{-1}$)	2	3	0.142 (0.050)	0.027 (0.024)	0.018 (0.016)	0.023 (0.013)	0.039 (0.024)

Fig. 3 shows the measured concentrations of PM_{10} and $PM_{2.5}$ during the time around oil spraying (days 25 and 31 in the second growth cycle). In comparison to the control treatment, PM_{10} and $PM_{2.5}$ concentrations were elevated in the 32 mL m^{-2} $(48\ h)^{-1}$ treatment on both measuring days by a mean factor of 1.8 for PM_{10} and 4.1 for $PM_{2.5}$. For the three rooms where 8 or 16 mL m^{-2} was applied, concentrations were similar to the control treatment, except for one $PM_{2.5}$ concentration value on day 25 in the 16 mL m^{-2} $(24\ h)^{-1}$ room. Based on Eq. 2, the mean (standard error of the mean; SEM) percentage of oil applied sampled as airborne oil particles was 1.84% (0.26%) for the PM_{10} fraction and 0.34% (0.02%) for the $PM_{2.5}$ fraction.

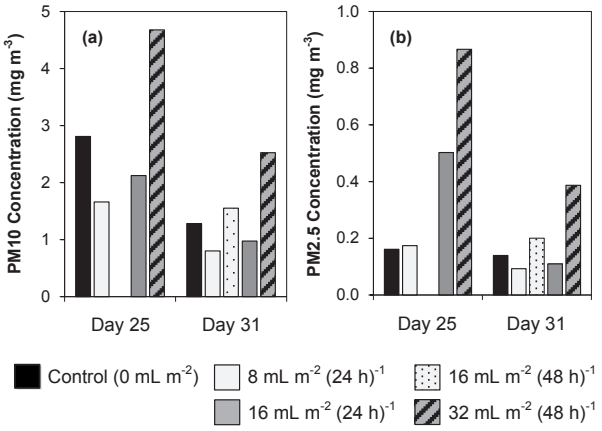


Fig. 3
Concentrations of PM_{10} (a) and $PM_{2.5}$ (b) around the time of oil spraying on day 25 (from 07:45 to 09:45) and day 31 (from 13:00 to 15:00) in the second growth cycle. Due to a technical problem, no values were obtained on day 25 in the 16 mL m^{-2} (48 h) $^{-1}$ room.

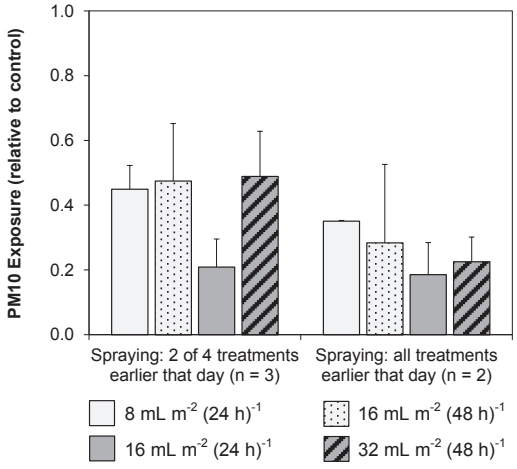


Fig. 4
PM_{10} exposure (concentration at human breathing height) for the oil treatments, relative to the mean of control rooms. Error bars represent standard errors of the mean.

The mean concentrations measured during personal PM_{10} sampling are presented in Fig. 4. From this figure, it is clear that, relative to the control treatment, PM_{10} exposure was lower in all oil spraying treatments. Two sets of data are shown in Fig. 4. The left set of bars shows results from days when oil was sprayed in the 'daily' treatments only. The right set of bars shows results from days when oil was sprayed in all ('daily' and 'every other day') treatments. In the left set of bars, exposure tends to be more reduced in the 'daily' treatments where oil had been applied

earlier that day. In the right set of bars, exposure tends to decrease with increasing oil application rate. The mean reduction in PM_{10} exposure was 60% for the 8 mL m^{-2} $(24\ h)^{-1}$ treatment, 61% for the 16 mL m^{-2} $(48\ h)^{-1}$ treatment, 80% for the 16 mL m^{-2} $(24\ h)^{-1}$ treatment, and 63% for the 32 mL m^{-2} $(48\ h)^{-1}$ treatment.

Ammonia emission

Fig. 5 shows the emission rate of ammonia throughout the first and second growth cycle. Emission patterns clearly differed between the two growth cycle but were similar between treatments, as seen by the treatment lines that mostly overlap each other. No significant differences were found in ammonia emission between any of the treatments. Mean (SD between treatments) ammonia emission rate was 6.45 (0.50) mg h^{-1} $bird^{-1}$ in the first growth cycle and 3.44 (0.52) mg h^{-1} $bird^{-1}$ in the second growth cycle.

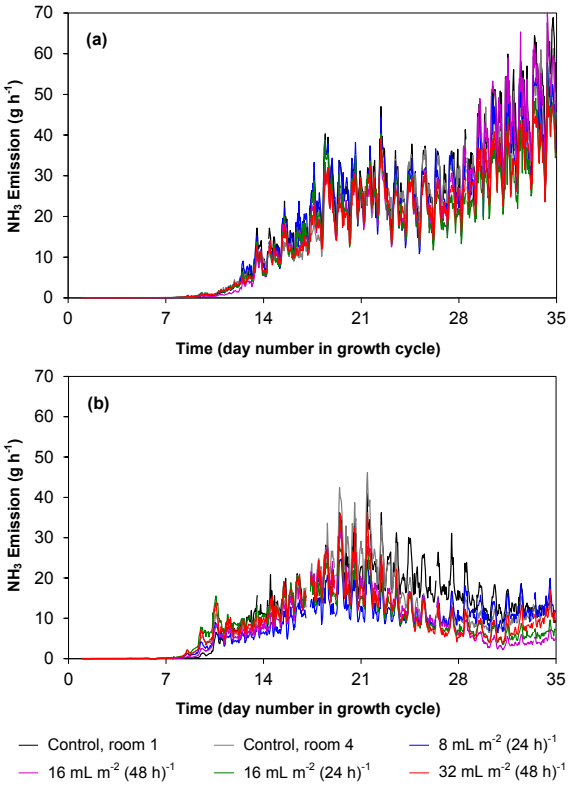


Fig. 5
Ammonia emission rates during the first (a) and second (b) growth cycle. Note that treatment lines mostly overlap.

Odor emission

No significant differences were found in odor emission between any of the treatments. Mean (SD between treatments) odor emission rate was 0.78 (0.18) OU_E s^{-1} $bird^{-1}$ in the first growth cycle and 1.30 (0.13) OU_E s^{-1} $bird^{-1}$ in the second growth cycle.

Animal variables

In Table 4 mean values of the birds' performance variables are presented. No significant differences were found in the performance variables between any of the treatments; neither in the data of days 0 to 21 (before oil spraying had started), nor in the data of days 21 to 35. We found no significant differences between the treatments for foot-pad score, breast dirtiness, breast irritations, scabby hips (thigh scratches), and hock burns. Mean foot-pad score was 88 for the control treatment, 82 for the 8 mL m^{-2} $(24\ h)^{-1}$ treatment, 85 for the 16 mL m^{-2} $(48\ h)^{-1}$ treatment, 101 for the 16 mL m^{-2} $(24\ h)^{-1}$ treatment, and 96 for the 32 mL m^{-2} $(48\ h)^{-1}$ treatment. The overall percentage of broilers falling in the classes 'none' or 'mild' was 60% for breast dirtiness, 96% for breast irritations, 93% for scabby hips, and 91% for hock burns.

Table 4
Mean values of bird performance variables over the two growth cycles (0 to 35 days). LSD: least significant difference.

Variable	Control Rooms (0 ml m^{-2})	8 mL m^{-2} d^{-1}		16 mL m^{-2} d^{-1}		LSD
		8 mL m^{-2} $(24\ h)^{-1}$	16 mL m^{-2} $(48\ h)^{-1}$	16 mL m^{-2} $(24\ h)^{-1}$	32 mL m^{-2} $(48\ h)^{-1}$	
Feed intake (g d^{-1} $bird^{-1}$)	93.0	92.5	93.2	91.8	92.3	2.8
Feed conversion (g feed g^{-1} growth)	1.633	1.632	1.650	1.629	1.633	0.028
Water intake (mL d^{-1} $bird^{-1}$)	161.4	160.3	161.7	159.9	161.6	5.3
Water/feed (g water g^{-1} feed)	1.74	1.74	1.74	1.74	1.75	0.04
Growth rate (g d^{-1} $bird^{-1}$)	57.0	56.7	56.6	56.4	56.5	1.6
Weight at day 35 (g)	2037	2026	2022	2016	2021	55
Mortality (%)	2.8	2.6	2.8	2.8	2.8	0.7

Litter

The dry matter (DM) content of the litter was similar between treatments. Mean (SEM) DM content of the litter was 62% (3%) for the control treatment, 66% (3%) for the 8 mL m^{-2} $(24\ h)^{-1}$ treatment, 63% (4%) 16 mL m^{-2} $(48\ h)^{-1}$ treatment, 62% (3%) for the 16 mL m^{-2} $(24\ h)^{-1}$ treatment, and 63% (3%) for the 32 mL m^{-2} $(48\ h)^{-1}$ treatment. Between growth cycles, there were differences, with the litter being damper in the second growth cycle (range in room means:

64% to 69%) than in the first (range in room means: 57% to 63%). On day 14 of the second growth cycle, mean DM content of the litter inside the rooms was 70%, which decreased in the second half of the cycle to mean levels of 52% on day 28 and 58% on day 35. It was observed that during the second half of the second growth cycle approximately 20% of the litter area in the rooms was friable but on 75% moist manure cakes were present. During the second half of the first growth cycle, cakes were present on approximately 45% of the litter area in the rooms.

Cleaning of the rooms

After removal of the litter by a front loader, application of the soaking agent took approximately 9 min, followed by 30 min of soaking time for all rooms. Pressure cleaning then took approximately 45 min for control rooms and 60 min for oil treatment rooms. The extra time for the oil treatment rooms was mainly needed for cleaning of the three ventilator shafts in each room.

DISCUSSION

In the present study, we found a reduction in PM_{10} emission of 59% at an application rate of 8 mL m^{-2} d^{-1} and a reduction of 64% at an application rate of 16 mL m^{-2} d^{-1}. Aarnink et al. (2011) found a relationship between these two parameters described by the equation $y = –0.021x + 0.64$ ($R^2 = 0.69$), where y is the PM_{10} emission relative to the control treatment (0 to 1) and x the oil application rate (mL m^{-2} d^{-1}). The reductions found in the present study agree reasonably well with the values that can be calculated by fitting the oil application rates in the aforementioned equation, namely 53% for 8 mL m^{-2} d^{-1} and 70% for 16 mL m^{-2} d^{-1}. Aarnink et al. (2011) found no relationship between oil application rate and $PM_{2.5}$ reduction: at 6 mL m^{-2} d^{-1} $PM_{2.5}$ emission was already reduced by 84% and this level did not increase further at higher application rates. In the present study, $PM_{2.5}$ emission was reduced by 81% at 8 mL m^{-2} d^{-1} and 74% at 16 mL m^{-2} d^{-1}. The data from the present study confirm that, at the same oil application rate, $PM_{2.5}$ emission is more reduced than PM_{10} emission, and that increasing the application rate from 8 to 16 mL m^{-2} d^{-1} does not increase the $PM_{2.5}$ reduction any further. Earlier, we hypothesized that some of the oil particles in the $PM_{2.5}$ fraction might still be present in the air during PM sampling, cancelling out any extra $PM_{2.5}$ reduction. This phenomenon could still play a role in the present study.

In the present study, emissions of PM_{10} or $PM_{2.5}$ did not differ significantly between the two spraying frequencies (daily or every other day). On days after spraying however, PM_{10} emission

was 44% higher (P = 0.05) than on spraying days. This suggests that the PM reduction is partially abolished on the second day after spraying. No significant difference was found for $PM_{2.5}$ emission between spraying days and days after spraying. An actual increase in $PM_{2.5}$ emission on the day after spraying however, might have been masked by elevated $PM_{2.5}$ oil particle concentrations the day before.

Our findings on effects of oil spraying rate and spraying frequency can be compared with three available studies. In experimental pens housing broilers, Griffin and Vardaman (1970) applied 338 or 565 mL of cotton seed oil per m^2 of litter floor area weekly (equivalent to 48 and 81 mL m^{-2} d^{-1} respectively) starting after the third week of the growth cycle. In that study, PM concentration within a 7-day spraying cycle increased with time after application: it approximately doubled from day one to day five. In our previous study, we hypothesized that the oil forms a film on top of the litter floor that prevents particles in the litter from becoming airborne. If this truly is the main working principle, the agitation and mixing of the top layer of the litter by the broilers, and the ongoing deposition of fresh droppings on top of each oil film applied, may explain the diminishing PM reduction between oil applications. In a study by Drost et al. (1999) carried out in a broiler house, daily oil spraying using a fogging system that generated droplets with diameters smaller than 10 µm, reduced concentrations of respirable PM by only 12%. The authors noted that the small droplets probably not settled out to the litter floor. These findings also point towards a working principle based on an oil film onto the litter floor rather than for instance a washout of particles from the air. Next to the litter (i.e., manure and wood shavings), the feathers of the broilers contribute significantly to PM_{10} and $PM_{2.5}$ mass concentration in broiler houses (Cambra-López et al., 2011). Since the oil droplets from the oil spraying system settled to both the litter surface and the broilers, it is likely that the oil film acted as a binding agent on the aerosolization of feather particles as well: in the end of the growth cycle, the feathering of the broilers in the oil treatment rooms had a slight yellowish taint whereas the feathers of the broilers in the control room were white. In a third study in broilers, McGovern et al. (1999) sprayed rapeseed oil onto the litter biweekly (0.8 L m^{-2} over a 42-day growth cycle, equivalent to 19 mL m^{-2} d^{-1}) and reported that the reduction in particle number concentration increased from no reduction in the first week, to 9% in the third week, 15% in the fourth week, and 40% in the fifth week. These results suggest that when large amounts of oil are sprayed at a time at low spraying frequencies, it may take considerable time for the oil to become fully effective. In the present study, we found no indications for a build-up of PM reduction in time during the second half of the growth cycle.

In the present study, PM concentrations in the control treatment ranged between 0.439 and 2.607 mg m^{-3} for PM_{10} and between 0.025 and 0.105 mg m^{-3} for $PM_{2.5}$. It is clear that these levels are in excess of the exposure limits of 2.4 mg m^{-3} for inhalable PM (~PM_{100}) and 0.16 mg m^{-3} for respirable PM (~PM_4) recommended for pig and poultry workers (Donham and Cumro, 1999), even though size fractions are not identical. Since rooms were ventilated identically, the reported reductions in PM emission in this study are attributable to reductions in PM concentrations. It is noteworthy that similar or slightly higher reduction levels (60% to 80%) were found by PM_{10} measurements at human breathing height during simulation of daily animal care routine activities, when broilers are stimulated to move and disperse particles into the air. These reductions are consistent with the levels found in our previous study (approximately 67% at 8 mL m^{-2} d^{-1} and 76% at 16 mL m^{-2} d^{-1}). This aspect can be regarded as an important advantage of oil spraying in comparison to 'end of pipe' abatement systems.

In line with Aarnink et al. (2011), we found no effect of oil spraying on emission rate of ammonia. Patterns in ammonia emission rate were similar between treatments, but clear differences were present between the two growth cycles. In the first growth cycle, ammonia emission rate increased during the first three weeks, then stabilized at a high level in the fourth week, and finally increased again in the last week. In the second growth cycle, an increase during the first three weeks was followed by a decline in emission rate. Probably, the higher water content of the litter and the formation of solid manure cakes during the second half of the second growth cycle were unfavourable conditions for ammonia production and volatilization (Chepete et al., 2012; Liu et al., 2007). Oil spraying had no effect on the DM content of the litter, which agrees with the findings of Griffin and Vardaman (1970). In the present study, we investigated for the first time the effects of oil spraying on odor emission and found that odor emission rate did not differ significantly between treatments. Apparently, the oil film is effective in aggregating particles in the litter for a certain amount of time, but the production and release of gaseous ammonia and odorous compounds from the litter remain unaffected. It must be noted however, that the air samples for odor analysis were filtered during sampling. Therefore, any reduction of odorous compounds adsorbed to particles, may have been missed.

An important side-effect noted by Aarnink et al. (2011) was a significantly higher mean foot-pad score of the broilers in the 24 mL m^{-2} d^{-1} treatment in comparison to the control treatment. In the present study, we tried to prevent this by starting with oil spraying only from day 21 of the growth cycle, by limiting the oil application rate to 16 mL m^{-2} d^{-1}, and by spraying the oil more uniformly over the litter area in the second growth cycle. Using this approach, we did not find an effect of oil spraying on the foot-pad score of the broilers. In the present study, as well as in the

previous study, we found no effect of oil spraying on bird performance parameters (feed intake, feed conversion, water intake, water to feed ratio, growth rate, end weight, and mortality). Earlier, McGovern et al. (2000) reported a significantly lower end weight of broilers housed on straw that was treated biweekly with rapeseed oil (1.1 L m^{-2} over 6 wk, equivalent to 26 mL m^{-2} d^{-1}), explained by the authors by a higher body heat loss caused by oil contamination of the feathers or due to consumption of oiled straw. In agreement with these possible explanations, Griffin and Vardaman (1970) observed that broilers scratched more in litter that had just been sprayed and that their feathers became oily from contact with the litter. In contrast to McGovern et al. (2000) however, we used a lower oil application rate and no oil was sprayed during the first three weeks of the growth cycle. Furthermore, neither negative nor positive effects on broiler performance were found by Griffin and Vardaman (1970) at 338 or 565 mL m^{-2} wk^{-1}, starting at three weeks of age, and by McGovern et al. (1999) at 800 mL m^{-2} over 6 wk.

In the present study, we experienced oil leakage from the nozzles of the oil spraying system, which has been previously identified as well (Aarnink et al., 2011). A possible cause for this could be that the timer-controlled valves did not shut immediately and completely after spraying due to pollution. To rule this out, we disassembled and cleaned the valves prior to both growth cycles and we filtered the rapeseed oil during each filling of the oil tank. This did, however, not solve the oil leakage. The following options could solve this problem and improve the system in general:

- The oil tank, main oil tube, and branched oil tubes could be placed below the level of the nozzles in the room to take away the oil pressure resulting from gravity; the oil tank in this study was positioned in a room in the attic of the building, higher than the nozzles.
- The oil and air pressure could be shut off completely in between spraying moments; in the current system, oil and air pressure were maintained on the main tubes (up to the timer-controlled valves) in between spraying moments.
- A timer-controlled valve could be used directly upstream of each nozzle, so that very little oil would remain in the piece of tube between the valve and the nozzle available for oil leakage.
- The air pressure could be applied shortly before opening the oil valves up to some time after shutting of the oil valves, to fog any leaking drops or trickles into the air, and to clean the nozzles after each spraying moment.

To reduce the generation of small oil particles, we brought the oil and air pressure down in the second growth cycle from 3.5 to 3.0 bar, which reduced the spray velocity from 8.4 to 7.2 m s^{-1}

and increased the volume median diameter ($D_{V0.5}$) of the oil droplets from 44 to 49 µm (Aarnink and Van Hattum, 2009). To compensate for the smaller litter area sprayed per nozzle at these lower pressure settings, and to improve the distribution of oil over the litter floor, we doubled the number of nozzles per room (fig. 1). Using Eq. 2, we estimated the mean (SEM) percentage of the total volume of oil applied sampled as airborne oil particles to be 1.84% (0.26%) in the PM_{10} fraction and 0.34% (0.02%) in the $PM_{2.5}$ fraction. When applying this equation to the dataset of Aarnink et al. (2011), where oil and air pressure were 3.5 bar, these values were 1.87% (0.22%) for PM_{10} and 0.39% (0.03%) for $PM_{2.5}$. Thus, the reduction of oil and air pressure in the second growth cycle of the present study did not result in a substantial shift towards larger oil droplets.

CONCLUSIONS

In this follow-up study, we further investigated the effect of oil spraying rate and spraying frequency inside an experimental broiler house, combined in four oil treatment (8 mL m^{-2} $(24\ h)^{-1}$, 16 mL m^{-2} $(48\ h)^{-1}$, 16 mL m^{-2} $(24\ h)^{-1}$, and 32 mL m^{-2} $(48\ h)^{-1}$), relative to a control treatment (0 mL m^{-2}). The oil treatments were randomly assigned to four rooms, whereas two rooms served as control. The experiment lasted for two consecutive growth cycles. In both growth cycles, oil spraying started on day 21. Our main results and conclusions are:

- The oil spraying system effectively reduces concentrations and emissions of PM_{10} and $PM_{2.5}$. The reduction in PM_{10} emission was 59% for 8 mL m^{-2} d^{-1} and 64% for 16 mL m^{-2} d^{-1}. The reduction in $PM_{2.5}$ emission was 81% for 8 mL m^{-2} d^{-1} and 74% for 16 mL m^{-2} d^{-1}. No significant difference in particulate matter (PM) emission was found between the application of 8 or 16 mL m^{-2} d^{-1}.
- Emissions of PM_{10} and $PM_{2.5}$ were not significantly different between oil spraying frequencies (daily or every other day). PM_{10} emission on days after spraying however, was 44% higher than on days of spraying. This suggests that PM reduction is partially abolished on the second day after spraying.
- The extention of the system from 8 to 16 oil spraying nozzles per room, implemented prior to the second growth cycle, improved the equal distribution of oil over the litter floor. A reduction of the oil and air pressure from 3.5 to 3.0 bar did result in a substantial shift towards larger oil droplets.
- The reduction in stock handlers' exposure to PM_{10} during daily routine activities ranged between 60% and 80%, even though birds are stimulated to move and disperse particles into

the air. Thus, oil spraying can contribute to the protection of workers inside broiler houses against hazardous PM levels.

- Our results show that the oil treatment tested do not affect ammonia emission, odor emission, bird performance, birds' exterior quality, and litter dry matter content.
- This study confirms that the application of a maximum oil application rate of 16 mL m^{-2} d^{-1}, starting from day 21 of the growth cycle, incidence of foot-pad lesions is not significantly increased.
- It is recommended to validate the effect of oil spraying inside full-scale commercial broiler houses at a daily application of 16 mL m^{-2} or less starting from day 21 of the growth cycle.

ACKNOWLEDGMENTS

This study was financed by the Dutch Ministry of Economic Affairs and the Dutch Ministry of Infrastructure and the Environment. We thank the staff of the Spelderholt experimental station for taking care of the animals, Mr. Theo van Hattum for maintenance of the oil spraying system, Mr. Eef Lovink for maintenance and calibration of measuring equipment, Mr. Jean Slangen for carrying out the lab analyses, and Mr. Johan van Riel for advice on the statistical analysis.

REFERENCES

Aarnink, A.J.A., Van Hattum, T.G., 2009. Measures to reduce fine dust emission from poultry houses; Laboratory study: characterizing oil spraying nozzles (droplet size and velocity) [in Dutch, with English summary]. Report 229. Animal Sciences Group, Wageningen University and Research Centre, Lelystad, the Netherlands.

Aarnink, A.J.A., Van Harn, J., Van Hattum, T.G., Zhao, Y., Ogink, N.W.M., 2011. Dust reduction in broiler houses by spraying rapeseed oil. *Trans. ASABE* 54:1479–1489.

Al Homidan, A., Robertson, J.F., Petchey, A.M., 2003. Review of the effect of ammonia and dust concentrations on broiler performance. *World's Poultry Sc. J.* 59:340–349.

Berg, C., 1998. Footpad dermatitis in broilers and turkeys: Prevalence, risk factors, and prevention. PhD diss. Swedish University of Agricultural Science, Uppsala, Sweden.

Brunekreef, B., Holgate, S.T., 2002. Air pollution and health. *Lancet* 360:1233–1242.

Cambra-López, M., Hermosilla, T., Lai, H.T.L., Aarnink, A.J.A., Ogink, N.W.M., 2011. Particulate matter emitted from poultry and pig houses: Source identification and quantification. *Trans. ASABE* 54:629–642.

CEN, 1998. EN 12341:1998. Air quality - Determination of the PM 10 fraction of suspended particulate matter - Reference method and field test procedure to demonstrate reference equivalence of measurement methods. European Committee for Standardization (CEN), Brussels, Belgium.

CEN, 2003. EN 13725:2003. Air quality - Determination of odour concentration by dynamic olfactometry. European Committee for Standardization (CEN), Brussels, Belgium.

CEN, 2005. EN 14907:2005. Ambient air quality - Standard gravimetric measurement method for the determination of the PM2.5 mass fraction of suspended particulate matter. European Committee for Standardization (CEN), Brussels, Belgium.

Chepete, H.J., Xin, H., Li., H., 2012. Effect of partially covering the turkey litter surface on ammonia emission. *J. Appl. Poult. Res.* 21:513–521.

Donham, K., Cumro, D., 1999. Setting maximum dust exposure levels for people and animals in livestock facilities. In International Symposium on Dust Control in Animal Production Facilities, pp. 93-110. Danish Institute of Agricultural Sciences, Aarhus, Denmark.

Drost, H., Beens, N., Dolehghs, B., Ellen, H., Oude Vrielink, H.H.E., 1999. Is fogging water or oil effective in reducing dust concentrations in poultry houses? In International Symposium on Dust Control in Animal Production Facilities, pp. 231-236. Danish Institute of Agricultural Sciences, Aarhus, Denmark.

EU, 2008. Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe. *Offic. J. Europ. Union* L152:1–44.

Griffin, J.G., Vardaman, T.H., 1970. Cottonseed oil spray for broiler houses: effects on dust control, Mycoplasma gallisepticum spread and broiler performances. *Poult. Sci.* 49:1664–1668.

Liu, Z., Wang, L., Beasley, D., Oviedo, E., 2007. Effect of moisture content on ammonia emissions from broiler litter: A laboratory study. *J. Atmos. Chem.* 58:41–53.

Madelin, T.M., Wathes, C.M., 1989. Air hygiene in a broiler house: comparison of deep litter with raised netting floors. *Brit. Poult. Sci.* 30:23–37.

McGovern, R.H., Feddes, J.J.R., Robinson, F.E., Hanson, J.A., 1999. Growth performance, carcass characteristics, and the incidence of ascites in broilers in response to feed restriction and litter oiling. *Poult. Sci.* 78:522–528.

McGovern, R.H., Feddes, J.J.R., Robinson, F.E., Hanson, J.A., 2000. Growth, carcass characteristics, and incidence of ascites in broilers exposed to environmental fluctuations and oiled litter. *Poult. Sci.* 79:324–330.

Ogink, N.W.M., Aarnink, A.J.A., 2011. Plan van aanpak bedrijfsoplossingen voor fijnstofreductie in de pluimveehouderij [Plan of action for particulate matter mitigation solutions in poultry; in Dutch, with English summary]. Report 113, Animal Sciences Group, Wageningen University and Research Centre, Lelystad, the Netherlands.

Omland, Ø., 2002. Exposure and respiratory health in farming in temperate zones - A review of the literature. *Ann. Agric. Environ. Med.* 9:119–136.

Radon, K., Danuser, B., Iversen, M., Jörres, R., Monso, E., Opravil, U., Weber, C., Donham, K.J., Nowak, D., 2001. Respiratory symptoms in European animal farmers. *Eur. Respir. J.* 17:747–754.

RIVM, 2014. Annual national emissions of PM10; in total and per sector/source, for 2012. Retrieved 11 February 2014, from http://www.emissieregistratie.nl. National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands.

Takai, H., 2007. Factors influencing dust reduction efficiency of spraying of oilwater mixtures in pig buildings. In DustConf 2007 - How to improve air quality. Maastricht, the Netherlands.

Van Harn, J., 2009. Comparison of four light schedules according to EU Directive 2007/43 for broilers [in Dutch, with English summary]. Report 172, Animal Sciences Group, Wageningen University and Research Centre, Lelystad, the Netherlands.

VSN, 2012. GenStat reference manual (release 15). Ver. 15.2.0.8821. VSN Int., Ltd, Hemel Hempstead, UK.

Winkel, A., Mosquera, J., Groot-Koerkamp, P.W.G., Ogink, N.W.M., Aarnink, A.J.A., 2015. Emissions of particulate matter from animal houses in the Netherlands. *Atmos. Environ.*111:202–212.

Zhao, Y., Aarnink, A.J.A., Hofschreuder, P., Groot Koerkamp, P.W.G., 2009. Evaluation of an impaction and a cyclone pre-separator for sampling high PM10 and PM2.5 concentrations in livestock houses. *J. Aerosol Sci.* 40:868–878.

Chapter 4

Abatement of particulate matter emission from experimental aviary housings for laying hens by spraying rapeseed oil

A. Winkel [a], J.W. van Riel [a], R.A. van Emous [a], A..J.A. Aarnink [a] , P.W.G. Groot Koerkamp [a,b], and N.W.M. Ogink [a]

[a] Wageningen UR Livestock Research, Wageningen, the Netherlands
[b] Farm Technology Group, Wageningen University, Wageningen, the Netherlands

Poultry Science (2016), in press

Available online at: http://dx.doi.org/10.3382/ps/pew261

ABSTRACT

In alternative systems for laying hens, concentrations and emission rates of particulate matter (PM) give reason for concern with regard to working conditions, bird health and productivity, and health of residents living near farms. Previously, we found that spraying a film of rapeseed oil onto the litter of broilers could substantially reduce PM concentrations and emissions. The objective of this study was to establish dose-response effects of oil spraying in aviaries on concentrations and emission rates of PM with aerodynamic diameters less than 10 μm (PM_{10}) and 2.5 μm ($PM_{2.5}$), on stockmen's exposure to PM_{10}, on egg production, exterior quality and behavior of the hens, and on the litter. An experiment was carried out with 4 treatments: 0 (control), 15, 30, and 45 mL/m^2 per day (oil treatments). Each treatment was applied in 2 rooms with different aviary systems (8 rooms in total). The experiment was repeated during a second period, both lasting 35 d. From day 11 to day 35, oil was applied daily using a spraying gun. Applying 15, 30, or 45 mL/m^2 per day significantly reduced emission rates of PM_{10} by 27, 62, and 82%, and emission rates of $PM_{2.5}$ by 71, 83, and 94% respectively. No significant effects of oil spraying were found on mortality, egg production, dust bathing behavior, scratching behavior, plumage soiling, DM content of the litter, or friability of the litter. A significant worsening of the plumage condition was only found for the body spot back/wings/tail (not for: throat/neck, chest/breast, or legs) in the 45 mL/m^2 per day treatment. Egg quality shifted significantly towards more second class eggs in the oil treatments (1.9% versus 1.4%; P = 0.004). Remarkably, foot soiling decreased with increasing oil application. In conclusion, PM concentrations and emission rates in aviaries can be effectively reduced by spraying 15 to 30 mL/m^2 per day with minor side effects within a 25 day application period.

INTRODUCTION

Due to the European Union (EU)-wide ban on conventional cages for laying hens (EU Directive 1999/74/EC), the use of alternative housing systems (i.e., floor systems and aviary systems) has increased in many European countries. In the Netherlands, the ratio of eggs produced in cage systems versus alternative systems shifted from 77% versus 23% in 2000 to 18% versus 82% in 2012 (PPE-PVV, 2012). To meet the needs of laying hens, the directive states that alternative systems must have nests, perches, and at least 250 cm^2 of littered area per hen, the litter occupying at least one third of the ground surface. It is difficult however, to adequately balance these welfare needs with healthy working conditions and a low environmental impact. In practice, the litter is usually composed of the birds' droppings (manure and uric acid), feathers, and bedding material spread onto the floor (Cambra-López et al., 2011). These materials deteriorate into tiny particles and become airborne through drying (i.e., by heat production by the birds and ventilation) and the mechanical nature of bird activity, such as scratching, dust bathing, wing-flapping, and so on (Calvet et al., 2009). Consequently, concentrations of particulate matter (PM) with aerodynamic diameters of 4 µm and smaller (PM_4) in alternative systems are on average a factor 7 (range: 1.7 to 14) higher than in cage systems (Takai et al., 1998). Furthermore, 24-h averaged PM concentrations in alternative housing systems (i.e., ranges: 1198 to 10,951 $\mu g/m^3$ for PM_{10} and 41 to 866 $\mu g/m^3$ for $PM_{2.5}$; Winkel et al., 2015) are the highest of all housing systems in livestock production. They exceed recommended health limits for workers and birds (e.g., 160 $\mu g/m^3$ for PM_4 and 2,400 $\mu g/m^3$ for PM_{100}; Donham and Cumro, 1999) and are hundred folds of the levels usually found in ambient air (i.e., <50 $\mu g/m^3$ for PM_{10}). Unlike non-organic particles from many other environments, poultry PM has a high content of endotoxin (a pro-inflammatory bacterial compound from the outer membrane of Gram negative bacteria) and contains micro-organisms, odorous compounds, and gaseous ammonia (Seedorf et al., 1998; Takai, 2002; Yang et al., 2014). Occupational exposure to PM puts poultry farmers at risk of respiratory problems, such as organic dust toxic syndrome (ODTS), chronic obstructive pulmonary disease (COPD), asthma, and increased lung function decline (Omland, 2002; Radon et al., 2001; Viegas et al., 2013). In chickens, the chronic inhalation of PM may cause lesions throughout their respiratory system, promote the invasion and pathogenic effects of micro-organisms, reduce growth, and increase mortality (Al Homidan et al., 2003; Guarino et al., 1999). Finally, neighboring residents of poultry farms may be exposed to elevated ambient PM concentrations that spread out from ventilation exhausts (Heederik et al., 2011; Li et al., 2012). In the Netherlands, the poultry industry has been

recognized as a major contributor (13%) to the national emission of primary PM_{10} (RIVM, 2011).

To develop effective and economically feasible PM abatement solutions for the poultry industry, a research programme was set up at our institute (Ogink and Aarnink, 2011). One of the solutions investigated in this programme was spraying a very thin film of pure rapeseed oil droplets onto the litter, which prevents particles in the litter from becoming airborne, thereby reducing both indoor concentrations (i.e., exposure of workers and birds) and emissions. In the past, this approach has successfully been used in pig housings (Takai, 2007; and references therin). We first developed and studied a spraying method in experimental broiler housings (Aarnink et al., 2011; Winkel et al., 2014). These studies showed that PM_{10} decreased with increasing oil application rate (from 48% at 6 mL/m^2 per day to 87% at 24 mL/m^2 per d), but also that no more than 16 mL/m per day should be applied to avoid increased numbers of foot-pad lesions. In laying hens, higher application rates may be needed because hens behave more actively and the litter is usually friable and dry. Some work has been done on spraying 1 to 10% rapeseed oil in water mixtures, but these were sprayed in cage houses (Ikeguchi, 2002) or above slatted areas of aviary and floor housings to avoid wet litter (Gustafsson and Von Wachenfelt, 2006; Von Wachenfelt, 1999). To our knowledge, no work has been done on spraying pure rapeseed oil onto the litter of alternative systems in relation to PM levels, the birds, their egg production, and litter quality. Such information is needed to adequately develop oil spraying systems for alternative laying hen houses, and especially for aviary houses, since the majority of poultry farmers in Europe choose aviaries over floor housing when switching from cages to an alternative system. Therefore, the objective of the current work was to experimentally determine dose-response effects of the application of pure rapeseed oil onto the litter floor of aviary housings on concentrations and emission rates of PM, on the exposure of birds and stockmen to PM, on the birds, their egg production, and litter quality.

MATERIALS AND METHODS

This experiment was approved by the Animal Experiments Committee of Wageningen UR.

General design of the experiment

The effects of spraying rapeseed oil were investigated in 4 application rates: 0 (control treatment), 15, 30, and 45 mL/m^2 per day (oil treatments). Effects of the oil treatments, relative

to the control treatment, were determined on concentrations and emissions of PM (PM_{10} and $PM_{2.5}$), on stockmen's exposure to PM_{10}, on the bird's egg production, mortality, scratching behavior, dust bathing behavior, plumage condition, plumage soiling, and foot soiling, and on the dry matter content and friability (cake formation) of the litter (Table 1).

Table 1
Summary of measured variables.

Variable	Measurement Method	Unit	Days [4]
Particulate matter concentration and emission			
Oil use	Weighing	g [1]	Daily
PM_{10} and $PM_{2.5}$	Cyclone sampler	mg/m^3	20, 27, 34
CO_2 (ventilation rate) [1]	Air sampling, Gas Chromatograph	ppm	20, 27, 34
Personal PM_{10} exposure	DustTrak Aerosol Monitor	mg/m^3	19, 25, 31 (EP 1) 19, 25, 33 (EP 2)
Bird performance			
Body weight [2]	Manual weighing	g	Once per EP
Mortality	Visual inspection, counting	%	Daily
Egg production [2]	Counting	Eggs/room per d	Daily
Egg quality [3]	Visual inspection, counting	First class, second class, third class, or mislaid	Daily
Bird behavior			
Dust bathing	Visual observation, counting	% of birds	7, 19, 29 (EP 1) 7, 19, 33 (EP 2)
Scratching	Visual observation, counting	% of birds	7, 19, 29 (EP 1) 7, 19, 33 (EP 2)
Bird exterior quality			
Plumage condition	Visual inspection, scoring	6-point scale (intact, ruffled, damaged, severely damaged, partly naked, naked	7, 19, 29 (EP 1) 7, 19, 33 (EP 2)
Plumage soiling	Visual inspection, scoring	4-point scale (clean, slightly dirty, dirty, very dirty)	7, 19, 29 (EP 1) 7, 19, 33 (EP 2)
Foot soiling	Visual inspection, scoring	4-point scale (clean, slightly dirty, dirty, very dirty)	7, 19, 29 (EP 1) 7, 19, 33 (EP 2)
Litter			
DM content	Oven-drying, weighing	g/kg	1, 11, 21, 35
Litter friability	Visual inspection, scoring	% of floor area with formation of cakes or clumps	7, 19, 29 (EP 1) 7, 19, 33 (EP 2)

[1] Recalculated to mL using a density of 0.93 g/mL.
[2] Input variable for the CO_2 balance method.
[3] Mislaid eggs: floor eggs and system eggs.
[4] EP: experimental period. Numbers refer to measurement days in the EP, otherwise: measurement interval.

The experiment was carried out in 8 climate-separated rooms. Each of the 4 treatment was applied in 2 rooms with different aviary systems (aviaries A and B) at the same time. The experiment was fully repeated: the first experimental period (EP) of 35 days took place in spring,

a second EP of 35 days took place in summer. From day 11 to day 35 of each EP, rapeseed oil was applied onto the litter daily using a manually operated spraying gun. Treatments were randomly allocated to the rooms prior to EP 1. This was repeated prior to EP 2 with the exception that a treatment was not allocated to the same room twice, to avoid confounding between treatments and rooms. To avoid interference between the EPs, 'standard litter' was made and spread inside the rooms prior to both EPs.

Housing and animals

The experiment was carried out at poultry research centre 'Het Spelderholt' in Lelystad, the Netherlands. The experimental house originally had 4 main rooms which each consisted of 2 sub rooms separated by chicken wire. Sub rooms within a main room had independently functioning aviary systems, egg collection systems, feed and water systems, lighting systems, etcetera; but identical ventilation controlled by 1 climate computer. The chicken wire fences were closed by sheets of plastic so that 8 climate-separated rooms (sub rooms are further called: 'rooms') were created. Rooms measured 10 × 5.3 × 4.5 × 6.5 m (length × width × side wall height × ridge height). Four rooms were equipped with a Natura Nova aviary (Big Dutchman Int. GmbH, Vechta, Germany; referred to as system A). The other 4 rooms were equipped with a BLA aviary (Meller Anlagenbou GmbH, Melle, Germany; referred to as system B). Details of the aviary systems are shown in Fig. 1. The ground surface covered with litter was 41.7 m^2 for aviary A and 38.8 m^2 for aviary B. Each room was lit by 6 roof skylights with adjustable lamellae, 6 high-frequency fluorescent tubes on the ceiling, and 3 LED light tubes under the aviary (Fig. 1). Lights were on from 06:00 to 21:00 (15L:9D). Fresh air entered the rooms through the manure belt aeration systems (Fig. 1; fixed at 1 m^3/h per bird) and through 6 side wall inlets. Polluted air was exhausted from the rooms by natural ventilation through adjustable ridge valves. The inlet and ridge valves were controlled through a climate computer (1 for each main room; type FSU.4; Fancom BV, Panningen, the Netherlands; room target temperature: 18 °C; connected to temperature sensors in the room). In each room, either 620 hens (aviary A) or 604 hens (aviary B) were placed (15 hens per m^2 floor area; Breed: Lohmann Brown Lite; Age: 18 weeks; hatchery and rearing: Het Anker BV, Ochten, the Netherlands). At the start of the first and second EP, hens were 23 weeks and 36 weeks old, respectively. Hens were fed a commercial mash diet (Layer 1, Superreeks; ForFarmers, Lochem, the Netherlands; crude protein content: 165 g/kg; energy content: 2775 kcal/kg) which was provided in 7 portions per day between 07:00 and 19:00. Water was provided during the light period only.

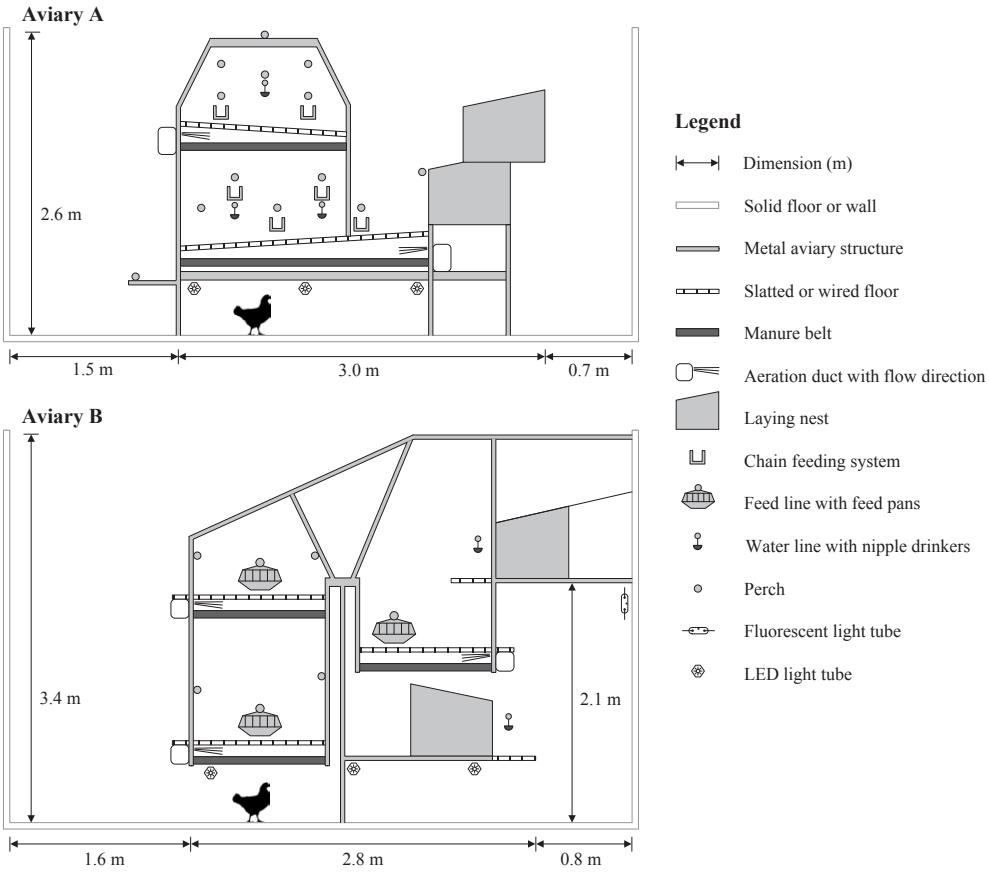


Fig. 1

Cross-sectional schematic of aviary systems A (Natura Nova, Big Dutchman Int. GmbH, Vechta, Germany) and B (BLA, Meller Anlagenbou GmbH, Melle, Germany).

Production of standard litter

During the 5 weeks prior to the EPs, the manure belts under the tiers in the aviary frame were run weekly and the collected manure was spread onto the floor of a drying room. Hot air blowers, box ventilators, and the mechanical ventilation system in this room were used to further dry the pre-dried manure to 70 to 80% of DM. The manure was mixed daily to enhance the drying process and to homogenize it. At day 0 of each EP, the litter inside the rooms was replaced by a mixture of dried manure (9 kg of DM per m^2) and wood shavings (0.4 kg per m^2). This layer of 'standard litter' was friable and approximately 10 cm thick.

Oil spraying

Pure rapeseed oil was used, meant for use as biofuel in vehicles (Solar Oil Systems BV, Boijl, the Netherlands; density: 0.93 g/mL). Oil was sprayed using a hand-held spraying lance (nozzle type SU26B-SSBR; Spraying Systems, Ridderkerk, the Netherlands) connected to tubes for oil and air which were fueled by an oil pressure vessel (12 L) and an air compressor. The oil pressure vessel was installed on a balance (reading in g) which allowed accurate application of the intended amount of oil (Table 1). At application rates of 15, 30, and 45 mL/m^2, the target amount of oil applied per day and per room was 626, 1251, and 1726 mL for aviary A, and 582, 1164, and 1746 mL for aviary B, respectively. The spraying rate of the lance was 260 mL/min and the application of the oil film took approximately 7 minutes for the highest (45 mL/m^2 per d) oil treatment. The pressure for air and oil were set at 2.0 and 3.5 bar respectively, which gave a round spray pattern of fine droplets up to 1.5 m distance without any drift of oil mist. The oil was sprayed directly onto the litter, without soiling the aviary frame or the hens on the litter. The hens quietly moved away from the spray without apparent anxiety.

Measurement of particulate matter concentration

Concentrations of PM_{10} and $PM_{2.5}$ were determined on day 20, 27, and 34 of both EPs (Table 1). Sampling was done during 24 h, starting 1 h after the application of oil. PM was sampled upwind of the aviary house, near the air inlet and at the exhaust point of each room. The exhaust point was chosen in the centre of the room at a height of approximately 5 m (1.5 m under the ridge exhaust). At this position, cyclone samplers (model URG-2000-30ENB for PM_{10} and URG-2000-30EG for $PM_{2.5}$; URG Corp., Chapel Hill) were suspended from a measuring mast. Single PM_{10} and $PM_{2.5}$ samples were taken at each sampling point. Air was drawn through the cyclones by air pumps (Tecora, model Charlie HV; Ravebo B.V., Brielle, the Netherlands) at a sampling rate of 16.7 L/min. Inside the cyclones, the aimed particle size was separated and collected on a glass fiber filter (type GF-3, Ø 47 mm, Macherey-Nagel, Düren, Germany). Unloaded (i.e., clean) and loaded (i.e., with PM) filters were weighed with a precise balance (AT261 DeltaRange, Mettler, Greifensee, Switzerland; resolution: 10 µg) under standard conditions (20 ± 1°C and 50 ± 5% relative humidity) as described in European Norm (EN) 12341 (CEN, 1998) and EN 14907 (CEN, 2005). After 48 h of stabilization, filters were weighed 4 times spread over 2 consecutive days. The average value was recorded as the filter weight. The PM mass concentration was calculated by dividing the mass of collected PM by the volume of

air drawn through the filter, as registered by the pump flow meter. Measured PM_{10} concentrations were calibrated to the reference impaction sampler described in EN 12341 (CEN, 1998) using the equations reported by Zhao et al. (2009): $y = 1.09x$ (when $x \leq 223$ μg/m^3) and $y = 0.83x + 57.5$ (when $x > 223$ μg/m^3), where x is the measured concentration and y is the calibrated concentration.

Measurement of personal PM_{10} exposure

The exposure of stockmen to PM_{10} was determined on day 19, 25, and 29 in EP 1 and on day 19, 25, and 33 in EP 2 (Table 1). A light-scattering device (DustTrak™ Aerosol Monitor, model 8520, TSI Inc., Shoreview; air flow rate: 1.7 L/min) was attached to the lapel of the stockman, who then mimicked a 10-min inspection round through each room. Concentrations of PM_{10} were measured every second. Minute-averaged values were downloaded from the DustTrak's memory.

Measurement of carbon dioxide concentration

Concentrations of carbon dioxide (CO_2) were determined at the same sampling positions and at the same time as PM concentrations (Table 1). These were used for estimation of the ventilation rate with the CO_2 balance method. Air was sampled at a constant flow to achieve a 24-h averaged sample using the 'lung principle' (vessels with 40 L Nalophan air sampling bags connected to electrical air pumps; Thomas Industries Inc., Wabasha, Minn.; model 607CD32; critical capillary: 0.02 L/min). The pumps sucked air from the vessels, which caused the sampling bags to be filled with air taken from the sampling position. Air samples were taken to the lab and analyzed by gas chromatography (Interscience/Carlo Erba Instruments Inc., Breda, the Netherlands, GC 8000 Top; column Molsieve 5A; detector: HWD).

Bird performance

Eggs were collected daily (Table 1) by running the egg conveyor belt in the aviary frame of each room separately. Mislaid eggs (i.e., eggs laid in the aviary frame or on the litter floor) and dead birds were collected during daily inspections rounds (Table 1). Eggs were counted and scored per room into 4 categories (Table 1): first class eggs, second class eggs (i.e., eggs contaminated with manure or blood, eggs with a cracked shell but intact membrane, double-

yolked eggs, and eggs with an abnormal shape), third class eggs (i.e., eggs with a broken membrane, shell-eggs and very small eggs), and mislaid eggs. The mean egg weight and mean BW of the hens (input variables for the CO_2 balance method) were determined once during each EP by weighing the eggs produced on 1 day and by weighing a selection of 30 hens per room respectively.

Bird behavior

The extent of dust bathing and scratching behavior was determined on day 7, 19, and 29 in EP 1 and on day 7, 19, and 33 in EP 2 (Table 1). On these days, observations were performed 4 times per room between 11:30 and 14:00. Within each room, observations were done at 2 litter floor sections: in the front and rear (each section: approximately 3 × 3 m). During each observation, we counted the total number of birds present in the section, the number of birds displaying dust bathing behavior, and the number of birds displaying scratching behavior.

Bird exterior quality

The plumage condition, the extent of plumage soiling, and the extent of foot soiling was determined on day 7, 19, and 29 in EP 1 and on day 7, 19, and 33 in EP 2 (Table 1). On these days, a sample of 30 hens per room was examined and scored. The plumage condition was examined at 4 body spots: throat/neck, chest/breast, back/wings/tail, and legs. The feathering at each of these spots received 1 of the following 6 scores: intact, ruffled, damaged, severely damaged, partly naked, or naked. The extent of plumage soiling was expressed in 1 of the following 4 scores for the entire body: clean, slightly dirty, dirty, or very dirty. The soiling of the featherless foot, including the foot pads, was scored following the same 4 scores.

Litter

Representative litter samples were taken in each room (approximately 500 g) on day 1, 11, 21, and 35 of both EPs (Table 1). The DM content of the samples was determined by weighing before and after oven-drying (24 h at 105 °C). On day 7, 19, and 29 in EP 1 and on day 7, 19, and 33 in EP 2 the percentage of floor area with formation of cakes or clumps of litter (in contrast to friable litter) was scored by visual observation (Table 1).

Estimation of ventilation rate

The ventilation rate was determined for each room on day 20, 27, and 34 of both EPs using the CO_2 balance method. The total heat production of a hen (Φ_{total}; kW) was calculated following the equations by CIGR (2002), using the actual BW and the egg mass produced per hen per day as input variables. The total heat production was multiplied by a factor (Fco_2) of 0.18 m^3 CO_2/h per kW as recommended by Pedersen et al. (2008) to yield the CO_2 production of a hen and its manure. The ventilation rate (Q; m^3/h per bird) was calculated using Eq. 1:

$$Q = \frac{\Phi_{total} \times Fco_2}{([CO_2]_{exhaust} - [CO_2]_{inlet}) \times 10^{-6}} \quad (1)$$

where $[CO_2]_{exhaust}$ is the CO_2 concentration (ppm) determined near the ridge opening and $[CO_2]_{inlet}$ is the CO_2 concentration (ppm) determined outside.

Calculation of PM emission rates

PM emission rates ($PM_{emission}$; mg/h per bird) were calculated by Eq. 2:

$$PM_{emission} = Q \times (PM_{exhaust} - PM_{inlet}) \quad (2)$$

where Q is the ventilation rate (m^3/h per bird), $PM_{exhaust}$ is the concentration of PM (mg/m^3) determined near the ridge opening, and PM_{inlet} is the concentration of PM (mg/m^3) determined outside the aviary house.

Statistical analysis

All statistical analyses were performed using the GenStat software (VSN, 2013). Significance was declared at probability levels ≤ 0.05. Rooms were the experimental units for all variables.

Ventilation rate and particulate matter

Ventilation rate, PM concentrations, PM emission rates, and personal PM_{10} exposure were analyzed by a mixed model using the REML directive, as described by Eq. 3:

$$\mathrm{Log}(\underline{Y}_{ijklmp}) = \beta_0 + T_i + A_j + D_p + \underline{\varepsilon}_k + \underline{\varepsilon}_{km} + \underline{\varepsilon}_{klm} + \underline{\varepsilon}_{kp} + \underline{\varepsilon}_{kmp} + \underline{\varepsilon}_{klp} \quad (3)$$

where $\mathrm{Log}(\underline{Y}_{ijklmp})$ = natural logarithm of the response variable at oil application rate i in aviary system j in EP k in room l of main room m at day p (for ventilation rate, a log-log transformation was used); β_0 = constant; T_i = fixed effect of treatment i (0, 15, 30, or 45 mL/m^2 per d); A_j = fixed effect of aviary system j (A or B); D_p = fixed effect of day p in the EP (20, 27, or 34 for PM concentrations, ventilation rate, and PM emissions; 19, 25, 31, or 33 for personal PM_{10} exposure); and the ε's are the random terms.

Bird performance: egg production, percentage of 1st class eggs, percentage of 2nd class eggs, percentage of 3rd class eggs, and percentage of mislaid eggs

Five out of 6 bird performance variables were analyzed by a mixed model using the REML directive, as described by Eq. 4:

$$\mathrm{Log}(\underline{Y}_{ijklmp}) = \{\beta_{0j} + \underline{\varepsilon}_{0klm}\} + \{\beta_{1j} + \underline{\varepsilon}_{1klm}\} \times t + \{\phi_i + \underline{\varepsilon}_{\phi klm}\} + \beta_{2ij} \times tt + \underline{\varepsilon}_k + \underline{\varepsilon}_{kl} + \underline{\varepsilon}_{klp} + \mathrm{Spline}(t_k) \quad (4)$$

where $\mathrm{Log}(\underline{Y}_{ijklmp})$ = natural logarithm of the response variable of measurement p on day t in the EP and on day tt of the oil spraying phase of the EP, at oil application rate i in aviary system j in EP k in room l of main room m; β_{0j} = constant: the response of aviary system j at the start of the EP (t = 0);t = time: day in the EP (1 through 35); tt = treatment time: day in the oil spraying phase (11 through 35); φ_i = fixed effect of treatment i (0, 15, 30, or 45 mL/m^2 per d) at the first day of oil spraying (at t = 11 and tt = 1); $\mathrm{Spline}(t_l)$ = spline effect that models the overall trend in EP k; the $\underline{\varepsilon}$'s are the random terms; and the β's are the linear regression coefficients.

Two-way and three-way interactions between the fixed model terms in Eq. 3 and 4 were also tested (not shown in the equations) but excluded from analysis when not significant. Mean values of model terms were estimated on the natural log-scale and back-transformed to geometric mean values on the original scale. Pairwise *t*-tests were used to determine significant differences between levels of fixed model terms.

Bird performance: mortality

The sixth bird performance variable, mortality, was analyzed by a logistic regression model using the GLMM directive, as described by Eq. 5:

$$\text{Logit}(\underline{Y}_{ijk}) = \beta_0 + T_i + A_j + \underline{\varepsilon}_k + \varepsilon_{ijk} \quad (5)$$

where $\text{Logit}(Y_{ijk})$ = logit value of the response variable of measurement l in EP k, oil spraying treatment i, and aviary system j. Because of the dichotomous nature of the response variable, the logit function (i.e., Log[P/1–P]) was used as link function; β_0 = constant; T_i = fixed effect of treatment i (0, 15, 30, or 45 mL/m^2 per d); A_j = fixed effect of aviary system j (A or B); and the $\underline{\varepsilon}$'s are the random terms.

Bird behavior and bird exterior quality

Bird behavior variables (dust bathing and scratching behavior) and bird exterior quality variables (plumage condition, plumage soiling, and foot soiling) were analyzed by a model almost identical to Eq. 4, with the exceptions that: (1) the continuous term t was replaced by a factor term ft (with levels: 7, 19, 29, and 33; day in the EP), and (2) no spline was used.

The bird exterior quality variables were analyzed using the IRCLASS procedure which fits a GLMM to ordinal data. For this procedure, the values of the response variable, i.e, the frequencies in each class for each room and day, were recalculated to fractions. No log-transformation was applied to the bird exterior quality variables.

Litter DM content

The DM content of the litter was analyzed by the model in Eq. 4 with the exceptions that no spline was used and no log-transformation was applied to this response variable.

RESULTS

Particulate matter concentrations and emissions

Table 2 shows the mean values of the ventilation rate, PM concentrations, PM emission rates, and personal PM_{10} exposure, presented per treatment. The statistical analysis showed that the ventilation rate was not significantly different between the treatments. The overall mean (SD) CO_2 concentration, used to calculate ventilation rate, was 970 (230) ppm inside the rooms and 453 (10) ppm outside the house. The overall mean BW of the hens, also used to calculate ventilation rates, was 1962 g. For these response variables, no significant differences were found between the 2 aviary systems.

Highly significant effects of the oil application rate were found on PM_{10} concentration ($P < 0.001$), PM_{10} emission rate ($P < 0.001$), $PM_{2.5}$ concentration ($P < 0.001$), $PM_{2.5}$ emission rate ($P < 0.001$), and personal PM_{10} exposure ($P < 0.001$): the levels of these response variables decreased with increasing oil application rate and most contrasts between the treatments were significantly different (Table 2). Table 2 and Fig. 2 furthermore show that, at the same oil application rate, reductions for $PM_{2.5}$ were higher than for PM_{10}. Since the ventilation rate did not differ significantly between treatments, reductions in PM emission rates in Table 2 are attributable to reductions in PM concentrations (see Eq. 2).

Table 2
Model-estimated[1] means[2] on the measured scale for ventilation rate, particulate matter concentrations, particulate matter emission rates, and personal PM_{10} exposure. Model-estimated means on the natural log-scale are given in parenthesis.

Variable	Treatment (mL/m^2 per d)				
	0	15	30	45	SEM[3]
Ventilation rate (m^3/h per bird)	4.46 (0.40)	4.33 (0.38)	4.57 (0.42)	4.33 (0.38)	(0.24)
PM_{10} concentration (µg/m^3)	2623 (0.96) [a]	1952 (0.67) [a]	998 (-0.002) [b]	544 (-0.61) [c]	(0.15)
PM_{10} concentration reduction (%)	--	26	62	79	--
PM_{10} emission rate (mg/h per	12.3 (2.51) [a]	8.95 (2.19) [a]	4.73 (1.55) [b]	2.27 (0.82) [c]	(0.28)
PM_{10} emission reduction (%)	--	27	62	82	--
$PM_{2.5}$ concentration (µg/m^3)	187 (-1.68) [a]	66 (-2.72) [b]	43 (-3.15) [c]	28 (-3.56) [d]	(0.18)
$PM_{2.5}$ concentration reduction (%)	--	65	77	85	--
$PM_{2.5}$ emission rate (mg/h per	0.81 (-0.21) [a]	0.24 (-1.44) [b]	0.14 (-1.96) [b]	0.05 (-2.96) [c]	(0.36)
$PM_{2.5}$ emission reduction (%)	--	71	83	94	--
Personal PM_{10} exposure (mg/m^3)	3.65 (1.29) [a]	1.54 (0.43) [b]	0.78 (-0.25) [c]	0.33 (-1.10) [d]	(0.12)
Personal PM_{10} exposure reduction	--	58	79	91	--

[1] See Eq. 3.
[2] n=12 for each mean.
[3] Pooled standard error on the natural log-scale.
[a, b, c, d] Means in the same row with different superscripts are significantly different ($P \leq 0.05$).

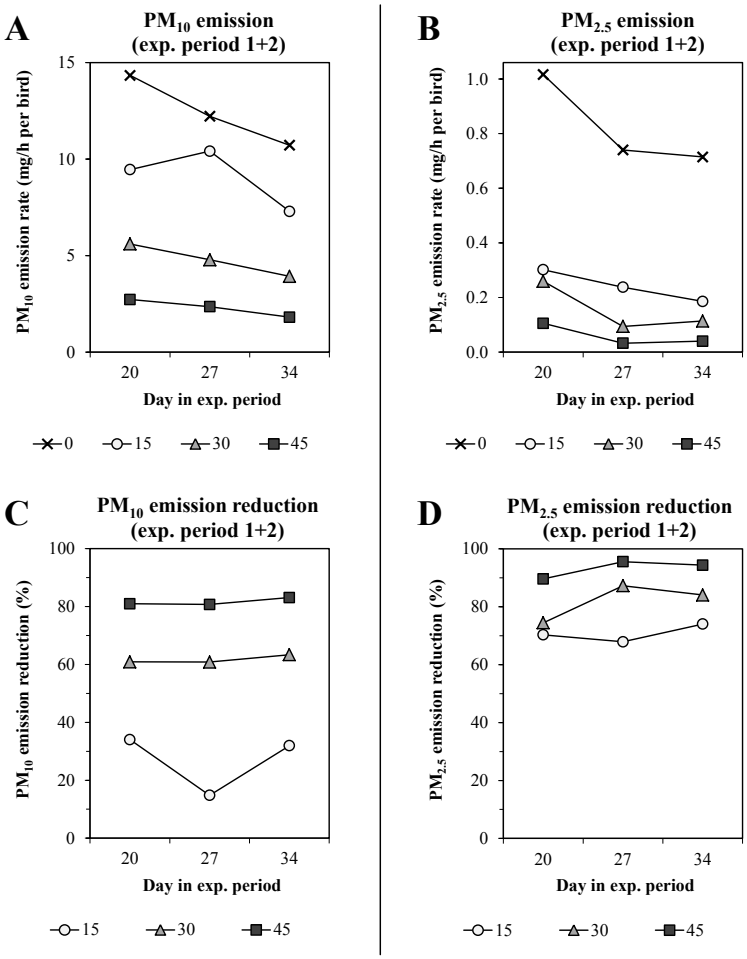


Fig. 2
Time trends in model-estimated mean emission rates of PM_{10} (A) and $PM_{2.5}$ (B), and of emission reductions of PM_{10} (C) and $PM_{2.5}$ (D). Each data point represents the mean of 4 values. Note that oil was sprayed from day 11. Legends: oil application rates in mL/m^2 per day. Note that the drop in $PM_{2.5}$ emission from day 20 to 27 in the 30 and 45 mL/m^2 per day treatments (Fig. B) was significantly different from each other and the 0 and 15 mL/m^2 per day treatments.

A significant interaction between oil application rate and day number was found for $PM_{2.5}$ concentration (P = 0.038), $PM_{2.5}$ emission rate (P = 0.004), and personal PM_{10} exposure (P = 0.003). Comparison of the differences between estimated means and the least significant difference showed that the interaction for $PM_{2.5}$ and day number was due to a significant drop in $PM_{2.5}$ from day 20 to 27 in the 30 and 45 mL/m^2 per day treatments; Fig. 2B). The same analysis of the interaction for personal PM_{10} exposure showed that this was caused by a total of 12 significant day to day differences within treatments. Since day number in the EP is included in

Eq. 3 as a factor term (D_p), significant day to day differences in concentrations and emissions within a treatment can result in a significant interaction without the presence of a general time trend. The effect of time on the effectiveness of the oil treatments is therefore further explored in Fig. 2 (C and D) and Fig. 3. From these figures it is clear that the reductions of PM_{10} and $PM_{2.5}$ emission were relatively stable in time, whereas the reductions of personal PM_{10} exposure tended to increase further from day 19 to 29/33 of the EP.

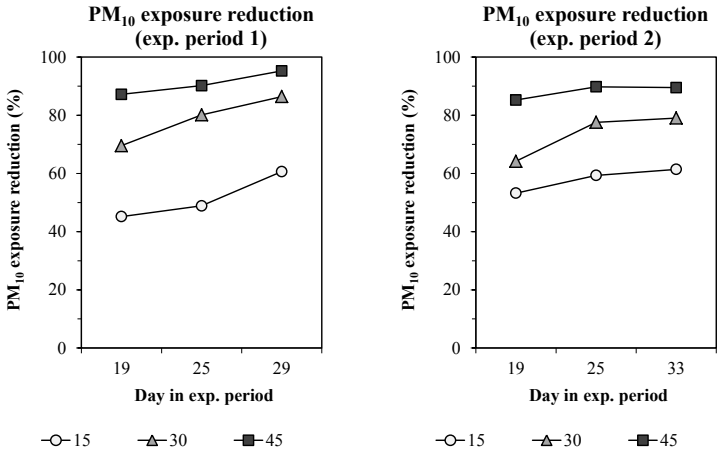


Fig. 3
Time trends in the reduction of PM_{10} exposure of stockman during experimental period 1 (left) and 2 (right). Each data point represents the mean of 2 values. Note that oil was sprayed from day 11. Legends: oil treatments in mL/m^2 per d.

Bird performance

Table 3 shows the mean values of the bird performance variables. The statistical analyses showed no significant effects of the application of oil on bird mortality and eggs/birds ratio. A significant effect of treatment time was found for the percentage of second class eggs. This response variable increased in time in the control treatment (term t in Eq. 4; $P < 0.001$; from 1.3% at day 1 to 1.4% at day 35), but in the oil spraying treatments, a stronger increase was found (term tt in Eq. 4; $P = 0.004$; from 1.3% at day 1 to 1.9% at day 35) which, however, was not significantly different between the 3 oil spraying treatments. No significant effects were found of the application of oil on the percentage of first class eggs, third class eggs, or mislaid eggs.

A general effect of time (term t in Eq. 4; $P = 0.042$) was found for the percentage of mislaid eggs. This variable decreased (in both control and oil spraying treatments) from 2.0% on day 1 to

1.4% on day 35 of the EP. The eggs/birds ratio was lower for aviary A (0.933) in comparison with aviary B (0.942; $P = 0.004$). Furthermore, the percentage of second class eggs was higher for aviary A (1.70%) in comparison with aviary B (1.28%; $P = 0.017$). Finally, the percentage of third class eggs was higher for aviary A (0.48%) in comparison with aviary B (0.38%; $P = 0.033$).

Table 3
Mean values of mortality, egg production, and egg quality per aviary system and treatment. Note that, relative to the control treatment, a significant shift was found towards more second class eggs in the oil spraying treatments, regardless of the aviary system.

Variable	Aviary A				Aviary B			
	Treatment (mL/m^2 per d)				Treatment (mL/m^2 per d)			
	0	15	30	45	0	15	30	45
Mortality (%)	0.00	0.49	0.32	0.16	2.21	1.34	1.01	1.86
Egg production (eggs/bird per d)	0.942	0.929	0.933	0.926	0.944	0.946	0.939	0.940
Egg quality								
First class eggs (%) [1]	96.8	95.7	96.7	95.9	97.0	96.4	96.3	95.9
Second class eggs (%) [2]	1.47	1.80	1.51	2.04	1.28	1.26	1.24	1.34
Third class eggs (%) [3]	0.54	0.46	0.42	0.50	0.34	0.39	0.39	0.39
Mislaid eggs (%) [4]	1.21	2.04	1.39	1.54	1.42	1.90	2.12	2.41

[1] Eggs with no imperfections.
[2] Eggs contaminated with manure or blood, eggs with a cracked shell but intact membrane, double-yolked eggs, and eggs with an abnormal shape.
[3] Eggs with broken membrane, shell-eggs, and very small eggs.
[4] Eggs laid outside the nest: in the aviary frame or on the litter floor.

Bird behavior

No significant effects were found of the application of oil, or any other model term, on the percentage of birds displaying dust bathing or scratching behavior. The mean percentage of birds displaying dust bathing behavior in the 0, 15, 30, and 45 mL/m^2 per day treatments was 17%, 21%, 19%, and 20% respectively (pooled SEM: 3.8; n = 8 per treatment). The mean percentage of birds displaying scratching behavior in the 0, 15, 30, and 45 mL/m^2 per day treatments was 5.0%, 4.9%, 5.9%, and 7.0% respectively (pooled SEM: 1.8; n = 8 per treatment).

Bird exterior quality

The statistical analysis showed no significant effects of the application of oil on the plumage condition for the body spots: throat/neck, chest/breast, and legs. A significant effect of time was found for these 3 response variables ($P = 0.006$ for throat/neck; $P < 0.001$ for chest/breast, and $P < 0.001$ for legs). The mean percentage of birds falling in the 'intact' class on days 7, 19, and

29/33 amounted 49%, 34%, and 11% for throat/neck, 48%, 42%, and 25% for chest/breast, and 95%, 71%, and 50% for legs respectively.

The plumage condition of back/wings/tail also worsened in time but different time trends were found for the aviary systems (P = 0.003). The percentage of birds falling in the 'intact' class on day 7, 19, and 29/33 amounted 51.4%, 50.4%, and 43.3% for aviary A and 50.8%, 50.1%, and 46.4% for aviary B respectively. Furthermore, a significant shift in the plumage condition of back/wings/tail was found from the initial phase of the EP (d 7) to the oil spraying phase (d 19 and 29/33), modelled by the term φ_i in Eq. 4, which differed between the oil spraying treatments (P = 0.027). This finding is presented in Fig. 4. Comparison of the differences between estimated means and the least significant difference showed that the interaction represented a significant worsening of the plumage condition of back/wings/tail in the 45 mL/m^2 per day treatment only. The existence of a general shift (a main effect; for all 3 oil spraying treatments) proved near-significant (P = 0.059).

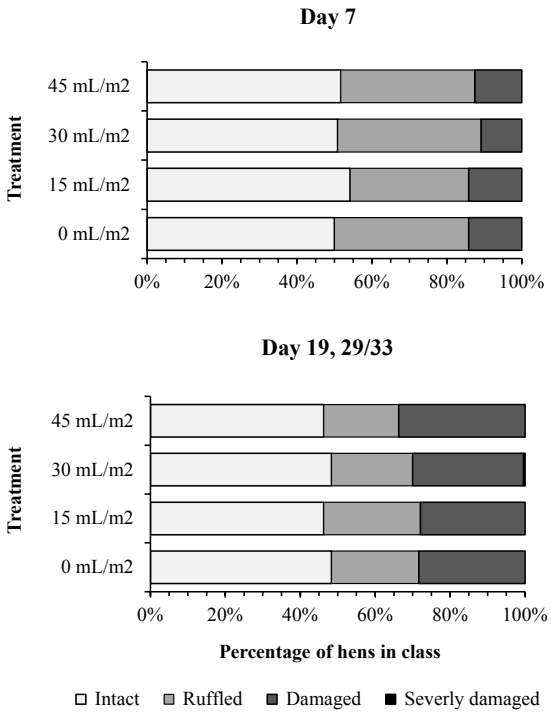


Fig. 4
Percentage of birds per plumage condition class for the body spot 'back/wings/tail', presented for the initial phase of the experimental period (day 7) and for the oil spraying phase (day 19 and 29/33). Note that a significant shift was found from day 7 to 19 and 29/33 for the 45 mL/m^2 per day treatment only (P = 0.027). None of the birds fell in the 'partly naked' or 'naked' class (therefore not shown in legend).

With regard to plumage soiling, the statistical analysis showed no significant effects of the application of oil, nor of any other of the model terms tested. With regard to foot soiling, a significant shift was found from the initial phase of the EP (d 7) to the oil spraying phase (d 19 and 29/33), modelled by the term φ_i in Eq. 4, which differed between each of the three oil spraying treatments ($P < 0.001$). This finding is further presented in Fig. 5, which shows that the extent of foot soiling decreased with increasing amounts of oil sprayed (hence, the foot became cleaner).

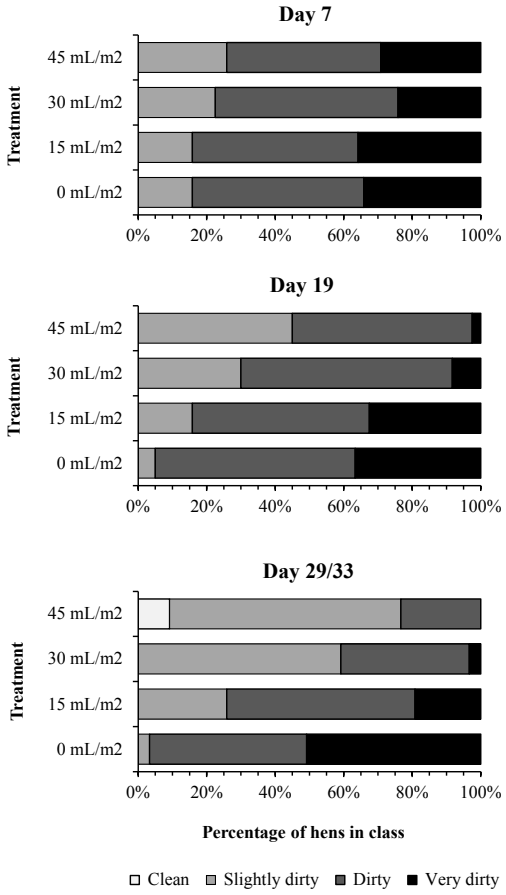


Fig. 5
Percentage of birds falling in each foot soiling class, presented for the initial phase of the experimental period (day 7) and for the oil spraying phase (day 19 and 29/33). Note that significant shifts were found from day 7 to 19 and 29/33, which differed significantly between the treatments ($P < 0.001$).

Litter

The statistical analysis showed no significant effects of the application of oil, or any other model term, on the DM content of the litter. The mean DM content of the litter in the 0, 15, 30, and 45 mL/m^2 per day treatments was 795, 798, 808, and 807 g/kg (pooled SEM: 20; n = 8 per treatment), respectively.

The formation of cakes or clumps of litter was not detected. The litter layer was fully friable and crumbly in all rooms throughout the EPs. Since there was no variation between scores of this response variable, no statistical analysis was performed.

DISCUSSION

PM concentrations and emission rates of control rooms were consistent with those reported in a recent emission survey in commercial farms in the Netherlands (Winkel et al., 2015). Substantially higher oil application rates were needed in the present study to reduce these PM levels in comparison with broilers on litter floors (Aarnink et al., 2011; Winkel et al., 2014). In the latter studies, the application of 16 mL/m^2 per day reduced PM_{10} by 64 to 70%. In the present study however, the application of 15 mL/m^2 per day reduced PM_{10} by only 27%. This difference is presumably the net result of several factors that differ between broiler housings and aviary housings. First, the average mass of birds per m^2 of litter in the aforementioned broiler studies was 20.6 kg over a 35 day growing cycle and 39.7 kg at the end of the cycle (Aarnink et al., 2011; Winkel et al., 2014), whereas in the present study, the average mass of birds per m^2 was only 8 kg, assuming 25% of the hens to be present on the litter floor and 75% in the aviary frame (Carmichael et al., 1999; Channing et al., 2001; Odén et al., 2002). Since the aerosolization of particles from the litter occurs by direct mechanical force (e.g., by dust bathing) and by air flow induced force (e.g., by wing flapping), aerosolization increases with the mass of animals which is able to exert such force. Hence, the lower bird mass per unit of litter area in the aviaries as such may have required less oil to be sprayed to achieve a certain level of PM reduction. In contrast, hens in aviaries presumably display more active behavior on the litter than broilers in floor housing. Hens travel between litter floor and aviary frame (e.g., by jumping and flying) (Campbell et al., 2016), whereas broilers are confined to a floor. Fast-growing broilers tend to display behaviors in a sitting posture (Bokkers and Koene, 2003) and their locomotor activity drastically declines with age (Bessei, 1992). Also, laying hen litter is usually more friable and dry (750 to 850 g/kg) (Groot Koerkamp and Bleijenberg, 1998; Groot Koerkamp et al., 1998) in

comparison with broiler litter (500 to 700 g/kg) (Van Harn et al., 2012; Winkel et al., 2014). The aforementioned three aspects each promote particle aerosolization in aviaries. Finally, in the present study, oil was sprayed onto the litter directly, using a spraying gun, whereas in broilers, oil was sprayed throughout the entire room, covering the equipment and the broilers as well. Because settled dust layers in the aviary frame, the manure on the belts in the aviary frame, and the feathering of the hens remained untreated by oil, it is likely that more oil needed to be sprayed onto the litter only to achieve a certain level of PM reduction in the room as a whole.

In previous research in broilers (Aarnink et al., 2011; Winkel et al., 2014), we found that $PM_{2.5}$ was reduced by 81 to 84% at oil application rates of 6 to 8 mL/m^2 per d, and this level did not increase further at higher application rates (12 to 24 mL/m^2 per d). It was hypothesized that some of the oil droplets in the $PM_{2.5}$ fraction might still have been present in the air during PM sampling, cancelling out any extra $PM_{2.5}$ reduction. The present study further supports this, since $PM_{2.5}$ reduction did increase with increasing oil application rate and oil droplets could not be erroneously sampled as $PM_{2.5}$ because the oil was sprayed directly onto the litter. In agreement with the aforementioned broiler studies, results of the present study show that, at a certain oil application rate, $PM_{2.5}$ is more reduced than PM_{10}. Earlier, we suggested that the oil film functions as a binding agent which confines particles in the upper litter layer (Winkel et al., 2015). Given that the oil was applied directly onto the litter, a wash out of particles from the air can be ruled out as the working principle. More likely, the oil aggregates tiny particles in the upper litter layer to bigger ones, which settle rapidly when dispersed in the air by movements of the birds. This would furthermore explain why oil spraying seems to be more effective for smaller particles.

In the present study, no significant effects were found of oil spraying on bird mortality. A positive relationship between PM concentration and mortality in laying hens was reported by Guarino et al. (1999). Such (long-term) effect however, may have well needed longer exposure times than 25 days to become apparent between control and oil treatments.

Furthermore, we found no significant effects of oil spraying on the DM content and friability of the litter. In broilers, the absence of such effects have been reported as well (Griffin and Vardaman, 1970; Winkel et al., 2014). The percentage of the hens present on the litter floor displaying dust bathing behavior in this work (overall mean: 19%) falls within the 14% to 22% presented for ‘good litter’, but outside the range of 3% to 12% presented for ‘bad litter’, in a study in 25 farms in Sweden by Odén et al. (2002; figure 7). Furthermore, the percentage of the hens present on the litter floor displaying scratching behavior in this work (overall mean: 6%) agrees very well with the 4% to 9% reported by Channing et al. (2001; figure 3). These results

indicate that, at the investigated application rates and application duration, oil spraying does not affect the litter quality or behavior of the hens.

Remarkably, the extent of foot soiling decreased with increasing oil application rate. The working principle behind this remains unclear. Perhaps, the rapeseed oil stimulates litter to aggregate to bigger particles which do not settle easily in the grooves of the foot pads. Alternatively, the oil may seal off the grooves, or oil coated litter particles may not easily adhere to the skin of the foot.

Two possible negative side-effects were found: (1) a stronger increase in the percentage of second class eggs in time in the oil treatments versus the control treatment, and (2) a worsening of the plumage condition of the body spot back/wings/tail in the 45 mL/m^2 per day treatment only. One of the reasons for rating eggs as second class was contamination of the shell with manure. When this finding reflects a true effect, eggs must have been contaminated directly after laying and before they had rolled onto the egg belt, since egg belts were clean and integrated within the nest box. It seems unlikely however, that such contamination has been caused by soiling of the nests, feathers or foot, since oil was not sprayed within the aviary frame (Fig. 1), no effects of oil application were found on feather soiling, and the foot of the hens became cleaner with increasing oil application rate. No effects of oil spraying were found on the quantity of eggs produced.

The worsening of the plumage condition of the body spot back/wings/tail may reflect a true negative side-effect, since this effect was only found in the highest (45 mL/m^2 per d) oil treatment and these body parts come into close contact with the top litter layer during dust bathing. The plumage condition of throat/neck, chest/breast, and legs remained unaffected by the application of oil.

In the present study, the oil was sprayed onto the litter manually, to ensure that an exact amount of oil was applied, spread out equally over the entire litter surface. It took 3, 7, or 10 seconds to spray 15, 30, or 45 mL on a squared meter of litter respectively. In large-scale commercial aviary houses, this approach may take up to an 8-h working day to complete and is therefore impractical. An automated, technical solution is needed in future which sprays the oil directly onto the litter without reaching the aviary or the hens, which can cover the entire litter surface, and does not cause the oil droplets to drift. An evaluation is currently in progress of two such solutions: a fixed system with nozzles positioned directly above the litter throughout the aviary house and an autonomously driving oil spraying vehicle. In conclusion, this study shows that such solutions should be able to reduce PM concentrations and emission rates in aviaries by spraying 15 to 30 mL/m^2 per day with minor side effects within 25 day of daily spraying.

ACKNOWLEDGMENTS

This study was financed by the Dutch Ministry of Economic Affairs and the Dutch Ministry of Infrastructure and the Environment. We thank the staff of poultry research centre 'Het Spelderholt' for taking care of the animals, Mr. Alfred Gerrits, Mr. Theo van Hattum, Mr. Jos Huis in't Veld, Mr. Guus Nijeboer and Mr. Johan Ploegaert for carrying out the measurements, Mr. Eef Lovink for maintenance and calibration of measuring equipment, and Mr. Jean Slangen and Mr. Geert Kupers for carrying out the lab analyses.

REFERENCES

Aarnink, A.J.A., Van Harn, J., Van Hattum, T.G., Zhao, Y., Ogink, N.W.M., 2011. Dust reduction in broiler houses by spraying rapeseed oil. *Trans. ASABE* 54:1479–1489.

Al Homidan, A., Robertson, J.F., Petchey, A.M., 2003. Review of the effect of ammonia and dust concentrations on broiler performance. *World's Poult. Sci. J.* 59:340–349

Bessei, W. 1992. The behaviour of broilers under intensive management conditions. *Archiv Für Geflügelkunde* 56: 1–7.

Bokkers, E.A.M., Koene, P., 2003. Behaviour of fast- and slow growing broilers to 12 weeks of age and the physical consequences. *Appl. Anim. Behav. Sci.* 81:59–72.

Calvet, S., van den Weghe, H., Kosch, R., Estellés, F., 2009. The influence of the lighting program on broiler activity and dust production. *Poult. Sci.* 88:2504–2511.

Cambra-López, M., Hermosilla, T., Lai, H.T.L., Aarnink, A.J.A., Ogink, N.W.M., 2011. Particulate matter emitted from poultry and pig houses: Source identification and quantification. Trans. ASABE 54:629–642.

Campbell, D.L.M., Makagon, M.M., Swanson, J.C., Siegford, J.M., 2016. Laying hen movement in a commercial aviary: Enclosure to floor and back again. *Poult. Sci.* 95:176–187.

Carmichael, N.L., Walker, A.W., Hughes, B.O., 1999. Laying hens in large flocks in a perchery system: Influence of stocking density on location, use of resources and behaviour. *Brit. Poult. Sci.* 40:165–176.

CEN, 1998. EN 12341:1998. Air quality - Determination of the PM 10 fraction of suspended particulate matter - Reference method and field test procedure to demonstrate reference equivalence of measurement methods. Comité Européen de Normalisation (CEN; European Committee for Standardization), Brussels, Belgium.

CEN, 2005. EN 14907:2005. Ambient air quality - Standard gravimetric measurement method for the determination of the PM2.5 mass fraction of suspended particulate matter. Comité Européen de Normalisation (CEN; European Committee for Standardization), Brussels, Belgium.

Channing, C.E., Hughes, B.O., Walker, A.W., 2001. Spatial distribution and behaviour of laying hens housed in an alternative system. *Appl. Anim. Behav. Sci.* 72:335–345.

CIGR, 2002. 4th Report of working group on climatization of animal houses. Heat and moisture production at animal and house levels (eds. Pedersen, S. and K. Sällvik). International Commission of Agricultural Engineering (CIGR), Section II.

Donham, K., Cumro, D., 1999. Setting maximum dust exposure levels for people and animals in livestock facilities. Pages 93–110 in Proc. Int. Symp. on Dust Contr. in Anim. Prod. Facilities, Aarhus, Denmark.

Griffin, J.G., Vardaman, T.H., 1970. Cottonseed oil spray for broiler houses: Effects on dust control, Mycoplasma gallisepticum spread, and broiler performances. *Poult. Sci.* 49:1664–1668.

Groot Koerkamp, P.W.G., Bleijenberg, R., 1998. Effect of type of aviary, manure and litter handling on the emission kinetics of ammonia from layer houses. *Brit. Poult. Sci.* 39:379–392.

Groot Koerkamp, P.W.G., Speelman, L., Metz, J.H.M., 1998. Litter composition and ammonia emission in aviary houses for laying hens. Part 1: Performance of a litter drying system. *J. Agric. Eng. Res.* 70:375–382.

Guarino, M., Caroli, A., Navarotto, P., 1999. Dust concentration and mortality distribution in an enclosed laying house. *Trans. Asae* 42:1127–1133.

Gustafsson, G., Von Wachenfelt, E., 2006. Measures against airborne dust in a floor housing system for laying hens. Agricultural Engineering International: the CIGR Ejournal Manuscript BC 06 018. Vol. VIII. December, 2006, 1–13.

Heederik, D.J.J., Opstal-van Winden, A.J.W., Smit, L.A.M., Wouters, I.M., Hooiveld, M., IJzermans, C.J., van der Sman-de Beer, F., Spreeuwenberg, P.P.M., de Bruin, A., van Rotterdam, B., 2011. Mogelijke effecten van intensieve-veehouderij op de gezondheid van omwonenden: onderzoek naar potentiële blootstelling en gezondheidsproblemen. Institute for Risk Assessment Sciences (IRAS), Universiteit Utrecht; Nederlands instituut voor onderzoek van de gezondheidszorg (NIVEL); Rijksinstituut voor Volksgezondheid en Milieu (RIVM), Utrecht, the Netherlands.

Ikeguchi, A., 2002. Ultra sonic sprayer controlling dust in experimental poultry houses. Agricultural Engineering International: the CIGR Ejournal Manuscript BC 01 002. Vol. IV. October, 2006, 1-10.

Li, Q.F., Wang-Li, L., Walker, J.T., Shah, S.B., Bloomfield, P., Jayanty, R.K.M., 2012. Particulate matter in the vicinity of an egg production facility: Concentrations, statistical distributions, and upwind and downwind comparison. *Trans. ASABE* 55:1965–1973.

Odén, K., Keeling, L.J., Algers, B., 2002. Behaviour of laying hens in two types of aviary systems on 25 commercial farms in Sweden. *Brit. Poult. Sci.* 43:169–181.

Ogink, N.W.M., Aarnink, A.J.A., 2011. Plan van aanpak bedrijfsoplossingen voor fijnstofreductie in de pluimveehouderij [Plan of action for particulate matter mitigation solutions in poultry; in Dutch, with English summary]. Animal Sciences Group, Wageningen University and Research Centre, Lelystad, the Netherlands.

Omland, Ø., 2002. Exposure and respiratory health in farming in temperate zones - A review of the literature. *Annals Agric. Environ. Med.* 9:119–136.

Pedersen, S., Blanes-Vidal, V., Joergensen, H., Chwalibog, A., Haeussermann, A., Heetkamp, M.J.W., Aarnink, A.J.A., 2008. Carbon dioxide production in animal houses: a literature review. Agricultural Engineering International: CIGR Ejournal. Manuscript BC 08 008. Vol. X. December, 2008.

PPE-PVV, 2012. Livestock, meat and eggs in the Netherlands: keyfacts 2011 (edition 2012). Dutch Product Board for Poultry and Eggs (PPE) and the Dutch Product Board for Livestock and Meat (PVV), Zoetermeer, the Netherlands.

Radon, K., Danuser, B., Iversen, M., Jörres, R., Monso, E., Opravil, U., Weber, C., Donham, K.J., Nowak, D., 2001. Respiratory symptoms in European animal farmers. *Eur. Respir. J.* 17:747–754.

RIVM, 2011. Annual national emissions of PM10; in total and per sector/source, for 2011. Emissieregistratie, Rijksinstituut voor Volksgezondheid en Milieu (RIVM) [Pollutant Release and Transfer Register, National Institute for Public Health and the Environment (RIVM)], Bilthoven, the Netherlands.

Seedorf, J., Hartung, J., Schröder, M., Linkert, K.H., Phillips, V.R., Holden, M.R., Sneath, R.W., Short, J.L., White, R.P., Pedersen, S., Takai, H., Johnsen, J.O., Metz, J.H.M., Groot Koerkamp, P.W.G., Uenk, G.H., Wathes, C.M., 1998. Concentrations and emissions of airborne endotoxins and microorganisms in livestock buildings in Northern Europe. *J. Agric. Eng. Res.* 70:97–109.

Takai, H., 2002. Ammonia contents and desorption from dusts collected in livestock buildings. CIGR ejournal IV:1–11.

Takai, H., 2007. Factors influencing dust reduction efficiency of spraying of oilwater mixtures in pig buildings, DustConf 2007 - How to improve air quality, Maastricht, the Netherlands.

Takai, H., Pedersen, S., Johnsen, J.O., Metz, J.H.M., Groot Koerkamp, P.W.G., Uenk, G.H., Phillips, V.R., Holden, M.R., Sneath, R.W., Short, J.L., White, R.P., Hartung, J., Seedorf, J., Schröder, M., Linkert, K.H., Wathes, C.M., 1998. Concentrations and emissions of airborne dust in livestock buildings in Northern Europe. *J. Agric. Eng. Res.* 70:59–77.

Van Harn, J., A. J. A. Aarnink, J. Mosquera, J. W. Van Riel, and N. W. M. Ogink. 2012. Effect of bedding material on dust and ammonia emission from broiler houses. Trans. ASABE 55:219-226.

Viegas, S., Faísca, V.M., Dias, H., Clérigo, A., Carolino, E., Viegas, C., 2013. Occupational exposure to poultry dust and effects on the respiratory system in workers. *J. Toxic. Environ. Health* 76:230–239.

Von Wachenfelt, E. 1999. Dust reduction in alternative production systems for laying hens. Pages 261-264 in Proc. Int. Symp. on Dust Contr. in Anim. Prod. Facilities, Aarhus, Denmark.

VSN. 2013. GenStat reference manual (release 16), Hemel Hempstead, UK.

Winkel, A., Cambra-López, M., Groot Koerkamp, P.W.G., Ogink, N.W.M., Aarnink, A.J.A., 2014. Abatement of particulate matter emission from experimental broiler housings using an optimized oil spraying method. *Trans. ASABE* 57:1853–1864.

Winkel, A., Mosquera, J., Groot-Koerkamp, P.W.G., Ogink, N.W.M., Aarnink, A.J.A., 2015. Emissions of particulate matter from animal houses in the Netherlands. *Atmos. Environ.*111:202–212.

Yang, X., Lorjaroenphon, Y., Cadwallader, K.R., Wang, X., Zhang, Y., Lee, J., 2014. Analysis of particle-borne odorants emitted from concentrated animal feeding operations. *Sci. Total Environ.* 490, 322–333.

Zhao, Y., Aarnink, A.J.A., Hofschreuder, P., Groot Koerkamp, P.W.G., 2009. Evaluation of an impaction and a cyclone pre-separator for sampling high PM10 and PM2.5 concentrations in livestock houses. *J. Aerosol Sci.* 40: 868–878.

Chapter 5

Evaluation of oil spraying systems and air ionization systems for abatement of particulate matter emission in commercial poultry houses

A. Winkel [a], J. Mosquera [a], A..J.A. Aarnink [a], P.W.G. Groot Koerkamp [a,b], and N.W.M. Ogink [a]

[a] Wageningen UR Livestock Research, Wageningen, the Netherlands
[b] Farm Technology Group, Wageningen University, Wageningen, the Netherlands

Biosystems Engineering (2016) 150:104–122

Reprinted with permission from Elsevier Ltd
Available online at: http://dx.doi.org/10.1016/j.biosystemseng.2016.07.014

ABSTRACT

The present study evaluated the performance of four systems for abatement of particulate matter (PM) emission inside full-scaled commercial poultry houses: a fixed oil spraying system (OSF) inside two broiler farms and one laying hen house, an autonomously driving oil spraying vehicle (OSV) in one laying hen house, a negative air ionization system (NAI) inside two broiler farms, and a positive air ionization system (PAI) inside two laying hen houses. The systems were evaluated using case-control approaches. At each farm, six 24-h measurements were scheduled of PM_{10}, $PM_{2.5}$, ammonia, odor, and carbon dioxide concentrations (the latter for estimation of the ventilation rate and herewith emissions). This paper presents the layout of the systems, compares their performance in practice with that under experimental conditions, discusses improvement possibilities, reports the baseline emission rates of the poultry houses, and discusses the validity of the case-control approaches. The emission reductions of PM_{10} and $PM_{2.5}$ were: 60% and 53% for the OSF in broilers (at 12 mL m^{-2} d^{-1}), 21% and 31% for the OSF in laying hens (at 15 mL m^{-2} d^{-1}), 32% and 38% for the OSV in laying hens (at 30 mL m^{-2} d^{-1}), 49% and 68% for the NAI in broilers, and 6% and zero for the PAI in laying hens. None of the systems significantly reduced the emission rate of odor or ammonia. On the basis of this work, emission reduction factors of the OSF, OSV, and NAI have been adopted in Dutch regulations.

NOMENCLATURE

B1, B2, B3, B4	Broiler farms 1, 2, 3, and 4, respectively
$C_{exhaust}$	Pollutant concentration in the exhaust air flow
C_{inlet}	Pollutant concentration in the inlet air flow
CO_2	Carbon dioxide
$[CO_2]_{exhaust}$	Concentration of carbon dioxide in the exhaust air flow (ppm)
$[CO_2]_{inlet}$	Concentration of carbon dioxide in the inlet air flow (ppm)
E	Emission rate of pollutant (mg h^{-1} $bird^{-1}$)
Fco_2	Factor for conversion of total heat to the volumetric carbon dioxide production by the animal and its manure (m^3 h^{-1} kW^{-1})
L1, L2, L3, L4	Laying hen farms 1, 2, 3, and 4, respectively
NAI	Negative air ionization system
NH_3	Ammonia
OSF	Fixed oil spraying system (installed in B1, B2, and L1)
OSV	Oil spraying vehicle (installed in L2)
OU_E	European Odour Unit
P	Level of significance
PAI	Positive air ionization system
PM	Particulate matter
PM_{10}	Particulate matter which passes through a size-selective inlet with a 50% efficiency cut-off at 10 µm aerodynamic diameter (EN 12341)
$PM_{2.5}$	Particulate matter which passes through a size-selective inlet with a 50% efficiency cut-off at 2.5 µm aerodynamic diameter (EN 14907)
SD	Standard deviation
Q	Total ventilation rate in the poultry house (m^3 h^{-1} $bird^{-1}$)
Φ_{total}	Total heat production by the animal (kW)

INTRODUCTION

Houses for broilers and laying hens with littered floors show the highest concentrations of airborne particulate matter (PM) among all housing systems for poultry, pigs, and dairy in the livestock sector (Takai et al., 1998; Winkel et al., 2015b). These high concentrations may affect the health and productivity of the birds (Al Homidan et al., 2003; Guarino, Caroli and Navarotto, 1999) and cause respiratory problems in workers (Omland, 2002; Radon et al., 2001). Since poultry houses exhaust up to 10 m^3 h^{-1} $bird^{-1}$ polluted air, a large number of PM is also released into the atmosphere and can contribute to local and regional background PM concentrations. Very little is known about health effects of ambient PM from intensive livestock houses to neighboring residents, but available studies suggest some effects, such as a higher incidence of pneumonia and a lower lung function in the general population, and more exacerbations in patients suffering from Chronic Obstructive Pulmonary Disease (COPD) (Borlée et al., 2015; Heederik et al., 2011; Radon et al., 2007; Schinasi et al., 2011). On a national scale, poultry houses in the Netherlands contribute 13% of the national primary emission of particles with aerodynamic diameters smaller than 10 μm (PM_{10}). To protect the health of its residents, maximum PM limit values for ambient air were set by the European Union (European Directive 2008/50/EC), namely: a daily average limit for PM_{10} of 50 μg m^{-3} with 35 exceedances allowed per year, and an annual average limit of 40 μg m^{-3} for PM_{10} and 25 μg m^{-3} for particles with aerodynamic diameters smaller than 2.5 μm ($PM_{2.5}$). In the Netherlands, the PM_{10} limit is regularly exceeded in the vicinity of animal houses (RIVM, 2014; Van Zanten et al., 2012).

Within a plan of action (Ogink and Aarnink, 2011), PM reduction principles were developed in the Netherlands into effective, economically feasible, and market-ready systems for the poultry industry. Within this plan, air cleaning companies were asked to adopt, co-develop, install, and maintain PM reduction systems inside test locations in collaboration with our research institute. Furthermore, our institute was responsible for the scientific testing of the principles under experimental conditions in small-scaled housings. Three of these principles showed perspective to reduce PM emissions by reducing PM concentrations inside the house: (1) spraying a thin film of pure rapeseed oil onto the litter, (2) negative air ionization, and (3) positive air ionization.

With regard to principle (1), some studies related to this principle are available, but they used 1 to 10% oil in water emulsions (instead of pure rapeseed oil) in laying hen houses, and these were not sprayed onto the litter (Gustafsson and Von Wachenfelt, 2006; Ikeguchi, 2002; Von Wachenfelt, 1999). Other studies did spray directly onto the litter but their focus was on air

quality and bird performance, not on emission abatement (Drost et al., 1999; Griffin and Vardaman, 1970; McGovern et al., 1999, 2000). Within the plan of action (Ogink and Aarnink, 2011), a fixed oil spraying system, consisting of air pipes and oil pipes fueling spraying nozzles, was developed and installed inside four rooms of an experimental broiler house (Aarnink et al., 2011). In that study, which was conducted over four growing cycles, the application of 6 to 24 mL m^{-2} d^{-1} could reduce PM_{10} emission by 48% to 87%, respectively. No effects were found on ammonia emission nor on the production performance of the broilers. It was recommended that the maximum rate should be 16 mL m^{-2} d^{-1} to prevent adverse effects on broilers' foot-pad quality. In a follow-up study (Winkel et al., 2014), the spraying system was extended to twice the number of nozzles to achieve more uniform spraying. It showed that, when oil was sprayed every other day, PM_{10} emission was 44% higher on days after spraying than on spraying days. The study furthermore confirmed that oil spraying (up to 16 mL m^{-2} d^{-1}) had no effect on ammonia emission, bird production performance, nor on the incidence of foot-pad lesions. Also, no effect on odor emission was found. A third study on oil spraying was carried out in eight rooms of an experimental aviary house (Winkel et al., 2016). Here, oil was applied to the litter floor using a hand-held spray gun in rates of 15, 30, or 45 mL m^{-2} d^{-1} which reduced PM_{10} emission with 27%, 62%, and 82%, respectively. Two small but significant negative side-effects were found: a shift in egg quality towards second class eggs for all oil doses and a worsening of the plumage condition of the body spot 'back/wings/tail' in the 45 mL m^{-2} d^{-1} treatment only. Egg production, plumage soiling, behaviour, and litter quality remained unaffected for all oil doses tested. From this study, it was recommended to spray oil in aviaries at 15 to 30 mL m^{-2} d^{-1}.

With regard to principle (2), two studies have shown that PM can be removed from broiler house air by negative air ionization by about 40% (Jerez et al., 2013; Ritz et al., 2006). Within the plan of action (Ogink and Aarnink, 2011), a negative air ionization system was installed inside two rooms of the same experimental broiler house as used earlier (Aarnink et al., 2011; Winkel et al., 2014) and tested during two growing cycles (Cambra-López et al., 2009). This system reduced PM_{10} emission by 36%, whereas no effects were found on airborne micro-organisms, ammonia, odor, or bird performance. From that study, it was recommended to evaluate the results in commercial houses.

In the present study, principle (3) is introduced, which uses a positive polarity to remove PM from the air, similarly to the principle of negative air ionization. This third principle was not experimentally tested before.

To establish causality between the PM reduction treatments and response variables, fully identical rooms were used in the experimental studies into principles (1) and (2), excluding any variation between rooms as much as possible, except for the varying treatments (according to the scientific principle of *ceteris paribus*). In commercial farms, there is much variation in a broad array of variables related to animal breed, housing design, management practices, and so on. Hence, the performance under experimental conditions may differ from practical conditions. The objective of the current work was to evaluate the performance of systems based on principles (1), (2), and (3) inside full-scale commercial broiler and laying hen farms. This evaluation was a last step of the plan of action, necessary to adopt PM abatement systems in Dutch regulations and become officially available for poultry farmers to install them inside their houses. Overall, this article presents the final technical design and the performance of four PM abatement systems which were evaluated at eight poultry farms: a fixed oil spraying system (OSF) inside two broiler farms and one laying hen house), an autonomously driving oil spraying vehicle (OSV) in one laying hen house, a negative air ionization system (NAI) inside two broiler farms, and a positive air ionization system (PAI) inside two laying hen houses. On the basis of this work, emission reduction factors of the OSF, OSV, and NAI have been adopted in Dutch regulations.

METHODOLOGY

General design of the study

This study used 'case-control' designs, following the requirements described in the 'test protocol for livestock housing and management systems' of the VERA organization (VERA, 2011) and the Dutch 'Protocol for the measurement of fine emissions from housings in animal production' (Ogink et al., 2011).

The OSF and NAI systems were each installed at two broiler farms (four in total; B1 through B4; Table 1), to include between farm variation in the design. Within each of these farms, one broiler house served as the treatment house and a second, identical, and adjacent house, served as the control (eight houses in total; Table 1). The treatment and the control were appointed to the identical houses within a farm randomly. At each farm, six 24-h measurements were scheduled. At broiler farms B1 and B2 with the OSF system (Table 1), measurements were only scheduled between day 22 and 42 of the growing cycle, when the oil was sprayed. At broiler farms B3 and B4 with the NAI system (Table 1), measurements were scheduled over the entire growing cycle, but more measurements were scheduled in the second half to improve the accuracy for that

period, since a major part of the total emission from a growing cycle takes place in the last two to three weeks (Aarnink et al., 2011; Winkel et al., 2015b).

Table 1
Main layout of the poultry houses.

Farm	Case-control design [a]	Evaluation period	Housing characteristics	Length × width; bird places [b]	Ventilation inlet, exhaust; ventilation capacity
Oil spraying, fixed system (OSF)					
Broilers 1 (B1)	T vs. C	April '09–Oct. '09	Litter floor (wood shavings), lines with feed pans and nipple drinkers, hot air blowers	65 × 14 m; 21,500	Side wall inlets, roof and end wall fans; 8.7 m^3 h^{-1} $bird^{-1}$
Broilers 2 (B2)	T vs. C	Sept. '09–Oct. '10	Same as Broilers 1	52 × 13 m; 14,000	Side wall inlets, roof fans; 6.3 m^3 h^{-1} $bird^{-1}$
Layers 1 (L1)	T	Aug. '13–May '14	Litter floor and aviary system with manure belts (forced drying), laying nests, feeders and nipple drinkers	51 × 16 m; 12,125	Manure belt aeration (0.7 m^3 h^{-1} $bird^{-1}$) and side wall inlets, end wall fans; 10.4 m^3 h^{-1} $bird^{-1}$
Oil spraying, autonomously driving vehicle (OSV)					
Layers 2 (L2)	T	Dec. '11–Dec '12	⅓ Litter area, ⅔ elevated slatted floor above manure pit, with laying nests, chain feeders and lines with nipple drinkers	40 × 20 m; 6130	Side wall inlets, end wall fans; 10.1 m^3 h^{-1} $bird^{-1}$
Negative air ionization system (NAI)					
Broilers 3 (B3)	T vs. C	April '09–Oct. '09	Same as Broilers 1 and additional floor heating/cooling system	75 × 20 m; 33,000	Side wall inlets, end wall fans; 7.6 m^3 h^{-1} $bird^{-1}$
Broilers 4 (B4)	T vs. C	Sept. '09–July '10	Same as Broilers 1 and additional air mixing system (litter drying)	65 × 20 m; 30,000	Side wall inlets and pad cooling (front wall inlets), end wall fans; 10.1 m^3 h^{-1} $bird^{-1}$
Positive air ionization system (PAI)					
Layers 3 (L3)	T	May '12–Dec. '12	Same as Layers 2 (floor housing)	72 × 12 m; 7420	Side wall inlets, end wall fans; 6.1 m^3 h^{-1} $bird^{-1}$
Layers 4 (L4)	T	May '12–Dec. '12	Same as Layers 1 (aviary housing)	55 × 17 m; 15,100	Manure belt aeration (0.2 m^3 h^{-1} $bird^{-1}$) and side wall inlets, end wall fans; 11.8 m^3 h^{-1} $bird^{-1}$

[a] T: treatment house. C: control house. Note that at each broiler farm a system was installed inside a treatment house, whereas an identical house served as the control house. At each layer farm a system was installed inside one house and this house also served as the control house (with the system turned off).
[b] Bird places: number of birds placed in the building following applicable legislation on stocking density.

The OSF, OSV, and PAI systems could not be tested using treatment houses and control houses for laying hen houses, because laying hen farms with fully identical houses could not be found. Instead, these systems were installed inside one house per farm (L1 through L4; Table 1) and a case-control approach was created by performing a 24-h measurement with the system

turned off (from noon on day 1 to noon on day 2), followed by a measurement with the system turned on (from noon on day 2 to noon on day 3). The OSF and OSV were each installed in one farm, whereas the PAI was installed in two farms. At each of the laying hen farms, six of these three-day measurement periods were scheduled, spread over the year (about once every two months) and the laying period of the hens.

At the exhaust points inside the buildings, approximately 2 m upstream of the ventilators in the end walls, measurements were performed of PM_{10}, $PM_{2.5}$, ammonia, odor, and carbon dioxide concentration, and air temperature and relative humidity. The inside air at this point was assumed to be homogenously mixed and representative for the air leaving the building. Concentrations of PM_{10}, $PM_{2.5}$, and ammonia were determined either in duplicate (upstream of a central group of end wall ventilators) or as two single measurements (one sampler upstream of each of two groups of end wall ventilators). Odor concentration, air temperature, and relative humidity were determined by single measurements. Upwind of the buildings, within 2 m from an inlet, single measurements were done of PM_{10}, $PM_{2.5}$, ammonia, and carbon dioxide concentrations, and of air temperature and relative humidity. In B1, B2, B3, B4, L1, and L2 the full set of variables was included in the sampling strategy. Since the results at these houses showed that the NAI system did not affect air quality variables other than PM, ammonia and odor concentrations were excluded from the sampling strategy for the PAI inside L3 and L4. Each measurement lasted 24 h. Bird performance variables were not included in the set of variables to be measured, because in all studies on the NAI and OSF in broilers so far (Aarnink et al., 2011; Cambra-López et al., 2009; Winkel et al., 2014) no effects were found on these variables, whereas for the OSF, OSV, and PAI in laying hens, effects were unlikely given the few treatment days within the case-control approach.

Description of the systems

Oil spraying, fixed system (OSF)

The OSF has been described in earlier articles on the testing of the system under experimental conditions (Aarnink et al., 2011; Winkel et al., 2014). A schematic of the OSF inside B2 is presented in Fig. 1 (left). In summary, an air compressor was used to generate air pressure to both an air pressure vessel and a pressure vessel containing pure rapeseed oil (both vessels are meant to buffer pressure drops). These components were located outside the animal space, in a separate room. The air and oil pressure could be set independently by pressure reducing valves installed between compressor and vessels. From the vessels, an air pressure pipe and an oil

pressure pipe, both stainless steel pipes, ran into the animal space fueling spraying nozzles (type SU26B-SSBR, Spraying Systems, Ridderkerk, the Netherlands). The SU26B-SSBR nozzle has 6 spray openings and produces a wide angle round spray (cone).

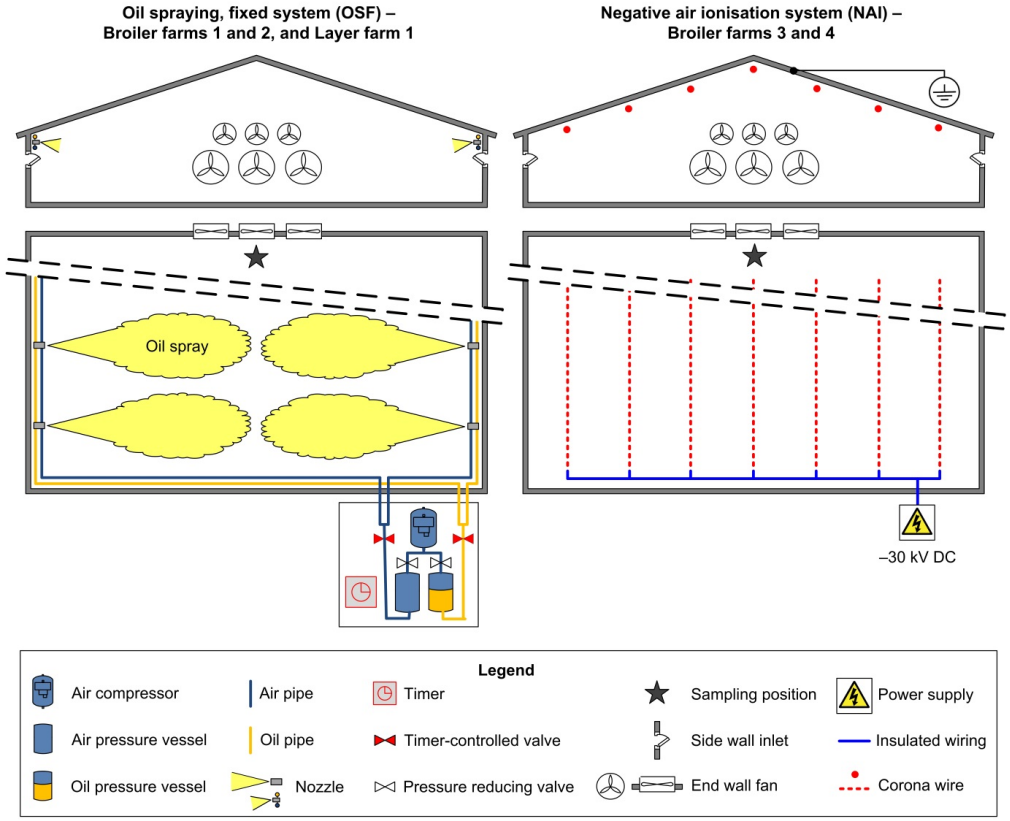


Fig. 1
Cross-sectional schematic (top) and plane schematic (bottom) of the fixed oil spraying system (OSF) at broilers farms 1 and 2 (left) and of the negative air ionization system (NAI) at broiler farms 3 and 4 (right). Note that a similar fixed oil spraying system was installed in layer farm 1.

In B1, a central set of one air pipe and one oil pipe ran under (i.e., parallel to) the roof ridge which had 10 nozzles facing each side wall (one pair of nozzles every 6 m; 20 in total; 46 m^2 of floor area per nozzle; air pressure: 3.0 bar, oil pressure: 3.0 bar). In this house, oil was sprayed from the central axis of the building towards the side walls. In B2, two sets of one air pipe and one oil pipe were used; one set mounted on each side wall, with 12 nozzles per side (one pair of nozzles every 4 m; 24 in total; 28 m^2 of floor area per nozzle; air pressure: 3.2 bar, oil pressure: 2.8 bar). In this house, oil was sprayed from the side walls to the centre of the building, as drawn

in Fig. 1 (left). A timer was used to simultaneously open the valves in the air and oil pipes once a day. The programmed oil application rate was 12 mL m^{-2} day^{-1} in both B1 and B2, and this was achieved by spraying times of 45 s in B1 and 24 s in B2. Differences in spraying time were due to differences in the surface area per nozzle and differences in the oil pressure applied to achieve a spraying pattern of sufficient length. Oil was sprayed from day 22 to the end of each growing cycle. Inside B1 and B2, the OSF sprayed a fog of oil droplets that filled the entire house and settled out to the litter, the birds, and any surface. Results from a laboratory study on the SU26B-SSBR nozzle showed that at 3.0 bar air and oil pressure, the median droplet size is 49 μm, 80% of the droplets fall within 18 and 157 μm (i.e., the 10- and 90-percentile), and the droplet velocity is 7.2 m s^{-1} (Aarnink and Van Hattum, 2009).

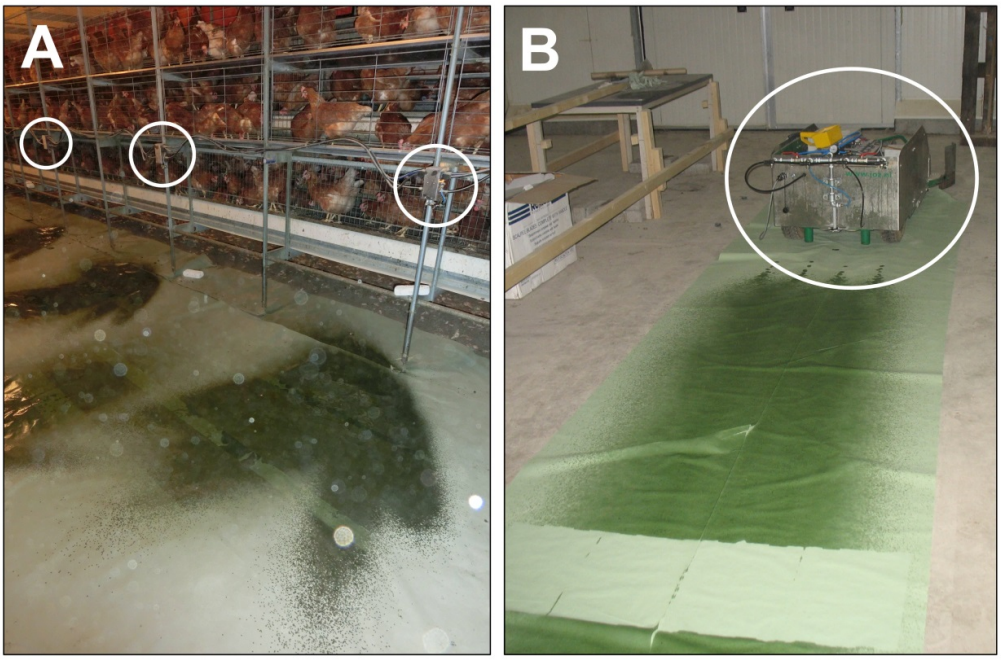


Fig. 2
A: photo of the oil spraying pattern of the fixed oil spraying system (OSF) inside layer farm 1 (spraying nozzles installed on the vertical aviary frame are circled white). Note that hens were locked inside the aviary during spraying. Furthermore, note that the SU26B-SSBR nozzle produces a wide round spray plume with 6 knobs; individual knobs are to some extent visible in the spraying pattern. B: photo of the oil spraying pattern of the autonomously driving oil spraying vehicle (OSV) applied in layer farm 2 (the OSV is circled white). Note that spraying patterns were determined on tracks of light green paper covering the floor in both photo's which stain darker where rapeseed oil droplets were applied.

In L1, a slightly modified OSF was used. Here, the solid stainless steel pipes were replaced by flexible tubes for air and oil which were each installed in a loop and remained under pressure continuously. The nozzles (76 in total) were not installed on the side walls but on the vertical aviary frames, facing the littered walking isles (Fig. 2B). Instead of using timer-controlled valves in the main tubes for air and oil, each nozzle had its own timer-controlled valve. Because oil was sprayed with one nozzle at a time, the flow rates and pressure drops during spraying were very low, which allowed the use of thinner tubes instead of pipes. The programmed oil application rate was 15 mL m^{-2} day^{-1}. The OSF in L1 was in operation during 'treatment days' only. Inside L1, the OSF sprayed oil droplets directly onto the unoccupied litter floor without the fog reaching the aviary frame or the birds. During spraying, in the early morning, the hens were locked inside the aviary system (Fig 2B; from the time the lights went off in the evening until 10:00 the next morning), which was the standard procedure at this farm. This also prevented the hens from being sprayed. The OSF systems were further developed, installed and maintained by Inter Continental BV (Ysselsteyn, the Netherlands).

Oil spraying, autonomously driving vehicle (OSV)

The prototype oil spraying vehicle (OSV) was the result of a development project carried out by JOZ BV (Westwoud, the Netherlands). A schematic of the OSV in L2 is shown in Fig. 3.This OSV was based on an autonomously driving vehicle for slurry scraping (JOZ-Tech type JT-100) which was transformed into a vehicle suitable for pure rapeseed oil spraying in laying hen houses. The body of the OSV measured 1.46 m long, 0.71 m wide, and 0.59 m high, weighed 410 kg, and drove on three foam filled tires: one centrally placed front wheel for driving/steering and two rear wheels (one at each side) for stability. The front wheel (turning radius: 180°) was directed by a 165 W driving motor and a 90 W steering motor which were powered by two Absorbed Glass Mat (AGM) batteries (12 V, 100 Ah), sufficient for 18 hours of operation. After driving a route, the OSV returned to a charging station (230 V AC, 5A). The slurry scraper on the front of the original vehicle was replaced by a v-shaped frame, designed to gently direct hens to the sides of the vehicle if necessary. Autonomous navigation took place by means of an antenna under the vehicle and passive transponders in the floor. The OSV could also be controlled manually by means of a remote control. The 80 L water tanks inside the original vehicle were removed and an 8 L oil pressure vessel was installed, next to a mini air compressor. Filling of the oil tank was done manually. On the rear of the OSV, a horizontal oil pipe was installed with four nozzles 0.20 m spaced apart. Oil was applied directly behind the OSV without spraying onto the hens (Fig. 2B).

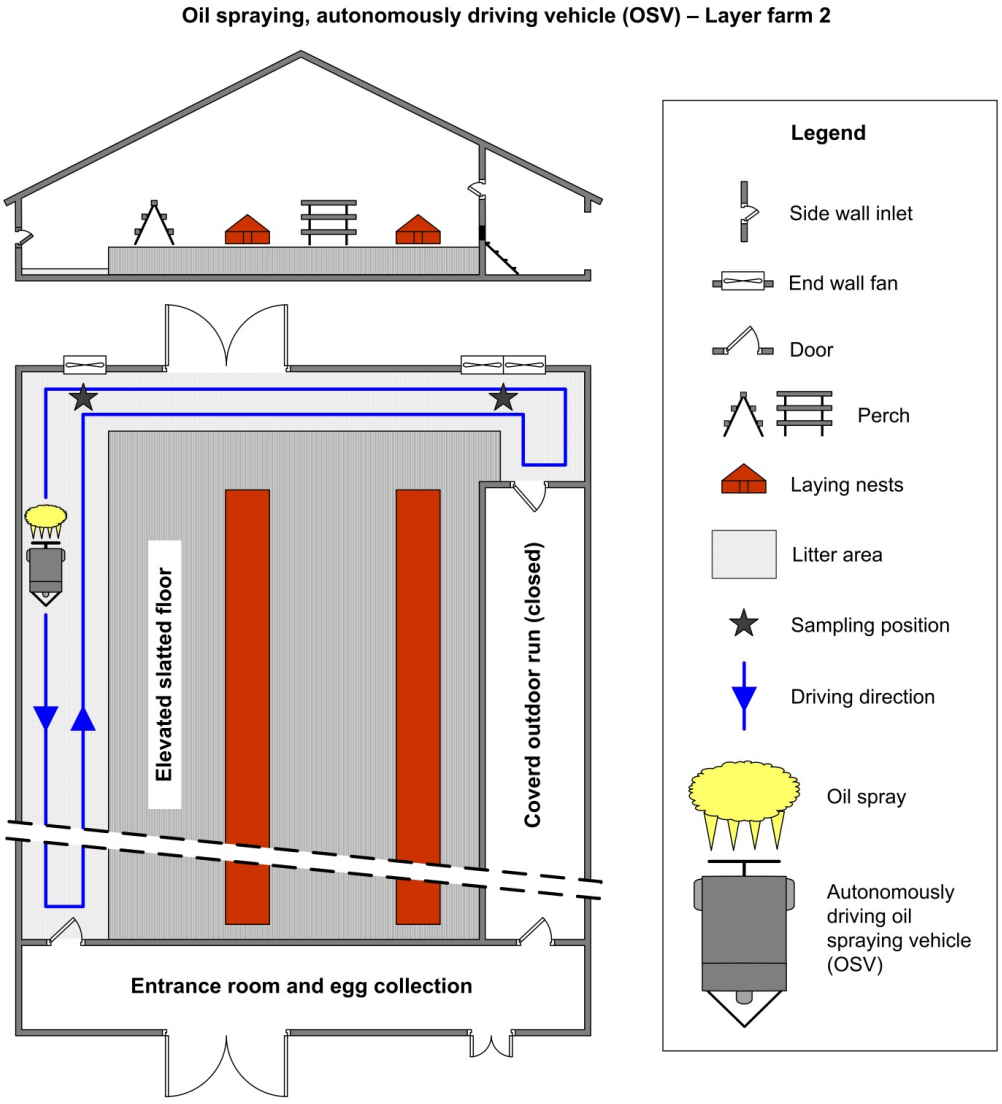


Fig. 3
Cross-sectional schematic (top) and plane schematic (bottom) of the autonomously driving oil spraying vehicle (OSV) inside layer farm 1.

After completion of a working prototype, preliminary driving tests inside the experimental aviary house, described by Winkel et al. (2016), showed that communication between antenna and transponders was not distorted by the presence of a litter layer up to 0.1 m. Preliminary spraying tests showed that four instead of two nozzles were needed on the rear spraying pipe to distribute the oil evenly across a spraying width of approximately 0.9 m. For the OSV, nozzles of

the type SU13-SSBR (Spraying Systems, Ridderkerk, the Netherlands) were chosen because they could produce a spray of fine droplets even at low air and oil pressures (see Fig. 2B for the spraying pattern). The oil application rate could be adjusted by means of pressure reducing valves for air and oil pressure in steps of 0.02 bar. Inside L2, transponders were drilled in the concrete floor and a charging station was placed inside a wooden box, accessible for the OSV through a front opening with vertical plastic flaps to keep out the hens. Air and oil pressure were programmed at 0.17 and 0.45 bar respectively, equivalent with an oil application rate of 30 mL m^{-2} (4590 mL in total; litter area: 153 m^2). On spraying days, the OSV drove a 110 m trajectory once at a speed of 3 m min^{-1} (total driving time: 35 to 40 min), starting at 10:00 in the morning. The OSV was in operation during 'treatment days' only.

Negative air ionization system (NAI)

The NAI has been described in an earlier article about the testing of the system under experimental conditions (Cambra-López et al., 2009) and is also known as the Electrostatic Space Charge System (ESCS) or the Electrostatic Particle Ionization (EPI) system (U.S. Patent No. 6,126,722; Baumgartner Environics, Inc., Olivia, Minn., USA). This system has been installed and maintained inside B3 and B4 throughout the present study by Inter Continental BV (Ysselsteyn, the Netherlands). A schematic of the NAI is presented in Fig. 1 (right). In summary, the system was composed of electrode wires with sharp pins that ran parallel to the longitudinal axis of the building, 0.15 to 0.30 m below the ceiling. A voltage of -30 kV was applied to the electrode wires by means of a power supply, limited to a maximum current of 2 mA. This causes electron emission from the wires, gas ionization, and subsequent charging of particles. These particles then travel to any grounded or oppositely charged object via the electric field lines that are created and by air turbulence. Once particles reach the roof surface, or any other surface that is grounded, they adhere to it and are thus removed from the air. Removal of the dust is done by frequent wet cleaning (in between flocks). Inside the treatment house of B3 and B4, nine electrode wires were installed, each connected to their own power supply. The total length of electrode wire was approximately 650 m for B3 and 565 m for B4. The total surface area of the roof was 1587 m^2 for B3 and 1350 m^2 for B4. The systems were in operation throughout the growing cycles.

Positive air ionization system (PAI)

The PAI system was developed by ENS Europe BV (Patent No. WO2013070078; Gassel, the Netherlands). A schematic of this system is presented in Fig. 4 and pictures are shown in Fig. 7.

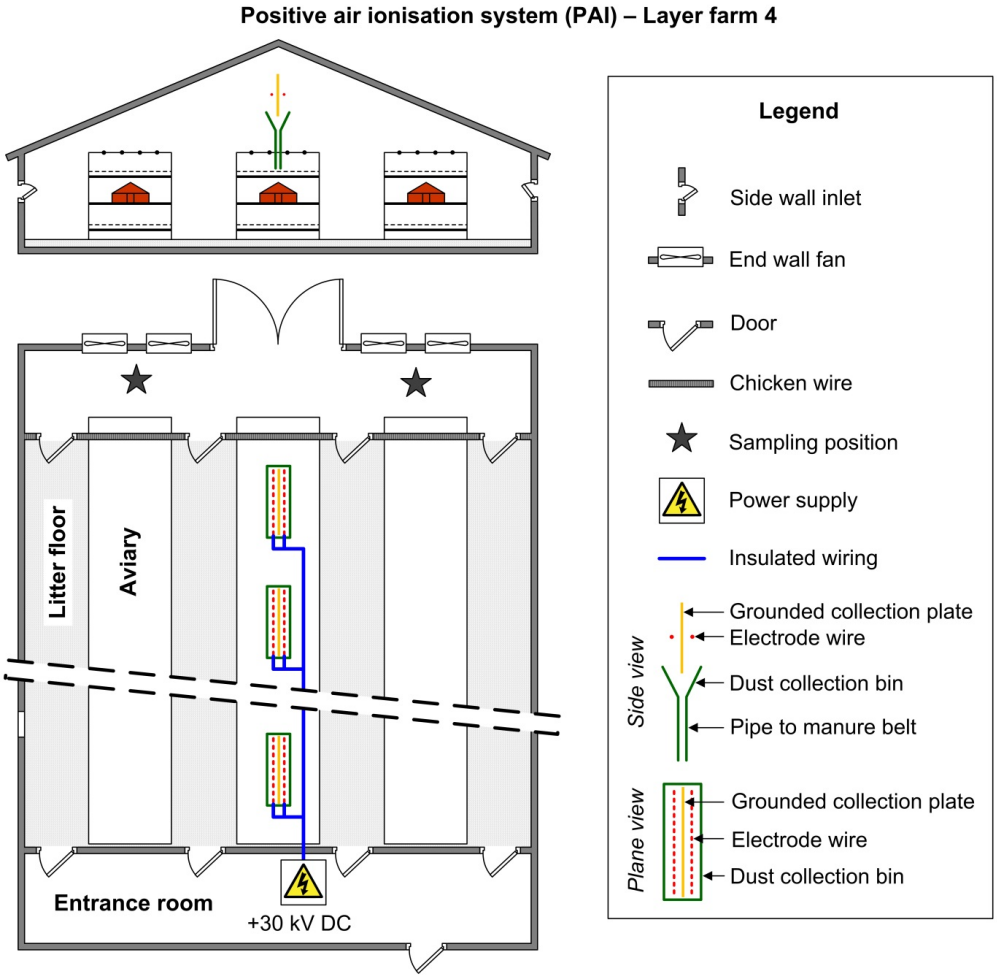


Fig. 4
Cross-sectional schematic (top) and plane schematic (bottom) of the positive air ionization system inside layer farm 4. Note that layer farm 3 had floor housing (see Fig. 3): therefore, in layer farm 3, the dust transport pipe led to the manure pit instead of the manure belt as shown above.

The system was composed of air ionization units mounted from the ridge of the building. This position was chosen so that the units were in the vortex-shaped longitudinal air stream pattern through the building (generated by the end wall fans and side wall inlets) which was assumed to increase the chance that particles in the air encountered the ionization units. In total, eight of

these units were installed in both L3 and L4. Each unit consisted of a sheet of stainless steel (approximately 2 m long and 1 m high) which functioned as grounded collection plate. The total surface area of the grounded collection plates was (8 units × 2 sides × 2 m in length × 1 m in height =) 32 m^2 in both L3 and L4. On both sides of the sheets, there was a horizontal electrode connected to a power supply (+30 kV DC), which was limited to a maximum current of 2 mA. The total length of electrodes was (8 units × 2 sides × 2 m of electrodes =) 32 m for both L3 and L4. The working principle of the PAI is very similar to that of the NAI with the exception that the PAI used a positive polarity (hence, positive ions were created) and the sheets instead of the ceiling functioned as PM collector. Below the collection plate, there was a dust collection bin and a dust transport pipe to the manure pit under the raised slatted floor (L3) or to the manure belt inside the aviary system (L4). The PAI was in operation during 'treatment days' only.

Measurements

Particulate matter concentrations

PM_{10} and $PM_{2.5}$ concentrations were determined by a filter-based method consisting of cyclone pre-separators (URG Corp., Chapel Hill, N.C., USA; model URG-2000-30ENB for PM_{10} and URG-2000-30 EG for $PM_{2.5}$), a filter holder (filter: Macherey–Nagel, Düren, Germany; type GF-3, Ø 47 mm), and air sampling pumps (Tecora, model Charlie HV; Ravebo B.V., Brielle, the Netherlands) at an air flow rate of 16.7 L min^{-1}. Unloaded and loaded filters were weighed four times during two consecutive days with a precise balance (Mettler, Greifensee, Switzerland; AT261 DeltaRange; resolution: 10 µg) at 20 ± 1 °C and 50 ± 5% relative humidity, following EN 12341 (CEN, 1998) and EN 14907 (CEN, 2005). PM_{10} concentrations were calibrated to the reference impaction sampler described in EN 12341 using the equations reported by Zhao, Aarnink, Hofschreuder, and Groot Koerkamp (2009): $y = 1.09x$ (when $x \leq 223$ µg m^{-3}) and $y = 0.83x + 57.5$ (when $x > 223$ µg m^{-3}), where x is the concentration measured with the cyclone sampler and y is the calibrated concentration.

Ammonia concentration

Ammonia concentration was determined by the 'wet chemical method' with acid traps (two impingers in series for a single measurement, with 100 mL of nitric-acid (HNO_3) solution at 0.05 M) connected to air sampling pumps (Thomas Industries Inc., Wabasha, MN, USA; model 607CD32) using a critical capillary of 1 L min^{-1}. The ammonium nitrogen content in the solution was determined by spectrophotometry. The total amount of ammonia was determined by

multiplying the NH_4^+-N concentration with the mass of the solution and the molecular weight of ammonia. The flow rate through the impingers was verified at the start and the end of the 24-h sampling period by an air flow meter (Defender 510-m, Bios Int. Corp, NJ, USA).

Odor and carbon dioxide concentrations

For determination of odor and carbon dioxide concentrations, air samples were taken using the 'lung principle'. Separate vessels for odor and carbon dioxide (with 40 L Nalophan air sampling bags inside, for one time use only) were connected to air sampling pumps (Thomas Industries Inc., Wabasha, MN; model 607CD32). In this principle, the pump sucks air from the vessel which causes the sampling bag to be filled with air taken from the sampling position. The sampling bags for odor were rinsed three times with odorless air before use and during sampling, the air first passed a dust filter (Savillex Corp., Minnetonka, MN, USA; #1130, Ø 50 mm, 1–2 μm). The air samples for odor were taken between 10:00 and 12:00 using a critical capillary of 0.4 L min^{-1}. The air samples for carbon dioxide were taken during the full 24-h sampling period using a critical capillary of 0.02 L min^{-1}. The air samples for determination of odor concentration were transported and stored following EN 13725 (CEN, 2003). Odor concentration (in European odor units: OU_E) was determined in the lab by dynamic olfactometry following European Standard EN 13725 (test panels with 4 to 6 participants) within 30 h after sampling. The air samples for determination of carbon dioxide concentration were analysed by gas chromatography (Interscience/Carlo Erba Instruments Inc., Breda, the Netherlands, GC 8000 Top; column Molsieve 5A; detector: HWD).

Environmental variables

Air temperature (°C) and relative humidity (%) were determined with combined sensors (Rotronic Instrument Corp., Hauppauge, N.Y.; accuracy of 1,0 °C and 2% relative humidity). Hourly mean values were stored in a data-logging system (Campbell Scientific Inc., Logan, UT, USA; types: CR10, CR10X, CR23 and CR23X).

Data preparation and analysis

Estimation of the ventilation rate

The ventilation rate was estimated in all houses by the CO_2 balance method which uses the carbon dioxide produced by the birds as tracer gas. First, the total heat production of one bird (Φ_{total}; kW) was calculated based on the body weight (in broilers and layers) and egg production

(for layers only), using the equations given by the CIGR (2002), in chapter two. Specific data on body mass and egg production were obtained from the farmer's records for each measurement date. Subsequently, the total heat production was multiplied by a factor (Fco_2) of 0.18 m^3 CO_2 h^{-1} kW^{-1} for layers and broilers up to 500 g body weight and 0.185 m^3 CO_2 h^{-1} kW^{-1} for broilers heavier than 500 g, as recommended in Table 6 of the paper by Pedersen et al. (2008). The ventilation rate (Q; m^3 h^{-1} $bird^{-1}$) was calculated for each measurement within a house using Eq. 1:

$$Q = \frac{\Phi_{total} \times Fco_2}{([CO_2]_{exhaust} - [CO_2]_{inlet}) \times 10^{-6}} \quad (1)$$

where $[CO_2]_{exhaust}$ is the carbon dioxide concentration measured in the exhaust air (ppm) and $[CO_2]_{inlet}$ the carbon dioxide concentration measured in the inlet air (ppm). Since Q was estimated on a 24-h basis, the diurnal variation in animal activity was not taken into account.

Calculation of emission rates

Emission rates (E) of PM_{10}, $PM_{2.5}$, and ammonia were calculated using Eq. 2:

$$E = Q \times (C_{exhaust} - C_{inlet}) \quad (2)$$

where $C_{exhaust}$ is the pollutant concentration measured in the exhaust air and C_{inlet} the pollutant concentration measured in the inlet air. For odor, Eq. 2 was applied without correction for background concentration (C_{inlet}) because odor concentrations from different sources cannot be added or subtracted.

Calculation of pollutant reductions

The emission reduction of a pollutant by a system was determined as the difference between the average emission of the control houses (or the control days), and the average emission of the treatment houses (or the treatment days), expressed as percentage of the control houses (or the control days).

Statistical analysis

For all measured variables, differences between treatment houses and control houses, or between treatment days and control days, were tested for statistical significance with the paired samples *t*-test. Relationships between treatment and control for ventilation rate were investigated

by regression analysis. For these procedures, the measurements carried out at one house were assumed to be statistically independent. All analyses were done using the GenStat software (VSN, 2014) and probability values ≤0.05 were considered statistically significant.

RESULTS AND DISCUSSION

Oil spraying in broiler houses (OSF)

Results obtained for the OSF in B1 and B2 are shown in Table 2. The statistical analysis showed that the climate conditions, carbon dioxide concentration, and ventilation rate did not differ significantly between treatment and control houses, indicating that the test was performed at a valid basis of comparison. Also, the absence of a significant difference in ventilation rate indicates that reductions of the emission rate was mainly attributable to reductions of concentrations (see Eq. 2).

Highly significant reductions were found for emission rates of PM_{10} and $PM_{2.5}$. Overall, spraying 12 mL m^{-2} d^{-1} reduced PM_{10} emission rate by 60% and $PM_{2.5}$ emission rate by 53%. In previous work under experimental conditions (Aarnink et al., 2011), the relationship between oil application rate and PM_{10} emission (relative to the control; ranging from 0 to 1) could be described by $y = -0.021x + 0.64$ ($R^2 = 0.69$), where y is the PM_{10} emission rate, and x the oil application rate. Fitting this equation for x = 12 mL m^{-2} d^{-1} yields a relative PM_{10} emission rate of 0.39 and a reduction of ((1 – 0.39) × 100 =) 61%. The 60% found in the present work fits that value very well. In previous work under experimental conditions (Aarnink et al., 2011), $PM_{2.5}$ emission was reduced by values in excess of 75% for all application rates tested. The 53% found in the current work is substantially lower. There are no apparent differences between the study of Aarnink et al. (2011) and the present work that might explain this difference; for example: all houses used stocking densities between 20 to 24 broilers per m^2, all houses used wood shavings as litter, the same type of oil was used, and in all houses, the $PM_{2.5}/PM_{10}$ ratio was about 0.06. In agreement to previous work (Aarnink et al., 2011; Winkel et al., 2014), emission rates of ammonia and odor were not significantly reduced by oil spraying (Table 2).

It should be noted that the reductions in Table 2 only apply to the second half of the growing cycle, since oil spraying started when the broilers were 22 days old. In a recent emission survey in the Netherlands, the PM_{10} emission pattern over the course of a growing cycle for 4 commercial broiler houses could be adequately described by $y = 0.0013x^{2.3855}$ ($R^2 = 0.89$) where y is the PM_{10} emission rate (mg h^{-1} $bird^{-1}$) and x is the day number in the growing cycle (Winkel

et al., 2015b). When this relationship is fitted for each of the 42 days, and expressed as a cumulative emission pattern on a relative scale, it can be calculated that 90% of the total mass of PM_{10} emitted during a 42-day growing cycle emits between day 22 and 42. Thus, the reduction of PM_{10} emission over an entire growing cycle is (61 × 0.90 =) 55%. Using the same method for $PM_{2.5}$ ($y = 0.00002x^{2.8032}$ ($R^2 = 0.83$); Winkel et al., 2015b), yields a reduction of $PM_{2.5}$ emission over an entire growing cycle of (53 × 0.93 =) 49%.

Table 2
Results of the fixed oil spraying (OSF) system in broiler farms 1 and 2 (SD = standard deviation between measurements; n.s. = not significant). Note that these data were collected in the second half of 6-week growing cycles (oil was sprayed from day 22 to 42) and therefore only apply to that part of a cycle.

Variable	Broiler farm	*n*	Control house; mean (SD)	Treatment house; mean (SD)	Difference	
					Mean [a]	Sign.
Air temperature (°C)	B1	5	24.1 (1.3)	23.5 (1.8)	–0.7	
	B2	5	24.2 (1.8)	25.4 (1.8)	1.2	
	B1 and B2	10	24.2 (1.5)	24.5 (2.0)	0.3	n.s. [b]
Relative humidity (%)	B1	6	63 (14)	67 (13)	4	
	B2	6	66 (18)	69 (9)	3	
	B1 and B2	12	65 (15)	68 (11)	3	n.s. [b]
CO_2 concentration (ppm)	B1	6	1488 (179)	1425 (174)	–4%	
	B2	6	2130 (745)	2370 (855)	11%	
	B1 and B2	12	1809 (616)	1898 (768)	5%	n.s. [b]
Ventilation rate ($m^3\ h^{-1}\ bird^{-1}$)	B1	6	2.77 (0.84)	2.97 (0.91)	7%	
	B2	6	2.13 (1.52)	1.95 (1.60)	–8%	
	B1 and B2	12	2.45 (1.22)	2.46 (1.35)	0%	n.s. [b]
PM_{10} concentration ($\mu g\ m^{-3}$)	B1	6	1559 (327)	423 (134)	–73%	
	B2	5	3410 (1444)	2064 (1137)	–39%	
	B1 and B2	11	2400 (1350)	1169 (1122)	–51%	$P < 0.001$ [c]
PM_{10} emission rate ($mg\ h^{-1}\ bird^{-1}$)	B1	6	4.12 (1.11)	1.16 (0.65)	–72%	
	B2	5	6.31 (2.60)	3.08 (1.20)	–51%	
	B1 and B2	11	5.12 (2.15)	2.03 (1.34)	–60%	$P < 0.001$ [c]
$PM_{2.5}$ concentration ($\mu g\ m^{-3}$)	B1	5	105 (18)	37 (21)	–65%	
	B2	5	259 (189)	170 (107)	–35%	
	B1 and B2	10	182 (150)	103 (101)	–43%	$P = 0.003$ [c]
$PM_{2.5}$ emission rate ($mg\ h^{-1}\ bird^{-1}$)	B1	5	0.27 (0.07)	0.09 (0.08)	–67%	
	B2	5	0.38 (0.15)	0.22 (0.07)	–43%	
	B1 and B2	10	0.33 (0.13)	0.15 (0.10)	–53%	$P < 0.001$ [c]
NH_3 concentration (ppm)	B1	6	2.95 (2.48)	2.25 (1.68)	–24%	
	B2	6	25.4 (13.5)	25.5 (10.6)	1%	
	B1 and B2	12	14.2 (14.9)	13.9 (14.2)	–2%	n.s. [c]
NH_3 emission rate ($mg\ h^{-1}\ bird^{-1}$)	B1	6	4.95 (3.81)	4.54 (4.43)	–8%	
	B2	6	27.0 (2.96)	26.0 (7.17)	–4%	
	B1 and B2	12	16.0 (12.0)	15.3 (12.6)	–4%	n.s. [c]
Odor concentration ($OU_E\ m^{-3}$)	B1	6	869 (443)	844 (359)	–3%	
	B2	6	1109 (551)	988 (392)	–11%	
	B1 and B2	12	989 (493)	916 (366)	–7%	n.s. [c]
Odor emission rate ($OU_E\ s^{-1}\ bird^{-1}$)	B1	6	0.69 (0.39)	0.75 (0.48)	9%	
	B2	6	0.51 (0.19)	0.44 (0.24)	–13%	
	B1 and B2	12	0.60 (0.30)	0.60 (0.40)	–7%	n.s. [c]

[a] Reduction of a variable in the treatment house is reflected by a negative mean difference.
[b] Determined by the two-sided paired-samples *t*-test.
[c] Determined by the one-sided paired-samples *t*-test.

The OSF functioned as planned throughout the evaluation period. During the first spraying days, spraying was started manually so that the response of the broilers could be observed, and in the case of fright reactions or bird piling, spraying could be stopped or lights could be dimmed. The birds did react with running and vocalizations when the fog of oil droplets suddenly appeared from the nozzles, but they calmed down again within the 45 seconds of spraying. Based on the experiences with the OSF systems in B1 and B2, the OSF was further developed in a number of ways. These developments, incorporated in the OSF in L1, are described in the Methodology section.

Oil spraying in laying hen houses (OSF and OSV)

Results obtained for the OSF in L1 and the OSV in L2 are shown in Table 3. The statistical analysis showed that climate conditions, carbon dioxide concentration, and ventilation rate did not differ significantly between control days and treatment days, indicating that the test took place at a valid basis of comparison. Also, the absence of a significant difference in ventilation rate indicates that reductions of the emission rate was attributable to reductions of concentrations (see Eq. 2).

Highly significant reductions were found for emission rates of PM_{10} and $PM_{2.5}$. Spraying 30 mL m^{-2} d^{-1} in L1 using the OSV reduced PM_{10} emission rate by 32% and $PM_{2.5}$ emission rate by 38%. Spraying 15 mL m^{-2} d^{-1} in L1 using the OSF reduced PM_{10} emission rate by 21% and $PM_{2.5}$ emission rate by 31%. These reductions are substantially lower than determined in previous experimental work in small-scaled aviaries (Winkel et al., 2016). In that study, 30 mL m^{-2} d^{-1} reduced PM_{10} emission rate with 62% and $PM_{2.5}$ emission rate with 83%, and for 15 mL m^{-2} d^{-1}, these values were 27% and 71%, respectively. In agreement with previous work (Aarnink et al., 2011; Winkel et al., 2014) and the results in Table 2, emission rates of ammonia and odor were not significantly reduced by oil spraying.

Two factors probably played a role in the lower PM reductions. First, the OSV and OSF could not distribute the oil over the entire litter floor area, in contrast to Winkel et al. (2016) where a hand-held spraying gun was used. Although the OSV created a very equally distributed spraying pattern (Fig. 2A), it could not drive within 0.8 m from the left side wall in Fig. 3, because of the presence of rafters protruding from that wall every 2 m. This untreated area made up 20% of the total litter floor area. A similar issue was encountered with the OSF in L1: here, a total of 78 nozzles was installed on the vertical aviary frames, facing the littered walking isles (Fig. 2B). This was done to spray the oil directly onto the litter, without reaching the hens (which were

Table 3
Results of the fixed oil spraying system (OSF) in layer farm 1 and the autonomously driving oil spraying vehicle (OSV) in layer farm 2 (SD = standard deviation between measurements; n.s. = not significant).

Variable	Layer farm	*n*	Control days; mean (SD)	Treatment days; mean (SD)	Difference	
					Mean [a]	Sign.
Air temperature (°C)	L1 (OSF)	5	21.6 (0.6)	21.8 (0.9)	0.2	
	L2 (OSV)	4	19.9 (1.1)	19.7 (0.9)	–0.2	
	L1 and L2	9	20.8 (1.2)	20.8 (1.4)	0.0	n.s. [b]
Relative humidity (%)	L1 (OSF)	5	76 (16)	64 (5)	–13	
	L2 (OSV)	3	78 (0.7)	73 (8)	–5	
	L1 and L2	8	77 (13)	68 (8)	–9	n.s. [b]
CO_2 concentration (ppm)	L1 (OSF)	6	1338 (548)	1367 (476)	2%	
	L2 (OSV)	5	1760 (434)	1933 (264)	10%	
	L1 and L2	11	1530 (524)	1624 (478)	6%	n.s. [b]
Ventilation rate (m^3 h^{-1} $bird^{-1}$)	L1 (OSF)	6	3.73 (2.12)	3.49 (2.00)	–7%	
	L2 (OSV)	5	2.07 (0.86)	1.55 (0.35)	–25%	
	L1 and L2	11	2.98 (1.82)	2.61 (1.75)	–12%	n.s. [b]
PM_{10} concentration (µg m^{-3})	L1 (OSF)	6	4060 (1065)	3640 (902)	–10%	
	L2 (OSV)	5	2860 (687)	2503 (797)	–12%	
	L1 and L2	11	3514 (1701)	3123 (1007)	–11%	$P = 0.025$ [c]
PM_{10} emission rate (mg h^{-1} $bird^{-1}$)	L1 (OSF)	6	14.3 (7.30)	11.3 (4.79)	–21%	
	L2 (OSV)	5	5.49 (1.24)	3.73 (1.16)	–32%	
	L1 and L2	11	10.3 (6.96)	7.88 (5.27)	–24%	$P = 0.005$ [c]
$PM_{2.5}$ concentration (µg m^{-3})	L1 (OSF)	6	261 (100)	212 (53)	–19%	
	L2 (OSV)	5	248 (190)	198 (172)	–20%	
	L1 and L2	11	255 (140)	206 (115)	–19%	$P = 0.003$ [c]
$PM_{2.5}$ emission rate (mg h^{-1} $bird^{-1}$)	L1 (OSF)	6	0.88 (0.50)	0.61 (0.26)	–31%	
	L2 (OSV)	5	0.47 (0.40)	0.29 (0.32)	–38%	
	L1 and L2	11	0.70 (0.48)	0.46 (0.32)	–33%	$P = 0.002$ [c]
NH_3 concentration (ppm)	L1 (OSF)	6	8.04 (7.72)	6.83 (5.05)	–15%	
	L2 (OSV)	5	42.4 (12.6)	46.7 (8.79)	10%	
	L1 and L2	11	23.7 (20.4)	25.0 (21.8)	5%	n.s. [c]
NH_3 emission rate (mg h^{-1} $bird^{-1}$)	L1 (OSF)	6	14.7 (7.27)	13.3 (8.20)	–10%	
	L2 (OSV)	5	56.6 (8.97)	49.1 (3.77)	–13%	
	L1 and L2	11	33.8 (23.2)	29.6 (19.8)	–12%	n.s. [c]
Odor concentration (OU_E m^{-3})	L1 (OSF)	6	610 (513)	743 (486)	22%	
	L2 (OSV)	5	866 (795)	918 (557)	6%	
	L1 and L2	11	713 (612)	813 (493)	14%	n.s. [c]
Odor emission rate (OU_E s^{-1} $bird^{-1}$)	L1 (OSF)	6	0.76 (1.13)	0.86 (0.99)	14%	
	L2 (OSV)	5	0.38 (0.20)	0.34 (0.13)	–9%	
	L1 and L2	11	0.61 (0.87)	0.65 (0.79)	8%	n.s. [c]

[a] Reduction of a variable in the treatment house is reflected by a negative mean difference.
[b] Determined by the two-sided paired-samples *t*-test.
[c] Determined by the one-sided paired-samples *t*-test.

temporarily locked inside the aviary frame; Fig. 2B), and to avoid soiling of the aviary frames, as recommended by Winkel et al. (2016). The drawback of this configuration is that the oil was applied very locally around the nozzles (Fig 2B) and a substantial part of the litter area was not directly treated with oil (indirectly, the scratching and dust bathing of the birds may spread treated litter to not directly treated areas). A second factor probably contributing to lower reductions in L1 and L2, was the single treatment of the litter by oil (i.e., only on treatment days), whereas in Winkel et al. (2016) the oil was applied every day for 25 days in a row. It is likely that, due to the study design, a build-up in the effectivity during the first spraying days was

missed and the reductions reported in Table 3 underestimate those with a prolonged daily spraying regime.

Several issues were encountered with the prototype OSV that need further development. They can be summarized as follows:

- *Size*: the present OSV measured 1.46 m long, 0.71 m wide, and 0.59 m high, and weighed 410 kg. A next version needs to be smaller and lighter. Such prototype would be easier to handle, needs a smaller battery, should be able to drive under the bottom tier of aviary frames, and migrate between separated sections or storeys of a laying hen house.
- *Maneuverability*: in sharp bends, the OSV needed to drive back and forth because its turning radius was to large. A next version needs to be able to make sharper bends so that it can change direction in small spaces.
- *Grip*: the present OSV drove on three foam filled tires which sometimes lacked sufficient grip on thick (0.05 to 0.20 m) and loose litter layers, or when there were solid cakes of litter. A next version needs to have better grip on such areas, for instance through use of caterpillars instead of tires.
- *Spraying system*: a next version of the OSV may need nozzles on both sides so that oil can also be sprayed side wards. This might increase the litter surface area that can be reached without having to drive over that area (such as litter under low bottom tiers of the aviary frame). Also, the OSV should be able to fill its oil tank autonomously.

Issues encountered with the OSF in L1 included the aforementioned local spraying of nozzles and problems with soiling of the nozzles with dust and red mites. To increase the litter area treated with oil, the number of nozzles could be further increased, but this would mean a substantial increase of the costs for the system. The nozzles installed on metal boxes with timer-controlled valves inside failed within weeks after installation. The interior of the boxes and nozzles proved to be soiled with dust and red mites. To solve this problem, the 78 metal boxes were uninstalled, disassembled, heated in an oven to kill the red mites, cleaned, and assembled again. In addition, all openings in the metal boxes were sealed off by a sealant.

Overall, the work carried out in L1 and L2 shows that it is very difficult to apply the principle of oil spraying in a practical, economically feasible, and effective solution. Further technical optimisations are needed before the OSV and OSF can be used inside commercial floor houses or aviary houses for laying hens. Once the above described optimisations have been successfully implemented, the OSV can be an effective and practical means of reducing PM in laying hen houses.

Negative air ionization in broiler houses (NAI)

Results obtained for the NAI in B3 and B4 are shown in Table 4. The statistical analysis showed that the indoor temperature was significantly lower in the treatment houses. This difference, however, was small (-0.5 °C) and a big effect of this difference on the emissions is not expected, since relative humidity, carbon dioxide concentration, and, especially the ventilation rate, did not differ significantly between treatment and control. The absence of a significant difference in ventilation rate indicates that reductions of the emission rate was attributable to reductions of concentrations (see Eq. 2).

Significant reductions were found for emission rates of PM_{10} (47%) and $PM_{2.5}$ (63%). It should be noted that the data in Table 4 were obtained from measurements scheduled mainly during the second half of the cycle). The data can be balanced by calculating a mean PM emission rate from three separate means for weeks 1+2, weeks 3+4, and weeks 5+6. This method yields mean PM_{10} emission rates of 3.27 and 1.66 mg h^{-1} $bird^{-1}$ (reduction: 49%) and mean $PM_{2.5}$ emission rates of 0.21 and 0.07 mg h^{-1} $bird^{-1}$ (reduction: 68%) for the control houses and treatment houses, respectively. These reductions are slightly higher than calculated from the uncorrected data.

The concentration of odor was significantly reduced by 12%. When these odor concentrations are multiplied with the ventilation rate (Eq. 2), the emission rate was reduced by 9%, which proved no longer significant (P = 0.172). In previous work under experimental conditions (Cambra-López et al., 2009), PM_{10} emission was reduced by 36% and no significant effect of the NAI was found on the emission rate of odor. The significant reduction of odor concentration found in the present work may be a coincidence, or may represent a true, but small effect of the NAI. In the case of a true effect, the removal of odor-carrying particles might be explained by oxidation of odor compounds. The PM removal by the NAI can be ruled out as working principle, because when sampling odorous air, the particles are filtered out, according the standard procedure.

Table 4
Results of the negative air ionization (NAI) system in broiler farms 3 and 4 (SD = standard deviation between measurements; n.s. = not significant). Note that these data were obtained from measurements that were distributed unevenly over the growing cycle (see the text for the corrected emission rates and removal efficiencies).

Variable	Broiler farm	*n*	Control house; mean (SD)	Treatment house; mean (SD)	Difference	
					Mean [a]	Sign.
Air temperature (°C)	B3	6	25.8 (2.7)	25.3 (2.6)	–0.5	
	B4	4	24.9 (4.0)	24.4 (4.0)	–0.5	
	B3 and B4	10	25.4 (3.1)	24.9 (3.0)	–0.5	$P = 0.003$ [b]
Relative humidity (%)	B3	6	70 (8)	65 (5)	–4	
	B4	2	69 (10)	67 (12)	–2	
	B3 and B4	8	69 (8)	66 (6)	–4	n.s. [b]
CO_2 concentration (ppm)	B3	6	1679 (954)	1595 (782)	–5%	
	B4	6	2108 (550)	1995 (502)	–5%	
	B3 and B4	12	1893 (776)	1795 (660)	–5%	n.s. [b]
Ventilation rate ($m^3\ h^{-1}\ bird^{-1}$)	B3	6	3.09 (2.81)	2.78 (2.09)	–10%	
	B4	6	1.50 (0.96)	1.70 (1.17)	13%	
	B3 and B4	12	2.29 (2.17)	2.24 (1.71)	–2%	n.s. [b]
PM_{10} concentration ($\mu g\ m^{-3}$)	B3	6	1274 (422)	756 (177)	–41%	
	B4	6	2004 (681)	819 (486)	–59%	
	B3 and B4	12	1639 (661)	787 (350)	–52%	$P < 0.001$ [c]
PM_{10} emission rate ($mg\ h^{-1}\ bird^{-1}$)	B3	6	4.01 (4.73)	2.16 (1.84)	–46%	
	B4	6	3.33 (2.66)	1.71 (1.83)	–49%	
	B3 and B4	12	3.67 (3.68)	1.93 (1.77)	–47%	$P = 0.012$ [c]
$PM_{2.5}$ concentration ($\mu g\ m^{-3}$)	B3	6	81 (27)	47 (20)	–41%	
	B4	6	116 (62)	49 (34)	–58%	
	B3 and B4	12	99 (50)	48 (26)	–51%	$P < 0.001$ [c]
$PM_{2.5}$ emission rate ($mg\ h^{-1}\ bird^{-1}$)	B3	6	0.27 (0.34)	0.08 (0.06)	–69%	
	B4	6	0.20 (0.19)	0.09 (0.10)	–55%	
	B3 and B4	12	0.23 (0.27)	0.09 (0.08)	–63%	$P = 0.018$ [c]
NH_3 concentration (ppm)	B3	6	5.12 (4.14)	6.72 (3.47)	31%	
	B4	6	7.54 (4.47)	7.16 (5.40)	–5%	
	B3 and B4	12	6.33 (4.30)	6.94 (4.33)	10%	n.s. [c]
NH_3 emission rate ($mg\ h^{-1}\ bird^{-1}$)	B3	6	9.57 (8.85)	13.3 (10.6)	39%	
	B4	6	5.87 (2.79)	5.88 (3.07)	0%	
	B3 and B4	12	7.72 (6.55)	9.61 (8.38)	19%	n.s. [c]
Odor concentration ($OU_E\ m^{-3}$)	B3	6	985 (931)	858 (802)	–13%	
	B4	6	1521 (721)	1351 (689)	–11%	
	B3 and B4	12	1253 (841)	1104 (758)	–12%	$P = 0.042$ [c]
Odor emission rate ($OU_E\ s^{-1}\ bird^{-1}$)	B3	6	0.47 (0.36)	0.40 (0.32)	–16%	
	B4	6	0.55 (0.34)	0.54 (0.32)	–2%	
	B3 and B4	12	0.51 (0.34)	0.47 (0.31)	–9	n.s. [c]

[a] Reduction of a variable in the treatment house is reflected by a negative mean difference.
[b] Determined by the two-sided paired-samples *t*-test.
[c] Determined by the one-sided paired-samples *t*-test.

In agreement with previous work (Cambra-López et al., 2009), emission rate of ammonia was not significantly reduced by the NAI. Other studies in commercial broiler houses have reported reductions of 43% for dust (fraction not specified) and 13% for ammonia (Ritz et al., 2006) and 39% for total suspended particles and 17% for ammonia (Jerez et al., 2013). The reductions (corrected for uneven distribution of measurements over the growing cycle) of 49% for PM_{10} emission rate and 68% for $PM_{2.5}$ emission rate are higher than the values of 36% and 10% respectively, found previously in our experimental work (Cambra-López et al., 2009). This may

be due to (1) the electrode wires being closer to the ceiling in the present work, and (2) a better type of collection area in the commercial broiler houses. The roof of both B3 and B4 was constructed from roof panels consisting of (from outside to inside): corrugated sheets, insulation material, and an aluminum coating. In both houses, the sheets of aluminum coatings were extra grounded to maximize dust collection ability. This may explain why reductions are generally higher than in previous research, but it does not explain why the $PM_{2.5}$ reduction was higher than the PM_{10} reduction in both B3 and B4 (Table 4). As reported and discussed by Cambra-López et al. (2009) for indoor air ionization systems, and by Winkel et al. (2015a) for end of pipe ionization systems, the removal efficiency of ionisers usually increases with increasing particle size. It is unclear why this seems to be vice versa for the NAI in these commercial broiler farms.

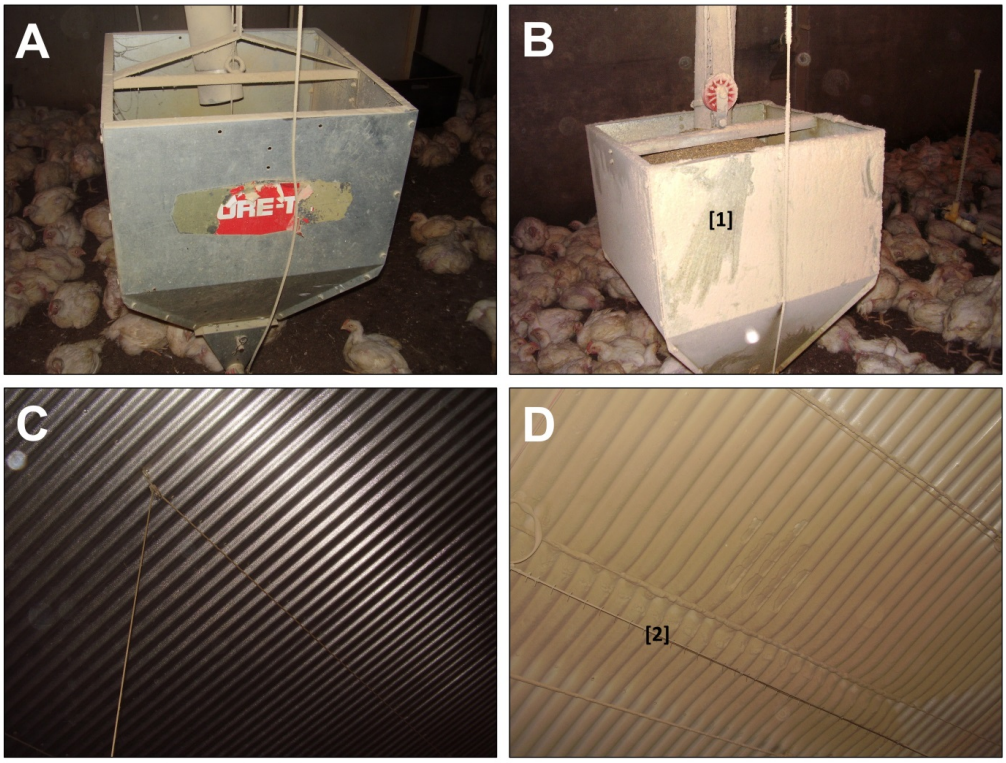


Fig. 5
A and C: photos of the ceiling and a feed hopper of the control house of broiler farm 3 on day 32 of the growing cycle. B and D: photos of dust accumulation onto the ceiling and a feed hopper of the treatment house (Negative Air Ionization system; NAI) of the same farm, taken on the same day. Number [1] in photo B marks a small part of the feed hopper where dust was wiped off. Number [2] in photo D marks an electrode wire.

The NAI functioned as planned throughout the evaluation period. PM accumulation to the ceiling and feed hoppers in the treatment houses was clearly visible (Fig. 5, B and D). The amperage of the NAI gradually decreased with the build-up of PM on the ceiling because it acted as an insulating layer. This was counteracted by bringing the electrode wires closer to the ceiling. Overall, the NAI proved very suitable for reduction of PM emission from broiler houses and no aspects for further optimization became apparent.

Positive air ionization in laying hen houses

Results obtained for the PAI in L3 and L4 are shown in Table 5. The statistical analysis showed that the inside relative humidity was significantly lower (5 percentage points) on treatment days. An additional analysis of the outside relative humidity however, showed no significant differences (81% relative humidity for control days and 80% relative humidity for treatment days; $P = 0.163$). The average carbon dioxide concentrations and ventilation rates also differed very little (5% or less; not significant). Overall, the test situation can be regarded as a sufficiently valid basis for comparison. The absence of a significant difference in ventilation rate indicates that reductions of the emission rate is attributable to reductions of concentrations (see Eq. 2).

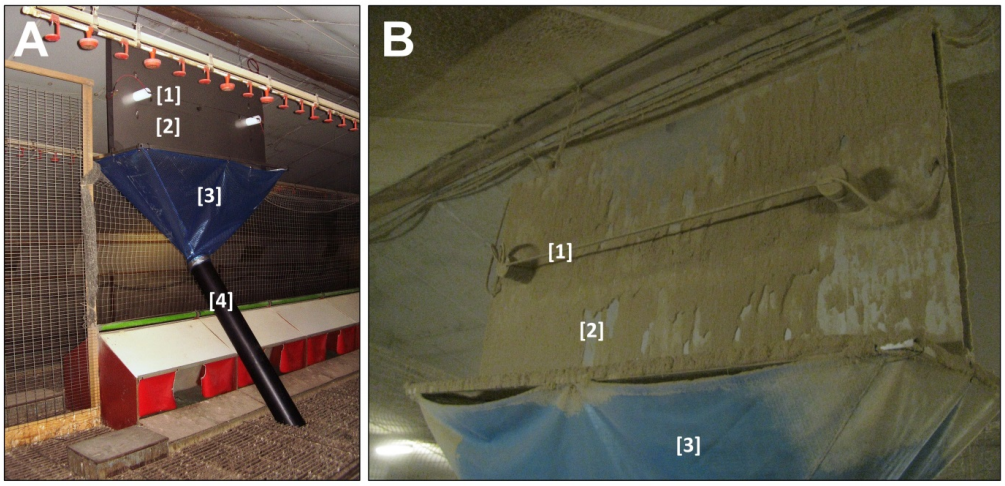


Fig. 6
A: photo of the positive air ionization (PAI) system after installation inside layer house 3. B: photo of dust accumulation onto the grounded collection plate and ceiling, running off into the collection bin. Meaning of numbers: [1] = positive electrode wire, [2] = grounded metal collection plate (note clean spots where some of the PM has fallen into the collection bin), [3] = dust collection bin, [4] dust transport pipe to the manure pit under the raised slatted floor.

Table 5
Results of the positive air ionization (PAI) system in layer farms 3 and 4 (SD = standard deviation between measurements; n.s. = not significant).

Variable	Layer farm	*n*	Control day; mean (SD)	Treatment day; mean (SD)	Difference	
					Mean [a]	Sign.
Air temperature (°C)	L3	5	22.7 (2.8)	23.4 (2.0)	0.6	
	L4	6	24.0 (1.6)	24.1 (1.3)	0.1	
	L3 and L4	11	23.4 (2.2)	23.7 (1.6)	0.3	n.s. [b]
Relative humidity (%)	L3	5	73 (7)	68 (9)	–4	
	L4	6	66 (6)	61 (8)	–5	
	L3 and L4	11	69 (7)	64 (9)	–5	$P = 0.007$ [b]
CO_2 concentration (ppm)	L3	5	1484 (374)	1453 (222)	–2%	
	L4	6	1303 (299)	1279 (207)	–2%	
	L3 and L4	11	1385 (331)	1358 (222)	–2%	n.s. [b]
Ventilation rate ($m^3\ h^{-1}\ bird^{-1}$)	L3	5	2.36 (0.74)	2.35 (0.54)	–1%	
	L4	6	3.03 (1.16)	2.87 (0.67)	–5%	
	L3 and L4	11	2.73 (1.01)	2.63 (0.65)	–4%	n.s. [b]
PM_{10} concentration ($\mu g\ m^{-3}$)	L3	5	3258 (506)	2816 (160)	–14%	
	L4	6	5003 (1127)	4865 (331)	–3%	
	L3 and L4	11	4210 (1252)	3934 (1100)	–7%	n.s. [c]
PM_{10} emission rate ($mg\ h^{-1}\ bird^{-1}$)	L3	5	7.44 (1.93)	6.54 (1.67)	–12%	
	L4	6	14.3 (3.26)	13.7 (2.56)	–4%	
	L3 and L4	11	11.2 (4.43)	10.5 (4.31)	–6%	$P = 0.03$
$PM_{2.5}$ concentration ($\mu g\ m^{-3}$)	L3	5	247 (88)	197 (60)	–20%	
	L4	6	380 (114)	387 (97)	2%	
	L3 and L4	11	320 (120)	300 (126)	–6%	n.s. [c]
$PM_{2.5}$ emission rate ($mg\ h^{-1}\ bird^{-1}$)	L3	5	0.53 (0.13)	0.44 (0.15)	–17%	
	L4	6	1.05 (0.36)	1.09 (0.39)	4%	
	L3 and L4	11	0.81 (0.38)	0.79 (0.45)	–3%	n.s. [c]

[a] Reduction of a variable in the treatment house is reflected by a negative mean difference.
[b] Determined by the two-sided paired-samples *t*-test.
[c] Determined by the one-sided paired-samples *t*-test.

A small (6%), but significant reduction of the PM_{10} emission rate was found. $PM_{2.5}$ emission rate was not significantly reduced. The system did remove PM from the air, as can be seen from the PM that adhered to the grounded collection plate and ceiling, and ran off into the collection bin (Fig. 6). Further analysis showed that, during the first 4 measurements in the first two months of the evaluation period, the PM_{10} emission reduction decreased from 27% to 13% in L3 and from 18% to 4% in L4. After these two months, the PM emission reductions fluctuated around the 0% level (± 10 percentage points). These results indicate that the system achieved a modest reduction which faded out after two months.

This modest reduction level might be due to the small size of the system relative to the size of the houses (only 32 m^2 of grounded collection area and 32 m of electrode length per house of 2525 m^3 and 7240 birds in L3 and of 3720 m^3 and 15,100 birds in L4) and the high PM concentrations in layers (Table 5). The fading out of the reduction level during the first two month of testing might be due to pollution of the interior of the laying hen houses with PM. This pollution may function as an insulating layer which builds up over the course of a production

cycle. In broilers (e.g., B3 and B4), such build up is removed after each cycle of 42 growing days. Production cycles of laying hens however, last for about 15 months. In conclusion, the current configuration of the PAI system proved ineffective for PM abatement in laying hen houses and the issues discussed need optimization for the system to become effective.

Baseline emission rates in control houses

Mean (SD) background concentrations, measured near the inlet of the eight houses of B1 through B4 were: 468 (40) ppm carbon dioxide, 32 (23) µg m^{-3} PM_{10}, 15 (9) µg m^{-3} $PM_{2.5}$, and 0.17 (0.11) ppm ammonia. At L1 through L4, these values were: 511 (44) ppm carbon dioxide, 37 (36) µg m^{-3} PM_{10}, 11 (10) µg m^{-3} $PM_{2.5}$, and 0.25 (0.15) ppm ammonia.

Mean (SD) emission rates from the four control houses of B1 through B4 (corrected for the unequal distribution of measurements over the growing cycle; by calculating a mean emission rate from three separate means for weeks 1+2, weeks 3+4, and weeks 5+6) were: 3.23 (3.07) mg PM_{10} h^{-1} $bird^{-1}$ (equivalent to 28.3 g $year^{-1}$ $bird^{-1}$), 0.20 (0.22) mg $PM_{2.5}$ h^{-1} $bird^{-1}$ (equivalent to 1.73 g $year^{-1}$ $bird^{-1}$), 9.00 (10.4) mg ammonia h^{-1} $bird^{-1}$ (equivalent to 78.8 g $year^{-1}$ $bird^{-1}$), and 0.44 (0.32) OU_E s^{-1} $bird^{-1}$.

Mean (SD) emission rates from L2 and L3 with floor housing (on control days) were 6.47 (1.84) mg PM_{10} h^{-1} $bird^{-1}$ (equivalent to 56.6 g $year^{-1}$ $bird^{-1}$), 0.50 (0.28) mg $PM_{2.5}$ h^{-1} $bird^{-1}$ (equivalent to 4.40 g $year^{-1}$ $bird^{-1}$), 56.6 (9.0) mg ammonia h^{-1} $bird^{-1}$ (equivalent to 496 g $year^{-1}$ $bird^{-1}$), and 0.38 (0.20) OU_E s^{-1} $bird^{-1}$.

Mean (SD) emission rates from L1 and L4 with aviary housing (on control days) were 14.3 (5.39) mg PM_{10} h^{-1} $bird^{-1}$ (equivalent to 125 g $year^{-1}$ $bird^{-1}$), 0.97 (0.42) mg $PM_{2.5}$ h^{-1} $bird^{-1}$ (equivalent to 8.46 g $year^{-1}$ $bird^{-1}$), 14.7 (7.3) mg ammonia h^{-1} $bird^{-1}$ (equivalent to 129 g $year^{-1}$ $bird^{-1}$), and 0.76 (1.13) OU_E s^{-1} $bird^{-1}$.

Comparison of the emission levels above to European emission studies (Groot Koerkamp et al., 1998; Hayes, Curran, and Dodd, 2006; Ogink and Groot Koerkamp, 2001; Winkel et al., 2015b) shows that they agree well with earlier reported values. Thus, the evaluation of the four systems has been carried out at representative emission levels.

The study design: considerations

In this study, two case-control designs were used. The first one, applied in broilers houses, consisted of using two identical houses within a farm, one with the applied system (treatment

house), and one without it (control house). In the second control-case design, applied in laying hen houses, the system was applied only in one house, and control and treatment days were measured after each other. Ideally, all circumstances (variables) other than those directly related to the treatment, should be identical between control and treatment. This generally was the case for important variables as air temperature, relative humidity, carbon dioxide concentration, and ventilation rate (Tables 2, 3, 4, and 5). In two cases (air temperature for B3 and B4, Table 4; and relative humidity for L3 and L4, Table 5), statistically significant but small differences were found.

Of the aforementioned four variables, the ventilation rate can be regarded as the most important variable not to be different between control and treatment. In Fig. 7, the values for ventilation rate of all farms in this study are presented for both control and treatment. Linear regression analysis of the data in Fig 7B showed that the regression coefficient of 1.0577 was not significantly different from 1 and the intercept of -0.0323 not significantly different from 0. Hence, the ventilation rate of control and treatment houses closely followed a 1:1 relationship, which underlines the validity of the study design for the OSF and NAI in broilers. The same analysis of the data in Fig 7D shows that the regression coefficient of 0.7681 was significantly different from one ($P = 0.036$) but the intercept of 0.4282 not significantly different from zero. Furthermore, the R^2 is clearly lower for laying hens than for broilers (Fig. 7, B and D). These findings indicate that measuring at the same days in separate control and treatments houses provides a more valid basis for comparison than measuring control and treatment at different periods within the same house. In addition, the OSF and OSV were evaluated in only one house, whereas the NAI in broilers, the OSF in broilers, and the PAI in layers, were each evaluated in two farm locations. This further adds uncertainty to the results obtained in this paper for the OSF and OSV in laying hens.

In the present study, the OSF and NAI were installed inside one of two houses of a farm and this treatment was not varied between the houses. This means that systematic house effects were not estimated and corrected for. From a methodological point of view, however, it would have been most valid to install the systems inside both houses, so that measurements of control and treatment could not only be done at the same time, but also that the control and treatment could be exchanged between the houses. In our study, however, the houses were quite identical, so systematic differences between houses are expected to be low.

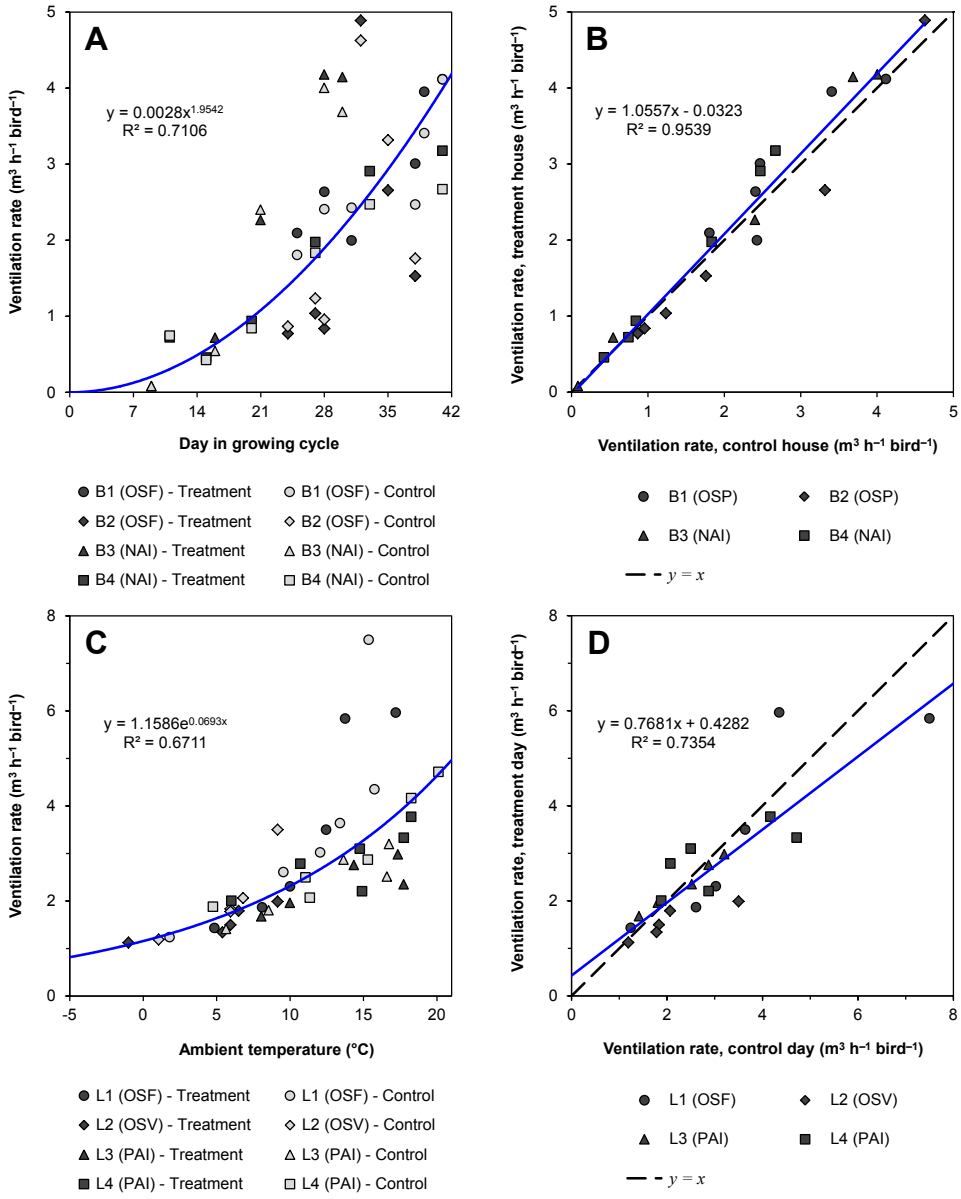


Fig. 7

A: ventilation rates of control and treatment broiler houses as a function of animal age. B: relationship between ventilation rates of treatment and control houses of broiler farms. C: ventilation rates of layer houses on control and treatments days as a function of the ambient air temperature. D: relationship between ventilation rates on treatment and control days in layer houses.

CONCLUSIONS

In this study, we evaluated the performance of four systems for abatement of particulate emission inside commercial poultry houses: a fixed oil spraying system (OSF) inside two broiler farms and one laying hen house, an autonomously driving oil spraying vehicle (OSV) in one laying hen house, a negative air ionization system (NAI) inside two broiler farms, and a positive air ionization system (PAI) inside two laying hen houses. Our main results and conclusions are:

- In commercial broiler farms, spraying 12 mL m^{-2} d^{-1} using the OSF reduced PM_{10} emission rate by 60% and $PM_{2.5}$ emission rate by 53%. The reduction of PM_{10} is similar to previous experimental work, the reduction of $PM_{2.5}$ lower (i.e., >75% in previous experimental work). In broiler houses, the OSF functioned well and effectively reduced PM concentrations and emissions.
- In commercial laying hen houses, spraying 30 mL m^{-2} d^{-1} using the OSV reduced PM_{10} emission rate by 32% and $PM_{2.5}$ emission rate by 38%. Spraying 15 mL m^{-2} d^{-1} using the OSF reduced PM_{10} emission rate by 21% and $PM_{2.5}$ emission rate by 31%. These reductions are substantially lower than in previous experimental work, probably because both systems could not distribute the oil over the entire litter floor area and oil was not sprayed daily for prolonged periods as done in experimental work.
- Before the OSF and OSV can be used inside commercial aviary houses or floor houses for laying hens, further technical optimisations are needed. The OSF should be able to spray more litter surface area and the system should be sealed off to prevent penetration by red mites. The OSV should be smaller and lighter, have a smaller turning radius, have more grip on loose litter and on litter cakes (e.g., caterpillars), have nozzles on multiple sides, and be able to fill its oil tank autonomously.
- This study confirms the results of previous experimental work that oil spraying has no effect on emission rates of ammonia or odor.
- In commercial broiler farms, the NAI reduced PM_{10} emission rate by 49% and $PM_{2.5}$ emission rate by 68%. These reductions are higher than in previous experimental work, possibly because the ceilings of the commercial houses were better PM collectors. This study confirms results of previous experimental work that the NAI has no effect on emission rates of ammonia or odor. The NAI functioned well and effectively reduced PM concentrations and emissions in broiler houses.
- In commercial laying hen houses, the PAI reduced PM_{10} emission rate by 6% but did not

reduce $PM_{2.5}$ emission rate. This low level of reduction was probably caused by the relatively small size of the system and pollution of the interior of the buildings. At the current configuration and dimensioning, the NAI is not effective.

ACKNOWLEDGMENTS

This study was financed by the Dutch Ministry of Economic Affairs and the Dutch Ministry of Infrastructure and the Environment. We are grateful to the participating poultry farmers for allowing the use of their farms as test sites. The companies Inter Continental, JOZ, and ENS Europe are acknowledged for providing the PM reduction systems. Finally, we thank our colleagues Mr. Sjoerd Bokma en Mr. Klaas Blanken for their contribution to the development of the OSV, Mr. Theo van Hattum, Mr. Guus Nijeboer and Mr. Henk Schilder for carrying out the measurements, Mr. Eef Lovink for maintenance and calibration of measuring equipment, and Mr. Jean Slangen and Mr. Geert Kupers for carrying out the lab analyses.

REFERENCES

Aarnink, A.J.A., Van Harn, J., Van Hattum, T.G., Zhao, Y., Ogink, N.W.M., 2011. Dust reduction in broiler houses by spraying rapeseed oil. *Trans. ASABE* 54:1479–1489.

Aarnink, A.J.A., Van Hattum, T.G., 2009. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij. Laproef: karakterisering van olievernevelaars [Measures to reduce fine dust emission from poultry houses. Laboratory study: characterizing oil spraying nozzles; in Dutch, with English summary]. Report 229. Animal Sciences Group, Wageningen University and Research Centre. Lelystad, the Netherlands.

Al Homidan, A., Robertson, J.F., Petchey, A. M., 2003. Review of the effect of ammonia and dust concentrations on broiler performance. *World's Poult. Sci. J.* 59:340–349.

Borlée, F., Yzermans, C.J., Van Dijk, C.E., Heederik, D.J.J., Smit, L.A.M., 2015. Increased respiratory symptoms in COPD patients living in the vicinity of livestock farms. *Eur. Resp. J.* 46:1605–1614.

Cambra-López, M., Winkel, A., Van Harn, J., Ogink, N.W.M., Aarnink, A.J.A., 2009. Ionization for reducing particulate matter emissions from poultry houses. *Trans. ASABE* 52:1757–1771.

CEN, 1998. EN 12341:1998. Air quality - Determination of the PM 10 fraction of suspended particulate matter - Reference method and field test procedure to demonstrate reference equivalence of measurement methods. Comité Européen de Normalisation (CEN; European Committee for Standardization), Brussels, Belgium.

CEN, 2003. EN 13725:2003. Air quality - Determination of odour concentration by dynamic olfactometry. Comité Européen de Normalisation (CEN; European Committee for Standardization), Brussels, Belgium.

CEN., 2005. EN 14907:2005. Ambient air quality - Standard gravimetric measurement method for the determination of the PM2.5 mass fraction of suspended particulate matter. Comité Européen de Normalisation (CEN; European Committee for Standardization), Brussels, Belgium.

CIGR, 2002. 4th Report of working group on climatization of animal houses. Heat and moisture production at animal and house levels (Eds.: S. Pedersen, & K. Sällvik). International Commission of Agricultural Engineering (CIGR), section II.

Drost, H., Beens, N., Dolehghs, B., Ellen, H., Oude Vrielink, H.H.E., 1999. Is fogging water or oil effective in reducing dust concentrations in poultry houses? In: proceedings of the international symposium on dust control in animal production facilities, Aarhus, Denmark, pp. 231–236.

Griffin, J.G., Vardaman, T.H., 1970. Cottonseed oil spray for broiler houses: effects on dust control, Mycoplasma gallisepticum spread and broiler performances. *Poult. Sci.* 49:1664–1668.

Groot Koerkamp, P.W.G., Metz, J.H.M., Uenk, G.H., Phillips, V.R., Holden, M.R., Sneath, R.W., Short, J.L., White, R.P., Hartung, J., Seedorf, J., Schröder, M., Linkert, K.H., Pedersen, S., Takai, H., Johnsen, J.O., Wathes,

C.M., 1998. Concentrations and emissions of ammonia in livestock buildings in Northern Europe. *J. Agric. Eng. Res.* 70:79–95.

Guarino, M., Caroli, A., Navarotto, P., 1999. Dust concentration and mortality distribution in an enclosed laying house. *Trans. ASAE* 42:1127–1133.

Gustafsson, G., Von Wachenfelt, E., 2006. Measures against airborne dust in a floor housing system for laying hens. Agricultural Engineering International: the CIGR Ejournal, Vol. VIII, December 2006. Manuscript BC 06 018.

Hayes, E.T., Curran, T.P., Dodd, V.A., 2006. Odour and ammonia emissions from intensive poultry units in Ireland. *Biores. Techn.* 97:933–939.

Heederik, D.J.J., Opstal-van Winden, A.J.W., Smit, L.A.M., Wouters, I.M., Hooiveld, M., IJzermans, C.J., Van der Sman-de Beer, F., Spreeuwenberg, P.P.M., De Bruin, A., Van Rotterdam, B., 2011. Mogelijke effecten van intensieve-veehouderij op de gezondheid van omwonenden: onderzoek naar potentiële blootstelling en gezondheidsproblemen [Possible effects of intensive livestock production on health of residents: research into possible exposure and health problems; in Dutch]. Institute for Risk Assessment Sciences (IRAS), Utrecht University; Netherlands institute for health services research (NIVEL); National Institute for Public Health and the Environment (RIVM), Utrecht, the Netherlands.

Ikeguchi, A., 2002. Ultra sonic sprayer controlling dust in experimental poultry houses. Agricultural Engineering International: the CIGR Ejournal, Vol. IV, October 2006. Manuscript BC 01 002.

Jerez, S.B., Mukhtar, S., Faulkner, W., Casey, K.D., Borhan, M.S., Smith, R.A., 2013. Evaluation of electrostatic particle ionization and BioCurtain™ technologies to reduce air pollutants from broiler houses. *Appl. Eng. Agric.* 29:975–984.

McGovern, R.H., Feddes, J.J.R., Robinson, F.E., Hanson, J.A., 1999. Growth performance, carcass characteristics, and the incidence of ascites in broilers in response to feed restriction and litter oiling. *Poult. Sci.* 78:522–528.

McGovern, R.H., Feddes, J.J.R., Robinson, F.E., Hanson, J.A., 2000. Growth, carcass characteristics, and incidence of ascites in broilers exposed to environmental fluctuations and oiled litter. *Poult. Sci.* 79:324–330.

Ogink, N.W.M., Aarnink, A.J.A., 2011. Plan van aanpak bedrijfsoplossingen voor fijnstofreductie in de pluimveehouderij [Plan of action for particulate matter mitigation solutions in poultry; in Dutch, with English summary]. Report 113. Animal Sciences Group, Wageningen University and Research Centre, Lelystad, the Netherlands.

Ogink, N.W.M., Groot Koerkamp, P.W.G., 2001. Comparison of odour emissions from animal housing systems with low ammonia emission *Water Sci. Techn.* 44:245–252.

Ogink, N.W.M., Hofschreuder, P., Aarnink, A.J.A., 2011. Protocol voor meting van fijnstofemissie uit huisvestingssystemen in de veehouderij 2010 [Protocol for the measurement of fine emissions from housings in animal production 2010; in Dutch, with English summary]. Report 492. Wageningen University and Research Centre, Livestock Research, Lelystad, the Netherlands.

Omland, Ø., 2002. Exposure and respiratory health in farming in temperate zones - A review of the literature. *Ann. Agric. Environ. Med.* 9:119–136.

Pedersen, S., Blanes-Vidal, V., Joergensen, H., Chwalibog, A., Haeussermann, A., Heetkamp, M.J.W., Aarnink, A.J.A., 2008. Carbon dioxide production in animal houses: a literature review. Agricultural Engineering International: CIGR Ejournal, Vol. X, December 2008. Manuscript BC 08 008.

Radon, K., Danuser, B., Iversen, M., Jörres, R., Monso, E., Opravil, U., Weber, C., Donham, K.J., Nowak, D., 2001. Respiratory symptoms in European animal farmers. *Eur. Respir. J.* 17:747–754.

Radon, K., Schulze, A., Ehrenstein, V., van Strien, R.T., Praml, G., Nowak, D., 2007,. Environmental exposure to confined animal feeding operations and respiratory health of neighboring residents. *Epidemiology* 18:300–308.

Ritz, C.W., Mitchell, B.W., Fairchild, B.D., Czarick Iii, M., Worley, J.W., 2006. Improving in-house air quality in broiler production facilities using an electrostatic space charge system. *J. Appl. Poult. Res.* 15:333–340.

RIVM, 2014. Annual national emissions of PM10; in total and per sector/source, for 2012. Retrieved February 2014, from http://www.emissieregistratie.nl.

Schinasi, L., Horton, R.A., Guidry, V.T., Wing, S., Marshall, S.W., Morland, K.B., 2011. Air pollution, lung function, and physical symptoms in communities near concentrated swine feeding operations. *Epidemiology* 22:208–215.

Takai, H., Pedersen, S., Johnsen, J.O., Metz, J.H.M., Groot Koerkamp, P.W.G., Uenk, G.H., Phillips, V.R., Holden, M.R., Sneath, R.W., Short, J.L., White, R.P., Hartung, J., Seedorf, J., Schröder, M., Linkert, K.H., Wathes, C. M., 1998. Concentrations and emissions of airborne dust in livestock buildings in Northern Europe. *J. Agric. Eng. Res.* 70:59–77.

Van Zanten, M.C., Van Alphen, A., Wesseling, J., Mooibroek, D., Nguyen, P.L., Groot Wassink, H., Verbeek, C., 2012. Monitoringsrapportage NSL 2012 [State of affairs of the National Air Quality Cooperation Programme 2012; in Dutch, with English summary]. National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands.

Von Wachenfelt, E. (1999). Dust reduction in alternative production systems for laying hens. In: proceedings of the international symposium on dust control in animal production facilities, Aarhus, Denmark, pp. 261–264.

VERA. (2011). Test protocol for livestock housing and management systems, version 2 / 2011-29-08.Available at: http://www.vera-verification.eu (accessed June 2016).

VSN. (2014). GenStat reference manual (release 17) (Version 17.1.0.14713). Hemel Hempstead, UK.

Winkel, A., Cambra-López, M., Groot Koerkamp, P.W.G., Ogink, N.W.M., Aarnink, A.J.A., 2014. Abatement of particulate matter emission from experimental broiler housings using an optimized oil spraying method. *Trans. ASABE* 57:1853–1864.

Winkel, A., Mosquera, J., Aarnink, A.J.A., Groot Koerkamp, P.W.G., Ogink, N.W.M., 2015a. Evaluation of a dry filter and an electrostatic precipitator for exhaust air cleaning at commercial non-cage laying hen houses. *Biosyst. Eng.* 129:212–225.

Winkel, A., Mosquera, J., Groot Koerkamp, P.W.G., Ogink, N.W.M., Aarnink, A.J.A., 2015b. Emissions of particulate matter from animal houses in the Netherlands. *Atmos. Environ.* 111:202–212.

Winkel, A., Van Riel, J.W., Van Emous, R.A., Aarnink, A.J.A., Groot Koerkamp, P.W.G., Ogink, N.W.M., 2016. Abatement of particulate matter emission from experimental aviary housings for laying hens by spraying rapeseed oil. *Poult. Sci*, accepted for publication.

Zhao, Y., Aarnink, A.J.A., Hofschreuder, P., Groot Koerkamp, P.W.G., 2009. Evaluation of an impaction and a cyclone pre-separator for sampling high PM10 and PM2.5 concentrations in livestock houses. *J. Aerosol Sci.* 40:868–878.

Chapter 6

Evaluation of a dry filter and an electrostatic precipitator for exhaust air cleaning at commercial non-cage laying hen houses

A. Winkel [a], J. Mosquera [a], A..J.A. Aarnink [a] , P.W.G. Groot Koerkamp [a,b], and N.W.M. Ogink [a]

[a] Wageningen UR Livestock Research, Wageningen, the Netherlands
[b] Farm Technology Group, Wageningen University, Wageningen, the Netherlands

Biosystems Engineering (2015) 129:212–225

Reprinted with permission from Elsevier Ltd
Available online at: http://dx.doi.org/10.1016/j.biosystemseng.2014.10.006

ABSTRACT

We evaluated the removal performance of two exhaust air cleaning systems for abatement of particulate matter (PM) emission in poultry houses: a commercially available dry filter (DF) and a full-scale prototype electrostatic precipitator (ESP). Each system was connected to two commercial, non-cage laying hen houses: one with aviary housing, the other with floor housing. At each house, six to nine 24-h measurements were carried out, spread over the year and the laying cycle. Upstream and downstream of the systems, we measured PM_{10}, $PM_{2.5}$, and carbon dioxide concentrations, temperature, and relative humidity. Additional measurements of particle size distribution only were carried out at the DF of another poultry house. The latter showed that removal of PM by the DF increased with increasing particle diameter. Mean removal efficiency of the DF for PM_{10} was 40.1%, whereas $PM_{2.5}$ was not significantly removed. The ESP reduced concentrations of PM_{10} by an average of 57.0% and concentrations of $PM_{2.5}$ by an average of 45.3%. For neither of the two systems an effect of upstream PM concentration on removal performance was found. Results of this study are compared with the available literature and possibilities to improve removal performance are discussed. The mean (SD between houses) untreated emissions rate from the non-cage layer houses was 7.81 (4.12) mg PM_{10} h^{-1} $bird^{-1}$ and 0.44 (0.28) mg $PM_{2.5}$ h^{-1} $bird^{-1}$. In conclusion, the evaluated systems show potential to reduce PM emissions from poultry houses.

NOMENCLATURE

C_a	Concentration in the air flow Q_a
C_e	Pollutant concentration in the air flow Q_e
C_t	Pollutant concentration in the airflow Q_t
CCD	Corona Current Density of an electrostatic precipitator (μA m^{-2} of collection area)
CO_2	Carbon dioxide
$[CO_2]_a$	Ambient concentration of carbon dioxide (ppm)
$[CO_2]_d$	Concentration of carbon dioxide downstream of the electrostatic precipitator (ppm)
$[CO_2]_u$	Concentration of carbon dioxide upstream of the electrostatic precipitator (ppm)
DF	Dry filter (also called: impaction curtain)
DC	Direct current
E	PM emission rate (mg h^{-1} $bird^{-1}$)
EU	European Union
ESP	Electrostatic precipitator
Fco_2	Factor for conversion of total heat to the volumetric CO_2 production by the animal and its manure (m^3 h^{-1} kW^{-1})
η	Particulate matter removal efficiency (%)
LU	Livestock Unit: 500 kg of live weight
n	Number of data points
P	Level of significance
P_a	Proportion of ambient air leaked into the downstream air flow
P_h	Proportion of poultry house air in the downstream air flow
PM	Particulate matter
PM_{10}	Particulate matter which passes through a size-selective inlet with a 50% efficiency cut-off at 10 μm aerodynamic diameter (EN 12341)
$PM_{2.5}$	Particulate matter which passes through a size-selective inlet with a 50% efficiency cut-off at 2.5 μm aerodynamic diameter (EN 14907)
PM_a	Ambient particulate matter concentration (μg m^{-3})
PM_{dc}	Corrected particulate matter concentration downstream of the electrostatic precipitator (μg m^{-3})
PM_{dm}	Particulate matter concentration measured downstream of the electrostatic precipitator (μg m^{-3})
PM_u	Particulate matter concentration upstream of the dry filter or electrostatic precipitator (μg m^{-3})
Q_a	Air flow from the ambient environment mixing with Q_e to form Q_t
Q_e	Airflow from the electrostatic precipitator entering the sampling duct
Q_t	Total airflow leaving the sampling duct downstream of the electrostatic precipitator
SCA	Specific collection area of an electrostatic precipitator (m^2 per 1000 m^3 h^{-1})
SCP	Specific corona power of an electrostatic precipitator (W per 1000 m^{-3} h^{-1})
SD	Standard deviation
Total PM	All particles that can be collected using filter cassettes (NIOSH method 0500)
V	Total ventilation rate in the poultry house (m^3 h^{-1} $bird^{-1}$)
Φ_{total}	Total heat production by the animal (kW)

INTRODUCTION

Particulate Matter (PM) can be defined as a complex mixture of tiny solid and liquid particles suspended in the air (Cambra-López et al., 2010). Upon inhalation, PM can penetrate into the respiratory system and cause adverse effects on respiratory and cardiovascular health (Brunekreef and Holgate, 2002). To protect the health of its residents, the European Union has set daily and annual concentration limits (EU, 2008) for ambient PM with aerodynamic diameters less than 10 μm (PM_{10}) and 2.5 μm ($PM_{2.5}$). These limits are exceeded in certain areas in the Netherlands, including areas with large numbers of livestock farms (RIVM, 2013; Van Zanten et al., 2012). In the Netherlands, poultry houses are estimated to be responsible for 13% of the total, primary PM_{10} emission (RIVM, 2011). Outside the exhausts of poultry houses, plumes of PM can be found which spread out in detectable concentrations downwind of these farms (Heederik et al., 2011; Li et al., 2012). In view of this, a research programme was set up in the Netherlands to develop and evaluate PM mitigation options for the poultry industry (Ogink and Aarnink, 2011). One of the possible approaches to reduce PM emissions from poultry houses is to treat the exhaust air by so-called 'end of pipe' systems. In several European countries, air scrubbing (i.e., washing pollutants from the air stream) and biofiltration (i.e., beds or walls filled with moist organic packing material) are widely used for odor, ammonia and PM mitigation. Their application in poultry houses, however, can be problematic, because high PM concentrations cause clogging of these systems (Melse et al., 2012). In recent years, two alternative end of pipe systems have been introduced into the livestock sector: a dry filter (DF; in some publications: 'impaction curtain') and electrostatic precipitators (ESPs).

The DF is placed as a filter wall between the animal space and the exhaust ventilators and removes PM by inertial impaction and gravitational settling. The first investigation into the potential of the DF was published by Lim et al. (2007), who evaluated the system in a cage layer house. In the following years, more data became available (Demmers et al., 2010; LUFA, 2009; Mostafa and Buescher, 2011; Ogink et al., 2009). The studies of LUFA (2009) and of Ogink et al., (2009) however, only consisted of a single measurement in an aviary house for layers, whereas the study of Mostafa and Buescher (2011) was carried out in a wind tunnel. Furthermore, the aforementioned studies show a rather high variation in removal efficiency (e.g., 19.9% to 82% for PM_{10}). Consequently, there is a need to further evaluate the efficacy of the DF in multiple non-cage laying hen houses over a prolonged period of time.

ESP systems are used in various industrial processes to remove PM from flue gas streams by electrostatic force. The working principle of ESPs includes five main steps: gas ionization, particle charging, particle migration, particle collection and PM removal. In ESPs, exhaust air is forced through a duct containing charging electrodes (usually wires, barbed plates or sharp pins) and a collection electrode (usually a grounded plate or a cylinder), with a high negative or positive voltage applied between the two. Close to the charging electrodes, gaseous ions are created that migrate to the collection electrode by ion wind along the electric field lines and by turbulent dispersion, thereby transferring their charge to particles they encounter. When charged particles reach the collection electrode, they are bound to form a PM cake which is removed periodically by a cleaning step, like washing or rapping (Jaworek et al., 2007; Mizuno, 2000). Inside animal houses, much research has been done on negative air ionization, e.g., by Cambra-López et al. (2009). Only few studies have been published on electrostatic treatment of exhaust air of pig houses (Lau et al. 1996; St. George and Feddes, 1995a, 1995b) or poultry houses (Chai et al., 2009; Manuzon and Zhao, 2009). The removal efficiencies of the ESPs tested in these studies varied from 18.6% to over 90%. In four of these studies (Chai et al., 2009; Manuzon and Zhao, 2009; St. George and Feddes, 1995a, 1995b) a small-scale ESP was tested in a laboratory setting using several types of dust (e.g., corn starch dust, poultry house dust, pig house dust), whereas Lau et al. (1996) tested an ESP in combination with internal recirculation inside a pig house. To our knowledge, no work has been done on full-scale ESPs connected to the exhaust of commercial poultry houses.

The objective of the present study was to gather insight into the PM removal performance of the DF and of a recently developed full-scale ESP prototype by evaluating these systems connected to commercial non-cage layer houses.

METHODOLOGY

General design of the study

The DF and ESP were each connected to two different layer houses. Each system was investigated at a house with aviary housing and at a house with floor housing. The DF was evaluated at houses 1 and 2, the ESP at houses 3 and 4. An overview of the main characteristics of each house is given in Table 1. Houses were large and modern buildings, representative for the European poultry sector. At these four houses, we performed 24-h measurements of PM_{10}, $PM_{2.5}$ and carbon dioxide (CO_2) concentrations, temperature, and relative humidity; both

upstream and downstream of the systems. After completion of this evaluation, additional measurements of particle number concentration in several size ranges were performed upstream and downstream of a DF at a fifth house for egg-laying broiler breeders (Table 1). At this time, houses 1 and 2 were no longer available for such measurements. In total, six measurements of particle size distribution were carried out at house 5 between August and October 2013. These measurements were carried out during the late morning and afternoon.

The evaluation at houses 1 through 4 was set up in line with the Dutch measurement protocol for determination of PM emissions from livestock houses (Ogink et al. 2011). For 'end of pipe' systems (air scrubbers), this protocol prescribes six measurements per house at two different locations, spread over the calendar year (in the case of laying hens), to include any between-house and within-house sources of variation on removal performance. At least 10 out of 12 measurements must be successful, yielding reliable data. An overview of the measuring periods and the number of measurements for each house are shown in Table 1.

Table 1
Main layout of the 5 commercial poultry houses in this study.

House	System evaluated	Evaluation period and number of measurements	Housing type	House length × width	Number of bird places	Ventilation inlet, exhaust; ventilation capacity; light scheme
1	Dry filter	April '10–Febr. '11 (6)	3-Storey building, floor housing	106 × 23 m	60,000	Side wall inlets and manure belt aeration, end wall fans; 609,600 $m^3 h^{-1}$; lights on from 06:00 to 21:00 (15L:9D)
2	Dry filter	May '10–Febr. '11 (6)	Aviary housing	158 × 12 m	38,860	Side wall inlets and manure belt aeration, side wall fans; 446,400 $m^3 h^{-1}$; lights on from 06:00 to 21:00 (15L:9D)
3	Electrostatic precipitator	Sept. '10–Aug. '11 (10)	2-Storey building, aviary housing	115 × 24 m	93,000	Side wall and ceiling inlets, end wall fans; 437,550 $m^3 h^{-1}$; lights on from 04:30 to 20:00 (15.5L:8.5D)
4	Electrostatic precipitator	Oct. '10–Febr. '11 (6)	Floor housing	100 × 25 m	21,800	Side wall inlets, end wall fans; 177,000 $m^3 h^{-1}$; lights on from 05:00 to 20:00 (15L:9D)
5	Dry filter	Aug. '13–Oct. '13 (6)	Floor housing	115 × 25 m	20,000	Side wall and ceiling inlets, side and end wall fans; 404,320 $m^3 h^{-1}$; lights on from 04:00 to 19:00 (15L:9D)

Description of the dry filter

The DF is a commercially available system of the company Big Dutchman (Vechta, Germany), named StuffNix. The system is composed of several filter screens, which are connected to form a filter wall between the dusty animal space and the exhaust ventilators. The DF material consists of two polyethylene/polypropylene foils connected and folded in such a way that v-shaped vertical canals exist between the front and rear foils (Fig. 1A). Both foils contain 25-mm holes; inlet holes in the front foil (Fig. 1A, nr. 2) and outlet holes in the rear foil (Fig. 1A, nr. 4). These holes are arranged in such a way that the air flow inside the DF is forced to make a sharp bend, both horizontally and vertically (Fig. 1A, nr. 3). The surface area of the screens and the volume of air drawn through them by the fans are set to create air velocities near the screens of approximately 0.5 to 1.5 m s^{-1} at a pressure difference across the DF of approximately 30 Pa. Inside the DF, air velocity increases further due to the narrowing of inlet and outlet holes. As a result of centrifugal force, especially the larger particles are expected to be removed from the air flow by inertial impaction, whereas small particles tend to behave like gaseous components, crossing the DF freely (Perry and Green, 1984). Upon impaction, particles adhere to the DF foils and aggregate (Fig. 1, nr. 3 and 5), fall down inside the canals between the foils, or sediment to the floor of the rooms. Eventually, PM is removed by frequent (e.g., monthly) cleaning of the screens and floors with an industrial vacuum cleaner.

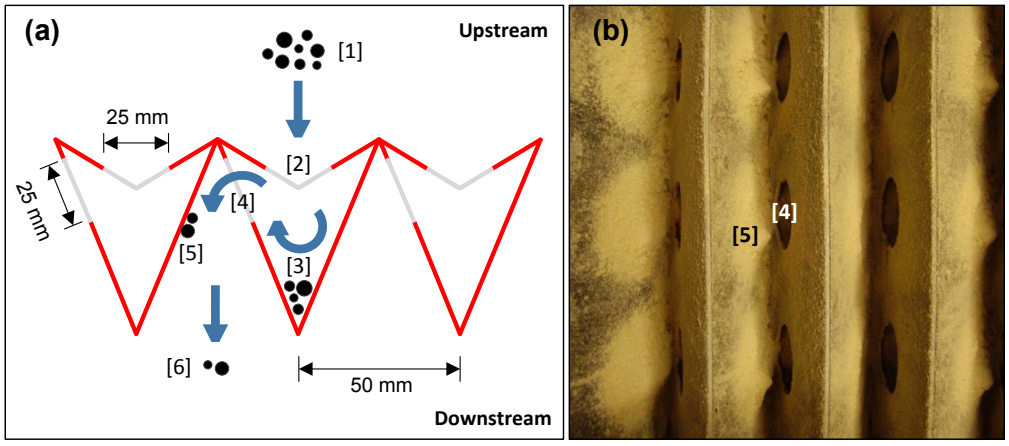


Fig. 1
Cross-sectional schematic diagram (a) of a part of the dry filter screen. Photograph (b) of a heavily polluted dry filter screen (view on the downstream side). Meaning of numbers: [1] = upstream air flow polluted with particulate matter; [2] = circular inlet hole in the front foil; [3] = impaction of particles inside the vertical canal of the dry filter; [4] = circular outlet hole in the rear foil; [5] = impaction of particles to the downstream foil; [6] = downstream, cleaned air flow from the dry filter to the ventilator(s).

At house 1, a cargo container was installed with a full-scale DF system inside (Fig. 2, left). This stand-alone functioning container was equipped with two DF screens (3 × 1.3 m each, width × height; total surface area: 7.8 m^2), a roof fan (92 cm diameter; frequency-controlled; ventilation capacity: 29,000 m^3 h^{-1}), a climate computer, and electricity supply. The fan was programmed at 72% of its ventilation capacity, creating an air velocity near the screens of approximately 0.7 m s^{-1}. The cargo container was connected to a door in the side wall of the house, where it took over part of the minimum required ventilation rate normally realized by the fans present in the house.

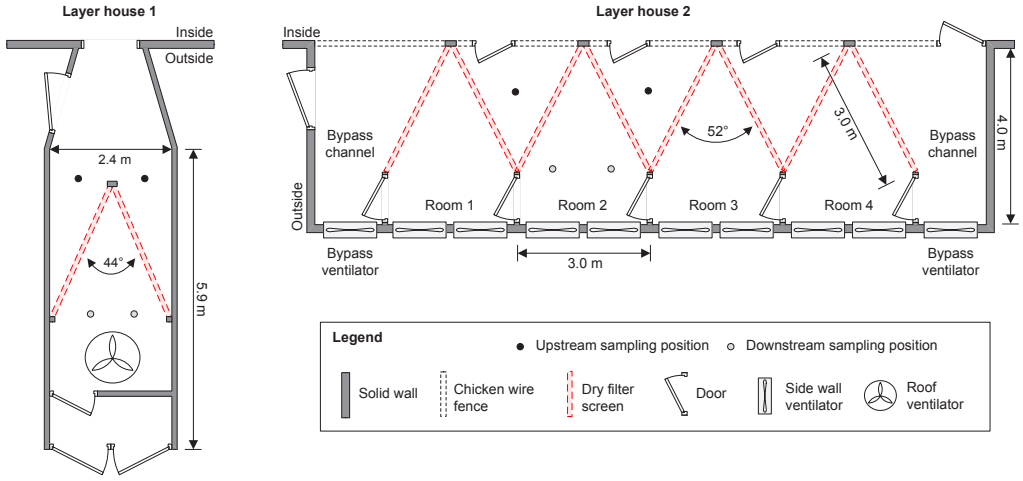


Fig. 2
Left: schematic plan view of the dry filter system inside a cargo container connected to house 1. Right: one of the two sections with the dry filter system in the side wall of house 2. Note that at house 2, measurements were done in room 2.

House 2 had the DF system since its construction. Halfway the length of each side wall, a section of the building was equipped with eight DF screens (3 × 2.3 m each, width × height; surface area: 13.8 m^2 per room), setup in such a way that four triangular rooms were present (Fig. 2, right). The exterior wall of each room contained two pressure fans (91 cm diameter; one on/off-controlled; ventilation capacity: 19,150 m^3 h^{-1} each). Measurements were only done in room 2. This room was programmed to ventilate at its maximum capacity. At this dimensioning, air velocity near the DF screens was approximately 0.8 m s^{-1}. In the exterior wall outside the rooms, a total of four bypass fans were present (1.3 m diameter, on/off-controlled, v-belt type, ventilation capacity: 35,000 m^3 h^{-1} each). When ventilation need exceeded the capacity of room

2, the other rooms switched on in subsequent steps. Bypass fans were used incidentally at high ventilation needs during summer days.

House 5 was equipped with the DF system since its construction as well. The setup of the DF at this location was very similar to the situation at house 2. At house 5 however, a total of 12 screens (3 × 2.8 m each, width × height; surface area: 16.8 m^2 per room) and six downstream rooms were present (instead of eight screens and four rooms in house 2; Fig. 2, right). Air was drawn through the DF by a total of 12 pressure fans (92 cm diameter, frequency-controlled, ventilation capacity: 21,660 m^3 h^{-1} each). At this dimensioning, air velocity near the DF screens was approximately 0.7 m s^{-1}. In the exterior walls outside the DF rooms, a total of four bypass fans were present (130 cm diameter, on/off-controlled, v-belt type, ventilation capacity: 36,100 m^3 h^{-1} each) for extra ventilation capacity in summer.

Description of the electrostatic precipitator

A single-stage and wire-to-belt type ESP prototype, recently developed for PM abatement in fan ventilated poultry houses, was provided by the manufacturer (ENS Europe B.V., Gassel, the Netherlands). The ESP worked as a stand-alone air cleaning unit and was equipped with (from inlet tot outlet): a mesh filter with an automatic scraper (Fig. 3, nr. 1) to a collection bin (nr. 2), a pressure fan (nr. 3; frequency-controlled; ventilation capacity: 27,000 m^3 h^{-1}), and one ionization section (internal dimensions: 3.0 × 0.8 × 0.8 m; length × width × height). Because of the on-board fan, the ESP could be evaluated at any available poultry house, independently from the ventilation system present. The mesh filter with scraper was used to prevent the ESP from overloading by feathers and large particles. Inside the ionization section, particles were electrically and positively charged by a high voltage unit (Fig. 3, nr. 4; +30 kV DC, 0.2 to 1.0 mA) connected to a rectangular circuit of thin electrode wires (Fig. 3, nr. 5; 0.25 mm diameter, total length: 6 m), spaced 15 cm above a grounded collecting surface (Fig. 3, nr. 6; a mesh conveyor belt; 2.4 m^2) at the bottom of the ESP duct. The mesh belt was automatically and regularly cleaned by moving it along a brush mounted above a PM collection bin underneath the ESP (Fig. 3, nr. 7). The fan was programmed to operate at approximately 20,000 m^3 h^{-1}, at which air velocity was approximately 9 m s^{-1} and the residence time approximately 0.33 s. The ESP was connected to layer houses 3 and 4 where it took over part of the ventilation of the fans present in the house.

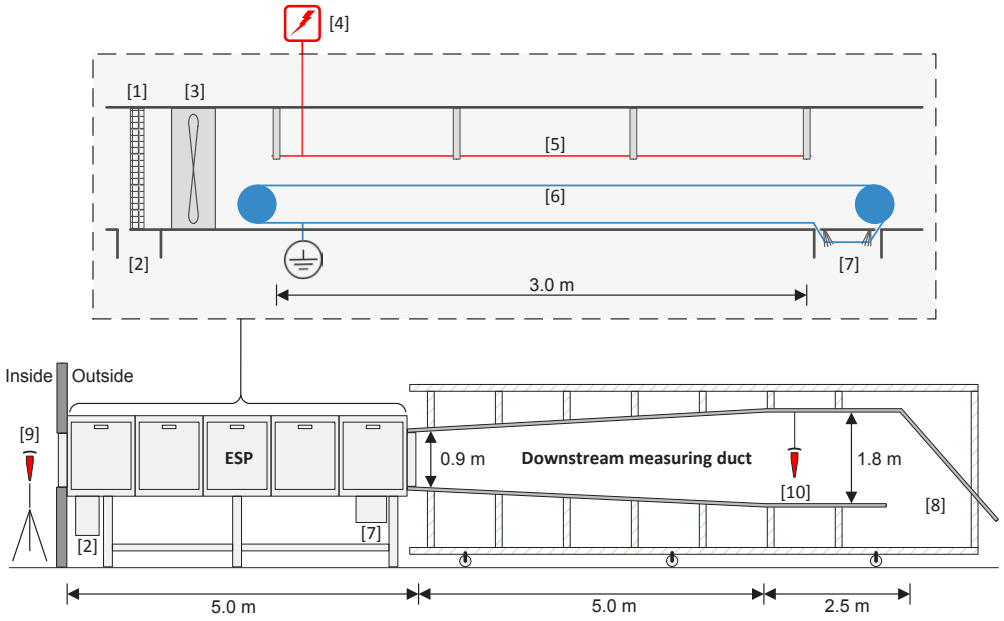


Fig. 3
Schematic side view of the electrostatic precipitator and the downstream measuring duct which were connected to layer houses 3 and 4. Meaning of numbers: [1] = mesh filter with scraper; [2] = PM collection bin; [3] = ventilator; [4] = power supply; [5] = discharge wire; [6] = grounded collection electrode (conveyor belt); [7] = brush mounted above a PM collection bin; [8] = downstream measuring duct outlet; [9] = upstream sampling position; [10] = downstream sampling position.

Measurements

Following the Dutch measurement protocol (Ogink et al., 2011), 24-h measurements were carried out at houses 1 through 4, usually from noon to noon. Sampling positions were upstream and downstream of the systems (Fig. 2 and 3). At these positions, we measured concentrations of PM_{10} and $PM_{2.5}$ in duplicate, next to air temperature and relative humidity (both single measurements). To be able to measure downstream of the ESP outside layer houses 3 and 4, a measuring duct was used (Fig. 3). Inside the duct, air velocity was reduced to <2 m s^{-1} so that PM could be sampled under isokinetic conditions. We further measured concentrations of CO_2 in duplicate, both upstream and downstream of the systems, for two purposes: to monitor any leakage of ambient air (with low concentrations of PM and CO_2) into the downstream measuring position, and to estimate the total ventilation rate of the building using the CO_2 balance method (CIGR, 2002; Pedersen et al., 2008). Finally, we measured air temperature and relative humidity outside the houses (both single measurements).

Particulate matter concentrations

PM_{10} and $PM_{2.5}$ concentrations were determined at houses 1 through 4 by gravimetric filtration, using sampling pumps (Tecora, model Charlie HV; Ravebo B.V., Brielle, the Netherlands) and cyclone samplers (URG, model URG-2000-30ENB for PM_{10} and URG-2000-30EG for $PM_{2.5}$; URG Corp., Chapel Hill, N.C.) at a sample flow rate of 16.7 L min^{-1}. Inside the cyclones, the aimed particle size was collected on a glass fiber filter (type GF-3, 47 mm diameter, Macherey-Nagel, Düren, Germany). Unloaded and loaded filters were weighed with a precise balance (AT261 DeltaRange, Mettler, Greifensee, Switzerland) under standard conditions (20 ± 1°C and 50 ± 5% relative humidity; (CEN, 1998, 2005). After 48 h of stabilization, filters were weighed four times spread over two consecutive days. The average value was recorded as the filter weight. The PM mass concentration was calculated by dividing the mass of collected PM by the volume of air drawn through the filter. PM_{10} concentrations were calibrated to the reference impaction sampler described in EN 12341 (CEN, 1998) using the equations reported by Zhao et al. (2009): $y = 1.09x$ (when $x \leq 223$ µg m^{-3}) and $y = 0.83x + 57.5$ (when $x > 223$ µg m^{-3}), where x is the concentration measured with the cyclone sampler and y is the calibrated concentration.

Continuous measurements of PM_{10} concentration upstream and downstream of the DF and ESP systems were carried out using light-scattering devices (DustTrak aerosol monitor, model 8520, TSI, Inc., Shoreview, Minn.). These data were used to identify time patterns in PM_{10} concentration and removal performance. Logging interval was set at 1 min and the data were stored in the memory of the device.

Particle size distribution

To gain insight into the removal efficiency of the DF for different particle sizes, additional measurements were performed upstream and downstream of a DF at house 5 using a light-scattering device (Portable Aerosol Spectrometer, model 1.109, GRIMM Aerosol Technique GmbH & Co. KG, Ainring, Germany). This device yields particle number concentrations for 31 size channels with diameters between 0.25 and >32 µm. One device was used and its position (downstream or upstream of the DF) was changed every 20 minutes for a total sampling duration of approximately 3 h per measurement day.

Carbon dioxide concentration

For the measurement of CO_2, air was sampled at a constant flow to achieve a 24-h mean sample using the 'lung principle' (vessels with 40 L Nalophan air sampling bags connected to

electrical air pumps; Thomas Industries Inc., Wabasha, Minn.; model 607CD32; critical capillary: 0.02 L min^{-1}). The pump sucked air from the vessel which caused the sampling bag to be filled with air taken from the sampling position. Air samples were taken to the lab and analysed by gas chromatography (Interscience/Carlo Erba Instruments Inc., Breda, the Netherlands, GC 8000 Top; column Molsieve 5A; detector: HWD).

Environmental variables

Air temperature (T; °C) and relative humidity (RH; %) were measured at houses 1 through 4 with combined sensors for T and RH (Rotronic Instrument Corp., Hauppauge, N.Y.). Hourly mean values were stored in a data-logging system (Campbell Scientific Inc., Logan, Utah; types: CR10, CR10X, CR23 and CR23X).

Data preparation and analysis

Estimation of ventilation rate

The total ventilation rate of the building was estimated at houses 1 through 4 using the CO_2 balance method. The total heat production of the birds (Φ_{total}; kW) was calculated based on their body weight and egg production, as given by CIGR (2002). Specific figures on body mass and egg production were obtained from the farmer's records for each measurement. The total heat production was multiplied by a factor (Fco_2) of 0.18 m^3 CO_2 h^{-1} kW^{-1} to yield the CO_2 production per hen (including manure), as recommended by (Pedersen et al., 2008). The ventilation rate (V; m^3 h^{-1} $bird^{-1}$) was calculated using Eq. 1:

$$V = \frac{\Phi_{total} \times Fco_2}{([CO_2]_u - [CO_2]_a) \times 10^{-6}} \quad (1)$$

where $[CO_2]_u$ is the measured concentration of CO_2 upstream of the system (ppm), and $[CO_2]_a$ is a fixed ambient CO_2 concentration as found outside eight layer farms in a recent emission survey (482 ppm) (Winkel et al., 2015).

Calculation of removal efficiency

Comparison of downstream versus upstream CO_2 concentrations of the ESP at houses 3 and 4 showed significantly lower downstream concentrations (Table 2), as a result of ambient air

leaking into the downstream measuring duct through its exhaust opening (Fig. 3, nr. 8). This situation can be described by Eq. 2:

$$Q_t \times C_t = (Q_e \times C_e) + (Q_a \times C_a) \quad (2)$$

where Q_t is the total air flow leaving the exhaust opening of the downstream sampling duct, C_t is the pollutant concentration in the air flow Q_t, Q_e is the air flow from the ESP entering the sampling duct, C_e is the pollutant concentration in the air flow Q_e, Q_a is the air flow from the ambient environment mixing with Q_e to form Q_t, and C_a is the pollutant concentration in the air flow Q_a. Given this situation, and assuming homogenous mixing of Q_e and Q_a at the downstream sampling position, we corrected downstream PM concentrations for dilution using the upstream and downstream CO_2 concentrations and the ambient CO_2 and PM concentrations. The derived correction method is described in Eq. 3.1 and Eq. 3.2:

$$PM_{dc} = \frac{PM_{dm} - (P_a \times PM_a)}{P_h} \quad (3.1)$$

where PM_{dc} is the corrected downstream PM concentration (µg m^{-3}), PM_{dm} is the measured downstream PM concentration (µg m^{-3}), PM_a is a fixed ambient PM concentration as found outside eight layer farms in a recent emission survey (55 µg m^{-3} PM_{10} and 15 µg m^{-3} $PM_{2.5}$) (Winkel et al., 2015), P_a is the proportion of ambient air leaked into the downstream air flow (calculated as: $P_a = 1 - P_h$), and P_h is the proportion of poultry house air in the downstream air flow. P_h is calculated using Eq. 3.2:

$$P_h = \frac{[CO_2]_d - [CO_2]_a}{[CO_2]_u - [CO_2]_a} \quad (3.2)$$

where: $[CO_2]_d$ is the measured downstream CO_2 concentration (ppm), $[CO_2]_a$ is a fixed ambient CO_2 concentration as found outside eight layer farms in a recent emission survey (482 ppm) (Winkel et al., 2015), and $[CO_2]_u$ is the measured upstream CO_2 concentration (ppm). For the ESP, PM removal efficiencies were calculated for each measurement as shown in Eq. 4:

$$\eta = \left(1 - \frac{PM_{dc}}{PM_u}\right) \times 100 \quad (4)$$

where: η is the removal efficiency (%) of a measurement, PM_u is the upstream PM concentration (μg m^{-3}), and PM_{dc} is the corrected downstream PM concentration (μg m^{-3}; see Eq. 2, 3.1, and 3.2). For the DF, PM removal efficiencies were calculated in the same manner, but the measured downstream concentration was used (i.e., PM_{dm} instead of PM_{dc} in Eq. 4). The overall PM removal efficiency of a system was calculated as the mean of the individual removal efficiencies for that system.

Calculation of PM emission rates

Untreated PM emission rates of the houses (E; mg h^{-1} $bird^{-1}$; without the application of any system) were estimated by Eq. 5:

$$E = V \times (PM_u - PM_a) \times 1000 \quad (5)$$

Furthermore, emission rates were expressed per Livestock Unit (LU; i.e., 500 kg live weight), using the recorded body weight of the hens.

Statistical analysis

For all measured variables at houses 1 through 4, differences between upstream and downstream daily mean values were tested for statistical significance with the one-tailed paired samples *t*-test. Relationships between removal efficiency and upstream PM concentrations were investigated by linear regression analysis. For the statistical procedures, we assumed the measurements carried out at one house to be statistically independent. All analyses were done using the GenStat software (VSN, 2012) and probability values ≤0.05 were considered statistically significant.

RESULTS AND DISCUSSION

The dry filter

Measurement conditions

Fig. 4 shows the meteorological conditions and the distribution of measurements over the year at houses 1 and 2. Ambient air temperature and relative humidity during measurements roughly followed the long-term trends for the Netherlands, indicating that the DF was evaluated under a representative range of ambient climate conditions. For one measurement at house 2, no

downstream PM concentrations were available due to a technical problem in PM sampling. In total, 11 out of 12 scheduled measurements were successful, fulfilling the requirements set in the PM measurement protocol (Ogink et al., 2011). At both houses, the DF system functioned according to the pre-set specifications throughout the evaluation period.

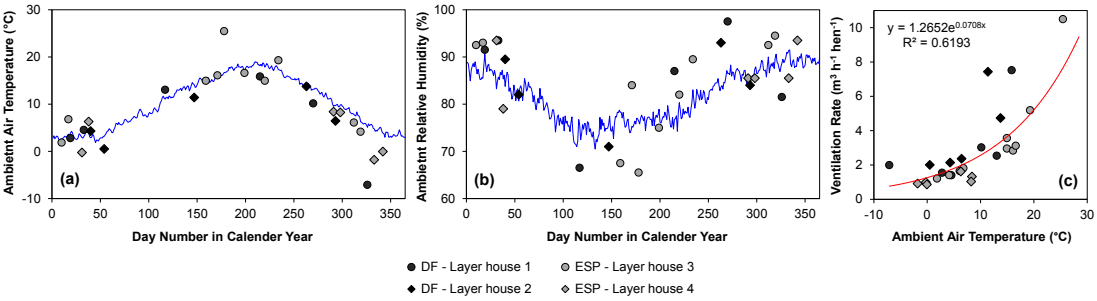


Fig. 4
Outdoor air temperature (a), outdoor relative humidity (b), distribution of measurements over the year (a and b), and mean ventilation rates (c) (total of bypass/house fans and DF or ESP fans) during the measurements in this study. Blue lines in (a) and (b) represent the trends in long-term daily means for the Netherlands (1981–2010; Royal Netherlands Meteorological Institute).

Table 2
Results of measurements carried out upstream and downstream of the dry filter (SD = standard deviation between measurements; n.s. = not significant).

Variable	House	*n*	Upstream; mean (SD)	Downstream; mean (SD)	Difference	
					Mean	Sign.
Air temperature (°C)	1	5	19.6 (1.1)	19.2 (1.2)	-0.3	
	2	4	17.6 (3.5)	15.6 (4.9)	-2.0	
	1 and 2	9	18.7 (2.4)	17.7 (3.5)	-1.0	$P = 0.041$
Relative humidity (%)	1	5	69 (5)	78 (8)	9	
	2	4	60 (9)	64 (6)	4	
	1 and 2	9	65 (8)	72 (10)	7	$P = 0.029$
CO_2 concentration (ppm)	1	3	1780 (252)	1817 (240)	2.1%	
	2	4	1234 (180)	1360 (278)	10.3%	
	1 and 2	7	1468 (350)	1556 (342)	6.0%	n.s.
PM_{10} concentration (µg m^{-3})	1	6	2860 (536)	1718 (583)	40.7% [a]	
	2	5	2915 (1156)	1767 (854)	39.4% [a]	
	1 and 2	11	2885 (824)	1741 (680)	40.1% [a]	$P < 0.001$
$PM_{2.5}$ concentration (µg m^{-3})	1	6	147 (42)	147 (36)	-4.6% [a]	
	2	5	188 (105)	172 (90)	7.1% [a]	
	1 and 2	11	166 (75)	158 (64)	0.7% [a]	n.s.

[a] Mean removal efficiencies based on the values obtained from Eq. 4.

Table 2 shows the mean values of variables measured upstream and downstream of the DF. On passing the DF, the air temperature dropped with 1°C on average, accompanied by a rise in humidity of on average 7 percentage points. This small change in air characteristics most likely

represents the normal heat loss of the exhaust air during its way from the core of the building to the outside environment, where air temperature was usually lower than 19°C to 20°C inside (Fig. 4). Neither in the cargo container setup at house 1, nor in house 2, indications of undesirable mixing of exhaust and ambient air were detected, as shown by similar upstream and downstream CO_2 concentrations (Table 2).

PM removal performance

Upstream concentrations of PM_{10} and $PM_{2.5}$ were about 100-fold of those typically found in ambient air and representative for layer houses with litter floors (Takai et al., 1998; Winkel et al., 2015). The mean upstream PM_{10} concentration amounted 2885 µg m^{-3} (Table 2) with individual 24-h mean values ranging between 1762 and 4485 µg m^{-3} (Fig. 5A and 5B).

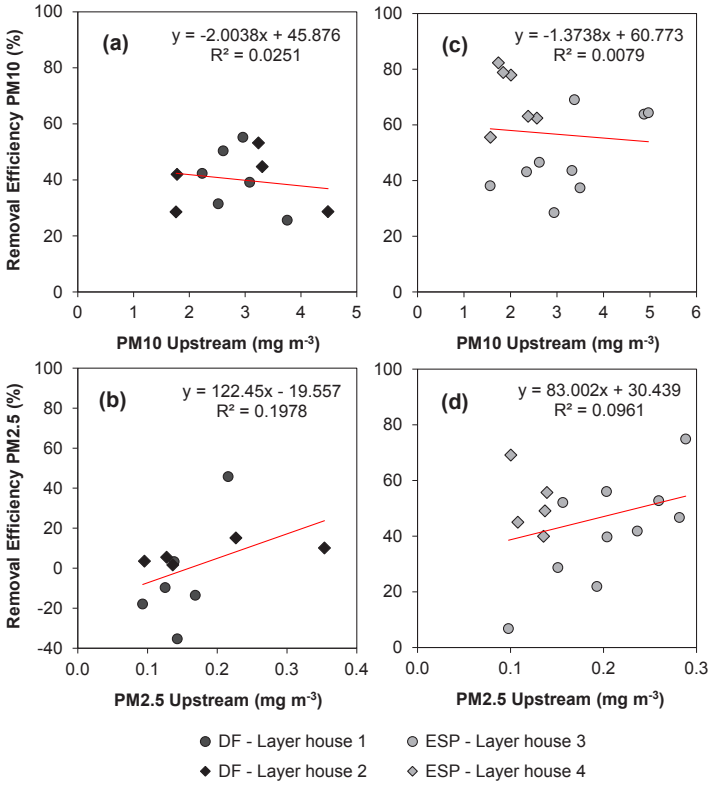


Fig. 5
Removal efficiencies of the dry filter at houses 1 and 2 (a and b) and of the electrostatic precipitator at houses 3 and 4 (c and d) for PM_{10} and $PM_{2.5}$ as a function of upstream PM concentration.

At these concentrations, mean PM_{10} removal efficiency was 40.1% (range: 26% to 55%). Mean PM_{10} removal efficiencies per house were 40.7% (Standard Deviation (SD): 11.1%) for house 1 and 39.4% (SD: 10.7%) for house 2. For $PM_{2.5}$, the mean upstream concentration amounted 166 μg m^{-3} with individual 24-h mean values ranging between 93 and 354 μg m^{-3}. The paired samples t-test on the 11 data pairs showed no significant removal of $PM_{2.5}$. At house 2, $PM_{2.5}$ removal efficiencies were in a narrow range between 2 and 15% (mean: 7.1%, SD: 5.4%), whereas for house 1 this range was -35% (increase) to 46% (mean: -4.6%; SD: 27.7%). Linear regression analysis of the data points available in this evaluation study, showed no significant effect (i.e., regression coefficient) of upstream PM concentration on removal efficiency (Fig. 5A and 5B).

In Fig. 6, continuous PM_{10} concentrations and removal efficiencies obtained from DustTrak measurement are shown as a function of time for two typical 24-h measurements: one measurement at house 1 (Fig. 6a) and one measurement at house 2 (Fig. 6b). At both houses, downstream PM_{10} concentrations were consistently lower than upstream concentrations and a sharp decline in upstream concentration was found in the evening, when lights were switched off. For most measurements, removal efficiency dropped during this dark period too at both houses (Fig. 6a and 6b). This cannot have been caused by a drop in ventilation rate (and air velocity) since ventilators were operated at a fixed ventilation rate at both houses. Particle re-entrainment from screens (Fig. 1B) and floors might have compensated the removal of the DF at low upstream concentrations during dark periods. Alternatively, reduced animal activity during dark hours might have shifted the particle size distribution towards smaller particles which are less susceptible to removal by impaction. The lower removal during dark hours will however hardly affect the 24-h mean mass removal, since this figure is mainly determined by the removal performance during light periods at high concentrations.

In Table 3, the results of this work are compared with those from previous studies into the removal efficiency of the DF for poultry PM. From this table, it becomes clear that the mean PM_{10} removal of 40.1% found in the present study is in close agreement with the mean removal levels (33.7% to 46%) found by Lim et al. (2007) in a caged layer house. LUFA (2009) and Ogink et al. (2009) each carried out a single measurement (during two days and several hours respectively) in house 2 of the present study. The removal efficiencies of 57.6% reported by LUFA (2009) and 19.9% reported by Ogink et al. (2009) are only just outside the range of individual daily mean values in this work (26% to 55%; Fig. 5). Since the DF is based on the working principle of inertial impaction, particle removal is expected to increase with air velocity

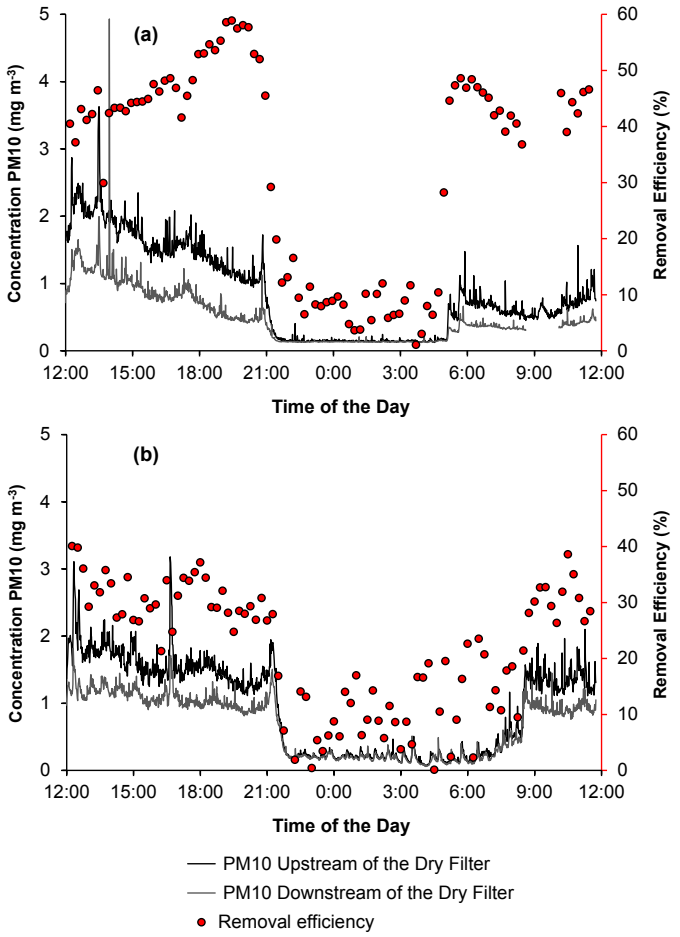


Fig. 6
Continuous DustTrak PM_{10} data of two typical 24-h measurements at the dry filter of house 1 (a) and house 2 (b). Note that no downstream concentration was recorded during approximately 1.5 h in graph (a).

and the diameter (mass) of particles (Perry and Green, 1984). In agreement to this, four out of six studies summarized in Table 3 show higher removal efficiencies for Total PM than for PM_{10} (Lim et al., 2007; LUFA, 2009) or for PM_{10} than for $PM_{2.5}$ (Demmers et al., 2010). In a study using a wind tunnel setup, removal efficiencies based on particle number concentrations reached levels over 80% (Mostafa and Buescher, 2011) and decreased with increasing particle diameter, as determined in 15 size ranges (Mostafa, 2008). In the study of Demmers et al. (2010) however, removal efficiency of a DF at a broiler house increased with particle size from ~20% at 1 µm particle diameter to a maximum of ~78% at 8 µm particle diameter (RVC, 2009). Results of the

wind tunnel experiments reported by Mostafa (2008) and Mostafa and Buescher (2011) therefore, seem to differ from the full-scale tests summarized in Table 3.

Table 3
Summary of studies into the PM removal efficiency of the dry filter (n.g.: not given in publication).

First author (year)	Country	Test situation	PM_{10} upstream ($\mu g\ m^{-3}$)	Air velocity ($m\ s^{-1}$)	PM removal efficiency (%)		
					Total PM	PM_{10}	$PM_{2.5}$
Lim (2007)	USA	Layer house, cages; pilot test	655	0.50	66.5	33.7 [a]	-
			656	0.73	65.5	46.0 [a]	-
		Full scale test	500	0.80	-	41.0 [b]	-
LUFA (2009)	Germany	Layer house, aviary	3308	1.59	65.1	57.6 [a]	-
Ogink (2009)	Germany	Layer house, aviary	3309	-	-	19.9 [a]	-
Demmers (2010)	UK	Broiler house	-	-	-	64	41
Mostafa (2008, 2011)	Germany	Wind tunnel tests, layer PM	n.g.	0.75	~28 [c]	~65 [c]	~66 [c]
				1.00	65 [c]	~82 [c]	~83 [c]
				1.25	~37 [c]	~70 [c]	~76 [c]
This work	Netherlands	Layer house, floor	2915	0.65	-	40.7 [a]	7.1 [a]
	Germany	Layer house, aviary	2860	0.65	-	39.4 [a]	0.1 [a]

[a] Based on downstream versus upstream mass concentrations.
[b] Based on emission reduction.
[c] Based on downstream versus upstream particle number concentrations.

Possibilities for optimization

Screens and floors were cleaned every four to eight weeks using an industrial vacuum cleaner. To avoid peak emissions, ventilators were switched off during cleaning. Within a few days after cleaning however, clear PM accumulation could be seen. The mountain-shaped PM depositions onto the downstream side of the DF screens in Fig. 1B indicate that part of the PM was intercepted after these particles had already passed the vertical canals of the DF. Another part of the PM accumulated on the floor by gravitational settling in layers of millimeters to centimeters thick. Additional long-term continuous PM measurements may be useful to gain insight into the removal efficiency of the DF as a function of the degree of dirtiness in time, to determine the optimal cleaning moment. Cleaning could be further improved trough addition of an automated, programmable system, such as an industrial vacuum cleaning system. Another approach to reduce particle resuspension from floors could be the use of slatted floors and PM collection pits in the rooms between DF screens and ventilators.

Particle Size distribution

Additional measurements of particle number concentrations in several size ranges were performed upstream and downstream of a DF at house 5. During measurements, air velocity ranged between 0.5 and 1.6 m s^{-1}. Results of the measurements are shown in Fig. 7. Consistent with the general principles of impaction (Perry and Green, 1984), removal efficiency increased with increasing particle diameter between 3 and 20 µm, up to a mean level of approximately 45%. Remarkably, a second peak in removal up to a level of approximately 20% was found for particles of approximately 1 µm in size. When these particles are truly removed from the air flow, their impact on the reduction of PM_{10} will be very small, since these particles have very little mass. An alternative explanation is that inside the DF multiple ~1 µm particles aggregate to form few bigger particles. Since particle number concentration was measured, this would lead to a peak in removal efficiency at ~1 µm, but only in a comparatively smaller drop of the removal efficiency at larger particle sizes, due to the few extra particles that are generated after aggregation. In this case, the observed peak might represent a shift in particle size distribution upon crossing the DF rather than actual particle removal and mass concentration rather than number concentration should be used for accurate determination of removal efficiency. As indicated by the standard deviation, the trend in Fig. 7 was reproducible in successive measurements for particles up to 10 µm. For larger particles, removal was more variable. The general trend in Fig. 7 is roughly in agreement with the trend of increasing removal efficiency with increasing particle diameter presented by RVC (2009). In the latter work, however, this trend was found at a higher level of removal and no peak for ~1 µm particles was found.

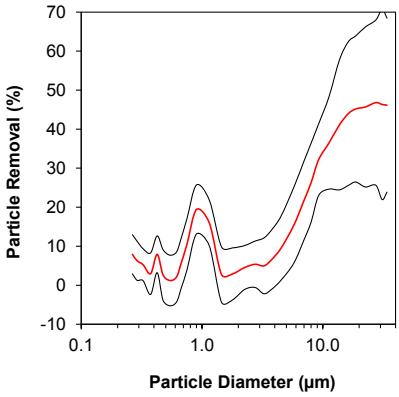


Fig. 7
Mean removal efficiency of the dry filter at house 5 as a function of particle diameter (bold red line). Black thin lines: mean ± one standard deviation between measurements (n = 6).

The electrostatic precipitator

Measurement conditions

Fig. 4 shows the meteorological conditions and the distribution of measurements over the year at houses 3 and 4. Ambient temperature and relative humidity during measurements roughly followed the long-term trends for the Netherlands, indicating that the ESP was evaluated under a representative range of ambient climate conditions. One measurement at house 3 did not yield a valid PM_{10} data pair, whereas one measurement at house 4 did not yield a valid $PM_{2.5}$ data pair. Both missing values were a result of technical problems in PM sampling. In total, we collected 15 data pairs for both PM_{10} and $PM_{2.5}$ out of 16 scheduled measurements, fulfilling the requirements set in the PM measurement protocol (Ogink et al., 2011). At both houses, the ESP system functioned according to the pre-set specifications throughout the evaluation period.

Table 4 shows the mean values of variables measured upstream and downstream of the ESP. Upon crossing the ESP, CO_2 concentration and air temperature decreased, and relative humidity increased, significantly. Smoke tests revealed that smoke released at the outlet of the duct (Fig. 3, nr. 8) partially re-entered the sampling duct and any breakdown of CO_2 by the ESP seems unlikely. Therefore, leaking of ambient air into the downstream measuring duct can be identified as the cause for the observed differences between sampling positions. This phenomenon was reduced as much as possible by applying a long measuring duct (to achieve a laminar flow) and by using a wind shield, with the exhaust opening facing the ground (preventing wind flow to enter the duct). All downstream PM concentrations were corrected for ambient air leaking (Eq. 3.1 and Eq. 3.2).

PM removal performance

Upstream of the ESP, mean PM_{10} concentration amounted 2775 μg m^{-3} (Table 4) with individual 24-h mean values ranging between 1565 and 4966 μg m^{-3} (Fig. 5C and 5D). The mean upstream $PM_{2.5}$ concentration amounted 179 μg m^{-3}, and ranged between 98 and 288 μg m^{-3}. At these concentrations, we found mean removal efficiencies of 57.0% for PM_{10} and 45.3% for $PM_{2.5}$. Mean PM_{10} removal efficiencies per house were 48.3% (SD: 14.1%) for house 3 and 70.0% (SD: 11.0%) for house 4. For $PM_{2.5}$, these values were 42.1% (SD: 19.3%) for house 3 and 51.8% (SD: 11.3%) for house 4. Precipitation of PM was visible as a yellowish dust layer on the collector belt. PM aggregated to coherent sheets onto the collector belt. Although air velocity and discharge voltage were kept constant, removal efficiencies of individual 24-h measurements ranged between 28 and 82% for PM_{10} and between 7 and 75% for $PM_{2.5}$ (Fig. 5C and 5D). By

linear regression analysis on the data points in this evaluation study, none of this variation could be explained by a significant effect (i.e., regression coefficient) of upstream PM concentration (Fig. 5C and 5D). Manuzon and Zhao (2009) also found no effect of poultry house PM concentrations ranging from 2500 to 5000 μg m^{-3} on removal efficiency of a commercial ESP in a laboratory study.

Table 4
Results of measurements carried out upstream and downstream of the dry filter (SD = standard deviation between measurements; n.s. = not significant).

Variable	House	*n*	Upstream; mean (SD)	Downstream; mean (SD)	Difference	
					Mean	Sign.
Air temperature (°C)	3	9	22.4 (1.3)	18.6 (4.7)	-3.8	
	4	5	20.3 (1.8)	14.7 (3.7)	-5.7	
	3 and 4	14	21.6 (1.8)	17.1 (4.6)	-4.5	$P = 0.003$
Relative humidity (%)	3	9	67 (2)	77 (10)	10.1	
	4	5	71 (5)	83 (15)	11.6	
	3 and 4	14	69 (4)	79 (12)	10.7	$P < 0.001$
CO_2 concentration (ppm)	3	10	1361 (512)	1072 (254)	-21.2%	
	4	6	2367 (470)	1763 (369)	-25.5%	
	3 and 4	16	1738 (695)	1331 (451)	-23.4%	$P < 0.001$
PM_{10} concentration (μg m^{-3})	3	9	3279 (1107)	1606 (440) [a]	48.3% [b]	
	4	6	2019 (385)	614 (273) [a]	70.0% [b]	
	1 and 2	11	2885 (824)	1741 (680)	40.1% [a]	$P < 0.001$
$PM_{2.5}$ concentration (μg m^{-3})	1	6	147 (42)	147 (36)	-4.6% [a]	
	2	5	188 (105)	172 (90)	7.1% [a]	
	1 and 2	11	166 (75)	158 (64)	0.7% [a]	n.s.

[a] Mean removal efficiencies based on the values obtained from Eq. 4.

The finding of this work that the ESP is able to remove layer house PM from exhaust air, is in agreement with studies which indicate that poultry PM is probably well collectable by ESPs. For pig house particles, St. George and Feddes (1995a) showed that they can be classified within the 'medium' electrical resistivity range (10^5 to 10^{11} Ω mm^{-1}), which is considered the ideal range for electrostatic precipitation. Considering that poultry and pig house particles originate from comparable organic sources (e.g., feces, skin, feed) (Cambra-López et al., 2011), this is also likely to be true for poultry PM. Furthermore, ESP systems applied in industry are known to be least effective for particles with aerodynamic diameters of 0.1 to 1.0 μm, but highly effective for particles larger than 3 μm (Jaworek et al., 2007; Mizuno, 2000; Perry and Green, 1984), which represent the main part of particle mass in poultry house air (Cambra-López et al., 2011). In comparison with several types of PM, poultry house PM was collected more efficiently by an ESP than inorganic standard road dust (Manuzon and Zhao, 2009), and pig house PM was collected more efficiently than PM from icing sugar and milk powder, comparable to PM from

corn starch, but less efficient than PM from flour (St. George and Feddes, 1995a). In Table 5, a summary is provided of the design and results of four studies conducted so far. This table furthermore describes the design parameters, air flow characteristics, and electrical properties of the ESPs employed in these studies. From this table it is clear that ESPs with various designs are able to remove pig and poultry house PM from exhaust air, with efficiencies ranging from 19% to more than 90%.

Table 5
Summary of studies investigating PM removal by electrostatic precipitators for animal house exhaust cleaning (n.g.: not given in publication).

Variable	First author (year)					Typical values industrial ESPs [a]
	St. George (1995b)	Lau (1996)	Chai (2009)	Manuzon (2009)	This Work	
Study details						
Setup	Laboratory	Pig house	Laboratory	Laboratory	Layer houses	-
Type of PM	Pig PM	Pig PM	Corn starch	Poultry PM	Layer PM	Various
PM loading (mg m^{-3})	n.g.	0.6–3.6	6.7–24.5	2.5 / 5.0	2.775 (PM_{10})	1–50 g Nm^{-3}
Removal performance						
Total PM (%)	18.6–96.4 [b]	20–66 [c]	23–95 [d]	>90% [b]	-	>90%
PM_{10} (%)	-	-	-	-	57.0 [d]	>90%
$PM_{2.5}$ (%)	-	-	-	-	45.3 [d]	>85%
ESP design parameters						
General type	Wire-to-plate; 1-stage	Plate; 2-stage	Wire-to-plate; 2-stage	Wire-to-plate; 2-stage	Wire-to-belt; 1-stage	Various
Discharge electrodes	11 Wires	n.g.	10 Wires	9 Wires	2 Wires	Various
Wire length (m)	0.4	n.g.	0.61	n.g.	3	<9
Wire radius (mm)	0.78	n.g.	5	n.g.	0.25	-
Collection electrodes	12 Plates	Plate	44 Plates	71 Plates	Moving belt	Various
Wire positions to plate	Between	n.g.	Upstream	Upstream	Above	Various
Wire-wire spacing (cm)	3	n.g.	5.08	n.g.	27	-
Wire-plate spacing (cm)	1.25	n.g.	Ca. 50–60 [e]	15	15	-
Plate-plate spacing (cm)	3	n.g.	1.27	0.36	–	20–30
Collection surface (m^2)	5.28 [e]	n.g.	1.332	n.g.	2.4	500–7500
SCA (m^2 per 1000 m^3 h^{-1})	1.1–5.4 [e]	n.g.	3.33 [e]	n.g.	0.12	11–45
Cleaning principle	n.g.	Washing	Manually	n.g.	Brushing	Various
Air flow characteristics						
Air velocity (m s^{-1})	0.55–0.95	n.g.	1.7	1.25 / 2.5	~9	0.5–3
Air flow rate (m^3 h^{-1})	976–4602	5700 [e]	400	n.g.	20,000	10^4–10^6
Residence time (s)	n.g.	n.g.	0.0015	n.g.	0.33	1–30
Electrical properties						
Discharge voltage (kV)	-10.3 to -12.1	13 DC	-60 to +60	7 / 10 DC	+30	4–100
Current (mA)	0.11–3	1.9	n.g.	n.g.	0.2–1	-
Power (W)	1–36 [e]	25 [e]	<12	n.g.	6–30	-
SCP (W per 1000 m^3 h^{-1})	0.3–37.2 [e]	4.3 [e]	0.2–4.5 [e]	n.g.	0.3–1.5	59–530
CCD (μA m^{-2})	21–568 [e]	n.g	28–140	n.g.	83–417	100–1000

[a] Values from: Coulson, Richardson, Backhurst, and Harker (1991), Jaworek et al. (2007), Perry and Green (1984), and White (1977).
[b] Based on particle number concentrations.
[c] ESP applied in a recirculation setup inside a finishing pig house; removal efficiency determined as the relative difference between ESP and control room.
[d] Based on particle mass concentrations.
[e] Estimated from information in publication.

Possibilities for optimization

Besides particle characteristics, ESP performance is affected by gas properties and ESP design parameters. For the ESP evaluated in this work, and for ESPs from previous studies, such parameters are listed in Table 5, and compared with typical settings of industrial ESPs. From this table it becomes clear that the ESP evaluated in this work has a conventional discharge wiring, voltage level and Corona Current Density. Despite that negative voltages may yield higher PM collection efficiencies at 30 kV (Chai et al., 2009), a positive electrical polarity was chosen by the manufacturer, because this is believed to cause less undesirable formation of ozone (Chen and Davidson, 2003; Perry and Green, 1984). The ESP was designed to be connected to fans already present in the end wall of poultry houses (without the on-board fan, which was only installed to allow stand-alone functioning). Fans in European poultry houses are mostly of the on-off controlled type with a constant ventilation rate up to 30,000 m^3 h^{-1}. Therefore, in this study, the ESP fan was evaluated at a constant ventilation rate of 20,000 m^3 h^{-1}. Potential drawbacks of this design approach are that the ESP has a high air velocity (~9 m s^{-1}; which may cause particle re-entrainment from the collection belt), a low residence time (0.33 s; which may impede particles to become fully loaded with elementary charges and reach the collection electrode) and a low Specific Collection Area (0.12 m^2 of collector belt area per 1000 m^3 h^{-1}). These aspects might explain why the mean removal of 57.0% for PM_{10} and 45.3% for $PM_{2.5}$ is rather low in comparison to industrial ESPs (Table 5). Performance of the ESP evaluated may be improved by reducing air velocity, increasing residence time (e.g., by extending the ESP length or enlarging its cross-sectional area) and by increasing its Specific Collection Area (e.g., by installing multiple vertical collection belts instead of one horizontal belt). The collection belt in the ESP was cleaned every 24 h. Manuzon and Zhao (2009) however found that removal of 5 to 10 μm particles dropped from 90% to 85% within 45 minutes after cleaning and removal of >10μm particles dropped from 90% to 80% in 30 minutes. Therefore, increasing the cleaning frequency may be a parameter for further study and improvement of removal performance as well. Finally, when the ESP and the DF are connected to large poultry buildings, they will collect hundreds of kilograms of PM per year. Consequently, it needs to be determined how the collected PM can be safely handled and disposed.

PM emissions of layer houses

Total ventilation rates of the houses are shown in Fig. 4C. Ventilation rate increased with increasing ambient air temperature. Based on the total ventilation rates and PM concentrations

upstream of the systems (Tables 2 and 4), mean (SD between houses) untreated PM_{10} emission rate for the non-cage layer houses was 7.81 (4.12) mg h^{-1} $bird^{-1}$ (n = 26), equivalent to 2282 (1125) mg h^{-1} LU^{-1}. Mean (SD between houses) untreated $PM_{2.5}$ emission rate amounted 0.44 (0.28) mg h^{-1} $bird^{-1}$ (n = 26), equivalent to 124 (70) mg h^{-1} LU^{-1}. The emission rates found here agree well with those found in eight non-cage layer houses in a recent PM emission survey in the Netherlands (Winkel et al., 2015).

CONCLUSIONS

In this study, we evaluated the removal performance of a dry filter (DF) and an electrostatic precipitator (ESP) for end of pipe abatement of particulate matter (PM) emissions by performing measurements upstream and downstream of these systems installed at commercial non-cage poultry houses. Our main results and conclusions are:

- The DF effectively reduced concentrations of PM_{10} in the exhaust air by an average of 40.1%, whereas particles in the $PM_{2.5}$ fraction were not significantly removed. Mean PM_{10} removal by the DF was similar between houses: 40.7% (SD: 11.1%) at house 1 and 39.4% (SD: 10.7%) at house 2. Removal efficiency was not affected by upstream PM concentration.
- Removal efficiency of the DF increased with increasing particle diameter, as shown by additional measurements of particle size distribution upstream and downstream of a DF. This finding is consistant with the first conclusion, the majority of available studies, and the underlying working principle of inertial impaction.
- The ESP effectively reduced concentrations of PM_{10} in the exhaust air by an average of 57.0%, and concentrations of $PM_{2.5}$ by an average of 45.3%. Mean PM_{10} removal by the ESP was 48.3 (SD: 14.1%) for house 3 and 70.0% (SD: 11.0%) for house 4. For $PM_{2.5}$, these values were 42.1% (SD: 19.3%) for house 3 and 51.8% (SD: 11.3%) for house 4. Removal efficiency was not affected by upstream PM concentration.
- Removal performance of both the DF and the ESP may be further improved by increasing the cleaning frequency. The use of slatted floors and dust collection pits downstream of the DF may prevent emission from particle resuspension. Implementation of industrial ESP design standards may further improve removal performance of the prototype evaluated.
- The mean (SD between houses) untreated emission rate from the four non-cage laying hen houses was 7.81 (4.12) mg PM_{10} h^{-1} $bird^{-1}$ and 0.44 (0.28) mg $PM_{2.5}$ h^{-1} $bird^{-1}$. This study

shows that the evaluated systems have potential to reduce these PM emissions.

ACKNOWLEDGMENTS

This study was financed by the Dutch Ministry of Economic Affairs and the Dutch Ministry of Infrastructure and the Environment. We thank the participating poultry farmers for allowing the use of their farms as test sites. The companies Big Dutchman and ENS Europe are acknowledged for providing the DF and EPS systems. We thank our co-workers Mr Theo van Hattum, Mr Jos Huis in't Veld, Mr Jorge Jorens Rubio, and Mr Guus Nijeboer for carrying out the measurements, Mr Eef Lovink for maintenance and calibration of equipment, and Mr Jean Slangen and Mr Geert Kupers for carrying out the lab analyses.

REFERENCES

Brunekreef, B., Holgate, S.T., 2002. Air pollution and health. *Lancet* 360:1233–1242.

Cambra-López, M., Aarnink, A.J.A., Zhao, Y., Calvet, S., Torres, A.G., 2010. Airborne particulate matter from livestock production systems: A review of an air pollution problem. *Environ. Pollut.* 158:1–17.

Cambra-López, M., Hermosilla, T., Lai, H.T.L., Aarnink, A.J.A., Ogink, N.W.M., 2011. Particulate matter emitted from poultry and pig houses: Source identification and quantification. *Trans. ASABE* 54:629–642.

Cambra-López, M., Winkel, A., Van Harn, J., Ogink, N.W. M., Aarnink, A.J.A., 2009. Ionization for reducing particulate matter emissions from poultry houses. *Trans. ASABE* 52:1757–1771.

CEN, 1998. EN 12341:1998. Air quality - Determination of the PM 10 fraction of suspended particulate matter - Reference method and field test procedure to demonstrate reference equivalence of measurement methods. European Committee for Standardization (CEN), Brussels, Belgium.

CEN, 2005. EN 14907:2005. Ambient air quality - Standard gravimetric measurement method for the determination of the PM2.5 mass fraction of suspended particulate matter. European Committee for Standardization (CEN), Brussels, Belgium.

Chai, M., Lu, M.M., Keener, T., Khang, S.J., Chaiwatpongsakorn, C., Tisch, J., 2009. Using an improved electrostatic precipitator for poultry dust removal. *J. Electrostat.* 67:870–875.

Chen, J.H., Davidson, J.H., 2003. Ozone production in the negative DC corona: The dependence of discharge polarity. *Plasma Chem. Plasma Process.* 23:501–518.

CIGR., 2002. 4th Report of Working Group on Climatization of animal houses. Heat and moisture production at animal and house levels (eds. Pedersen, S. and Sällvik, K.). Int. Commission of Agric. Eng. (CIGR), Section II.

Coulson, J.M., Richardson, J.F., Backhurst, J.R., Harker, J.H., 1991. Coulson & Richardson's Chemical Engineering, Vol. 2: Particle Technology & Separation Processes, 4th ed. Butterworth-Heinemann, Oxford, UK.

Demmers, T.G.M., Saponja, A., Thomas, R., Phillips, G.J., McDonald, A.G., Stagg, S., Bowry, A., Nemitz, E., 2010. Dust and ammonia emissions from UK poultry houses. In: XVII-th World Congress of the Int. Commission of Agric. and Biosyst. Eng. (CIGR), Québec City, Canada.

EU, 2008. Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe. *Offic. J. Europ. Union* L152:1–44.

Heederik, D.J.J., Opstal-van Winden, A.J.W., Smit, L.A.M., Wouters, I.M., Hooiveld, M., IJzermans, C.J., van der Sman-de Beer, F., Spreeuwenberg, P.P.M., de Bruin, A., van Rotterdam, B., 2011. Mogelijke effecten van intensieve-veehouderij op de gezondheid van omwonenden: onderzoek naar potentiële blootstelling en gezondheidsproblemen. Institute for Risk Assessment Sciences (IRAS), Universiteit Utrecht; Nederlands instituut voor onderzoek van de gezondheidszorg (NIVEL); Rijksinstituut voor Volksgezondheid en Milieu (RIVM), Utrecht, the Netherlands.

Jaworek, A., Krupa, A., Czech, T., 2007. Modern electrostatic devices and methods for exhaust gas cleaning: A brief review. *J. Electrostat.* 65:133–155.

Lau, A.K., Vizcarra, A.T., Lo, K.V., Luymes, J., 1996. Recirculation of filtered air in pig barns. *Can. Agric. Eng.* 38:297–304.

Li, Q.F., Wang-Li, L., Walker, J.T., Shah, S.B., Bloomfield, P., Jayanty, R.K.M., 2012. Particulate matter in the vicinity of an egg production facility: Concentrations, statistical distributions, and upwind and downwind comparison. *Trans. ASABE* 55:1965–1973.

Lim, T.T., Sun, H., Ni, J.Q., Zhao, L., Diehl, C.A., Heber, A.J., Hanni, S.M., 2007. Field tests of a particulate impaction curtain on emissions from a high-rise layer barn. *Trans. ASABE* 50:1795–1805.

LUFA, 2009. Messbericht über die durchführung von emissionsmessungen [Measurement report on the execution of emission measurements; in German]. LUFA Nord-West, Institut für Boden und Umwelt, Oldenburg, Germany.

Manuzon, R.B., Zhao, L.Y., 2009. Laboratory evaluation and modeling of electrostatic precipitation of PM emissions from poultry buildings. *Ashrae Trans.* 115: 831–849.

Melse, R.W., Hofschreuder, P., Ogink, N.W.M., 2012. Removal of particulate matter (PM10) by air scrubbers at livestock facilities: results of an on-farm monitoring program. *Trans. ASABE* 55:689–698.

Mizuno, A., 2000. Electrostatic precipitation. *Ieee Trans. Dielectrics Electr. Insul.* 7:615–624.

Mostafa, E., 2008. Improvement of air quality in laying hens barn using different particle separation techniques. PhD thesis. Rheinischen Friedrich-Wilhelms-Universität Bonn, Bonn, Germany.

Mostafa, E., Buescher, W., 2011. Indoor air quality improvement from particle matters for laying hen poultry houses. *Biosyst. Eng.* 109:22–36.

Ogink, N.W.M., Aarnink, A.J.A., 2011. Plan van aanpak bedrijfsoplossingen voor fijnstofreductie in de pluimveehouderij [Plan of action for particulate matter mitigation solutions in poultry; in Dutch, with English summary]. Report 113, Animal Sciences Group, Wageningen University and Research Centre, Lelystad, the Netherlands.

Ogink, N.W.M., Hofschreuder, P., Aarnink, A.J.A., 2011. Protocol for the measurement of fine dust emissions from housings in animal production 2010 [in Dutch]. Report 492, Wageningen UR Livestock Research, . Lelystad, the Netherlands.

Ogink, N.W.M., Van Hattum, T.G., Winkel, A., 2009. Measures to reduce fine dust emission from poultry facilities: indicative evaluation of the Stuffnix system of Big Dutchman [in Dutch, with English summary]. Report 203, Animal Sciences Group, Wageningen University and Research Centre, Lelystad, the Netherlands.

Pedersen, S., Blanes-Vidal, V., Joergensen, H., Chwalibog, A., Haeussermann, A., Heetkamp, M.J.W., Aarnink, A.J.A., 2008. Carbon dioxide production in animal houses: a literature review (Manuscript BC 08 008). *Agric. Eng. Int.: CIGR Ejournal* X.

Perry, R.H., Green, D., 1984. Perry's Chemical Engineers' Handbook (6th ed.). MacGraw-Hill, New York, USA.

RIVM, 2011. Annual national emissions of PM10; in total and per sector/source, for 2011 (website). Retrieved 18 June 2013, from http://www.emissieregistratie.nl.

RIVM, 2013. Online records of days with a daily mean PM10 concentration exceeding the limit value of 50 µg/m^3, per sampling site in the Dutch National Air Quality Monitoring Network (website). Retrieved 10 July 2013, from http://www.lml.rivm.nl/data/overschrijding/overschrijdingpm10.html.

RVC, 2009. Characterising poultry dust properties, assessing the human health implications, quantifying emission levels and assessing the potential for abatement. Project report, Royal Veterinary College (RVC), Hatfield, Hertfordshire, UK.

St. George, S.D., Feddes, J.J.R., 1995a. Electrical properties of organic and respirable swine dusts. *Can. Agric. Eng.* 37:97–102.

St. George, S.D., Feddes, J.J.R., 1995b. Removal of airborne swine dust by electrostatic precipitation. *Can. Agric. Eng.* 37:103–107.

Takai, H., Pedersen, S., Johnsen, J.O., Metz, J.H.M., Groot Koerkamp, P.W.G., Uenk, G.H., Phillips, V.R., Holden, M.R., Sneath, R.W., Short, J.L., White, R.P., Hartung, J., Seedorf, J., Schröder, M., Linkert, K.H., Wathes, C.M., 1998. Concentrations and emissions of airborne dust in livestock buildings in Northern Europe. *J. Agric. Eng. Res.* 70:59–77.

Van Zanten, M.C., Van Alphen, A., Wesseling, J., Mooibroek, D., Nguyen, P.L., Groot Wassink, H., Verbeek, C., 2012. State of affairs of the National Air Quality Cooperation Programme 2012 [in Dutch, with English summary]. National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands.

VSN, 2012. GenStat reference manual (release 15). Version 15.2.0.8821. VSN-Int., Ltd, Hemel Hempstead, UK.

White, H.J., 1977. Electrostatic precipitation of fly ash. APCA Reprint Series, Parts I, II, II, and IV. *J. Air Pollut. Contr. Assoc.* 27.

Winkel, A., Mosquera, J., Groot-Koerkamp, P.W.G., Ogink, N.W.M., Aarnink, A.J.A., 2015. Emissions of particulate matter from animal houses in the Netherlands. *Atmos. Environ.*111:202–212.

Zhao, Y., Aarnink, A.J.A., Hofschreuder, P., Groot Koerkamp, P.W.G., 2009. Evaluation of an impaction and a cyclone pre-separator for sampling high PM10 and PM2.5 concentrations in livestock houses. *J. Aerosol Sci.* 40:868–878.

Chapter 7

Evaluation of manure drying tunnels to serve as dust filters in the exhaust of laying hen houses: emissions of particulate matter, ammonia, and odor

A. Winkel [a], J. Mosquera [a], A..J.A. Aarnink [a], P.W.G. Groot Koerkamp [a,b], and N.W.M. Ogink [a]

[a] Wageningen UR Livestock Research, Wageningen, the Netherlands
[b] Farm Technology Group, Wageningen University, Wageningen, the Netherlands

Manuscript submitted to *Biosystems Engineering*

ABSTRACT

Poultry houses are important emission sources of ammonia, odor, and particulate matter (PM). Manure drying tunnels (MDTs) might act as 'end of pipe' PM filters, but might also emit additional ammonia and odor. This study aimed to gain insight into this matter (part A and B) and into the perspective of two strategies to reduce additional emissions: (1) by pre-drying the manure on the belts inside the house (part C), and (2) by reducing manure accumulation time (MAT) in the house to 24-h followed by rapid drying inside the MDT (part D). This study was set up as an emission survey at 16 laying hen farms with a MDT. Results from parts A through C showed that PM_{10} removal efficiency of the MDTs increases linearly with manure layer thickness: from about 35% at 4 cm to 84% at 17 cm. Ammonia and odor concentrations in the drying air increased substantially upon passing the manure layers, from on average 5.5 to 13.9 ppm ammonia and from 822 to 1178 OU_E m^{-3}. In part C, ammonia emission decreased with increasing DM content of the manure, but even at DM content levels beyond 50%, substantial ammonia emission remained. In part D, the emission rates of houses and MDTs together were 44% lower for PM_{10}, 20% higher for ammonia, and 40% higher for odor compared with the theoretical situation of the houses without MDT. Further shortening MAT to 18, 12, or 6 h might be needed to reduce emissions from MDTs.

NOMENCLATURE

CO_2	Carbon dioxide
COPD	Chronic Obstructive Pulmonary Disease
DSA	Drying surface area of the manure drying tunnel (cm^2 $bird^{-1}$)
DT	Drying time inside the manure drying tunnel (days or hours)
E	Emission rate of pollutant (mg h^{-1} $bird^{-1}$ or OU_E s^{-1} $bird^{-1}$)
EF	Emission factor for ammonia in Dutch regulation (g $year^{-1}$ bird $place^{-1}$)
Fco_2	Factor for conversion of total heat to the volumetric carbon dioxide production by the animal and its manure (m^3 h^{-1} kW^{-1})
MAT	Manure accumulation time: time between a full running cycle of the belts inside the housing system. Note that at a MAT of 24 hours, the manure has a manure residence time (MRT) of 12 hours
MBA	Manure belt aeration; inside the housing system
MDT	Manure drying tunnel
MLT	Manure layer thickness inside the manure drying tunnel (cm)
MRT	Manure residence time: the time a dropping resides on average on the manure belt inside the housing system
NH_3	Ammonia
OU_E	European odour unit (EN 17025)
P	Level of significance
PM	Particulate matter
PM_{10}	Particulate matter which passes through a size-selective inlet with a 50% efficiency cut-off at 10 µm aerodynamic diameter (EN 12341)
$PM_{2.5}$	Particulate matter which passes through a size-selective inlet with a 50% efficiency cut-off at 2.5 µm aerodynamic diameter (EN 14907)
SD	Standard deviation
SE	Standard error
Q_{drying}	Ventilation rate through the MDT (m^3 h^{-1} $bird^{-1}$)
Q_{bypass}	Ventilation rate from the poultry house not directed through the MDT (m^3 h^{-1} $bird^{-1}$): $Q_{bypass\_during\_drying} + Q_{bypass\_during\_loading}$
$Q_{bypass\_during\_drying}$	Ventilation rate from the poultry house during drying of the MDT (m^3 h^{-1} $bird^{-1}$)
$Q_{bypass\_during\_loading}$	Ventilation rate from the poultry house during loading of the MDT (m^3 h^{-1} $bird^{-1}$)
$Q_{total\_during\_drying}$	Total ventilation rate of MDT and house during drying (m^3 h^{-1} $bird^{-1}$): $Q_{drying} + Q_{bypass\_during\_drying}$
Q_{total}	Total ventilation rate (m^3 h^{-1} $bird^{-1}$): $Q_{drying} + Q_{bypass}$
Φ_{total}	Total heat production by the animal (kW)

INTRODUCTION

In areas with high densities of livestock houses, emissions from poultry houses represent an important source of airborne pollutants, such as malodorous compounds (Mielcarek and Rzeźnik, 2015; Ogink and Groot Koerkamp, 2001), gaseous ammonia (Groot Koerkamp et al., 1998; Wood et al., 2015), and particulate matter (PM) (Takai et al., 1998; Winkel et al., 2015b). These pollutants are associated with adverse effects on the environment and on the health and wellbeing of residents in these areas. The chronic exposure of residents to odors from nearby livestock houses may cause an array of physical and emotional complaints, either directly by exposure to irritant odorants, or indirectly, through mechanisms related to annoyance, sensitization, stress, and conditioning (Hooiveld et al., 2015; Nimmermark, 2004). Gaseous ammonia causes acidification and eutrophication of soils and surface waters (ApSimon et al., 1987), but is also an important precursor of secondary PM (i.e., inorganic, fine, and solid ammonium nitrate and ammonium sulfate) that is formed through chemical reactions in the atmosphere (Erisman and Schaap, 2004). The association between secondary PM and adverse health outcomes has been well established in epidemiological studies, although clinical exposure studies find no toxicity of ambient levels and causal mechanisms are not well understood (Brunekreef et al., 2015; Schlesinger, 2007). In contrast to secondary PM, primary PM is emitted as particles from livestock houses which mainly fall in the size range larger than 2.5 μm (Lai et al., 2014). It originates from mechanical processes and organic sources inside the house, such as manure, feathers, and skin debris (Cambra-López et al., 2011), and contains micro-organisms and pro-inflammatory endotoxins (Seedorf et al., 1998; Zhao et al., 2014). Concentrations of these particles decrease with increasing distance from the emission point of livestock houses (Heederik et al., 2011; Li et al., 2012) because they settle out to the ground and impact to vegetation, but also because they disperse and their concentration becomes diluted with cleaner air. Fine and course primary particles that remain airborne contribute to background levels of PM and may cause adverse health effects in residents (Brunekreef and Forsberg, 2005), although little is known about direct associations between indicators of PM exposure (e.g., number and distance of farms or a modelled PM exposure) and health of residents. In recent years, a limited number of studies has been published on this matter, which, so far, suggest both protective and adverse effects, such as a higher prevalence of pneumonia and more exacerbations in patients suffering from Chronic Obstructive Pulmonary Disease (COPD) (Borlée et al., 2015; Hooiveld et al., 2016; O'Connor et al., 2010; Schinasi et al., 2011; Smit et al., 2014).

Although ambient PM concentrations in the Netherlands as a whole have decreased in recent years, exceedances of the European limit values for PM with aerodynamic diameters smaller than 10 µm (PM_{10}), laid down in EU Directive 2008/50/EC (EU, 2008), are persistent in specific areas. In addition, PM_{10} levels in many other areas are only just below the limit values, making those areas vulnerable for future exceedances (Van Zanten et al., 2014). These two situations occur in several typical intensive livestock farming areas in the centre and southeast of the Netherlands where a substantial part of airborne PM_{10} comes from agriculture in general and livestock houses in particular (Hendriks et al., 2013; Velders et al., 2008). In the Netherlands as a whole, about 13% of the national yearly emission of primary PM_{10} is attributable to poultry houses (RIVM, 2014).

To facilitate the mitigation of primary PM emissions from poultry farms, an action plan was set up for the Netherlands (Ogink and Aarnink, 2011). Within the framework of this plan, PM reduction principles were developed in cooperation with air cleaning companies into effective, economically feasible, and market-ready systems for the poultry industry. One of the systems studied was the so called manure drying tunnel (MDT), which could be applied for both manure drying and filtration of primary PM from the exhaust air of poultry houses. In Dutch regulation on ammonia emissions from livestock houses, MDTs are allowed only for use in hen-rearing and hen-laying houses under the requirements that the manure must be pre-dried by manure belt aeration (MBA) inside the housing system to a dry matter (DM) content of at least 45%, and that the manure inside the MDT must reach a DM content of at least 80% within 72 hours. The MDTs have an emission factor (EF) of 2 g $year^{-1}$ bird $place^{-1}$ (additional to the housing system; no EF for odor). The use of a MDT is attractive for poultry farmers because it reduces the volume and mass of manure to be transported (e.g., to arable farms) and makes the manure more suitable for burning in biomass power plants or processing into organic fertilizer. This can cut the costs of manure disposal or even create revenues for poultry farmers.

Inside MDTs, drying takes place by forcing the exhaust air (~20 °C) through layers of pre-dried droppings spread onto perforated conveyor belts composed of polyethylene/polypropylene sheets or metal plates/panels. Emission studies on MDTs in the 1990s in the Netherlands (Table 1) suggest that MDTs can substantially reduce PM concentrations in the drying air. Presumably, dust particles are filtered out by impaction and subsequent adherence to the moist, sticky droppings when the drying air makes its way through the pores between the droppings. The studies in Table 1, however, further suggest that this is accompanied with the undesirable release of gaseous ammonia and odorous compounds.

Table 1
Overview of emission studies on manure drying tunnels in the 1990s in the Netherlands (n.d.: not determined or reported).

Reference; first author (year)	Housing system; number of birds	Manure belt aeration [a] (m^3 h^{-1} $bird^{-1}$); manure accumulation time	Drying / bypass vent. capacity (m^3 h^{-1} $bird^{-1}$); drying time	Emission, manure drying tunnel [b]		
				NH_3 (mg h^{-1} $bird^{-1}$)	Odor	PM
Demmers (1992)	Battery cages; 33,000 hens	Off; MAT: 2 days	0.9–1.8 / n.d.; DT: 28 h	0.97–2.91	50% increase	70% red.
Uenk (1994)	Battery cages; 33,000 hens	Off; MAT: 5, 18, or 24 h	0.9–1.8 / n.d.; DT: 28–44 h	1.14–5.71 [c]	100% increase	70% red.
Kroodsma (1996)	Battery cages; 10,525 hens	Yes (unknown); MAT: 4.5 days	1.2 / n.d.; DT: 3.5 days	1.14–1.83	100% increase	n.d.
Groot Koerkamp (1999)	Battery cages; 13,410 hens	No; MAT: 6 h	3.1 / 4.0; DT: 18 h	1.24	n.d.	n.d.
Huis in't Veld (1999)	Aviary; 16,500 hens, 1320 cocks	0.58[d]; MAT: 3.5 days	0.14 / 9.3; DT: 3.5 days	0.24 [e]	n.d.	n.d.

[a] Manure belt aeration inside the housing system for reduction of ammonia formation; capacity or absence/presence.
[b] As determined by comparison of downstream/upstream concentrations (for odor and PM) or by multiplying downstream/upstream concentration difference with the drying ventilation rate (for ammonia). Ammonia concentrations in mg h^{-1} $bird^{-1}$ are our recalculations.
[c] The highest reported ammonia emission rate of 5.71 mg h^{-1} $bird^{-1}$ in this table is equivalent with 50 g $year^{-1}$ $bird^{-1}$.
[d] The capacity of the manure belt aeration system was 0.82 m^3 h^{-1} $bird^{-1}$, but was used during 17 hours a day.
[e] The lowest reported ammonia emission rate of 0.24 mg h^{-1} $bird^{-1}$ in this table is equivalent with 2 g $year^{-1}$ $bird^{-1}$.

In order for MDTs to serve as dust filtration systems in future, both the potential dust filtering effect and the potential additional emissions need to be elucidated in modern MDTs. Furthermore, when the expectations from older studies prove valid, the question arises how the additional emissions can be minimized. To our knowledge, studies on these issues in MDTs are not available in literature. Therefore, the aim of the work described in this paper was first to gain insight into the filtration and emission aspects for current MDTs applied at poultry farms in the Netherlands (part A and B of this work).

Two strategies may effectively reduce emissions of ammonia and odor from MDTs. Results from the study by Uenk et al. (1994) suggest that the emission of ammonia from the MDT is strongly dependent of the time between manure production and the end of the drying process in the MDT. When this period lasted about 70 hours, ammonia emission rates up to 50 g $year^{-1}$ $bird^{-1}$ were found. When the manure accumulation time (MAT; time between a full running cycle of the belts inside the housing system) was set to <24 or even <12 hours, ammonia emission rates were only 5–10 and <5 g $year^{-1}$ $bird^{-1}$, respectively. The authors hypothesize that after this short MAT microbial multiplication and activity has not yet or only partially developed around the time the drying process starts. Such explanation agrees with the findings of Chepete et al. (2011) that ammonia emission from laying hen manure increases progressively with MAT from day 1 to 5. A second strategy might be to pre-dry the manure on the belts in the housing

system by manure belt aeration (MBA) beyond a (possible) critical DM content which inhibits most of the microbial multiplication and microbial degradation of uric acid and proteins into volatile ammonia, as shown in Fig. 7 in a review paper by Groot Koerkamp (1994).

The second aim of this study was to elucidate the perspective of the above described strategies to reduce ammonia and odor emissions from MDTs, namely (1) by pre-drying the manure by manure belt aeration (MBA) systems inside the house (part C of this work), and (2) by shortening MAT to 24 hours followed by rapid drying (beyond 55% DM within another 24 hours) inside the MDT (part D of this work).

METHODOLOGY

General description of manure drying tunnels

This study was performed at a total of 16 poultry farms with a MDT. The main characteristics of these farms and MDTs are given in Table 2. Fig. 1 shows a simplified schematic of the general structure and working principle of MDTs. MDTs are installed inside a separate room or shed, outside the animal room (Fig. 1A). Between the animal room and the MDT, a pressure chamber is constructed (Fig. 1A and C). Drying fans (usually axial-type pressure fans, sometimes v-belt type fans) are used to create overpressure inside the pressure chamber so that the drying air is forced through the perforated belts and the manure layer, and through an exhaust opening in the room or shed, into the outside environment (Fig. 1A and C). The drying fans always realize the minimum required ventilation rate (up to 2 to 3 m^3 h^{-1} $bird^{-1}$) and, for some farms, more (Table 2). When the required ventilation rate exceeds the drying ventilation capacity (e.g., on summer days), so called 'bypass fans' are switched on which exhaust additional air directly to the outside environment, bypassing the MDT (Fig. 1A). MDTs can only be used in combination with housing systems with manure belts which, in Dutch regulation, must have manure belt aeration (MBA; so-called pre-drying). These manure belts run frequently and deliver the pre-dried manure to a central belt that runs towards the MDT. A loader above the top drying level of the MDT spreads the manure evenly across the width of the top (first) drying belt. During loading, all belts inside the house and inside the MDT are running. When manure inside the MDT reaches the end of a belt, it falls down onto the next belt below. During loading of one batch of manure, the previous batches drop down to underlying belts whereas the oldest (fully dried) batches are removed from the MDT and transported to a storage room or container (Fig. 1B). Two main types of MDTs are used in the Netherlands: a belt-type MDT which has flexible

polyethylene/polypropylene belts, and a type MDT which has belts composed from metal plates or hingeable metal panels. The latter type MDT usually can handle thicker manure layers (Table 2).

Table 2
Overview of the poultry farms with the housing system, number of birds and manure belt aeration, and of the characteristics of the manure drying tunnels.

Farm	Part	Housing system [a]; manure accumulation time; number of hens	Manure belt aeration [b] (m^3 h^{-1} $bird^{-1}$)	Characteristics of the manure drying tunnel [c]	Drying / bypass vent. capacity (m^3 h^{-1} $bird^{-1}$)
1	A	Aviary; MAT: 2 days; 65,000	Yes (unknown)	Plate-type; 4 levels; DSA: 22 cm^2 $bird^{-1}$; MLT: 11–17 cm; DT: 4 days	2.1 / 3.9
2	A	Cage; MAT: 4–5 days; 76,800	0.7	Belt-type; 10 levels; DSA: 78 cm^2 $bird^{-1}$; MLT: 10 cm; DT: 5 days	2.0 / 4.6
3	B	Aviary; MAT: 4 days; 27,000	No	Plate-type; 2 levels; DSA: 24 cm^2 $bird^{-1}$; MLT: 13–20 cm; DT: 4 days	1.9 / 4.4
4	B	Aviary; MAT: 3 days; 22,500	No	Belt-type; 5 levels; DSA: 84 cm^2 $bird^{-1}$; MLT: 12 cm; DT: 3 days	3.9 / 5.3
5	B, C	Cage; MAT: 3 days; 47,000	0.7	Belt-type; 10 levels; DSA: 103 cm^2 $bird^{-1}$; MLT: 7 cm; DT: 3 days	2.6 / 7.7
6	B, C	Cage; MAT: 2 days; 65,300	0.5	Belt-type; 10 levels; DSA: 99 cm^2 $bird^{-1}$; MLT: 4 cm; DT: 2 days	3.7 / 6.1
7	B	Floor; MAT: 3 days; 24,000	No	Belt-type; 12 levels; DSA: 90 cm^2 $bird^{-1}$; MLT: 6 cm; DT: 3 days	3.3 / 11.6
8	B	Aviary; MAT: 3–4 days; 22,500	No	Belt-type; 8 levels; DSA: 73 cm^2 $bird^{-1}$; MLT: 10 cm; DT: 3.5 days	4.0 / 2.4
9	C	Aviary; MAT: 1 day; 93,600	0.7	Belt-type; 12 levels; DSA: 34 cm^2 $bird^{-1}$; MLT: 6 cm; DT: 4 days	2.7 / 4.0
10	C	Aviary/cage; MAT: 1 day; 172,500	0.7	Belt-type; 2 systems of 12 levels each; DSA: 83 cm^2 $bird^{-1}$; MLT: 6 cm; DT: 4 days	1.8 / 6.7
11	C	Aviary; MAT: 1 day; 20,000	0.1 [d]	Belt-type; 6 levels; DSA: 172 cm^2 $bird^{-1}$; MLT: 10 cm; DT: 7 days	5.5 / 4.0
12	C	Cage; MAT: 33 hours; 100,000	0.35 [e]	Plate-type; 6 levels; DSA: 23 cm^2 $bird^{-1}$; MLT: 14 cm; DT: 2 days	2.5 / 3.8
13	C	Aviary; MAT: 56 hours; 78,000	0.4	Plate-type; 4 levels; DSA: 20 cm^2 $bird^{-1}$; MLT: 13 cm; DT: 2,5 days	2.5 / 4.6
14	C	Aviary; MAT: 1.5 day; 64,240	0.7	Plate-type; 4 levels; DSA: 29 cm^2 $bird^{-1}$; MLT: 10 cm; DT: 3 days	3.1 / 4.4
15	D	Floor; MAT: set to 1 day; 60,000	0.3	Plate-type; 4 levels; DSA: 31 cm^2 $bird^{-1}$; MLT: 10 cm; DT: 2 days	1.9 / 9.9
16	D	Aviary; MAT: set to 1 day; 69,000	No	Belt-type; 4 (originally 9) levels; DSA: 26 cm^2 $bird^{-1}$; MLT: 9 cm; DT: 27 hours	2.6 / 5.1

[a] At farms 2, 10, 11, and 12, the MDT was supplied with manure and exhaust air from multiple houses.
[b] Manure belt aeration inside the housing system for reduction of ammonia formation; capacity or absence/presence.
[c] DSA = drying surface area; MLT = manure layer thickness; DT = drying time.
[d] The capacity of this manure belt aeration system was 1.1 m^3 h^{-1} $bird^{-1}$, but was used at 50% of its capacity for 4 hours per day, equivalent with 0.1 m^3 h^{-1} $bird^{-1}$ on a 24-h basis.
[e] The capacity of this manure belt aeration system was 0.7 m^3 h^{-1} $bird^{-1}$, but was used at 50% of its capacity.

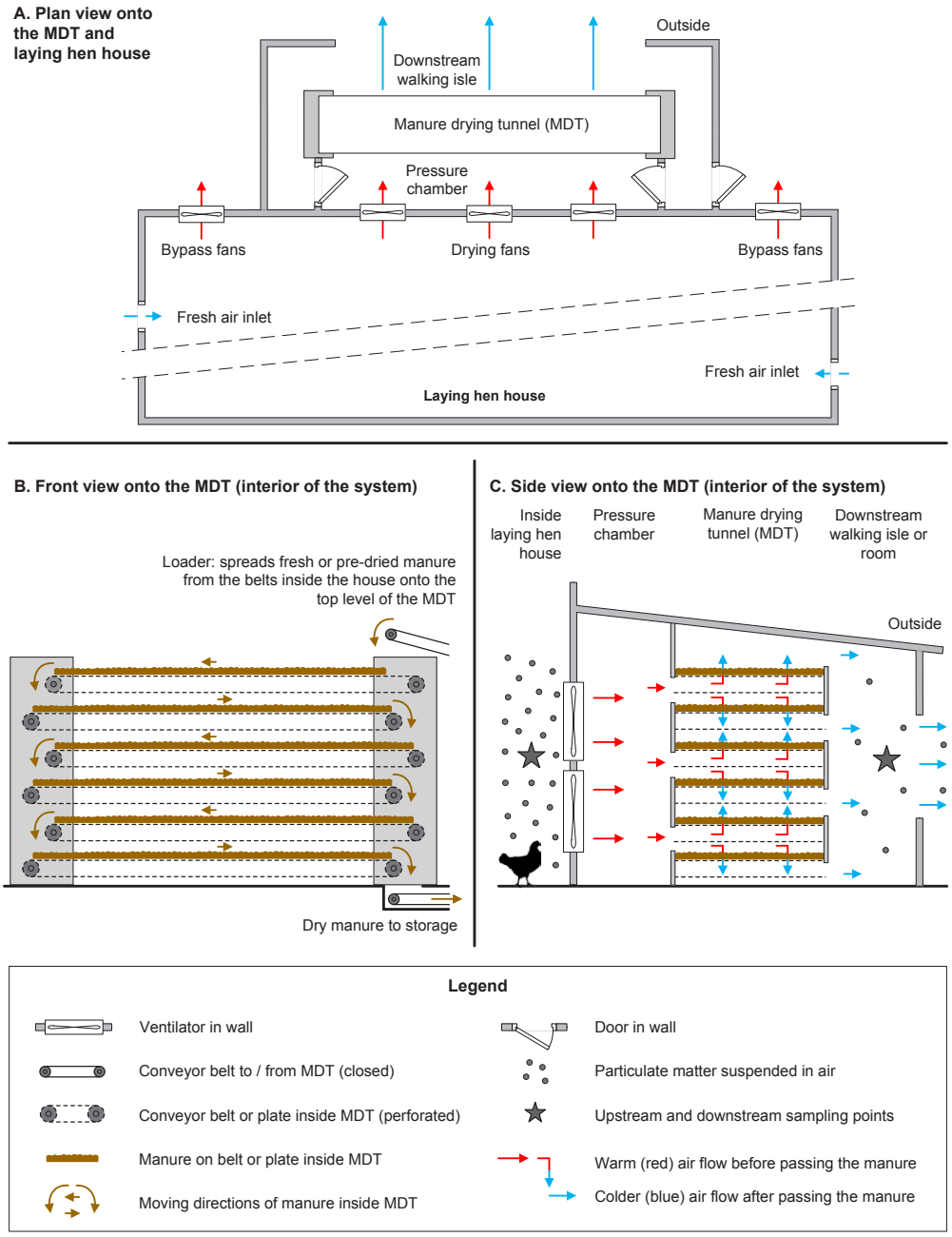


Fig. 1
Schematic describing the general structure, application and working principle of manure drying tunnels (MDTs).

General design of the study: parts A, B, C, and D

The present study was designed as an emission survey in four parts (A through D) and was performed at a total of 16 MDTs (Table 2).

Part A of the survey was intended to gain a first impression of the PM abatement potential and possible extra emissions of current MDTs under worst-case (winter) conditions for drying. This part took place at farms 1 and 2 (Table 2). Series of six 24-h measurements were carried out per farm (12 in total) between December 2008 and February 2009. Measurements were performed upstream and downstream of the MDTs and included concentrations of PM_{10}, $PM_{2.5}$, ammonia, odor, and carbon dioxide, and of air temperature and relative humidity (Table 3).

Part B of the survey was intended to reproduce the first impression from part A under summer conditions and for a larger number of MDTs. This part took place at farms 1 and 2 (repetitions), and to farms 3 through 8 (Table 2) in July and August 2009. One visit was made to each farm and 2-h measurements were performed upstream and downstream of the MDT. Measurement included PM_{10} and ammonia concentrations, air temperature and relative humidity, and manure temperature. In addition, manure samples were taken throughout the MDT for determination of the DM content (Table 3).

Since parts A and B indeed showed that the MDTs reduced PM but emitted additional ammonia and odor, part C of the survey was intended to determine the relationship between DM content of the ingoing and drying manure and the release of ammonia from the MDT. This relationship could clarify the perspective of pre-drying the manure beyond a (possible) critical DM content which inhibits most of the microbial multiplication and microbial degradation of uric acid and proteins into volatile ammonia. This part took place at farms 5, 6, and 9 through 14 (Table 2) between October 2011 en August 2012. These eight farms were selected because they all had some kind of MBA (pre-drying) inside their housing system (as demanded in Dutch legislation for houses with a MDT). A series of five visits were made to each farm (39 visits in total; about once every 2 months per farm) and 2-h measurements were performed upstream and downstream of the MDT. Measurements included PM_{10} and ammonia concentrations, air temperature and relative humidity, and manure temperature (Table 3). Manure samples were taken from three spots in the MDT (the wettest, middle, and driest belt/plate) inside the MDT, from the pre-dried manure inside the house, and from the storage (dried manure), for determination of the DM content. Except for PM_{10} concentration, all other variables were measured at the same location inside the MDT as where manure was sampled, so that the

association between measurement results (e.g., ammonia concentrations) and DM contents of the manure could be studied.

Finally, part D of the survey was intended to explore the perspective of applying a MAT of 24 hours followed by rapid drying inside the MDT. This part took place at farms 15 and 16 (Table 2) from December 2011 to November 2012. The general idea behind this strategy was first to shorten the manure residence time during accumulation inside the house to an average of 12 hours (minimum of ~0 hours for manure excreted just before the current removal; maximum of 24 hours for manure excreted directly after the previous removal), so that at the start of the drying process inside the MDT the microbial multiplication and activity in the manure, would not or only partly have developed. Second, we adapted the MDTs in such a way that drying took place rapidly (see next section; aim: ≥ 55% DM content within another 12 hours). The measurement strategy in Part D was identical to that of part A (Table 3), except that, besides the MDT emissions, we also determined the 'bypass' emissions directly from the house.

Modifications to the MDTs in part D

The MDTs at farms 15 and 16 were adapted in comparison to conventional MDTs in four ways. First, the MBA system inside house 15 was turned off because MBA is rather useless when all manure is removed from the house daily and turning off the MBA cut electricity costs substantially. House 16 lacked a MBA system. Second, the speed and running time of the manure belts inside the housing system were programmed such that all manure present in the building was removed every 24 hours. Running of the belts (i.e., manure removal from the house and loading of the MDT) took place twice a day for farm 15 and eight times a day for farm 16. Third, the climate computers of the houses were programmed such that the bypass fans automatically took over the required ventilation from the drying fans during loading of the MDT. This prevented peak emissions of PM from the MDTs due to the dust generated during falling of the manure onto the next level (Fig. 1B). In addition, the exhaust opening of the drying shed of farm 15 was automatically closed by a computerized system because in this shed the manure was not only dried but also dumped afterwards into heaps onto the floor of the shed by means of auger transport pipes. Furthermore, closing the shed exhaust further prevented excessive emission peaks (during these two daily periods of 2.5 hours each, PM was not sampled gravimetrically). Fourth, drying was enhanced at farm 15 by using an over-dimensioned MDT with a manure layer thickness of only 10 cm. At farm 16, drying was enhanced by directing two-third of the total drying ventilation rate (max. 2.6 m^3 h^{-1} $bird^{-1}$) through the youngest (wettest)

manure on the upper two belts and by limiting the manure layer thickness to 7 cm for those two belts (belts 3 and 4: 10 cm). The inlet openings between belts 5 through 9 (Fig. 1C) were closed from the drying air flow, making belts 5 through 9 redundant.

Measurements: part A and D

Measurement strategy

An overview of measured variables in part A through D of this study is given in Table 3. Note that, apart from manure temperature and manure DM content, in part A and D, the same variables were measured. Concentrations of PM_{10}, $PM_{2.5}$, ammonia, odor, and carbon dioxide were determined by single measurements at two different positions upstream of the MDTs and at two different positions downstream of the MDTs. Upstream samplers were placed either within 2 m from the drying fans (inside the house) or inside the pressure chamber. In the pressure chamber, and downstream of the MDTs, samplers were placed at about one-third and two-third of the path of manure through the MDT. Air temperature and relative humidity comprised single measurements, upstream and downstream of the MDT. The measurement duration amounted 24 hours (from noon to noon) for all variables except odor concentration. Air for odor analysis was sampled from 10:00 to 12:00 in the morning.

Measurement of PM_{10} and $PM_{2.5}$ concentration

PM_{10} and $PM_{2.5}$ concentrations were determined by a filter-based method consisting of cyclone pre-separators (URG Corp., Chapel Hill, N.C., USA; model URG-2000-30ENB for PM_{10} and URG-2000-30 EG for $PM_{2.5}$), a filter holder (filter: Macherey–Nagel, Düren, Germany; type GF-3, Ø 47 mm), and air sampling pumps (Tecora, model Charlie HV; Ravebo B.V., Brielle, the Netherlands) at an air flow rate of 16.7 L min^{-1}. Unloaded and loaded filters were weighed four times during two consecutive days with a precise balance (Mettler, Greifensee, Switzerland; AT261 DeltaRange; resolution: 10 µg) at 20 ± 1 °C and 50 ± 5% relative humidity, following EN 12341 (CEN, 1998) and EN 14907 (CEN, 2005). PM_{10} concentrations were calibrated to the reference impaction sampler described in EN 12341 using the equations reported by Zhao, Aarnink, Hofschreuder, and Groot Koerkamp (2009): $y = 1.09x$ (when $x \leq 223$ µg m^{-3}) and $y = 0.83x + 57.5$ (when $x > 223$ µg m^{-3}), where x is the concentration measured with the cyclone sampler and y is the calibrated concentration.

In addition, PM_{10} concentration was measured using the DustTrak light scattering device. Concentrations were determined each second and minute-averaged values were stored in the memory of the DustTrak. Since this device systematically underestimates true concentrations, all measured values where calibrated by a factor 2.1 based on the equivalence studies of Cambra-López et al. (2015) and Winkel et al. (2015a).

Table 3
Summary of measured variables, methods, and standards used in part A, B, C, and D of this study.

Variable (unit)	Measurement method	Applicable standard or protocol followed	Part of this study			
			A	B	C	D
Airborne pollutants						
PM_{10} (mg m^{-3})	Filter-based cyclone sampler and air pump; filter weighing	EN 12341 (CEN, 1998); Ogink et al. (2011)	×	-	-	×
PM_{10} (mg m^{-3})	TSI DustTrak light-scattering device, model 8520	-	-	×	×	×
$PM_{2.5}$ (mg m^{-3})	Filter-based cyclone sampler and air pump; filter weighing	EN 14907 (CEN, 2005); Ogink et al. (2011)	×	-	-	-
Ammonia (ppm)	Acid traps and air pumps; photometry	Ogink et al. (2011)	×	-	-	×
Ammonia (ppm)	Kitagawa gas detection tubes (types: 105SD, 105SC)	-	-	×	×	-
Odor (OU_E m^{-3})	Sampling vessel and air pump; dynamic olfactometry	EN 13725 (CEN, 2003); Ogink (2011)	×	-	-	×
Carbon dioxide (ppm)	Sampling vessel and air pump; gas chromatography		×	-	-	×
Air characteristics						
Air temperature (°C)	Rotronic combined sensor for T and RH and data storage	-	×	-	-	×
Air temperature (°C)	Testo device, model 435-4 with combined T/RH sensor	-	-	×	×	-
Rel. humidity (%)	Rotronic combined sensor for T and RH and data storage	-	×	-	-	×
Rel. humidity (%)	Testo device, model 435-4 with combined T/RH sensor	-	-	×	×	-
Air velocity (m s^{-1})	Testo device, model 435-4 with hot wire anemometer	-	-	×	×	×
Ventilation rate	CO_2 balance method; fan capacities and functioning	CIGR (2002); Pedersen et al. (2008)	×	-	-	×
Manure						
Manure temperature (°C)	Rod thermometer	-	-	-	×	×
Manure DM content (%)	Oven-drying, weighing	-	-	-	×	×

Measurement of ammonia concentration

Ammonia concentration was determined by the 'wet chemical method' with acid traps (two impingers in series for a single measurement, with 100 mL of nitric-acid (HNO_3) solution at 0.05 M) connected to air sampling pumps (Thomas Industries Inc., Wabasha, MN, USA; model 607CD32) using a critical capillary of 1 L min^{-1}. The ammonium nitrogen content in the solution was determined by spectrophotometry. The total amount of ammonia was determined by multiplying the ammonium nitrogen with the mass of the solution and the molecular weight of ammonia. The flow rate through the impingers was verified at the start and the end of the 24-h sampling period by an air flow meter (Defender 510-m, Bios Int. Corp, NJ, USA).

Odor and carbon dioxide concentrations

For determination of odor and carbon dioxide concentrations, air samples were taken using the 'lung principle'. Separate vessels for odor and carbon dioxide (with 40 L Nalophan air sampling bags inside, for one time use only) were connected to air sampling pumps (Thomas Industries Inc., Wabasha, MN; model 607CD32). In this principle, the pump sucks air from the vessel which causes the sampling bag to be filled with air taken from the sampling position. The sampling bags for odor were rinsed three times with odorless air before use and during sampling, the air first passed a dust filter (Savillex Corp., Minnetonka, MN, USA; #1130, Ø 50 mm, 1–2 μm). The air samples for odor were taken between 10:00 and 12:00 using a critical capillary of 0.4 L min^{-1}. The air samples for carbon dioxide were taken during the full 24-h sampling period using a critical capillary of 0.02 L min^{-1}. The air samples for determination of odor concentration were transported and stored following EN 13725 (CEN, 2003). Odor concentration (in European odor units: OU_E) was determined in the lab by dynamic olfactometry following European Standard EN 13725 (test panels with 4 to 6 participants) within 30 h after sampling. The air samples for determination of carbon dioxide concentration were analysed by gas chromatography (Interscience/Carlo Erba Instruments Inc., Breda, the Netherlands, GC 8000 Top; column Molsieve 5A; detector: HWD).

Environmental variables

Air temperature (°C) and relative humidity (%) were determined with combined sensors (Rotronic Instrument Corp., Hauppauge, N.Y.; accuracy of 1,0 °C and 2% relative humidity). Hourly mean values were stored in a data-logging system (Campbell Scientific Inc., Logan, UT, USA; types: CR10, CR10X, CR23 and CR23X).

Measurements: part B and C

An overview of measured variables in part B and C of this study is given in Table 3. In both parts, short farm visits were made and measurements were performed for two hours. For PM_{10} concentration, ammonia concentration, air temperature, and relative humidity, single instruments were used which were intermittently changed from position (upstream or downstream of the MDT) every 15 minutes to avoid instrument bias. Ammonia concentration was determined upstream and downstream of the MDTs by writing down the average value of two consecutive strokes with a hand pump (Kitagawa gas detection tubes; type 105SD, measuring range: 0.2 to 20 ppm; type 105SC, measuring range: 10 to 260 ppm; Komyo Rikagaku Kogyo, Japan) every 15 minutes. In part B, ammonia concentration was measured in the total air flows upstream and downstream of the MDTs (i.e., mixed air from the house entering the MDT or mixed air from the MDT leaving the drying room). In part C, however, measurements were performed at the individual drying belt level (i.e., at the inlet or outlet opening of a belt; Fig. 1C). The enthalpy of the drying air was calculated using the equations given by Albright (1990).

Data preparation and analysis

Estimation of ventilation rate: part A and D

The total ventilation rate (Q_{total}; i.e., the sum of the drying ventilation rate, Q_{drying}, and the bypass ventilation rate, Q_{bypass}) was estimated in houses 1, 2 (part A), 15, and 16 (part D) by the CO_2 balance method. This method uses the CO_2 produced by the birds as a tracer gas. First, the total heat production of one bird (Φ_{total}; kW) was calculated based on the body weight and egg production, using the equations given by the CIGR (2002), in chapter two. Specific data on body mass and egg production were obtained from the farmer's records for each measurement. Subsequently, the total heat production was multiplied by a factor (Fco_2) of 0.18 m^3 CO_2 h^{-1} kW^{-1} as recommended in Table 6 of the paper by Pedersen et al. (2008). Q_{total} (m^3 h^{-1} $bird^{-1}$) was calculated using Eq. 1:

$$Q_{total} = \frac{\Phi_{total} \times Fco_2}{([CO_2]_{upstream} - [CO_2]_{ambient}) \times 10^{-6}} \quad (1)$$

where $[CO_2]_{upstream}$ is the CO_2-concentration measured upstream of the MDT (ppm) and $[CO_2]_{ambient}$ a fixed CO_2 concentration (505 ppm), as found for laying hen houses in a recent

emission survey by Winkel et al. (2015b). Since Q_{total} was estimated on a 24-h basis, as were pollutant concentrations, the diurnal variation in animal activity was not taken into account. This approach yields reliable estimates of the 'true' 24-h averaged ventilation rate as determined with fan wheel anemometry (Mosquera, Groenestein, Ogink, & Aarnink, 2012).

In part A, which was conducted in winter, the ventilation requirement never exceeded the drying ventilation rate, therefore no bypass ventilation occurred ($Q_{total} = Q_{drying}$). In part D, however, bypass ventilation did take place, therefore, Q_{total} needed to be differentiated into Q_{drying} and Q_{bypass} to be able to estimate emission rates from both air flows (through the MDT versus and from the house directly). It should be noted that Q_{bypass} can be further differentiated into bypass ventilation during loading of the MDT ($Q_{bypass\_during\_loading}$) and bypass ventilation during drying ($Q_{bypass\_during\_drying}$) when the ventilation requirement exceeded the drying capacity. Consequently, $Q_{total\_during\_drying}$ is the sum of Q_{drying} and $Q_{bypass\_during\_drying}$. We differentiated Q_{total} into Q_{drying} and Q_{bypass} in three steps.

First, we determined the total daily loading time of the MDT during which the bypass fans took over the drying ventilation. This duration amounted 5 h (two daily periods of 2.5 hour each) in farm 15 and 0.8 h (eight daily periods of 6 min each) in farm 16. Using these durations, we estimated the part of Q_{total} attributable to loading periods ($Q_{bypass\_during\_loading}$) for each measurement by Eq. 2:

$$Q_{bypass\_during\_loading} = \frac{Loading\_time}{24} \times Q_{total} \quad (2)$$

Second, we estimated the part of Q_{total} attributable to drying periods ($Q_{total\_during\_drying}$), which lasted (24 – 5 =) 19 hours in farm 15 and (24 – 0.8 =) 23.2 hours in farm 16, for each measurement by Eq. 3:

$$Q_{total\_during\_drying} = \frac{Drying\_time}{24} \times Q_{total} \quad (3)$$

Third, this figure needed to be further differentiated into the drying ventilation flow (Q_{drying}) and the bypass ventilation flow during drying ($Q_{bypass\_during\_drying}$) which together make up $Q_{total\_during\_drying}$. To be able to enable this differentiation before each measurement the drying ventilation was set to a fixed level ($Q_{drying\_capacity}$) by putting a number of ventilators on at maximum capacity and others were shut off. The number of ventilators turned on was depending

on the expected ventilation requirement at that moment. We then estimated Q_{drying}, $Q_{bypass\_during\_drying}$, and Q_{bypass} by Eq. 4, Eq. 5, and Eq. 6, respectively:

$$Q_{drying} = \frac{Drying\_time}{24} \times Q_{drying\_capacity} \quad (4)$$

$$Q_{bypass\_during\_drying} = Q_{total\_during\_drying} - Q_{drying} \quad (5)$$

$$Q_{bypass} = Q_{bypass\_during\_loading} + Q_{bypass\_during\_drying} \quad (6)$$

Calculation of emission rates: part A and D

Four different emission rates were calculated for each measurement and pollutant (PM_{10}, $PM_{2.5}$, NH_3, and odor): the actual emission rate through the MDT (E_{drying}), the actual emission rate directly from the house (E_{bypass}), the actual total emission rate (E_{total}) and the emission rate for a theoretical situation as if there would be a poultry house with 24-h manure removal but no MDT ($E_{24h\_manure\_removal}$), as described in Eq. 7, Eq. 8, Eq. 9, and Eq. 10, respectively:

$$E_{drying} = Q_{drying} \times (C_{downstream} - C_{ambient}) \quad (7)$$

$$E_{bypass} = Q_{bypass} \times (C_{upstream} - C_{ambient}) \quad (8)$$

$$E_{total} = E_{drying} + E_{bypass} \quad (9)$$

$$E_{24h\_manure\_removal} = Q_{total} \times (C_{upstream} - C_{ambient}) \quad (10)$$

where $C_{downstream}$ is the pollutant concentration measured downstream of the MDT, $C_{ambient}$ a fixed outside pollutant concentration as found for laying hen houses in a recent emission survey by Winkel et al. (2015b), and $C_{upstream}$ the pollutant concentration measured upstream of the MDT. The fixed outside pollutant concentrations were 0.056 mg m^{-3} for PM_{10}, 0.015 mg m^{-3} for $PM_{2.5}$, and 0.13 mg m^{-3} for ammonia. In the equations, pollutant concentrations of PM_{10}, $PM_{2.5}$, and ammonia were expressed in mg m^{-3} and ventilation rates (Q) in m^{-3} h^{-1} $bird^{-1}$, yielding emission rates in mg h^{-1} $bird^{-1}$. The odor concentration was expressed in OU_E m^{-3} and the emission rate in OU_E s^{-1} $bird^{-1}$. For odor, no correction for outside concentration was applied because concentrations of odor from (potentially) different sources cannot be subtracted from each other.

Statistical analysis

In part A and D, differences between upstream versus downstream pollutant concentrations were tested for statistical significance with the paired samples *t*-test. The relationships between numeric variables (i.e., manure temperature as a function of manure DM content; removal efficiency of PM_{10} as a function of MLT) were investigated by linear regression analysis. All analyses were done using the GenStat software (VSN, 2014). Probability values ≤0.05 were considered statistically significant.

RESULTS AND DISCUSSION

Part A: particulate matter abatement and extra emissions

Part A of this study aimed to gain a first impression of the PM abatement potential and possible extra emissions of current MDTs and was carried out at farms 1 and 2 (Table 2) in winter. On measurement days, the maximum temperature ranged from 0.8 to 10.4 °C, the minimum temperature ranged from -7.3 to 3.7 °C, and the daily mean relative humidity ranged from 71 to 95%. The results of part A are shown in Table 4.

Upon passing the manure layer, the temperature of the drying air flow decreased significantly with an average of 3.4 °C whereas the relative humidity increased significantly with an average of 26% percentage points to levels beyond 90% (Table 4). These changes represent the evaporation of water from the manure which requires the input of thermal energy from the drying air and manure. Concentrations of carbon dioxide were not significantly different between upstream and downstream sampling positions (Table 4). In agreement with the studies of Demmers et al. (1992) and Uenk et al. (1994), concentrations of PM were significantly reduced by an average of 77% for PM_{10} and an average of 56% for $PM_{2.5}$ (Table 4). In agreement with all five studies performed in the 1990s in the Netherlands (Table 1), concentrations of ammonia increased significantly by an average of 26.7 ppm. In agreement with the studies by Demmers et al. (1992), Uenk et al. (1994), and Kroodsma et al. (1996), concentration of odor increased significantly with an average of 356 $OU_E\ m^{-3}$.

Table 4
Results of part A at farms 1 and 2: man (SD) temperature, relative humidity, and concentrations of carbon dioxide, particulate matter, ammonia, and odor in the upstream and downstream air of the manure drying tunnel, and their difference (mean and significance).

Variable	Farm	*n*	Upstream of the MDT; mean (SD)	Downstream of the MDT; mean (SD)	Difference	
					Mean	Sign.
Air temperature (°C)	1	5	17.0 (0.6)	12.8 (1.0)	–4.2	
	2	6	20.4 (1.4)	17.6 (0.8)	–2.8	
	1 and 2	11	18.8 (2.0)	15.4 (2.6)	–3.4	$P < 0.001$ [a]
Relative humidity (%)	1	6	65 (3)	98 (4)	33	
	2	6	71 (7)	91 (6)	20	
	1 and 2	11	68 (6)	94 (6)	26	$P < 0.001$ [a]
CO_2 concentration (ppm)	1	6	1881 (487)	1595 (442)	–286	
	2	6	2155 (597)	2536 (1203)	381	
	1 and 2	12	2018 (539)	2066 (994)	48	n.s. [b]
PM_{10} concentration (µg m^{-3})	1	6	2580 (371)	416 (74)	–2164	
	2	6	422 (36)	281 (17)	–141	
	1 and 2	12	1501 (1155)	348 (87)	–1153 [c]	$P = 0.002$ [a]
$PM_{2.5}$ concentration (µg m^{-3})	1	6	174 (50)	70 (23)	–104	
	2	6	33 (10)	22 (7)	–11	
	1 and 2	12	104 (82)	46 (30)	–58 [d]	$P = 0.006$ [a]
NH_3 concentration (ppm)	1	6	4.3 (0.9)	23.8 (15.7)	19.4	
	2	6	14.6 (3.5)	48.7 (5.4)	34.1	
	1 and 2	12	9.5 (5.9)	36.2 (17.2)	26.7	$P < 0.001$ [a]
Odor concentration (OU_E m^{-3})	1	6	658 (211)	963 (420)	305	
	2	6	986 (182)	1393 (252)	407	
	1 and 2	12	822 (254)	1178 (400)	356	$P < 0.001$ [a]

[a] Determined by the one-sided paired-samples *t*-test.
[b] Determined by the two-sided paired-samples *t*-test.
[c] Mean reduction of PM_{10} concentration: 77%.
[d] Mean reduction of $PM_{2.5}$ concentration: 56%.

Table 5 shows the emission rate of the theoretical situation as if there were no MDTs (based on upstream concentrations) and of the actual situation with MDTs (based on downstream concentrations). During the measurements at farms 1 and 2 in winter all ventilation air was exhausted through the MDT. The emission rates of the theoretical situation fall within normal ranges for these housing systems (Costa et al., 2012; Demmers et al., 2010; Groot Koerkamp et al., 1998; Ogink and Groot Koerkamp, 2001; Winkel et al., 2015b). The reductions of PM_{10} and $PM_{2.5}$ emission of 77% and 56% respectively, are accompanied by an additional emission of ammonia from the MDTs of 28.8 mg h^{-1} $bird^{-1}$, equivalent with 252 g $year^{-1}$ $bird^{-1}$ (Table 5) or about a factor 4 relative to that of the houses. The additional emission of odor was 0.14 OU_E s^{-1} $bird^{-1}$ or about a factor 1.4 relative to that of the houses. It should be noted that these emissions only apply to the winter period and are not representative for year-averaged rates.

Overall, part A of this study shows that MDT are indeed capable of reducing PM emissions, but also emit substantial amounts of extra ammonia and odor.

Table 5
Results of part A at farms 1 and 2: emission rates of a theoretical situation as if there were no manure drying tunnels (MDTs) and all air was exhausted directly from the houses (based on upstream concentrations) and of the actual situation with MDT (based on downstream concentrations).

Variable	Farm	*n*	Theoretical situation: without MDT; Mean (SD)	Actual situation: with MDT; Mean (SD)	Difference	
					Mean	Sign.
Ventilation rate (m^3 h^{-1} $bird^{-1}$)	1	6	1.7 (0.6)		-	-
	2	6	1.4 (0.6)		-	-
	1 and 2	12	1.5 (0.6)		-	-
PM_{10} emission rate (mg h^{-1} $bird^{-1}$)	1	6	4.14 (1.44)	0.59 (0.20)	–3.56	
	2	6	0.53 (0.26)	0.32 (0.15)	–0.20	
	1 and 2	12	2.34 (2.13)	0.46 (0.22)	–1.88 [a]	$P = 0.003$ [b]
$PM_{2.5}$ emission rate (mg h^{-1} $bird^{-1}$)	1	6	0.27 (0.13)	0.08 (0.03)	–0.18	
	2	6	0.03 (0.02)	0.01 (0.01)	–0.02	
	1 and 2	12	0.15 (0.15)	0.05 (0.04)	–0.10 [c]	$P = 0.010$ [b]
NH_3 emission rate (mg h^{-1} $bird^{-1}$)	1	6	4.91 (2.17)	27.7 (18.4)	22.7	
	2	6	13.5 (4.34)	48.3 (22.3)	34.8	
	1 and 2	12	9.20 (5.54)	38.0 (22.3)	28.8 [d]	$P < 0.001$ [b]
Odor emission rate (OU_E s^{-1} $bird^{-1}$)	1	6	0.29 (0.12)	0.42 (0.19)	0.13	
	2	6	0.40 (0.24)	0.55 (0.27)	0.15	
	1 and 2	12	0.34 (0.19)	0.49 (0.23)	0.14	$P = 0.001$ [b]

[a] Mean reduction of PM_{10} emission: 80%.
[b] Determined by the one-sided paired-samples *t*-test.
[c] Mean reduction of $PM_{2.5}$ emission: 67%.
[d] Equivalent with 252 g $year^{-1}$ $bird^{-1}$.

Part B: verification of part A

Part B of this study aimed to reproduce the results from part A, but then under summer conditions and for a larger number of MDTs, namely on farms 1 through 8 (Table 2). During these visits, the drying fans were operated at their maximum capacity (Table 2). The outside temperature / relative humidity during the visits was 19–22°C / 60–85% for farms 1 through 4, 25–26°C / 60–65% for farms 5 and 6, and 30–36°C / 30–60% for farms 7 and 8. The drying air temperature and relative humidity upstream of the MDTs ranged from 21 to 34 °C and 50 to 67%, respectively. The air temperature and relative humidity downstream of the MDTs ranged from 20 to 33 °C and 52 to 82%, respectively. Furthermore, the DM content of the oldest batch of manure inside the MDTs ranged from 73 to 90%. The manure temperature was 1 to 4 °C lower than the upstream drying air temperature. These variables show that drying conditions were favorable. The results from 2-h measurements of PM_{10} and ammonia concentrations are shown in Table 6. In agreement with part A, all MDTs reduced PM_{10} concentration (by 57% on average), but added extra ammonia to the drying air (4.9 ppm on average).

Table 6
Results of part B of this study at farms 1 through 8: mean concentrations of PM_{10} and ammonia; upstream and downstream of the manure drying tunnel, and their difference.

Farm	PM_{10} concentration			NH_3 concentration		
	Upstream of the MDT; mean (µg m^{-3})	Downstream of the MDT; mean (µg m^{-3})	Difference (%)	Upstream of the MDT; mean (ppm)	Downstream of the MDT; mean (ppm)	Difference (ppm)
1	2446	685	–72	2.3	8.8	6.6
2	652	433	–34	2.1	4.4	2.3
3	4154	778	–81	6.5	20.6	14.1
4	3635	1393	–62	6.3	13.0	6.7
5	792	428	–46	2.1	9.0	6.9
6	976	569	–42	1.0	3.0	2.0
7	10,834	5274	–51	3.0	3.6	0.6
8	8914	4440	–50	4.8	4.9	0.1[a]
Average	4050	1750	–57	3.5	8.4	4.9

[a] In contrast to the other seven farms, farm 8 used an all-in/all-out manure loading scheme with only one batch of manure inside the MDT. During the measurement, the drying time of 3.5 days was nearly completed, which may explain the minimal extra release of ammonia. Farms 1 through 7 practiced daily loading (comprising 20, 25, 33, or 50% of the manure belts inside the house per loading).

Part C: ammonia and manure DM content

Part C of this study aimed to determine the relationship between the DM content of the manure and the release of ammonia at farms 5, 6, and 9 through 14 (Table 2). This relationship could clarify the perspective of pre-drying the manure beyond a (possible) critical DM content which inhibits most of the microbial multiplication and microbial degradation of uric acid and proteins into volatile ammonia.

On the days on which the 39 farm visits were made, the outside air temperature (24-h basis) was on average 10.8 °C and the outside relative humidity 81%, which closely resemble long-term averages for the Netherlands (10.2 °C and 80.4%; 1981–2010). The mean (range) temperature of the drying air was 22.1 °C (18.7 to 27.2 °C) upstream of the MDTs and 19.8 °C (12.5 to 24.9 °C) downstream of the MDTs. The mean (range) manure temperature was 20.6 °C (7.0 to 27.5 °C) and manure temperatures were consistently between the upstream and downstream air temperatures. The mean (±SE) enthalpy of the drying air upstream of the MDTs (48.2 ± 1.0 kJ kg^{-1}) was not significantly different from the air downstream of the MDTs (48.3 ± 1.3 kJ kg^{-1}), which suggests that no heat was released from the manure due to aerobic composting. The mean (range) relative humidity of the drying air was 65% (37 to 84%) upstream of the MDTs and 83% (41 to 100%) downstream of the MDTs. The mean (range) ammonia concentration was 5.5 ppm (0.8 to 22.5 ppm) upstream of the MDTs and 13.9 ppm (1.9 to 70 ppm) downstream of the MDTs.

The increase of ammonia concentration was considerably higher in belt-type MDTs (10.2 ppm; range: 0 to 38 ppm; n = 25, from farms 5, 6, 9, 10, and 11) than in plate-type MDTs (2.9 ppm; range 0.6 to 6.6 ppm; n = 14, from farms 12, 13, and 14). This difference does not seem to be caused by differences in how the manure was handled inside the house, since the mean MAT (38 h for the belt-type MDTs versus 42 h for the plate-type MDTs) and the mean MBA capacity (0.54 m^3 h^{-1} $bird^{-1}$ for the belt-type MDTs versus 0.48 m^3 h^{-1} $bird^{-1}$ for the plate-type MDTs) seem reasonably similar. The most striking differences between the two types of MDTs were their MLT (on average: 7 cm for the belt-type MDTs versus 12 cm for the plate-type MDTs), the amount of manure they contain (on average: 708 cm^3 $bird^{-1}$ for the belt-type MDTs versus 291 cm^3 $bird^{-1}$ for the plate-type MDTs; calculated from the data in Table 1), their drying intensity (on average: 6599 m^3 air per m^3 manure per h for the belt-type MDTs versus 9356 m^3 air per m^3 manure per h for the plate-type MDTs; calculated from the data in Table 1), and their DT (on average: 4 days for the belt-type MDTs versus 2.5 days for the plate-type MDTs). Possibly, the more rapid drying inside plate-type MDTs could soon raise the DM content of the manure beyond a critical DM content (i.e., a DM content which inhibits most of the microbial multiplication and microbial degradation of uric acid and proteins into volatile ammonia).

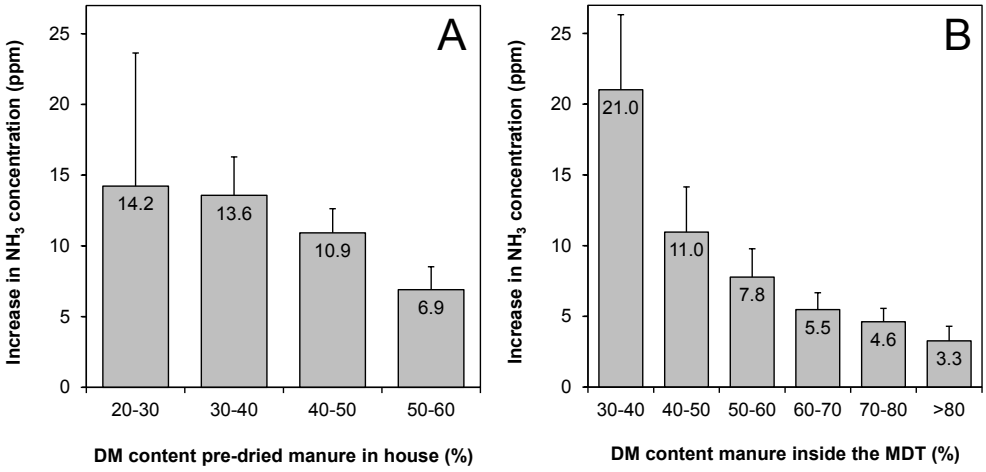


Fig. 2
Mean increase of the ammonia concentration in the drying air upon passing the manure drying tunnel (MDT) at farms 5, 6, and 9 through 14 (part C of this study), for A: four classes of dry matter (DM) content of the pre-dried manure from the house entering the MDT (n = 32, from eight farms), and B: six classes of DM content of the drying manure inside the MDT (part C; n = 107, from eight farms). Error bars represent standard errors.

The relationship between the DM content of the pre-dried manure inside the house and the increase of the ammonia concentration inside the MDT at the same moment, is shown in Fig. 2A. The relationship between the DM content of the manure inside the MDT and the release of ammonia from that particular batch is shown in Fig. 2B. Both figures show that the release of ammonia decreases with increasing DM content of the manure. Relative to the increase of ammonia concentration in the 20 to 30 % DM class in Fig. 2A, the reductions are 5% for the 30 to 40% DM class, 23% for the 40 to 50% DM class, and 51% for the 50 to 60% DM class. Relative to the increase of ammonia concentration in the 30 to 40 % DM class in Fig. 2B, the reductions are 48% for the 40 to 50% DM class, 63% for the 50 to 60% DM class, 74% for the 60 to 70% DM class, 78% for the 70 to 80% DM class, and 84% for the >80% DM class.

It must be noted, however, that the data in Fig. 2 were obtained from momentaneous measurements of ammonia concentration and manure DM content at three spots in the MDT (the wettest, middle, and driest belt/plate). This means that the measurement at a certain spot in the MDT at a certain moment in the drying process does not take into account what happened to that manure prior to the measurement. Presumably, the DM content (as the inhibitor of microbial activity and ammonia formation) is confounded with other factors that change in time along with manure DM content, such as a gradual decrease in nitrogen content due to ammonia volatilization. To exclude such confounding and focus on the single effect of water availability, it is advisable for future studies to determine nitrogen content in the samples as well. Alternatively, future studies can use batches of manure of known and varying DM contents and ages (MAT) to be subjected to drying in a lab setting, similar to the situation in MDTs. Other confounding factors may have been MLT, air flow rate and velocity through the manure layer, manure temperature, and pH. Indeed, the manure volume gradually decreased during drying which may have promoted the air flow rate and extent of ammonia dilution in the course of the drying process, but in most MDTs the MLT was kept fairly constant throughout the MDT. Furthermore, the inlet/outlet openings of MDTs were the same size for each drying level (Fig. 1) and air velocity was similar for different drying levels within MDTs (overall range: 0.5 to 4.8 m s^{-1}). Fig. 3 shows that manure temperature (presented as absolute difference to the upstream air temperature, assuming air temperature upstream from the house to be fairly constant) increased with increasing DM content through the MDT which may have promoted microbial activity and ammonia volatilization in the course of the drying process. The drop in air temperature when the drying air passes the manure layer is caused by the evaporation of water from the manure. This process requires input of thermal energy which is subtracted from the manure and the drying air. In the course of the drying process, the water content decreases (i.e., DM content increases)

which results in a gradual reduction of the water vapor pressure between manure and drying air, and herewith the required thermal energy for evaporation. This is reflected by a decreasing temperature difference between the ingoing air versus manure and outgoing air (Fig. 3).

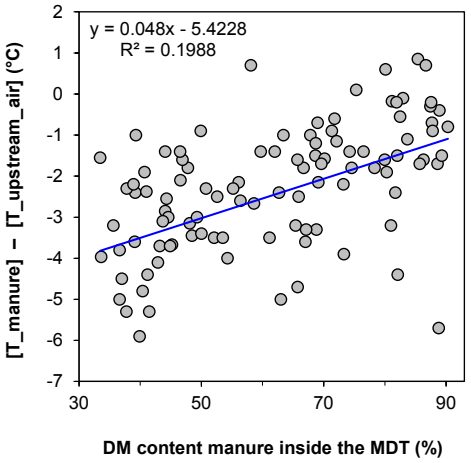


Fig. 3
The temperature difference between the manure and the drying air upstream of the MDT, as a function of the dry matter (DM) content of that manure (part C of this study; n = 100, from eight farms). Both the regression coefficient (0.048) and the intercept (–5.4228) are significantly different from zero ($P < 0.001$).

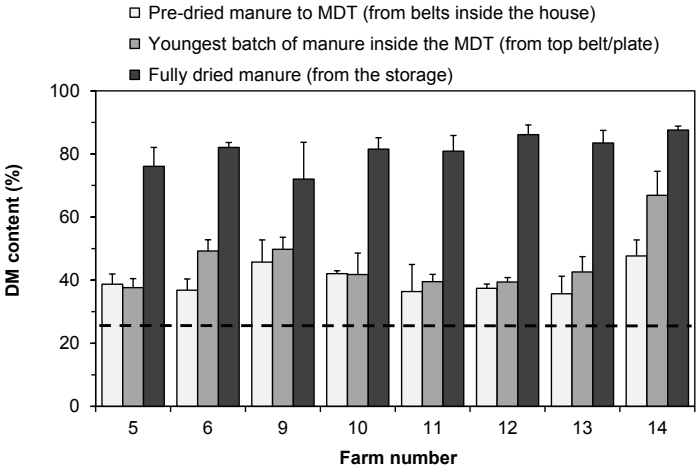


Fig. 4
Mean dry matter (DM) content of the manure samples from the pre-dried manure inside houses 5, 6, and 9 through 14 (part C of this study), from the youngest batch of manure inside the manure drying tunnels, and from the fully dried manure in the storages. The dashed line represents the level of 25% DM as approximate value for freshly excreted manure. Error bars represent standard errors.

In the Dutch regulation on ammonia emissions from livestock housings, MDTs are allowed only under the requirement that the manure is pre-dried (by MBA, incorporated in the housing system) to a DM content of at least 45% to avoid excessive ammonia emissions from the MDT. Fig 4, however, shows that, at the pre-drying capacities installed (range: 0.1 to 0.7 m^3 h^{-1} $bird^{-1}$; Table 2), this level is usually not reached in six out of eight farms, presumably resulting in substantial emissions of ammonia from the MDT (Fig. 2).

A rough impression of the magnitude of actual emission levels can be obtained by converting the mean increase in ammonia concentrations (10.2 ppm for belt-type MDTs; 2.9 ppm for plate-type MDTs) to mass concentrations, and by multiplying those with an assumed drying ventilation rate. A (conservative) drying ventilation rate of 1.5 m^3 h^{-1} $bird^{-1}$ hereby results in an emission estimate of 10.8 mg h^{-1} $bird^{-1}$ (equivalent with 95 g $year^{-1}$ $bird^{-1}$) for belt-type MDTs and an emission estimate of 3.0 mg h^{-1} $bird^{-1}$ (equivalent with 27 g $year^{-1}$ $bird^{-1}$) for plate-type MDTs. Even though these are very rough estimates, it is clear that, in reality, emissions of MDTs are considerably higher than the EF of 2 g $year^{-1}$ bird $place^{-1}$ in the Netherlands. This EF was based on the very low (~2.1 g $year^{-1}$ animal $place^{-1}$) emission rate reported by Huis in 't Veld et al. (1999). Two reasons may explain why that study found such low ammonia emissions from the MDT: (1) the MAT was 3.5 days during which the manure was aerated with 0.82 m^3 h^{-1} $bird^{-1}$ during 17 hours a day, resulting in a mean DM content of the ingoing manure of 60%; and (2) the drying ventilation rate was only 0.14 m^3 h^{-1} $bird^{-1}$.

Table 2, in contrast, shows that current farms with MDTs often don't use MBA inside their housing system. This means that manure accumulates in those houses during 3 to 4 days (MAT) during which ammonia formation is not limited by pre-drying and ammonia generation can take place undisturbedly. Subsequently, the manure is brought into the MDT where drying ventilation rates of 1.8 to 5.5 m^3 h^{-1} $bird^{-1}$ are forced through the droppings. This presumably leads to the stripping of ammonia, already formed in the house, from the manure, and thus much higher ammonia emissions than reported by Huis in 't Veld et al. (1999).

Part D: 24-h manure removal and rapid drying

Part D of this study explored the perspective of applying a 24-h manure accumulation time (MAT) followed by rapid drying inside the MDT. In the farms of part A to C MAT amounted 1 to 5 days (Table 2). As described earlier, the Dutch regulation on ammonia emissions from livestock housings only allows the use of MDTs under the requirement that the manure is pre-dried to a DM content of at least 45%. In practice, however, part of the poultry farmers that

operate a MDT have no MBA inside their housing system, turn the MBA off, or use it only under weather conditions unfavourable for drying (Table 2). Three reasons argue for not using MBA systems in combination with a MDT: (1) the ventilator of a MBA system consumes much electricity (~0.2 kW 1000 m^{-3} of air; e.g., yielding a yearly consumption of ~49,000 kWh for a modern 40,000 bird laying hen house at 0.7 m^3 h^{-1} $bird^{-1}$), whereas (2) the manure becomes sufficiently dry in the MDT regardless of the use of MBA, which makes a MBA-MDT combination energetically and economically inefficient. And, (3) To effectively pre-dry the manure by MBA to DM contents beyond 45% requires several days of pre-drying. During this MAT, ammonia may be generated which may subsequently be stripped from the manure inside the MDT.

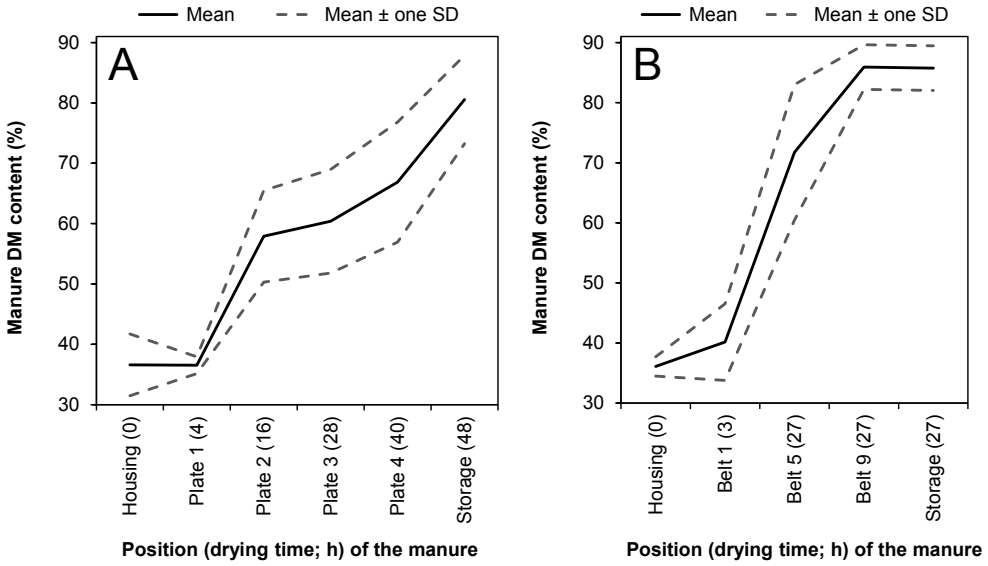


Fig. 5
Dry matter content of the manure from the hen house, at consecutive stages in the MDT, on either plate 1 through 4 at farm 15 (A) or belts 1, 5, and 9 at farm 16 (B), and in the storage.

The MDTs at farms 15 and 16 were adapted as described in section 2.2 to achieve rapid drying (≥ 55% DM content within 12 hours of drying). Fig. 5 shows the actual drying performance of the adapted MDTs. This figure shows that the aimed level of 55% DM content was reached in little less than 16 hours of drying at farm 15, whereas at farm 16, a DM content of almost 70% was reached within 24 hours.

Table 7
Results of part D at farms 15 and 16: mean (SD) temperature, relative humidity, and concentrations of carbon dioxide, particulate matter, ammonia, and odor in the upstream and downstream air of the manure drying tunnel, and their difference (mean and significance).

Variable	Farm	*n*	Upstream of the MDT; mean (SD)	Downstream of the MDT; mean (SD)	Difference	
					Mean	Sign.
Air temperature (°C)	15	5	21.8 (1.4)	19.2 (1.7)	–2.6	
	16	5	21.5 (1.9)	20.2 (2.1)	–1.2	
	15 and 16	10	21.6 (1.6)	19.7 (1.8)	–1.9	$P < 0.001$ [a]
Relative humidity (%)	15	5	65 (4)	95 (4)	30	
	16	5	64 (7)	73 (6)	9	
	15 and 16	10	64 (6)	84 (13)	19	$P < 0.001$ [a]
CO_2 concentration (ppm)	15	5	1470 (247)	1395 (202)	–75	
	16	5	1284 (270)	1299 (281)	15	
	15 and 16	10	1377 (263)	1347 (236)	–30	n.s. [b]
PM_{10} concentration (µg m^{-3})	15	5	2473 (477)	995 (226)	–1478	
	16	5	4623 (1027)	1625 (224)	–2998	
	15 and 16	10	3548 (1362)	1310 (394)	–2238 [c]	$P < 0.001$ [a]
NH_3 concentration (ppm)	15	5	14.1 (8.5)	17.6 (7.6)	3.5	
	16	5	7.5 (5.6)	10.8 (5.1)	3.3	
	15 and 16	10	10.8 (7.6)	14.2 (7.1)	3.4	$P < 0.001$ [a]
Odor concentration (OU_E m^{-3})	15	5	952 (435)	1712 (1014)	761	
	16	5	462 (116)	764 (267)	302	
	15 and 16	10	707 (396)	1238 (859)	531	$P = 0.011$ [a]

[a] Determined by the one-sided paired-samples *t*-test.
[b] Determined by the two-sided paired-samples *t*-test.
[c] Mean reduction of PM_{10} concentration: 63%.

Table 8
Results of part D at farms 15 and 16: mean emission rates of a theoretical situation as if there were no MDTs and all air was exhausted directly from the houses and of the actual situation (differentiated into emission through the manure drying tunnel (MDT), through the bypass ventilation, and of both air flows in total), as well as their difference.

Variable	Farm	*n*	Theoretical situation, no MDT; mean (SD)	Actual situation			Diff.; mean
				MDT; mean (SD)	Bypass; mean (SD)	Total; mean (SD)	
Ventilation rate (m^{-3} h^{-1} $bird^{-1}$)	15	5	2.38 (0.81)	1.20 (0.18)	1.17 (0.64)	2.38 (0.81)	-
	16	5	3.13 (1.23)	0.87 (1.02)	2.26 (0.25)	3.13 (1.23)	-
	15 and 16	10	2.76 (1.06)	1.73 (0.59)	1.02 (0.82)	2.76 (1.06)	-
PM_{10} emission rate (mg h^{-1} $bird^{-1}$)	15	5	5.52 (1.10)	1.12 (0.22)	2.66 (0.99)	3.78 (0.96)	–1.74
	16	5	13.8 (4.41)	3.51 (0.36)	3.59 (4.19)	7.10 (4.35)	–6.67
	15 and 16	10	9.64 (5.30)	2.31 (1.29)	3.13 (2.91)	5.44 (3.45)	–4.20 [a]
NH_3 emission rate (mg h^{-1} $bird^{-1}$)	15	5	21.0 (9.8)	14.4 (5.3)	9.6 (4.0)	24.0 (8.7)	3.0
	16	5	13.6 (8.3)	17.0 (8.4)	2.1 (1.6)	19.1 (8.2)	5.5
	15 and 16	10	17.3 (9.4)	15.7 (6.8)	5.6 (4.8)	21.5 (8.4)	4.2 [b]
Odor emission rate (OU_E s^{-1} $bird^{-1}$)	15	5	0.66 (0.47)	0.56 (0.31)	0.33 (0.30)	0.89 (0.46)	0.23
	16	5	0.38 (0.11)	0.47 (0.14)	0.09 (0.10)	0.57 (0.13)	0.19
	15 and 16	10	0.52 (0.35)	0.52 (0.23)	0.21 (0.25)	0.73 (0.36)	0.21

[a] Mean reduction of PM_{10} emission: 44%.
[b] Equivalent with 37 g $year^{-1}$ $bird^{-1}$.

The results of variables measured upstream and downstream of the MDT at farms 15 and 16 are shown in Table 7. Upon passing the manure layer, the temperature of the drying air decreased significantly with an average of 1.9 °C whereas the relative humidity increased significantly with an average of 19% percentage points. Furthermore, PM_{10} concentration was reduced significantly with an average of 63%, whereas concentrations of ammonia and odor increased significantly with 3.4 ppm and 531 OU_E m^{-3}, respectively.

Table 8 shows the emission rates of a theoretical situation as if there were no MDTs and all air was exhausted directly from the houses and of the actual situation with the MDT in place. From this table, it becomes clear that, compared to the theoretical situation, the actual emission rate of house and MDT together is 44% lower for PM_{10} but 24% higher for ammonia and 40% higher for odor. Thus, the adapted drying strategy at farms 15 and 16 cannot fully prohibit the release of extra ammonia and odor from the MDTs. Based on the findings of Uenk et al. (1994), shortening MAT to 18, 12, or 6 hours may further reduce the additional emissions from MDTs.

Part D: PM concentrations during loading

In Fig. 6, two examples are shown of continuous DustTrak measurements of the PM_{10} concentration upstream and downstream of the MDTs at farms 15 and 16. In these figures, typical concentration profiles are visible of upstream concentrations that are higher than downstream concentrations (i.e., PM reductions) and of concentration peaks when the belts inside the MDTs are running. The excessive peaks in Fig. 6A are caused by the dry manure that is removed from the MDT and dumped into heaps onto the floor inside the manure drying shed by means of auger transport pipes. It should be noted that during these two periods (of 2.5 hours each), PM was not sampled gravimetrically, the exhaust opening of the drying shed was automatically closed off by a computerized system, and the required ventilation rate was taken over by the bypass fans of the house. The latter two measures were aimed to prevent peak emissions from the drying shed. At farm 16, the dry manure from the MDT was transported through an underground channel to a nearby storage shed. Therefore, the peaks in Fig. 6B represent the PM release from the running of the MDT only. Since this MDT was positioned in an open shed which was not closed during running of the MDT, these peaks could emit by wind dispersion. Overall, the concentration profiles in Fig. 6 emphasize the importance of taking adequate emission abatement measures during manure drying, transport, handling, and storage.

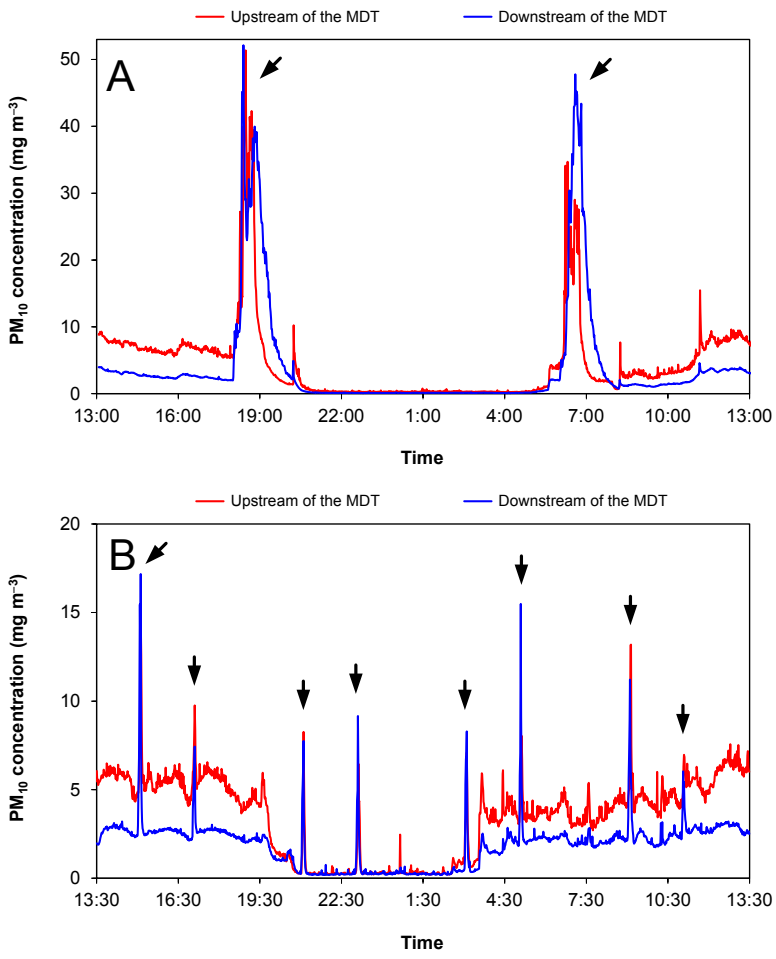


Fig. 6
Two typical concentration profiles of PM_{10} upstream and downstream of the manure drying tunnels (MDTs) at farms 15 (A) and 16 (B) in part D of this study. Arrows indicate loading/running periods of the MDTs: two times 2.5 hours in farm 15 and eight times 6 minutes in farm 16.

Part A through D: PM reduction and MLT

Presumably, the PM reduction by MDTs is achieved by impaction and subsequent adherence of dust particles to the moist, sticky droppings when the drying air makes its way through the pores between the droppings. In Fig. 7, this presumption is further examined by plotting the mean PM_{10} removal efficiency for each of the 16 MDTs in this study as a function of their mean MLT. As should be the case under this assumption, the PM_{10} removal efficiency significantly increased with increasing MLT.

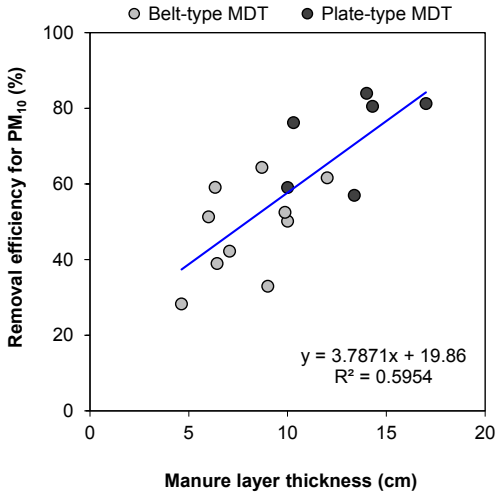


Fig. 7
Removal efficiency of the manure drying tunnels in this study as a function of their manure layer thickness (part A through D of this study; $n = 16$). Both the regression coefficient (3.7871; $P < 0.001$) and the intercept (19.86; $P = 0.04$) are significantly different from zero.

CONCLUSIONS

In this study, we aimed to gain insight into the PM abatement potential and possible extra emissions of ammonia and odor of manure drying tunnels (MDTs) applied at poultry farms in the Netherlands (part A and B of this work). In addition, we aimed to elucidate the perspective of two strategies to reduce ammonia and odor emissions from MDTs: (1) by pre-drying the manure by manure belt aeration (MBA) systems inside the house (part C of this work), and (2) by applying a manure accumulation time (MAT) of 24 hours followed by rapid drying inside the MDT (part D of this work). Our main results and conclusions are:

- MDTs are able to remove particulate matter from the exhaust air of poultry houses. PM_{10} removal efficiency increases linearly with manure layer thickness: from approximately 35% at 4 cm to approximately 84% at 17 cm;
- during loading/unloading of the MDT, downstream particulate matter concentrations may peak excessively. Adequate measures, such as temperarily transferring the ventilation requirement from drying fans to bypass fans and temperarily closure of the drying shed, are needed to prevent that emission reductions during drying periods are compensated by emission peaks during loading periods;
- upon passing the MDT, the concentration of ammonia in the drying air increases

substantially; from an average of 5.5 ppm (range: 0.8 to 22.5 ppm) upstream to an average of 13.9 ppm (range: 1.9 to 70 ppm) downstream the MDT in part C of this study. The increase of ammonia concentration was considerably higher for belt-type MDTs (mean: 10.2 ppm; range 0 to 38 ppm) than for plate-type MDTs (mean: 2.9 ppm; range: 0.6 to 6.6 ppm), possibly due to more rapid drying. Estimations based on the aforementioned ammonia concentrations indicate that actual ammonia emission rates in MDT's may easily be ten to fifty times higher than the official EF of 2 g $year^{-1}$ bird $place^{-1}$ in the Netherlands;

- upon passing the MDT, the concentration of odor in the drying air increases substantially; from an average of 822 OU_E m^{-3} to 1178 OU_E m^{-3} (approximately a factor 1.4) in part A of this study;
- the extra emission of ammonia from the drying manure decreases with increasing dry matter (DM) content of the manure. Pre-drying the manure inside the housing system probably prohibits excessive ammonia release from the MDT later on, but even at DM content levels beyond 50%, substantial ammonia emission remains;
- at a MAT of 24 hours followed by rapid drying inside the MDT, the emission rates of house and MDT together were 44% lower for PM_{10}, 24% higher for ammonia, and 40% higher for odor, as compared to emissions from the house alone. Thus, this adapted drying strategy cannot fully prohibit the release of extra ammonia and odor from the MDTs. Further research is needed to determine whether shortening MAT to 18, 12, or 6 hours further reduces the additional emissions from MDTs.

ACKNOWLEDGMENTS

This study was commissioned by the Dutch Ministry of Economic Affairs and the Dutch Ministry of Infrastructure and Environment. We thank all poultry farmers for allowing us the conduct of measurements at their farms and for their kind assistance in many occasions. This study included MDTs of the companies Big Dutchman (Vechta, Germany), Dorset (Aalten, the Netherlands), Farmer Nederland (Nunspeet, the Netherlands), Jansen Poultry Equipment (Barneveld, the Netherlands), Rijvers (Ulicoten, the Netherlands), and Salmet (Zonne-Ei-Farm, Terschuur, the Netherlands). We thank all companies for their participation in this project. Furthermore, we thank Jansen Poultry Equipment for adapting the MDT at farm 16, and Mr. Arjan Gussinklo and Mr. Harrie Beekmans for sharing their practical expertise on manure drying. We thank our colleagues Mr. Klaas Blanken, Mr. Jos Huis in't Veld, Mrs. Annemieke Hol, Mr. Geert Kupers, Mr. Eef Lovink, Mr. Guus Nijeboer, Mr. Johan Ploegaert, and Mr. Jean

Slangen for data collection, maintenance and calibration of instruments, and conducting lab analyses.

REFERENCES

Albright, L.D., 1990. Algorithms for determining the Psychrometric conditions of humid air. Environment control for animals and plants. ASAE, St. Joseph, Michigan, USA.

ApSimon, H.M., Kruse, M., Bell, J.N.B., 1987. Ammonia emissions and their role in acid deposition. *Atmos. Environ.* 21:1939–1946.

Borlée, F., Yzermans, C.J., Van Dijk, C.E., Heederik, D., Smit, L.A.M., 2015. Increased respiratory symptoms in COPD patients living in the vicinity of livestock farms. *Eur. Respir. J.* 46:1605–1614.

Brunekreef, B., Forsberg, B., 2005. Epidemiological evidence of effects of coarse airborne particles on health. *Eur. Respir. J.* 26:309–318.

Brunekreef, B., Harrison, R.M., Künzli, N., Querol, X., Sutton, M.A., Heederik, D.J.J., Sigsgaard, T., 2015. Reducing the health effect of particles from agriculture. *Lancet Respir. Med.* 3:831–832.

Cambra-López, M., Hermosilla, T., Lai, H.T.L., Aarnink, A.J.A., Ogink, N.W.M., 2011. Particulate matter emitted from poultry and pig houses: Source identification and quantification. *Trans. ASABE* 54:629–642.

Cambra-López, M., Winkel, A., Mosquera, J., Ogink, N.W.M., Aarnink, A.J.A., 2015. Comparison between light scattering and gravimetric samplers for PM10 mass concentration in poultry and pig houses. *Atmos. Environ.* 111:20–27.

CEN, 1998. EN 12341:1998. Air quality - Determination of the PM 10 fraction of suspended particulate matter - Reference method and field test procedure to demonstrate reference equivalence of measurement methods. Comité Européen de Normalisation (CEN; European Committee for Standardization), Brussels, Belgium.

CEN, 2003. EN 13725:2003. Air quality - Determination of odour concentration by dynamic olfactometry. Comité Européen de Normalisation (CEN; European Committee for Standardization), Brussels, Belgium.

CEN, 2005. EN 14907:2005. Ambient air quality - Standard gravimetric measurement method for the determination of the PM2.5 mass fraction of suspended particulate matter. Comité Européen de Normalisation (CEN; European Committee for Standardization), Brussels, Belgium.

Chepete, J.H., Xin, H., Li, H. (2011). Ammonia emissions of laying-hen manure as affected by accumulation time. *J. Poult. Sci.* 48:133–138.

CIGR, 2002. 4th Report of Working Group on Climatization of animal houses. Heat and moisture production at animal and house levels (eds. Pedersen, S. and K. Sällvik). International Commission of Agricultural Engineering (CIGR), Section II.

Costa, A., Ferrari, S., Guarino, M., 2012. Yearly emission factors of ammonia and particulate matter from three laying-hen housing systems. *Animal Prod. Sci.* 52:1089–1098.

Demmers, T.G.M., Hissink, M.G., Uenk, G.H., 1992. Het drogen van pluimveemest in een droogtunnel en het effect hiervan op de ammoniakemissie [The drying of poultry manure in a drying tunnel and the effect on ammonia emission; in Dutch, with English summary]. Report 92-6. IMAG-DLO, Wageningen, the Netherlands.

Demmers, T. G. M., Saponja, A., Thomas, R., Phillips, G. J., McDonald, A. G., Stagg, S., Bowry, A., Nemitz, E. (2010). Dust and ammonia emissions from UK poultry houses. In: XVII-th World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR), June 13–17, 2010, Québec City, Canada.

Erisman, J. W., Schaap, M. (2004). The need for ammonia abatement with respect to secondary PM reductions in Europe. *Environmental Pollution, 129*(1), 159–163.

EU, 2008. Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe. *Official J. Eur. Union* L152:1–44.

Groot Koerkamp, P.W.G., 1994. Review on emissions of ammonia from housing systems for laying hens in relation to sources, processes, building design and manure handling. *J. Agric. Eng. Res.* 59:73–87.

Groot Koerkamp, P.W.G., Metz, J.H.M., Uenk, G.H., Phillips, V.R., Holden, M.R., Sneath, R.W., Short, J.L., White, R.P., Hartung, J., Seedorf, J., Schröder, M., Linkert, K.H., Pedersen, S., Takai, H., Johnsen, J.O., Wathes, C.M., 1998. Concentrations and emissions of ammonia in livestock buildings in Northern Europe. *J. Agric. Eng. Res.* 70:79–95.

Groot Koerkamp, P.W.G., Wever, A.C., Huis in 't Veld, J.W.H., Hol, J.M.G., 1999. Ammoniakemissie uit een batterijstal voor leghennen met droging van de mest in droogtunnels boven de kooien in de stal [Ammonia

emission from a battery house for laying hens with manure drying in tunnels above the cages in the house; in Dutch]. Report P 99-06. IMAG-DLO, Wageningen, the Netherlands.

Heederik, D.J.J., Opstal-van Winden, A.J.W., Smit, L.A.M., Wouters, I.M., Hooiveld, M., IJzermans, C.J., Van der Sman-de Beer, F., Spreeuwenberg, P.P.M., De Bruin, A., Van Rotterdam, B., 2011. Mogelijke effecten van intensieve-veehouderij op de gezondheid van omwonenden: onderzoek naar potentiële blootstelling en gezondheidsproblemen [Possible effects of intensive livestock production on health of residents: research into possible exposure and health problems; in Dutch]. Institute for Risk Assessment Sciences (IRAS), Utrecht University; Netherlands institute for health services research (NIVEL); National Institute for Public Health and the Environment (RIVM), Utrecht, the Netherlands.

Hendriks, C., Kranenburg, R., Kuenen, J., van Gijlswijk, R., Wichink Kruit, R., Segers, A., Denier van der Gon, H., Schaap, M., 2013. The origin of ambient particulate matter concentrations in the Netherlands. *Atmos. Environ.* 69:289–303.

Hooiveld, M., Smit, L.A.M., Van Der Sman-De Beer, F., Wouters, I.M., Van Dijk, C.E., Spreeuwenberg, P., Heederik, D.J.J., Yzermans, C.J., 2016. Doctor-diagnosed health problems in a region with a high density of concentrated animal feeding operations: A cross-sectional study. *Environ. Health* 15:24, 9 pp.

Hooiveld, M., van Dijk, C.E., van der Sman-De Beer, F., Smit, L.A.M., Vogelaar, M., Wouters, I.M., Heederik, D.J.J., Yzermans, C.J., 2015. Odour annoyance in the neighbourhood of livestock farming – Perceived health and health care seeking behaviour. *Ann. Agric. Environ. Med.* 22:55–61.

Huis in 't Veld, J.W.H., Groot Koerkamp, P.W.G., Scholtens, R., 1999. Voletage volièresysteem voor legouderdieren en een droogtunnel met geperforeerde mestbanden [Aviary housing system for layer breeders and drying tunnel for manure; in Dutch, with English abstract]. Report 99-10. IMAG, Wageningen, the Netherlands.

Kroodsma, W., Bleijenberg, R., Ogink, N.W.M., Wintjens, Y., 1996. Nadroging van voorgedroogde leghennenmest volgens het HELI-systeem en de laagsgewijze composteermethode [Drying of pre-dried layer droppings with the HELI-system and the in layers compost method; in Dutch, with English abstract]. Report 96-08. IMAG-DLO, Wageningen, the Netherlands.

Lai, H.T.L., Aarnink, A.J.A., Cambra-López, M., Huynh, T.T.T., Parmentier, H.K., Groot Koerkamp, P.W.G., 2014. Size distribution of airborne particles in animal houses. *Agricultural Engineering International: CIGR Journal,* 16:28–42.

Li, Q.F., Wang-Li, L., Walker, J.T., Shah, S.B., Bloomfield, P., Jayanty, R.K.M., 2012. Particulate matter in the vicinity of an egg production facility: Concentrations, statistical distributions, and upwind and downwind comparison. *Trans. ASABE* 55:1965–1973.

Mielcarek, P., Rzeźnik, W., 2015. Odor emission factors from livestock production. *Polish J. Environ. Studies* 24: 27–35.

Mosquera, J., Groenestein, C.M., Ogink, N.W.M., Aarnink, A.J.A., 2012. Evaluation of the CO2 mass balance method to calculate ventilation rates from mechanically ventilated livestock buildings. In: 9th International Livestock Environment Symposium (ILES), July 8–12, 2012, Valencia, Spain.

Nimmermark, S., 2004. Odour influence on well-being and health with specific focus on animal production emissions. *Ann. Agric. Environ. Med.* 11:163–173.

O'Connor, A.M., Auvermann, B., Bickett-Weddle, D., Kirkhorn, S., Sargeant, J.M., Ramirez, A., Von Essen, S.G., 2010. The association between proximity to animal feeding operations and community health: A systematic review. *PLoS ONE* 5(3), 13 pp.

Ogink, N.W.M., 2011. Protocol voor meting van geuremissie uit huisvestingssystemen in de veehouderij 2010 [Protocol for the measurement of odour emissions from housings in animal production 2010; in Dutch]. Report 491. Wageningen University and Research Centre, Livestock Research, Lelystad, the Netherlands.

Ogink, N.W.M., Aarnink, A.J.A., 2011. Plan van aanpak bedrijfsoplossingen voor fijnstofreductie in de pluimveehouderij [Plan of action for particulate matter mitigation solutions in poultry; in Dutch, with English summary]. Report 113. Animal Sciences Group, Wageningen University and Research Centre, Lelystad, the Netherlands.

Ogink, N.W.M., Groot Koerkamp, P.W.G., 2001. Comparison of odour emissions from animal housing systems with low ammonia emission. *Water Sci. Techn.* 44:245–252.

Ogink, N.W.M., Hofschreuder, P., Aarnink, A.J.A., 2011. Protocol voor meting van fijnstofemissie uit huisvestingssystemen in de veehouderij 2010 [Protocol for the measurement of fine emissions from housings in animal production 2010; in Dutch]. Report 492. Wageningen University and Research Centre, Livestock Research, Lelystad, the Netherlands.

Ogink, N.W.M., Mosquera, J., Hol, J.M.G., 2011. Protocol voor meting van ammoniakemissie uit huisvestingssystemen in de veehouderij 2010 [Measurement protocol for ammonia emission from housing systems in livestock production 2010; in Dutch]. Report 454. Wageningen University and Research Centre, Livestock Research, Lelystad, the Netherlands.

Pedersen, S., Blanes-Vidal, V., Joergensen, H., Chwalibog, A., Haeussermann, A., Heetkamp, M.J.W., Aarnink, A.J.A., 2008. Carbon dioxide production in animal houses: a literature review. Agricultural Engineering International: CIGR Ejournal, Vol. X, December 2008. Manuscript BC 08 008.

RIVM (2014). Annual national emissions of PM10; in total and per sector/source, for 2012. Retrieved 11 February 2014, from http://www.emissieregistratie.nl.

Schinasi, L., Horton, R.A., Guidry, V.T., Wing, S., Marshall, S.W., Morland, K.B., 2011. Air pollution, lung function, and physical symptoms in communities near concentrated swine feeding operations. *Epidemiology* 22:208–215.

Schlesinger, R.B., 2007. The health impact of common inorganic components of fine particulate matter (PM2.5) in ambient air: A critical review. *Inhal. Toxic.* 19:811–832.

Seedorf, J., Hartung, J., Schröder, M., Linkert, K.H., Phillips, V.R., Holden, M.R., Sneath; R.W., Short, J.L., White, R.P., Pedersen, S., Takai, H., Johnsen, J.O., Metz, J.H.M., Groot Koerkamp, P.W.G., Uenk, G.H., Wathes, C.M., 1998. Concentrations and emissions of airborne endotoxins and microorganisms in livestock buildings in Northern Europe. *J. Agric. Eng. Res.* 70: 97–109.

Smit, L.A.M., Hooiveld, M., Van Der Sman-de Beer, F., Opstal-van Winden, A.W.J., Beekhuizen, J., Wouters, I.M., Yzermans, C.J., Heederik, D., 2014. Air pollution from livestock farms, and asthma, allergic rhinitis and COPD among neighbouring residents. *Occup. Environ. Med.* 71:134–140.

Takai, H., Pedersen, S., Johnsen, J.O., Metz, J.H.M., Groot Koerkamp, P.W.G., Uenk, G.H., Phillips, V.R., Holden, M.R., Sneath, R.W., Short, J.L., White, R.P., Hartung, J., Seedorf, J., Schröder, M., Linkert, K.H., Wathes, C.M., 1998. Concentrations and emissions of airborne dust in livestock buildings in Northern Europe. *J. Agric. Eng. Res.* 70:59–77.

Uenk, G.H., Monteny, G.J., Demmers, T.G.M., Hissink, M.G., 1994. Praktijkonderzoek naar het drogen van leghennenmest in een droogtunnel en het effect op de ammoniak-, geur, en stofemissie [Drying of poultry manure in a tunnel and the effect on the emission of ammonia, odour and dust; in Dutch, with English summary]. Report 94-21. IMAG-DLO, Wageningen, the Netherlands.

Van Zanten, M.C., Van Alphen, A., Wesseling, J., Mooibroek, D., Nguyen, P.L., Groot Wassink, H., Verbeek, C., 2014. Monitoringsrapportage NSL 2014 [State of affairs of the National Air Quality Cooperation Programme 2014; in Dutch with English summary]. National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands.

Velders, G.J.M., Aben, J.M.M., Blom, W.F., Van Dam, J.D., Elzenga, H.E., Geilenkirchen, G.P., Hammingh, P., Hoen, A., Jimmink, B.A., Koelemeijer, R.B.A., Matthijsen, J., Peek, C.J., Schilderman, C.B.W., Van der Sluis, O.C., De Vries, W.J., 2008. Concentratiekaarten voor grootschalige luchtverontreiniging in Nederland, rapport 2008 [Large-scale air quality concentrations maps in the Netherlands, report 2008; in Dutch with English abstract]. Report 500088002. Milieu- en Natuurplanbureau, Bilthoven, the Netherlands.

VSN, 2014. GenStat reference manual (release 17). Version 17.1.0.14713. Hemel Hempstead, UK.

Winkel, A., Llorens Rubio, J., Huis in't Veld, J.W.H., Vonk, J., Ogink, N.W.M., 2015a. Equivalence testing of filter-based, beta-attenuation, TEOM, and light-scattering devices for measurement of PM10 concentration in animal houses. *J. Aerosol Sci.* 80:11–26.

Winkel, A., Mosquera, J., Groot Koerkamp, P.W.G., Ogink, N.W.M., Aarnink, A.J.A., 2015b. Emissions of particulate matter from animal houses in the Netherlands. *Atmos. Environ.* 111:202–212.

Wood, D., Cowherd, S., Van Heyst, B., 2015. A summary of ammonia emission factors and quality criteria for commercial poultry production in North America. *Atmos. Environ.* 115:236–245.

Zhao, Y., Aarnink, A.J.A., De Jong, M.C.M., Groot Koerkamp, P.W.G., 2014. Airborne microorganisms from livestock production systems and their relation to dust. *Crit. Rev. Environ. Sci. Techn.* 44:1071–1128.

Zhao, Y., Aarnink, A.J.A., Hofschreuder, P., Groot Koerkamp, P.W.G., 2009. Evaluation of an impaction and a cyclone pre-separator for sampling high PM10 and PM2.5 concentrations in livestock houses. *J. Aerosol Sci.* 40:868–878.

Chapter 8

Equivalence testing of filter-based, beta-attenuation, TEOM, and light-scattering devices for measurement of PM_{10} concentration in animal houses

A. Winkel [a], J. Llorens Rubio [b], J. W.H. Huis in't Veld [a], J. Vonk [c] and N.W.M. Ogink [a]

[a] Wageningen UR Livestock Research, Wageningen, the Netherlands
[b] Institute of Animal Science and Technology,Universidad Politécnica de Valencia, Valencia, Spain
[c] National Institute for Public Health and the Environment, Bilthoven, the Netherlands

Journal of Aerosol Science (2015) 80:11–26

Available online at: http://dx.doi.org/10.1016/j.jaerosci.2014.10.009

ABSTRACT

Emissions of particulate matter (PM) from poultry and pig houses may contribute significantly to ambient concentrations. Yet, our knowledge on the accuracy and comparability of samplers available for measuring the high PM_{10} concentrations (>100 μg m^{-3}) in the inside air directly upstream of the ventilation exhausts of these buildings is very limited. The aim of this study was to provide insight into this matter for five candidate samplers: a filter-based cyclone sampler (CYS), the Thermo Scientific FH 62 I-R beta-attenuation sampler (BAS), the Thermo Scientific Tapered Element Oscillating Microbalance, model 1400ab (TEOM), the TSI DustTrak model 8520 (DT), and the GRIMM Portable Aerosol Spectrometer model 1.109 (PAS). Equivalence tests were carried out following European Standard EN 12341 using two devices for each candidate sampler (CAS) and four filter-based low-volume reference samplers (RES). Measurements were performed inside three major animal housings (a fattening pig house, a laying hen house, and a broiler house) and inside an office room. Our key results and conclusions are: (1) neither one of the five CASs, nor the RES itself, met the EN 12341 requirement for comparability between devices of the same sampler type. Using a less strict boundary for this aspect – in concert with performing duplicate sampling – may be appropriate. (2) The CYS met the EN 12341 accuracy requirements in pigs and layers, but overestimated the RES concentration in broilers. The BAS, TEOM, and DT underestimated, and the PAS overestimated, RES concentrations in a systematic manner. The use of correction factors seems to be a promising method to calibrate measured values to RES concentrations. (3) The BAS, TEOM, DT, and PAS started to show scattered regression after 432–500 h of sampling, which stresses the need for shortened time intervals between full services. In conclusion, some of the samplers tested could be regarded acceptable when appropriate measures (such as duplicate sampling, correction factors, and more frequent servicing) are applied.

NOMENCLATURE

$95\%\text{-}CI_a$	The two-sided 95% confidence interval for Y_i on the original scale (µg m^{-3})
$95\%\text{-}CI_r$	The two-sided 95% confidence interval for Y_i on a relative scale (%)
CAS	Candidate sampler
CYS	Cyclone sampler
$D_i = Y_{i1} - Y_{i2}$	The difference between the i^{th} concentration values measured by candidate samplers 1 and 2
DT	DustTrak, model 8520
BAS	FH 62 I-R beta-attenuation sampler
N	The number of performed measurements
n	The number of valid data pairs in the comparability or accuracy analysis
PAS	Portable Aerosol Spectrometer, model 1.109
PM_{10}	Particulate matter which passes through a size-selective inlet with a 50% efficiency cut-off at 10 µm aerodynamic diameter (EN 12341)
$PM_{2.5}$	Particulate matter which passes through a size-selective inlet with a 50% efficiency cut-off at 2.5 µm aerodynamic diameter (EN 14907)
RES	Reference sampler, described in standard EN 12341, annex B.1
RIVM	Rijksinstituut voor Volksgezondheid en Milieu (National Institute for Public Health and the Environment)
S_a	Absolute standard deviation
S_r	Relative standard deviation
$t_{(0.975;n-2)}$	Value from the Student's *t* distribution at the 0.975-quantile and *n*–2 degrees of freedom
TEOM	Tapered Element Oscillating Microbalance, model 1400ab
WLR	Wageningen University and Research Centre, Livestock Research
$Y_i = (Y_{i1} + Y_{i2}) / 2$	The average of the i^{th} measured concentration values of candidate samplers 1 and 2
Y_{i1}	The i^{th} concentration value measured by candidate sampler 1
Y_{i2}	The i^{th} concentration value measured by candidate sampler 2

INTRODUCTION

Ambient particulate matter (PM) concentrations are associated with respiratory and cardiovascular morbidity, may shorten life expectancy, and are linked to variations in public health indicators, such as hospital admissions and mortality figures (Brunekreef and Holgate, 2002; Pope and Dockery, 2006). In areas with high numbers of poultry and pig houses, a relevant portion of the PM present in the atmosphere is expected to originate from the ventilation exhausts of these houses. In the Netherlands, in 2011, the total primary PM_{10} emission was estimated at 32.6 kTon with contributions of 4.2 kTon (or 13%) for poultry houses, 1.2 kTon (or 4%) for pig houses and 0.3 kTon (or 1%) for cattle houses (RIVM, 2011). In order to determine emissions of PM_{10} and $PM_{2.5}$ from animal houses, it is essential to have samplers available that yield concentrations that are consistent with the 'true' concentration (referred to in this paper as accuracy) and comparable between devices when tested simultaneously and side by side (referred to in this paper as comparability).

The development of such a sampler was described by Hofschreuder et al. (2007) who used the low volume filter-based reference samplers (RESs) described in Annex B1 of European standard EN 12341 for PM_{10} (CEN, 1998) and in par. 5.1.2.2 of European standard EN 14907 for $PM_{2.5}$ (CEN, 2005) as basic systems. These systems were adapted in a number of ways, including substitution of the impaction pre-separators by cyclonic pre-separators. Equivalence tests were performed by Zhao et al. (2009) who showed that both cyclone samplers (CYSs) achieved good comparability between samplers and accuracy to the RES at low concentrations. For high poultry and pig house PM_{10} concentrations, correction equations were published to calibrate measured CYS values to RES values. Since 2007, these CYSs have been used in a national survey quantifying PM_{10} and $PM_{2.5}$ emissions from 13 types of animal houses in the Netherlands (Winkel et al., 2014).

Several other samplers have been used to determine PM_{10} and $PM_{2.5}$ emissions from animal houses that may be portable, battery-powered and yielding continuous data, almost instantly available in digital format. In recent years, the Thermo Fisher Scientific Tapered Element Oscillating Microbalance (TEOM) has been used by research groups in Spain (Adell et al., 2012; Calvet et al., 2009), the UK (Demmers et al., 2010), and the USA (Hayes et al., 2013; Joo et al., 2013; Koziel et al., 2004; S. Li et al., 2011; Lin et al., 2012; Ni et al., 2012). Joo et al. (2013) and Lin et al. (2012) furthermore used the Thermo Scientific FH 62 C14 beta-attenuation monitor to measure inlet concentrations. Others groups have used light-scattering devices, such as the TSI DustTrak model 8520 by researchers in Canada (Morgan et al., 2014; Roumeliotis et al., 2010a,

2010b; Roumeliotis and Van Heyst, 2007) and the USA (Modini et al., 2010; Visser et al., 2006), the SKC EPAM-5000 by researchers in Italy and Germany (Costa et al., 2012; Costa and Guarino, 2009; Fabbri et al., 2007; Haeussermann et al., 2008), and the GRIMM Portable Aerosol Spectrometer model 1.109 by researchers in Belgium (Van Ransbeeck et al., 2012; Van Ransbeeck et al., 2013a).

When choosing a sampler for PM measurement in animal houses, it is important to consider that each sampler has its specific sensitivities and potential sources of bias (McMurry, 2000) that may lead to under- or overestimation of 'true' concentrations and emissions. At the high concentrations usually found in the inside air directly upstream of ventilation exhausts, pre-separation methods of samplers (e.g., greased impactors) may be sensitive to overloading. Particles outside the target size fraction then travel further into the measuring section of the sampler, resulting in overestimations (Van Ransbeeck et al., 2013b; Zhao et al., 2009). Filter-based systems that require manual weighing are sensitive to agitation and loss of PM during filter transport, storage, and handling, especially when filters are heavily loaded. Furthermore, compounds in the gas phase might be adsorbed to the filter material or absorbed into the PM and erroneously weighed as PM (Andersen et al., 2014). When light-scattering devices are used that have been factory-calibrated with a standard type of aerosol, they are likely to show substantial bias (Cambra-López et al., 2014; Costa et al., 2012; Costa and Guarino, 2009; Post et al., 2010; Van Ransbeeck et al., 2013b) due to differences in refractive index, density, size, and shape between the calibration aerosol and the actual aerosol sampled (Görner et al., 1995). For the standard configured TEOM, heating of the sample stream to 50°C may drive off part of the volatile components of PM, such as particle-bound water, ammonium nitrate, and (semi-)volatile organic compounds. This artifact plays a role in ambient PM (Allen et al., 1997), but also in livestock PM (Q. F. Li et al., 2012), and is more pronounced for the smaller fractions (e.g., $PM_{2.5}$) than for larger fractions. Next to desorption, water vapor in the sample stream may also adsorb to the PM present on the TEOM filter, especially when the filter load exceeds ~50% of its capacity, as demonstrated by Heber et al. (2006) for laying hen PM. It is evident that PM volatilization is also likely when loaded filters are conditioned by oven-drying prior to weighing (as can be found in literature incidentally), which is therefore not allowed when following the procedures described in EN 12341 (Annex C).

Measures to control the aforementioned error sources may include intensified schedules for servicing, cleaning and calibration (Heber et al., 2006; Zhao et al., 2009), decreasing the sample flow rate to avoid high PM loadings (Heber et al., 2006), technical modifications to standard samplers (Heber et al., 2006; Hofschreuder et al., 2007), lowering the sample stream heating

temperature (Li et al., 2012), re-calibration of light-scattering samplers using the aerosol of interest, programming correction factors in the samplers' operating software, or to apply such corrections to datasets produced (Costa et al., 2012; Costa and Guarino, 2009; Morgan et al., 2014; Roumeliotis et al., 2010a, 2010b). Most papers on livestock PM emissions however, do not or very briefly, describe how samplers were configured and error sources controlled.

Despite that some studies found that data from co-located samplers varied significantly (Cambra-López et al., 2014; Post et al., 2010), studies focusing on the accuracy of samplers to reference methods, their comparability and applicability, or adequate measures to ensure their proper functioning, are still scarce (Heber et al., 2006; Li et al., 2012; Van Ransbeeck et al., 2013b; Zhao et al., 2009). Consequently, a review on PM from livestock production systems identified the validation and harmonization of PM sampling devices as one of the major priorities for future research (Cambra-López et al., 2010).

The aim of the work presented here was to gain insight into the accuracy and comparability of five commonly used samplers when measuring high PM_{10} concentrations (>100 μg m^{-3}) inside a fattening pig house, a laying hen house, and a broiler house, following the main principles described in EN 12341 (CEN, 1998).

METHODOLOGY

Outline of the study

Emissions of PM from animal houses are often determined from concentration measurements in the inside air within 3 m upstream of exhaust fans or shafts. This approach has the advantages that air velocity is below 1 m s^{-1} (avoiding non-isokinetic conditions inside shafts due to varying ventilation rates) and that the air can be assumed to be homogenously mixed and representative for that emitted from the building. The sampling conditions directly upstream of exhausts (e.g., air velocity, air flow patterns, air temperature, and air humidity) show similarities to the conditions in ambient air. For the latter situation, European Standard EN 12341 (CEN, 1998) prescribes PM_{10} reference samplers, procedures and statistical tests to be used to demonstrate reference equivalence of candidate samplers. For animal house environments however, such reference samplers or standards do not exist. In view of these considerations, we followed the main principles of EN 12341 to perform equivalence tests inside animal houses.

In this study, tests were carried out inside three animal houses (a fattening pig house, a laying hen house, and a broiler house), and inside an office room, using four devices of the European

reference sampler (RES) and two devices of five candidate samplers (CASs; referred to in this work as devices A and B). CASs included the aforementioned Cyclone Sampler (CYS), the FH 62 I-R beta-attenuation sampler (BAS), the TEOM 1400ab (TEOM), the DustTrak model 8520 (DT), and the Portable Aerosol Spectrometer model 1.109 (PAS). Prior to the start of the project, all samplers were serviced, cleaned, and calibrated extensively, to assure their proper functioning (details of these procedures repeated during the project are given in Table 2). Between October 2012 and February 2013, we subsequently performed 30 measurements in pigs, 24 in layers, and 46 in broilers (the latter referred to in this work as 'broilers-1'), which were all 3-h measurements. In comparison to the pig house and layer house data, broiler-1 data of BAS, TEOM, DT, and PAS showed poor regression to the RES concentration, which we believed to be the result of pollution of these devices. Therefore, all devices were again serviced, cleaned, and calibrated extensively to bring them back into their condition at the beginning of the project. Then, we performed fifteen 24-h office measurements and a second series of nineteen 3-h broiler house measurements (the latter referred to in this work as 'broilers-2') between February and April 2013. In total, 134 successful measurements were included in this work.

Sampling devices and their operation

Samplers were operated by either Wageningen UR Livestock Research (WLR) or the National Institute for Public Health and the Environment (RIVM). An overview of the samplers used in this study is given in Table 1. Table 2 lists the service schedule adopted for each sampler in this work. A description of their working principle, settings, and operation is given in the following sections.

Table 1
Overview of main characteristics of the reference sampler and the five candidate samplers evaluated in this work.

Sampler	Operated by	In use since	Sample flow rate (L min^{-1})	Sample flow heating	Pre-separation system	Measuring principle	Measuring range (µg m^{-3})
RES	WLR	2012	38.3	None	Impactor (EN 12341, Annex B.1)	Filter weighing	Not specified
CYS	WLR	2012	16.7	None	Cyclone (model URG-2000-30ENB)	Filter weighing	Not specified
BAS	RIVM	2007	16.7	Ambient + <5°C	Impactor (EN 12341, Annex B.1)	Beta-ray attenuation	4 to 10,000
TEOM	RIVM	2004	16.7 [a] 3.0 [b]	50°C	Impactor (US-EPA 40 CFR 50, App. L)	Micro-balance	5 to >10,000
DT	WLR	2008	1.7	None	TSI PM_{10} impaction inlet nozzle	Light-scattering	1 to 100,000
PAS	WLR	2009	1.2	None	None	Light-scattering	0.1 to 100,000

[a] Total sample flow pulled through impactor.
[b] Sample flow to measuring chamber after passing a flow splitter.

Table 2
Service schedule adopted in this study.

Sampler	Service point	Frequency in this work	Service interval operating manual
RES/CYS	Cleaning (and greasing) of pre-separator	Every 1–3 measurements	-
	Disassembly and wet cleaning	Every 5–10 measurements	-
	Calibration of temperature sensor	Between sampling locations	-
	Calibration of gas meter inside the pump	Between sampling locations	-
BAS	Inspection of filter tape (breaks, tension)	Prior to each measurement	3 months
	Cleaning (and greasing) of pre-separator	Every 1–3 measurements	2 months
	Check on heating system, cleaning of sampling tube, calibration of temperature, pressure, and flow rate, offset check, mass calibration	Between sampling locations	3–6 months
	Full internal cleaning	After broilers-1	Annually
TEOM	Cleaning of pre-separator	Every 1–3 measurements	1–3 months
	Cleaning of air inlet system	Between sampling locations	Annually
	Leak check, calibration of flow rate	Between sampling locations	Annually
	Replacement of inline filters	After broilers-1	6 months
	Full internal cleaning	After broilers-1	Annually
DT	Cleaning of inlet nozzle	Every 1–3 measurements	350 h at 1 mg m^{-3}
	Zero-check and re-zeroing	Every 1–3 measurements	Daily
	Flow check and adjustment	Every 5–10 measurements	Each sample
	Replacement of internal filters	Between sampling locations	700 h at 1 mg m^{-3}
	Internal cleaning and mass calibration	After broilers-1	Annually
PAS	Cleaning of inlet piece	Every 1–3 measurements	Not specified
	Replacement of PTFE filter, cleaning chamber	Every 5–10 measurements	<20 mg loading
	Cleaning of optical chamber by air blowing	Between sampling locations	Not specified
	Internal cleaning and mass calibration	After broilers-1	Annually

Reference sampler (RES)

The low-volume PM_{10} RES described in annex B.1 of EN 12341 (CEN, 1998) was used for determination of the 'true' PM_{10} concentration. The RES consisted of an air inlet head with a circumferential slit, an impaction pre-separator composed of eight impaction nozzles and a greased impaction plate, and a filter holder. Photographs of these RES components are given by Zhao et al. (2009). RESs were assembled from newly purchased components. Air was drawn through the RES using sampling pumps (Tecora, model Charlie HV; Ravebo B.V., Brielle, the Netherlands). These pumps use the temperature measured by a sensor near the inlet head of the RES and the temperature, pressure, and airflow of the gas meter inside the pump to automatically adjust the air flow rate to the programmed value. Hereby, pumps are able to maintain a constant air flow rate (nominal value ± 2%) when filter load and pressure difference across the filter increases.

After pre-separation, the PM_{10} fraction was collected on glass fiber filters (type GF-3, Ø 47 mm, Macherey-Nagel, Düren, Germany) inside the filter holder. Unloaded and loaded filters were weighed in a weighing room under standard conditions (20 ± 1°C and 50 ± 5% relative humidity), as described in EN 12341 (CEN, 1998). After 48 h of stabilization, each filter was weighed four times spread over two consecutive days using a balance with a resolution of 10 µg (AT261 DeltaRange, Mettler, Greifensee, Switzerland). The average value was recorded as the filter weight and the mass difference between loaded and unloaded filters equaled the mass of collected PM_{10}. PM_{10} concentrations were calculated by dividing the mass of collected PM_{10} by the volume of air drawn through the filter. During transport, filter cassettes were put in Petri dishes and kept in a small barrel.

Cyclone Sampler (CYS)

The CYS developed by WLR (Hofschreuder et al., 2007) is very similar to the RES described above, but has three main differences. First, the inlet head has been modified: the eight impaction nozzles are replaced by eight short tubular screws that fit the holes for the impaction nozzles and the impaction body of the inlet is replaced by a cylinder with a hollow cone frustum. Second, a PM_{10} cyclone (model URG-2000-30ENB; URG Corp., Chapel Hill NC, USA) is used for particle pre-separation which requires a flow rate of 16.7 L min^{-1} (1 m^3 h^{-1}). Third, the inlet head, cyclone, and filter holder are applied as separate components, connected by one U-shaped and one J-shaped air pipe, air-sealed with locknuts. The adapted inlet body, tubular screws, air pipes, and locknuts were custom made in the central workshop of WLR, since they are not

commercially available. Photographs of CYS components are given by Zhao et al. (2009). For the CYS, air sampling and filter weighing was carried out as described for the RES.

FH 62 I-R beta-attenuation sampler (BAS)

The BASs were two FH 62 I-R devices (Thermo Fisher Scientific, Breda, the Netherlands). The FH 62 models have been approved as equivalent method for ambient PM_{10} monitoring in Europe (according to EN 12341) (Thermo, 2004) and in the USA (models FH 62 I-N and FH 62 C14; Designation Numbers EQPM-0990-076 and EQPM-1102-150) (US-EPA, 2013). The BASs are currently used by the RIVM as PM_{10} samplers in the National Air Quality Monitoring Network of the Netherlands. Air is drawn through their inlet head, a greased impactor (described in EN 12341, Annex B.1), and a vertical sampling pipe by a rotary vane pump outside the BAS. The sampling pipe was equipped with an 'automatic sample condition system' which slightly heats the sample stream flow (with <5°C) to prevent condensation of water vapor inside the BAS without severe loss of volatile compounds. Inside the device, PM_{10} is collected on a glass fiber filter tape (filter nr. 10, 40 mm width; Schleicher and Schuell Bioscience, Dassel, Germany). A dual beam of beta-radiation, originating from a gaseous Krypton-85 source, is directed upwards through the filter tape and subsequently measured in an ionization chamber. The weakening of the beam intensity upon crossing the filter tape is a measure for the mass of PM collected (Thermo, 2004). A filter tape replacement was initiated automatically by the BAS at the start of each measurement and at maximum filter load (2400 μg). Each filter tape replacement was followed by an automatic zero-calibration. Since the BAS needs about 1 h to reach stable concentrations, BASs (and TEOMs) were started 2 h earlier than the other samplers, which data were excluded from analyses.

Tapered Element Oscillating Microbalance (TEOM)

The TEOMs (1400ab; Thermo Fisher Scientific, Breda, the Netherlands) have been used by the RIVM for $PM_{2.5}$ sampling (using the Sample Equilibrium System) in the National Air Quality Monitoring Network of the Netherlands from 2004 to 2009. The Sample Equilibrium Systems were removed prior to this study so that the TEOMs were in their standard configuration. The TEOM 1400ab has been approved as equivalent method for ambient PM_{10} monitoring in Europe (according to EN 12341) (Rupprecht and Patashnick, 2004) and in the USA (Designation No. EQPM-1090-079) (US-EPA, 2013). TEOMs were equipped with the impactor described in US-EPA 40 CFR 50, App. L. Inside the sensor unit of the TEOM, a filter cartridge is placed over a hollow tapered glass element that oscillates when air is drawn through

the filter. The mass of PM that accumulates is determined from the decrease in oscillation frequency it causes. In order to obtain a constant baseline oscillation frequency, the sample stream is heated to a fixed temperature of 50°C having a low and stable humidity (Rupprecht and Patashnick, 2004). As recommended by Heber et al. (2006), we replaced filters at PM loadings of approximately 50% to avoid large amplitudes in concentration readings due to adsorption and desorption of moisture from the collected PM. The TEOMs were operated without the default adjustment equation given in the operating manual; values for the slope and offset were set at 1.00 and 0 µg respectively. Since the TEOM needs about 1 h to reach its target temperature, TEOMs (and BASs) were started 2 h earlier than the other samplers, which data were excluded from analyses.

DustTrak light scattering device (DT)

The battery-powered and portable DT (DustTrak aerosol monitor, model 8520, TSI Inc., Shoreview MN, USA) is designed for exposure sampling, but is used by WLR to determine time-patterns or relative differences in PM_{10} concentrations in animal houses. The internal pump of the DT pulls air at 1.7 L min^{-1} through a PM_{10} inlet nozzle into a sensing chamber where it is illuminated by a beam of light (780 nm wavelength) from a laser diode. A lens at 90° to both the air stream and the laser beam collects light scattered by the particles and focuses it onto a photodetector, which converts the amount of captured light into a proportional voltage. The voltage is multiplied by a calibration constant to yield a mass concentration. This relationship between voltage and mass concentration is pre-set in the factory by a calibration to the respirable fraction of standard ISO 12103-1 A1 test dust. Part of the air stream is directed through a filter and used to create a sheet of clean air which confines the sample stream and protects the optics against particle deposition (TSI, 2010).

Portable Aerosol Spectrometer (PAS)

The battery-powered PAS (Portable Aerosol Spectrometer, model 1.109, GRIMM Aerosol Technique GmbH & Co. KG, Ainring, Germany) is designed as size-specific particle counter for various fields of application. The PAS is used by WLR to determine particle-size distributions in animal houses. Its working principle has many similarities to the DT. The sample flow generated by the internal pump (1.2 L min^{-1}) is fully analyzed, and subsequently cleaned by an internal filter, after which 0.3 L min^{-1} is recirculated to form a sheet of clean air in the sensing chamber. Laser beams (655 nm wavelength) scattered by the particles are captured by a wide angle mirror positioned 90° to both the air stream and the laser beam and reflected to a photodetector.

Particles are not only counted by their individual light impulses, but also attributed to one of 31 particle size channels based on the intensity of the beam (GRIMM, 2010). Besides particle number concentrations, mass concentrations of a number of size fractions are determined, including the PM_{10} fraction.

Description of sampling locations

To minimize bias associated with transport of samplers and filters, animal houses were selected within a 5 km radius from the WLR institute in Wageningen, the Netherlands.

The fattening pig house consisted of a central corridor with five rooms at each side of the corridor. Each room was divided into a central feeding alley with four pens at each side of the feeding alley. Pens measured 3.2 m long and 2.4 m wide and had partially slatted floors with manure pits. No bedding material was used. Liquid feed was delivered to a trough in each pen by an automatic feeding system twice per day. Fresh air entered the room through a ceiling baffle over the feeding alley. Polluted air was drawn from the room through two ceiling shafts with throttling valves to a central air duct by mechanical ventilation. Samplers were placed in one of the pens which was kept unoccupied for the purpose of this study. The other seven pens in the room each housed 11 or 12 pigs of the same age. The age of the pigs during the measurements was 12 to 17 weeks. Air pumps of the RESs and CYSs were placed in the central corridor to reduce recirculation of cleaned sample air inside the room.

The layer house consisted of an entrance hall and a single animal space. The animal space measured 72 m long and 14.8 m wide, housed 18,000 laying hens, and was equipped with so-called aviary systems (loose housing). The concrete floor was covered with a bedding layer composed of dry and friable manure and feathers. Fresh air entered the house through inlets distributed along the length of both side walls and polluted air was removed by fans in the end wall of the building. Samplers were placed inside a sampling area separated from the hens by concrete wire mesh from floor to ceiling, whereas the air pumps of the RESs and CYSs were placed in the entrance hall.

The broiler house consisted of a single animal space that measured 24 m long and 9 m wide. On day one of the growing cycle, 2650 one-day old broiler chicks were placed onto a concrete floor with wood shavings. Broilers were processed at 9 weeks of age. The age of the broilers was 4 to 9 weeks for broilers-1 and 2 to 5 weeks for broilers-2. The house was equipped with lines with feed pans and drinking nipples, a hot air blower, side wall air inlets and roof fans. Samplers

(including their air pumps) were placed inside a sampling area separated from the broilers by a 0.5 m high mesh wire fence.

The office location was a room inside the WLR institute of 7.2 m long and 7 m wide. The room is mainly used for maintenance of measuring devices and storage of equipment. The room has a concrete floor, side wall windows, radiator heaters, a mechanical ventilation system and several work desks and storage cabinets.

Sampling strategy and quality assurance

We performed simultaneous measurements with a set of co-located samplers, consisting of five CASs (each in duplicate) and the RES (in fourfold); 14 devices in total. Samplers were set up in a 2 by 2 m sampling area with each sampler inlet positioned approximately 1.7 m above the floor and spaced 0.4 m apart. Within each location, sampling areas were chosen away from sources that might create local gradients, such as air inlets or feeding systems. To verify the presence of a flat spatial concentration profile, we performed grid measurements in the 2 by 2 m horizontal measuring plane at each sampling location. PM_{10} concentrations were measured with four DustTraks mounted 1.7 m above the floor to the corners of a 2 by 2 m horizontal square wooden beam structure. The structure was rotated 90° every 15 minutes to compensate for systematic differences between instruments and measurements were done during 2 h. This procedure was repeated two or three times at each sampling location. The mean relative standard deviation of grid point means was 6.6%, indicating the presence of a flat spatial concentration profile and thus a valid basis of comparison.

In addition, we used four RES devices (instead of two, prescribed by EN 12341) to determine the 'true' PM_{10} concentration (as their mean). Furthermore, to avoid potential bias in the reference measurements, we randomly placed samplers within the 2 by 2 m sampling area prior to each measurement. CASs were positioned side-by-side, whereas RESs were spread over the sampling area. At all sampling locations, air velocity was less than 1 m s^{-1}, to avoid non-isokinetic sampling conditions.

In previous work on the RES, Zhao et al. (2009) showed that 0, 1, 2, or 3 impaction plate replacements within a 24-h sampling period (equivalent to 24, 12, 8, and 6 h of sampling with one impaction plate) did not influence PM_{10} concentration of the RES at high concentrations. Based on this finding, impaction plates were cleaned and re-greased every 2 to 3 measurements (equivalent to 6–9 h of sampling) to avoid particle bouncing from the impaction plate to the filter.

To ascertain the unbiasedness of our procedures for the CYS and RES, filter blanks underwent the procedures for weighing, transport, and sampling during every tenth measurement (but no sample air was drawn through them). The mass difference of filter blanks weighing 90 mg remained <0.06 mg throughout this study. A paired-samples *t*-test by the GenStat software (VSN, 2012) on the data pairs (n=16) showed no significant difference ($P > 0.05$) between filter mass before and after sampling.

To achieve accurate weighing, we set the sampling duration for animal houses to 3 h, based on the sample flow rates of the CYS and RES (1 and 2.3 m^3 h^{-1} respectively), the resolution of the balance (10 μg), and the expected PM_{10} concentrations (0.2 to 5 mg m^{-3}). The actual mass of PM_{10} collected on the filters ranged from 380 to 14,110 μg for the CYS and from 840 to 29,030 μg for the RES. For the office location, we set the sampling duration to 24 h. At 3 h of sampling, each measurement yielded one PM_{10} concentration value for both the RES and CYS, 6 values for the BAS (logging interval: 30 min), 18 values for the TEOM (logging interval: 10 min), 180 values for the DT (logging interval: 1 min), and 18 values for the PAS (logging interval: 10 min). The mean of values collected within one measurement was used as the PM_{10} concentration for that measurement. All mass concentrations were recorded at the actual (non-standardized) conditions for air temperature and barometric pressure. No correction factors were programmed in the operating software of TEOM, BAS, DT, or PAS.

To be able to compare CASs to the RES over the full range of PM_{10} concentrations and climate conditions normally encountered in animal house air, we distributed the measurements over the growing cycle of pigs and broilers as much as possible, since PM_{10} concentrations usually increases and air temperature decreases with the age of these animals. In addition, we planned measurements both during the night (when lights are off, animals are inactive, and concentrations are low) and during the day (when concentrations are high; e.g., around feeding time).

Along with PM_{10} concentration, we monitored air temperature (T; °C) and relative humidity (RH; %) with combined sensors for T and RH (Rotronic Instrument Corp., Hauppauge NY, USA). Hourly mean T and RH values were stored in a data-logging system (Campbell Scientific Inc., Logan UT, USA).

Data checking, preparation, and analysis

In total, 139 measurements were carried out. Two measurements in pigs and one measurement in layers were excluded from this work because RES concentrations were below the EN 12341

breakpoint of 100 µg m^{-3}. Two measurements were excluded because no RES concentration was obtained. In total, 134 measurements were included in the dataset (Table 3). Data were checked for aberrant values which were excluded from the dataset only when they could be attributed to procedural or technical errors. All data collected with PAS device A in pigs and layers were excluded from the dataset, because a defect was discovered inside the inlet piece during layer house measurements. No statistical outlier test was performed. All analyses described in this paper were carried out using the GenStat software (VSN, 2012) and probability values <0.05 were considered statistically significant.

Table 3
Overview of measurements carried out per sampling location and summary statistics of PM_{10} concentration, indoor temperature and relative humidity.

Sampling location	Sampling period	*N*	PM_{10} (µg m^{-3}) [a]			Temperature (°C)			Relative humidity (%)		
			Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Pigs	Oct–Nov, '12	30	159	1402	511	24.6	27.0	25.5	51.1	66.4	58.7
Layers	Nov–Dec, '12	24	199	4100	2660	17.5	19.6	18.8	58.9	75.5	69.1
Broilers-1	Jan–Feb, '13	34 (46) [b]	857	3402	1881	18.3	24.8	22.5	57.0	76.0	65.4
Broilers-2	Apr, '13	19	497	2256	1543	19.5	29.2	25.0	43.6	80.1	63.5
Office	Feb–Mar, '13	15	4.1	21.3	10.4	21.6	24.0	22.6	17.9	31.8	24.3

[a] EN 12341 reference sampler concentration.
[b] For the CYS versus RES comparison only, an additional series of 12 measurements was carried out in broilers-1.

Comparability between devices A and B of the same sampler

A comparability analysis was performed to assess the degree to which two devices of the same sampler yield the same concentration values (Y_{i1} and Y_{i2}) when tested simultaneously and side by side. The analysis was performed as prescribed in paragraph 5.2.3 of EN 12341 (CEN, 1998). Ideally, devices yield identical concentration values ($D_i = Y_{i1} - Y_{i2} = 0$). For each combination of sampling location and sampler type, the absolute and relative standard deviation (S_a and S_r) were calculated (Eq. 1 and Eq. 3). Parameters S_a and S_r were multiplied by a Student's *t* factor to yield a two-sided confidence interval for the average concentration values (Y_i) at both the absolute and relative scale (Eq. 2 and Eq. 4):

$$S_a = \sqrt{\sum (D_i^2)/2n} \quad (1)$$

$$95\%\text{-}CI_a = S_a \times t_{(0.975;n-2)} \quad (2)$$

$$S_r = \sqrt{\sum (D_i / Y_i)^2 / 2n} \quad (3)$$

$$95\%\text{-}CI_r = S_r \times t_{(0.975;n-2)} \quad (4)$$

For data pairs with mean concentration values <100 µg m^{-3} (i.e., data from the office sampling) the CAS meets the EN 12341 requirement for comparability when 95%-$CI_a \leq 5$ µg m^{-3}. For data pairs with mean concentration values >100 µg m^{-3}, (i.e., data from pigs, layers, and broilers), the CAS meets the requirement for comparability when 95%-$CI_r \leq 0.05$ (i.e., 5% relative to Y_i).

For the RES however, Eq. 1 and Eq. 3 could not be used, because D_i cannot be determined for four samplers. Therefore, we used a nested model with RES concentration as dependent variable and measurement number as a single random term to estimate the variance within measurements for each sampling location. The square root of this variance was used as S_a to perform Eq. 2. The same procedure was carried out on the natural log scale to yield the S_r for Eq. 4.

Accuracy of candidate samplers with respect to the reference sampler

An accuracy analysis was performed to assess the degree to which CAS concentrations are consistent with RES concentrations. The analysis was carried out as prescribed in paragraph 5.2.4 of EN 12341 (CEN, 1998). Linear regression analysis was performed using the REML directive of GenStat, with the CAS concentration as the dependent variable, and the RES concentration and an intercept as model terms. We used deviance tests to determine whether location-specific model variances or a general (pooled) model variance could be used. In all cases, location-specific variances were used for the random part of the model. Ideally, in this linear model, the CAS yields concentrations identical to the RES, yielding a slope of 1 (y=x) and a zero intercept. In case of a zero intercept, a slope >1 reflects overestimation and a slope <1 reflects underestimation of the PM_{10} concentration by the CAS. An interaction term (RES concentration × sampling location) was used to test the null-hypothesis that slopes were identical between sampling locations. Pairwise *t*-tests were used to determine the significance of pairwise differences between slopes of sampling locations and of pairwise differences between intercepts of sampling locations. Data of a CAS obtained at different sampling locations were pooled when both slopes and intercepts were not significantly different and concentration ranges overlapped. The CAS meets the EN 12341 accuracy requirements when: a) the R^2 is greater than 0.95, and b) the computed regression falls within the two-sided acceptance envelop described by $y = x \pm 10$ µg m^{-3} for RES concentrations <100 µg m^{-3}, and ($y = 0.9x \mid y = 1.1x$) for RES concentrations >100 µg m^{-3}. Correction equations were determined by simple linear regression analysis, using the RES as dependent and the CAS as independent variable. Slope and intercept were included in the correction equation only when they were significantly different from 1 and zero respectively.

RESULTS AND DISCUSSION

An overview of performed measurements, RES concentrations, and climate conditions is given in Table 3.

Comparability between devices A and B of the same sampler

Results of the comparability analyses are given in Table 4. The comparability between devices A and B of samplers is also shown by differential symbols in Fig. 1. For concentrations greater than 100 μg m^{-3}, standard EN 12341 states that the relative 95%-confidence interval (95%-CI_r) must be smaller than 5% (relating here to the data from pigs, layers, and broilers). From Table 4 it is clear that none of the CASs met this requirement in any of the animal houses. Devices were best comparable for the TEOM in layers (6.6%), the CYS (9.4–14.4%; all animal houses), and the BAS in pigs (11.1%). For BAS, TEOM, and DT, 95%-CI_r values were highest in broilers-1 (39.2%, 37.1%, and 30.8% respectively). These values coincided with poor regression (Table 5), and were probably caused by pollution of these devices. When data of broilers-1 are disregarded, 11 of the remaining 13 values from pigs, layers, and broilers-2 range from 6.6 to 19.0%, whereas the BAS in layers (26.9%) and the PAS in broilers-2 (33.0%) are less comparable. For the CYS, the 95%-CI_r values found in this work (9.4–14.4%) are higher than the 6.0% found by Zhao et al. (2009). As mentioned earlier by Zhao et al. (2009), the 5% boundary in EN 12341 for ambient field tests may be too strict for animal house PM sampling. For the latter environments, a higher boundary seems appropriate for three reasons. First, even when devices were used that had recently been serviced, cleaned, and calibrated (i.e., in pigs and broilers-2), none of the CASs met this requirement. Second, Table 4 shows that, although comparability of the RES is better than for most CASs, its 95%-CI_r values exceeded the boundary too at all locations (range: 7.5–9.8%). Third, where the CYS, BAS, TEOM, and PAS did not meet the boundary for 95%-CI_r, they did meet the boundary of 5 μg m^{-3} for the 95%-CI_a at low office concentrations. Only the DT did not meet the 95%-CI_a boundary (Table 4). The uncertainty introduced by using a less strict 95%-CI_r boundary for animal houses may be compensated by using an average concentration value obtained from duplicate sampling (Hofschreuder et al., 2007). This approach is currently prescribed in the Dutch measurement protocol for determination of livestock PM emissions (Ogink et al., 2011).

Table 4
Results of the comparability analysis between devices A and B of the same sampler.

Sampler	Sampling location	*n*	PM_{10} (µg m^{-3})			95%-CI_a (µg m^{-3})	95%-CI_r (%)
			Min	Max	Mean		
RES	Pigs	30	159	1402	511	62.3	9.5
	Layers	24	199	4100	2660	245.6	7.9
	Broilers-1	46	857	3402	1881	186.1	9.8
	Broilers-2	19	497	2256	1543	126.0	7.5
	Office	15	4.1	21.3	10.4	2.3	20.8
CYS	Pigs	28	156	1302	457	40.4	12.9
	Layers	23	179	4425	2782	287.5	9.4
	Broilers-1	42	1010	4923	2701	252.2	10.7
	Broilers-2	19	500	2675	1702	199.8	14.4
	Office	15	2.9	20.7	9.9	2.1	30.1
BAS	Pigs	21	108	786	308	38.9	11.1
	Layers	18	207	2573	1752	445.2	26.9
	Broilers-1	30	282	1309	707	275.3	39.2
	Broilers-2	19	276	1233	817	160.9	18.1
	Office	14	2.4	18.9	7.7	1.8	16.6
TEOM	Pigs	20	116	962	423	82.6	19.0
	Layers	24	111	3022	1993	115.4	6.6
	Broilers-1	34	384	1860	1079	319.6	37.1
	Broilers-2	19	296	1529	1023	159.2	15.4
	Office	15	2.1	18.6	7.0	0.5	11.1
DT	Pigs	28	108	933	331	72.1	17.9
	Layers	23	107	2048	1445	287.9	18.9
	Broilers-1	29	553	1985	1261	377.9	30.8
	Broilers-2	19	277	1428	958	169.3	15.6
	Office	15	1.8	52.5	22.2	10.3	38.6
PAS	Broilers-1	32	1394	4449	2199	786.8	39.5
	Broilers-2	19	562	3632	2208	634.1	33.0
	Office	7	4.5	15.3	8.9	1.2	14.6

Accuracy of candidate samplers with respect to the reference sampler

Cyclone Sampler (CYS)

Results of the accuracy analysis for the CYS are given in Fig. 1A through 1E, Fig. 2, and Table 5. The CYS yielded concentrations very similar to the RES in layers and in the office environment, gave a small underestimation in pigs, and a small overestimation in broilers. For pigs, layers, and the office, CYS results are equivalent to the RES, since computed regression lines fall within the two-sided acceptance envelope (Figs. 1A, 1B, 1E) and R^2 values are greater than 0.95 (Table 5). For the broiler location, R^2 values were satisfactory too, but the regression lines slightly exceeded the upper boundary (Figs. 1C and 1D). The second measurements series at the broiler location (broilers-2) yielded a slope statistically identical to the slope of broilers-1. The tendency of the CYS to exceed the upper boundary in broilers is in accordance with the data

of Zhao et al. (2009) obtained at three fattening pig houses and one broiler house, but in the latter study the overestimation was more pronounced (slope: 1.20; intercept: -68 µg m^{-3}; R^2 = 0.99; n = 20). The correction equation computed from that data for CYS values greater than 223 µg m^{-3} was $y = 0.83x + 57.5$ µg m^{-3}. Based on the data presented here, however, a correction equation ($y = 0.85x + 89.5$ µg m^{-3}) would only be necessary for broilers, but not for pigs and layers. Pooling valid data from all animal houses (Fig. 2) resulted in equivalency to the RES, i.e., a regression within the two-sided acceptance envelope and a R^2 value of 0.98 (Table 5).

FH 62 I-R beta-attenuation sampler (BAS)

Results of the accuracy analysis for the BAS are given in Fig. 1F through 1J, Fig. 2, and Table 5. The BAS underestimated the RES concentration at all four sampling locations, with mean underestimations ranging from 16% for the office to 52% in pigs. For pigs and broilers-2, the underestimation was similar, as shown by their statistically undistinguishable slopes (Table 5). For these sampling locations, a correction factor of 1.88 would be appropriate (Table 6). The underestimation in layers (mean: 40%) is statistically different from those of pigs and broilers-2 and would require a different correction factor of 1.56 (Table 6). Pooling data from pigs, layers, and broilers-2 (Table 5 and Fig. 2) still yields a regression with a high fit (R^2 = 0.94), but it just fails the 0.95 requirement of EN 12341. It is possible however, that the differential regression in layers has been caused by a higher degree of pollution in comparison to pigs and broilers-2. We feel that these results need further confirmation, since to our knowledge only one study has been published on the comparison of a beta-attenuation sampler to a reference method in animal houses (Van Ransbeeck et al., 2013b). In the latter study, a limited number of data pairs obtained inside a pig house pointed towards an underestimation as well. In National Air Quality Monitoring Networks of European countries, correction factors ranging between 0.84 and 1.37 are used to adjust PM_{10} concentrations measured by beta-attenuation samplers (Gebicki and Szymańska, 2011). Thus, our data suggest that, compared to ambient aerosol sampling, underestimations are greater when sampling animal house PM.

Fig. 1

PM_{10} concentrations of candidate samplers (y-axes) as a function of the EN 12341 reference sampler concentration (x-axes), for five candidate samplers (one sampler in each row), tested at four sampling locations (one location in each column), presented following the procedure described in paragraph 5.2.4 of EN 12341. Dashed green lines represent the ideal reference equivalence function $y = x$. Solid black lines adjacent to the $y = x$ function represent the two-sided acceptance envelopes for concentrations >100 µg m^{-3} ($y = 0.9x \mid y = 1.1x$; shown for pigs, layers, and broilers), and for concentrations <100 µg m^{-3} ($y = x \pm 10$; shown for the office). Differential symbols are used for devices A (round symbols) and B (square symbols). Regression lines are given by solid red lines through the observations (see Table 5 for regression coefficients and statistical tests).

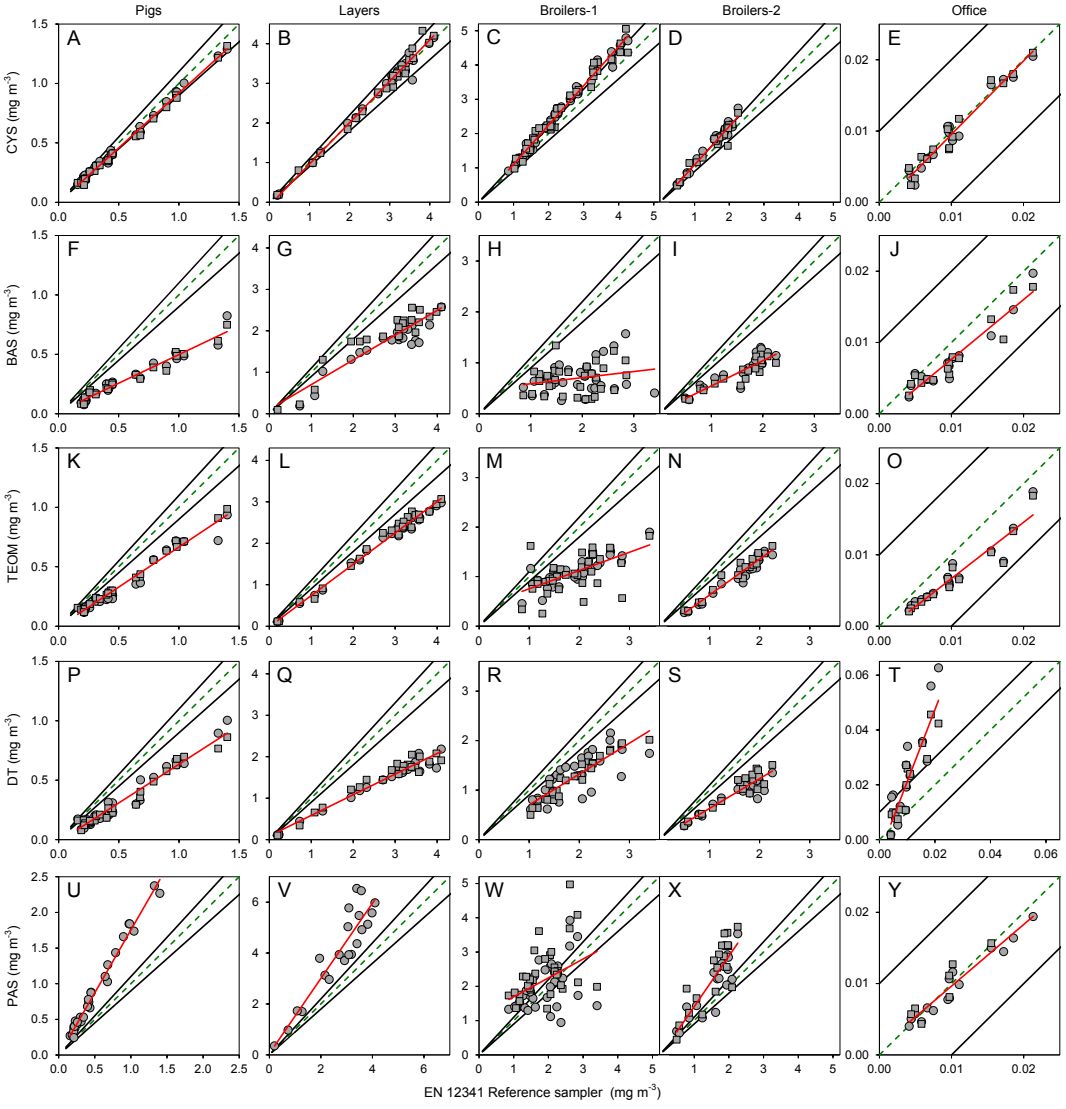


Table 5
Results of the linear regression analysis on PM_{10} concentration of candidate samplers as a function of EN 12341 reference sampler concentration. Each slope was tested against the null-hypothesis that it equals one (representing a $y = x$ relationship when the intercept is zero) and each intercept was tested against the null-hypothesis that it equals zero. Slopes or intercepts followed by $^{n.s.}$ are not significantly different from one and zero respectively, whereas star symbols indicate rejection of the null-hypothesis at a significance level of 0.05 (*), 0.01 (**), or 0.001 (***). Slopes or intercepts followed by different letters in parenthesis within the same column are significantly different ($P < 0.05$) between sampling locations. Intercepts in μg m^{-3}.

Sampler	Sampling location	Device	*n*	Slope (se)	Intercept (se)	R^2
CYS	1. Pigs	A and B	58	0.92 (0.01) *** [a]	-3.5 (5.6) n.s. [a]	0.995
	2. Layers	A and B	47	1.04 (0.02) * [b]	-81.2 (63.2) n.s. [a]	0.981
	3. Broilers-1	A and B	87	1.15 (0.02) *** [c]	-47.0 (44.5) n.s. [a]	0.980
	4. Broilers-2	A and B	38	1.12 (0.04) ** [b, c]	-28.6 (67.7) n.s. [a]	0.952
	5. Office (<100 μg m^{-3})	A and B	30	1.03 (0.04) n.s. [b]	0.8 (0.5) n.s. [a]	0.960
	Pooled: 2 and 4	A and B	85	1.01 (0.02) n.s.	70.5 (42.3) n.s.	0.976
	Pooled: 3 and 4	A and B	125	1.15 (0.01) ***	-58.2 (33.2) n.s.	0.981
	Pooled: 1, 2, 3, and 4	A and B	230	1.10 (0.01) ***	-46.6 (22.0) *	0.981
BAS	1. Pigs	A and B	47	0.48 (0.02) *** [a]	16.4 (10.2) n.s. [a]	0.956
	2. Layers	A and B	41	0.60 (0.04) *** [b]	106 (113) n.s. [a]	0.856
	3. Broilers-1	A and B	63	0.12 (0.06) *** [c]	470 (120) *** [b]	0.043
	4. Broilers-2	A and B	38	0.50 (0.04) *** [a, b]	51.8 (66.4) n.s. [a]	0.800
	5. Office (<100 μg m^{-3})	A and B	29	0.84 (0.05) ** [d]	0.8 (0.6) n.s. [a]	0.907
	Pooled: 1 and 4	A and B	85	0.52 (0.02) ***	6.0 (18.2) n.s.	0.932
	Pooled: 2 and 4	A and B	79	0.65 (0.03) ***	-102 (59.2) n.s.	0.898
	Pooled: 1, 2, and 4	A and B	126	0.63 (0.01) ***	-70.0 (27.3) *	0.942
TEOM	1. Pigs	A and B	49	0.67 (0.02) *** [a]	-7.8 (11.5) n.s. [a]	0.970
	2. Layers	A and B	48	0.76 (0.01) *** [b]	-15.0 (36.3) n.s. [a]	0.987
	3. Broilers-1	A and B	68	0.37 (0.05) *** [c]	385 (102) *** [b]	0.426
		A	34	0.41 (0.05) ***	330 (91.2) ***	0.701
		B	34	0.33 (0.09) ***	441 (185) *	0.255
	4. Broilers-2	A and B	38	0.73 (0.03) *** [a, b]	-98.4 (48.6) n.s. [a]	0.941
	5. Office (<100 μg m^{-3})	A and B	30	0.79 (0.05) *** [b]	-1.2 (0.6) * [c]	0.903
	Pooled: 1 and 4	A and B	87	0.68 (0.01) ***	-22.0 (14.2) n.s.	0.974
	Pooled: 2 and 4	A and B	86	0.78 (0.01) ***	-130 (27.3) ***	0.983
	Pooled: 1, 2, and 4	A and B	135	0.76 (0.01) ***	-76.7 (14.1) ***	0.988
DT	1. Pigs	A and B	59	0.65 (0.02) *** [a]	-16.5 (10.7) n.s. [a]	0.961
	2. Layers	A and B	47	0.50 (0.02) *** [b]	85.5 (47.3) n.s. [b]	0.954
	3. Broilers-1	A and B	59	0.62 (0.05) *** [a]	74.9 (99.1) n.s. [a, b]	0.730
		A	29	0.54 (0.09) ***	254 (185) n.s.	0.542
		B	30	0.71 (0.03) ***	-103.5 (69.7) n.s.	0.934
	4. Broilers-2	A and B	38	0.60 (0.04) *** [a]	29.5 (68.5) n.s. [a, b]	0.846
	5. Office (<100 μg m^{-3})	A and B	30	2.63 (0.24) *** [c]	-5.2 (2.8) n.s. [a, b]	0.801
	Pooled: 1 and 4	A and B	97	0.62 (0.01) ***	-1.2 (16.0) n.s.	0.953
	Pooled: 1, 2, 3(B), and 4	A and B	174	0.53 (0.01) ***	79.6 (18.9) ***	0.945
PAS	1. Pigs	A	30	1.76 (0.04) *** [a]	-8.8 (26.5) n.s. [a]	0.983
	2. Layers	A	21	1.48 (0.14) ** [a]	53.0 (405) n.s. [a]	0.849
	3. Broilers-1	A and B	66	0.55 (0.14) ** [b]	1142 (284) *** [b]	0.175
	4. Broilers-2	A and B	38	1.47 (0.15) ** [a]	-66.0 (247) n.s. [a]	0.717
	5. Office (<100 μg m^{-3})	A and B	22	0.86 (0.06) * [c]	1.0 (0.7) n.s. [a]	0.908
	Pooled: 1, 2, and 4	A and B	89	1.46 (0.05) ***	55.5 (84.5) n.s.	0.917

Fig. 2
PM_{10} concentrations of candidate samplers (*y*-axes) as a function of the EN 12341 reference sampler concentration (*x*-axes), pooled for pigs (white symbols), layers (grey symbols), and broilers (black symbols). Broiler data points are based on the broiler-2 measurements for the BAS, TEOM, and PAS. For the CYS, broiler data points are based on broilers-1 and broilers-2. For the DT, broiler data points are based on device B of broiler-1 and all data from broilers-2. Dashed green line: the ideal reference equivalence function $y = x$. Solid black lines adjacent to the $y = x$ function represent the two-sided acceptance envelope for concentrations >100 µg m^{-3} ($y = 0.9x \mid y = 1.1x$). Regression lines are given by solid red lines through the observations (see the lowest row of each sampler in Table 5 for regression coefficients and statistical tests of the pooled data).

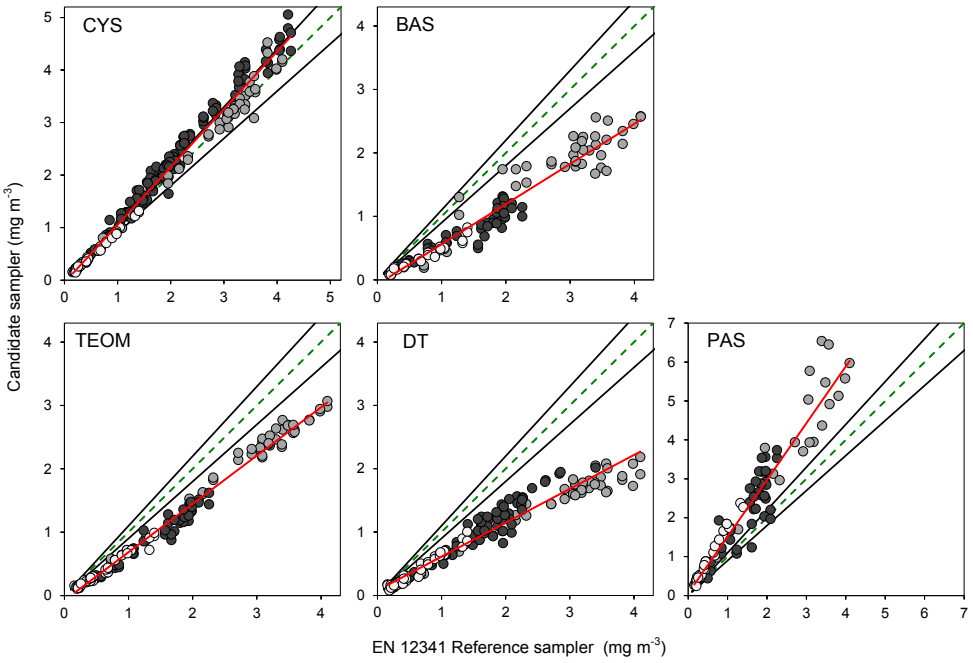


Table 6
Equations for calibration of candidate sampler PM_{10} concentrations (*x*) to EN 12341 reference sampler concentrations (*y*).

Sampler	Animal category			
	Pigs	Layers	Broilers	All data
CYS	$y = 1.09x$ [a]	$y = 0.96x$ [a, b]	$y = 0.85x + 89.5$ [c]	$y = 0.89x + 76.1$ [a, d]
BAS	$y = 1.88x$ [e]	$y = 1.56x$	$y = 1.88x$ [e]	$y = 1.49x + 195$ [f]
TEOM	$y = 1.42x + 56.4$ [e]	$y = 1.26x + 201$ [b]	$y = 1.30x + 216$	$y = 1.30x + 118$ [f]
DT	$y = 1.58x$ [e]	$y = 1.89x$	$y = 1.58x$ [e]	$y = 1.73x$ [g]
PAS	$y = 0.66x$ [f]	$y = 0.66x$ [f]	$y = 0.66x$ [f]	$y = 0.66x$ [f]

[a] Equivalent to the RES, i.e., regression falls within the two-sided acceptance envelope and R^2>0.95.
[b] Based on the pooled data of layers and broilers-2.
[c] Based on the pooled data of broilers-1 and broilers-2.
[d] Based on the pooled data of pigs, layers, broilers-1, and broilers-2.
[e] Based on the pooled data of pigs and broilers-2.
[f] Based on the pooled data of pigs, layers, and broilers-2.
[g] Based on the pooled data of pigs, layers, broilers-1A, and broilers-2.

Tapered Element Oscillating Microbalance (TEOM)

Results of the accuracy analysis for the TEOM are given in Fig. 1K through 1O, Fig. 2, and Table 5. The TEOM underestimated the RES concentration at all four sampling locations, with mean underestimations ranging from 21% for the office to 33% in pigs. The slope in pigs (0.67) was lower than in layers (0.76), but the slopes of pigs versus broilers-2, and the slopes of layers versus broilers-2 were undistinguishable (Table 5). Pooling data from all three animal houses (Table 5 and Fig. 2) resulted in a regression with a very good fit ($R^2 = 0.99$), meeting the 0.95 requirement of standard EN 12341. Therefore, one might consider to use a single, overall correction equation ($y = 1.30x + 118$; Table 6) for the TEOM. The underestimations in our work are in agreement with Q. F. Li et al. (2012), who found that a standard configured TEOM underestimated PM_{10} concentrations in a caged layer house too, as compared to a filter-based PM_{10} Federal Reference Method (slope: 0.858; intercept: 71.3 μg m^{-3}; $R^2 = 0.86$; $n = 15$). However, in the latter study, a US PM_{10} impactor (US-EPA, 2014) was used for both the TEOM and RES, whereas in our work, a European impactor was used for the RES. Furthermore, our results are in agreement with ambient field tests which generally show that the TEOM underestimates the RES concentration (e.g., Charron et al., 2004, and references therein). Consequently, correction factors ranging between 1 and 1.47 are used in National Air Quality Monitoring Networks of European countries (Gebicki and Szymańska, 2011). Several studies on ambient aerosols have shown that TEOM to RES differences vary between sampling sites and between seasons as a result of differences in aerosol composition and meteorological conditions. Generally, differences increase with increasing aerosol fractions of volatile compounds (e.g., ammonium nitrate), decreasing air temperature, and increasing air humidity (Allen et al., 1997; Charron et al., 2004; Hauck et al., 2004). Consequently, Green et al. (2001) showed that the use of a single TEOM correction factor is not sufficient to adequately adjust these effects. Two reasons however, may explain why in this work a single correction factor does seem to be a satisfactory solution. First, the composition of animal house PM may be more homogeneous and relatively low in ammonium nitrate content in comparison with ambient PM. Animal house PM consists mainly of primary particles from fecal material, feathers, and skin debris, generated by drying and the mechanical forces exerted on these materials by the animals. These sources show similarities between animal categories (Cambra-López et al., 2011). Q. F. Li et al. (2012) recently showed that ammonium nitrate made up a negligible part of the $PM_{2.5}$ mass concentration in a caged layer house. This suggests that underestimations related to the volatilization of ammonium nitrate play a minor role in animal houses. Second, in many countries, pig and poultry houses are insulated and equipped with mechanical ventilation systems

to keep indoor temperature and relative humidity within optimal boundaries (Table 3). In contrast to the ambient environment, indoor temperatures in these houses usually remain above 15°C and relative humidity usually remains between approximately 40 and 85% (Winkel et al., 2014), conditions under which volatilization is less present in ambient air studies.

DustTrak light scattering device (DT)

Results of the accuracy analysis for the DT are given in Fig. 1P through 1T, Fig. 2, and Table 5. The DT underestimated the RES concentration at all animal houses, with mean underestimations of 35% in pigs, 40% in broilers-2, and 50% in layers. The statistical analysis showed that the underestimation was identical for pigs and broilers-2, whereas the underestimation was greater in layers (Table 5). For the DT, pooling of animal house data (Table 5 and Fig. 2) resulted in a regression with a good fit ($R^2 = 0.95$), equal to the requirement of EN 12341. Therefore, the use of a single, overall correction factor ($y = 1.73x$; Table 6) may be a reasonable procedure for the DT too.

Recently, Cambra-López et al. (2014) compared the DT to the CYS as a filter-based reference and found a relationship of $y = 0.61x + 50$ μg m^{-3} for pig houses (16 houses; $n = 64$; $R^2 = 0.84$) and $y = 0.41x + 160$ μg m^{-3} for poultry houses (16 houses; $n = 55$; $R^2 = 0.91$), where y is the PM_{10} concentration of the DT and x the CYS concentration. In the present dataset, computed DT to CYS relationships were $y = 0.73x - 3$ μg m^{-3} for the pig house ($n = 49$; $R^2 = 0.98$) and $y = 0.76x - 144$ μg m^{-3} for layers and broilers-2 ($n = 86$; $R^2 = 0.96$). Post et al. (2010) reported that the DT gave lower concentrations than the TEOM in a broiler house (mean difference: 600 μg m^{-3}). In the present dataset, however, DT and TEOM underestimated the RES concentration in a very similar manner, yielding a $y = x$ relationship between the two ($R^2 = 0.998$; $n = 128$). Hence, the underestimation of the DT to the CYS reported by Cambra-López et al. (2014) can be found in the present dataset too, but the DT seems to approach both the CYS and TEOM more closely than reported in other studies.

In contrast to animal houses, the DT overestimated RES concentrations in the office by a factor 2.63 (Fig. 1 and Table 5). Overestimation of the DT model 8520 to a filter-based PM_{10} reference method was also reported by Cheng (2008) in an iron foundry (slope: 1.37; intercept: -98.82 μg m^{-3}; $R^2 = 0.91$; approximate PM_{10} range: 120–710 μg m^{-3}), and by Heal et al. (2000) in an urban indoor environment (slope: 2.2; intercept: -12 μg m^{-3}; r=0.95; approximate PM_{10} range: 5–33 μg m^{-3}). Our results and those presented in the papers discussed illustrate that DT to RES differences may vary significantly between sampling environments and stress the necessity of

either recalibrating DTs with the aerosol of interest or using specific correction factors for standard-calibrated DTs in animal houses.

Portable Aerosol Spectrometer (PAS)

Results of the accuracy analysis for the PAS are given in Fig. 1U through 1Y, Fig. 2, and Table 5. The PAS overestimated the RES concentration at all animal houses. The statistical analysis showed that this underestimation was statistically undistinguishable between pigs, layers, and broilers-2 (Table 5). Therefore, a single, overall correction factor $y = 0.66x$ (Table 6) would be appropriate when using the PAS in animal houses. The regression of the pooled data of pigs, layers, and broilers-2, underlying this correction factor, showed a fit of 0.92, which is however, below the 0.95 requirement of EN 12341. Recently, Van Ransbeeck et al. (2013b) investigated the equivalence of two PAS devices to a filter-based PM_{10} reference method in a pig house and found PAS to RES relationships of $y = 1.28x - 5$ μg m^{-3} for device 1 and $y = 1.67x - 112$ μg m^{-3} for device 2. The relationship found in the pig house in this work (based on one device; $y = 1.76x - 8.8$ μg m^{-3} ; Table 5), agrees reasonably well with these previously found relationships.

Estimation of non-routine service intervals

In Fig. 1 the CAS to RES concentration values obtained at the pig house, layer house, and broilers-1 are presented in chronological order from left to right. From Fig. 1 it is clear that the accuracy of BAS, TEOM, DT, and PAS in broilers-1 was substantially worse as compared to pigs and layers. This impression is more precisely reflected by slopes significantly different from other sampling locations, by the finding of substantial intercepts significantly different from zero, and by relatively low R^2 values for broilers-1 (Table 5). For the TEOM, aberrant values were mainly produced by device B, and for the DT by device A, whereas TEOM device A and DT device B showed somewhat better results (Table 5). The poor regressions in broilers-1 are also visible from the high 95%-CI_r values obtained from the comparability analysis (Table 3).

This poor CASs performance has probably been caused by a too long time interval between full service events (e.g., non-routine cleaning of the interior of the sampler and mass calibration), in addition to frequent service points, like cleaning inlets and replacing internal filters (Table 2). Pollution of the interior of the samplers may have been a main cause for three reasons. First, good regression was still found in broilers-1 for the CYS (Fig. 1 and Table 5) which was not sensitive to pollution because it was fully disassembled and wet cleaned every 15–30 h of operation. Second, during a full service of the BAS, TEOM, DT, and PAS after broilers-1, the

interior of these devices proved to be clearly polluted by dust, despite our intensive care to minimize this (Table 2). Pollution of devices became apparent by a brown discoloration of internal filters, by thin layers or clots of PM inside tubes and chambers, and by PM deposited onto the optics of the DT and the PAS. Third, after samplers had been fully cleaned and calibrated, results obtained in the office and during the second measurement series in broilers (broilers-2) were again satisfactory.

Our results suggest that CAS performance deteriorated quite rapidly after it had reached a critical operating time during the broilers-1 phase of this study. By the end of the layer house measurements, BAS, TEOM, DT, and PAS had been operated for 432, 453, 500, and 469 h respectively (equivalent to 18–21 sampling days) at a mean PM_{10} concentration of 1466 μg m^{-3}. Assuming that internal pollution was the main cause of the poor CAS performances in broilers-1, the total load of PM_{10} drawn through each CAS might be a better indicator to obtain 'safe' time intervals between non-routine (full) services. This loading can be determined by accumulating the multiplication products of sampling duration, samplers' flow rate (Table 1) and RES concentration, for each measurement. After the measurement series in pigs and layers, these loadings amounted 557 mg for the BAS, 116 mg for the TEOM, 66 mg for the DT, and 43 mg for the PAS. Safe time intervals between full services may then be estimated by dividing these loadings by the sampling flow applied and a (mean) PM_{10} concentration expected. For a number of concentration levels, time intervals are calculated and given in Table 7. From this table it is clear that the time intervals obtained from this approach for concentrations less than 100 μg m^{-3} agree well with those prescribed in operating manuals (i.e., 6 to 12 months; Table 2). At high concentrations in animal houses however, samplers should be serviced more frequently, as reported by Heber et al. (2006) as well.

Table 7
Computed 'safe' time intervals (sampling days) between non-routine services.

Sampler	Mean PM_{10} concentration level (μg m^{-3})					
	25	100	500	1000	2500	5000
BAS	928	232	46	23	9	5
TEOM	1074	269	54	27	11	5
DT	1078	270	54	27	11	5
PAS	995	249	50	25	10	5

Advantages, limitations and implications of this study

Rather than performing an in-depth study into the artifacts associated with one specific sampler, this study attempted to provide a broad knowledge basis on the accuracy and

comparability of multiple samplers with various working principles in three main animal housings. An advantage of this approach is that a solid impression could be obtained for many samplers on a valid basis of comparison. At the same time, this approach makes it difficult to elucidate to what extent a CAS to RES relationship varies over prolonged periods of time within a house, varies between houses of a housing system, between housing systems within an animal category, or between animal categories. Some insight into the reproducibility of the CYS performance can be obtained from comparing results from broilers-1 and broilers-2 (Table 5). Despite that broilers-2 was carried out two months later in a next flock of broilers, both the slope and intercept of this series were statistically undistinguishable from broilers-1, indicating that the CYS to RES relationship was reproducible in time within this specific farm location. Variation in a CAS to RES relationship, both within and between houses, could arise from differences in in air humidity, particle size distribution, particle shape, chemical composition, and so on. Such variables might interact with the sampler's pre-separation or measuring principle to yield varying relationships. This reasoning might explain why in a previous comparison in three pig houses and one broiler house (Zhao et al., 2009), the CYS overestimated the RES concentration, whereas in the present study, an overestimation was found for broilers but only slightly for layers and not for pigs. With regard to these variations, it seems promising that: (1) air temperature and relative humidity in most housing systems for poultry and pigs are kept within limits that are narrower than the meteorological conditions outdoors (Winkel et al., 2015), (2) sources of PM show similarities between animal categories (Cambra-López et al., 2011), (3) relationships between CASs and the RES were reasonably consistent between the three animal categories (Fig. 2 and Table 5), and (4) relationships are reasonably consistent with those reported in literature so far.

In summary, this study implies that, for the present, duplicate sampling can be applied to reduce random errors related to differences between samplers, whereas correction factors (specific to the level of animal categories or animal housing systems) can be determined and applied to reduce systematic deviations from a reference sampler. Furthermore, shortened time intervals between full servicing of samplers can be adopted to avoid malfunctioning due to pollution. When such measures are applied, some of the samplers tested could be regarded acceptable. In future, in-depth studies are needed to further increase our understanding of specific artifacts of samplers, of their comparability and their accuracy to reference samplers, and of adequate measures to ensure their proper functioning.

CONCLUSIONS

In this study we investigated the accuracy and comparability of five candidate samplers when measuring high PM_{10} concentrations (>100 μg m^{-3}) inside a fattening pig house, a laying hen house, and a broiler house, following the main principles of European standard EN 12341. Our key results and conclusions can be summarized as follows:

1. Neither one of the five candidate samplers, nor the reference sampler itself, met the EN 12341 requirement for comparability between devices of the same sampler type. Using a less strict boundary for animal house environments may be appropriate. The uncertainty from using a less strict boundary may subsequently be compensated by using an average concentration value obtained from duplicate sampling.
2. The CYS met the EN 12341 accuracy requirements in pigs and layers, but overestimated RES concentrations in broilers. When pooling data of all three houses, the CYS fulfilled the accuracy requirements. The BAS, TEOM, and DT underestimated, and the PAS overestimated, RES concentrations in a very systematic manner. The use of correction factors seem to be a promising method to calibrate measured values to RES concentrations.
3. The BAS, TEOM, DT, and PAS started to show scattered regression with regard to the RES after 432–500 h of sampling, which was probably caused by pollution of the interior of these devices. Shortened time intervals between non-routine (full) services should be adopted when using these samplers inside animal houses.
4. Some of the samplers tested could be regarded acceptable when appropriate measures (such as duplicate sampling, correction factors, and frequent servicing) are applied.

ACKNOWLEDGMENTS

This work was financed by the Dutch Ministry of Economic Affairs and the Dutch Ministry of Infrastructure and Environment. We would like to express our gratitude to the participating farmers for allowing our presence in their buildings for many weeks. We thank Mr. Eef Lovink for carefully servicing the equipment, Mr. Jean Slangen for weighing the filters, Mr. Peter Hofschreuder for stimulating discussions, and Mr. Johan van Riel for advice on the Genstat procedures.

REFERENCES

Adell, E., Calvet, S., Torres, A.G., Cambra-López, M.M., 2012. Particulate matter concentrations and emissions in rabbit farms. *World Rabbit Sci.* 20:1–11.

Allen, G., Sioutas, C., Koutrakis, P., Reiss, R., Lurmann, F.W., Roberts, P.T., 1997. Evaluation of the TEOM(R) method for measurement of ambient particulate mass in urban areas. *J. Air Waste Manag. Assoc.* 47:682–689.

Andersen, K.B., Glasius, M., Feilberg, A., 2014. Gas-particle partitioning of odorants in a pig house measured by thermal desorption GC/MS. *Environ. Sci. Process. Impacts* 16:1059–1068.

Brunekreef, B., Holgate, S.T., 2002. Air pollution and health. *Lancet* 360:1233–1242.

Calvet, S., van den Weghe, H., Kosch, R., Estellés, F., 2009. The influence of the lighting program on broiler activity and dust production. *Poult. Sci.* 88:2504–2511.

Cambra-López, M., Aarnink, A.J.A., Zhao, Y., Calvet, S., Torres, A.G., 2010. Airborne particulate matter from livestock production systems: A review of an air pollution problem. *Environ. Pollut.* 158:1–17.

Cambra-López, M., Hermosilla, T., Lai, H.T.L., Aarnink, A.J.A., Ogink, N.W.M., 2011. Particulate matter emitted from poultry and pig houses: Source identification and quantification. *Trans. ASABE* 54:629–642.

Cambra-López, M., Winkel, A., Mosquera, J., Ogink, N.W.M., Aarnink, A.J.A., 2014. Comparison of light scattering devices and gravimetric samplers for PM10 mass concentration in livestock houses. *Atm. Environ* 111:20–27.

CEN, 1998. EN 12341:1998. Air quality - Determination of the PM 10 fraction of suspended particulate matter - Reference method and field test procedure to demonstrate reference equivalence of measurement methods. European Committee for Standardization (CEN), Brussels, Belgium.

CEN, 2005. EN 14907:2005. Ambient air quality - Standard gravimetric measurement method for the determination of the PM2.5 mass fraction of suspended particulate matter. European Committee for Standardization (CEN), Brussels, Belgium.

Charron, A., Harrison, R.M., Moorcroft, S., Booker, J., 2004. Quantitative interpretation of divergence between PM10 and PM2.5 mass measurement by TEOM and gravimetric (Partisol) instruments. *Atm. Environ.* 38:415–423.

Cheng, Y.H., 2008. Comparison of the TSI model 8520 and Grimm Series 1.108 portable aerosol instruments used to monitor particulate matter in an iron foundry. *J. Occup. Environ. Hyg.* 5:157–168.

Costa, A., Ferrari, S., Guarino, M., 2012. Yearly emission factors of ammonia and particulate matter from three laying-hen housing systems. *Anim. Prod. Sci.* 52:1089–1098.

Costa, A., Guarino, M., 2009. Definition of yearly emission factor of dust and greenhouse gases through continuous measurements in swine husbandry. *Atm. Environ.* 43:1548–1556.

Demmers, T.G.M., Saponja, A., Thomas, R., Phillips, G.J., McDonald, A.G., Stagg, S., Bowry, A., Nemitz, E., 2010. Dust and ammonia emissions from UK poultry houses. In: XVII-th World Congress of the Int. Comm. of Agric. and Biosyst. Eng. (CIGR). Québec city, Canada.

Fabbri, C., Valli, L., Guarino, M., Costa, A., Mazzotta, V., 2007. Ammonia, methane, nitrous oxide and particulate matter emissions from two different buildings for laying hens. *Biosyst. Eng.* 97:441–455.

Gebicki, J., Szymańska, K., 2011. Comparison of tests for equivalence of methods for measuring PM10 dust in ambient air. *Polish J. Environ. Stud.* 20:1465–1472.

Görner, P., Bemer, D., Fabries, J.F., 1995. Photometer measurement of polydisperse aerosols. *J. Aerosol Sci.* 26: 1281–1302.

Green, D., Fuller, G., Barratt, B., 2001. Evaluation of TEOM (TM) 'correction factors' for assessing the EU Stage 1 limit values for PM10. *Atm. Environ.* 35:2589–2593.

GRIMM. (2010). Portable laser aerosolspectrometer and dust monitor model 1.108/1.109. Ooperating manual, GRIMM Aerosol Technique GmbH & Co. KG, Ainring, Germany.

Haeussermann, A., Costa, A., Aerts, J.M., Hartung, E., Jungbluth, T., Guarino, M., Berckmans, D., 2008. Development of a dynamic model to predict PM10 emissions from swine houses. *J. Environ. Qual.* 37:557–564.

Hauck, H., Berner, A., Gomiscek, B., Stopper, S., Puxbaum, H., Kundi, M., Preining, O., 2004. On the equivalence of gravimetric PM data with TEOM and beta-attenuation measurements. *J. Aerosol Sci.* 35:1135–1149.

Hayes, M.D., Xin, H., Li, H., Shepherd, T.A., Zhao, Y., Stinn, J.P., 2013. Ammonia, greenhouse gas, and particulate matter emissions of aviary layer houses in the Midwestern U.S. *Trans. ASABE* 56:1921–1932.

Heal, M.R., Beverland, I.J., McCabe, M., Hepburn, W., Agius, R.M., 2000. Intercomparison of five PM10 monitoring devices and the implications for exposure measurement in epidemiological research. *J. Environ. Monit.* 2:455–461.

Heber, A.J., Lim, T.T., Ni, J.Q., Tao, P.C., Schmidt, A.M., Koziel, J.A., Hoff, S.J., Jacobson, L.D., Zhang, Y.H., Baughman, G.B., 2006. Quality-assured measurements of animal building emissions: Particulate matter concentrations. *J. Air Waste Manag. Assoc.* 56:1642–1648.

Hofschreuder, P., Aarnink, A.J.A., Zhao, Y., Ogink, N.W.M., 2007. Measurement protocol for determining fine dust emission factors of animal housing systems. In: DustConf 2007, How to improve air quality, Maastricht, the Netherlands.

Joo, H.S., Ndegwa, P.M., Heber, A.J., Ni, J.Q., Bogan, B.W., Ramirez-Dorronsoro, J.C., Cortus, E.L., 2013. Particulate matter dynamics in naturally ventilated freestall dairy barns. *Atm. Environ.* 69:182–190.

Koziel, J.A., Baek, B.H., Bush, K.J., Balota, A., Bayley, C.L., Sweeten, J.M., 2004. Emissions of particulate matter from swine finish barns in Texas. In: Proceedings of the AgEng 2004 "Engineering the Future" Conference, Europ. Soc. of Agric. Eng. (EurAgEng), Leuven, Belgium.

Li, Q.F., Lingjuan, W.L., Liu, Z.F., Heber, A.J., 2012. Field evaluation of particulate matter measurements using tapered element oscillating microbalance in a layer house. *J. Air Waste Manag. Assoc.* 62:322–335.

Li, S., Li, H., Xin, H., Burns, R.T., 2011. Particulate matter concentrations and emissions of a high-rise layer house in Iowa. *Trans. ASABE* 54:1093–1101.

Lin, X.J., Cortus, E.L., Zhang, R., Jiang, S., Heber, A.J., 2012. Air emissions from broiler houses in California. *Trans. ASABE* 55:1895–1908.

McMurry, P.H., 2000. A review of atmospheric aerosol measurements. *Atm. Environ.* 34:1959–1999.

Modini, R.L., Agranovski, V., Meyer, N.K., Gallagher, E., Dunlop, M., Ristovski, Z.D., 2010. Dust emissions from a tunnel-ventilated broiler poultry shed with fresh and partially reused litter. *Anim. Prod. Sci.* 50:552–556.

Morgan, R.J., Wood, D.J., Van Heyst, B.J., 2014. The development of seasonal emission factors from a Canadian commercial laying hen facility. *Atm. Environ.* 86:1–8.

Ni, J.Q., Chai, L., Chen, L., Bogan, B.W., Wang, K., Cortus, E.L., Heber, A.J., Lim, T.T., Diehl, C.A., 2012. Characteristics of ammonia, hydrogen sulfide, carbon dioxide, and particulate matter concentrations in high-rise and manure-belt layer hen houses. *Atm. Environ.* 57:165–174.

Ogink, N.W.M., Hofschreuder, P., Aarnink, A.J.A., 2011. Protocol for the measurement of fine dust emissions from housings in animal production 2010 [in Dutch, with English summary]. Report 492, Wageningen University and Research Centre, Livestock Research, Lelystad, the Netherlands.

Pope, C.A., Dockery, D.W., 2006. Health effects of fine particulate air pollution: Lines that connect. *J. Air Waste Manag. Assoc.* 56:709–742.

Post, J.P., Bajwa, S.G., Liang, Y., Costello, T.A., 2010. A comparison of particulate matter concentration measured by TEOM and DustTrak. ASABE publication number 711P0510cd. In: International Symposium on Air Quality and Manure Management for Agriculture. American Society of Agricultaral and Biological Engineers (ASABE), Dallas, TX, USA.

RIVM, 2011. Annual national emissions of PM10; in total and per sector/source, for 2011 (website of the Pollutant Release and Transfer Register). http://www.emissieregistratie.nl (Last accessed: 18 June 2013). National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands.

Roumeliotis, T.S., Dixon, B.J., Van Heyst, B.J., 2010a. Characterization of gaseous pollutant and particulate matter emission rates from a commercial broiler operation part I: Observed trends in emissions. *Atm. Environ.* 44: 3770–3777.

Roumeliotis, T.S., Dixon, B.J., Van Heyst, B.J., 2010b. Characterization of gaseous pollutant and particulate matter emission rates from a commercial broiler operation part II: Correlated emission rates. *Atm. Environ.* 44: 3778–3786.

Roumeliotis, T.S., Van Heyst, B.J., 2007. Size fractionated particulate matter emissions from a broiler house in Southern Ontario, Canada. *Sci. Total Environ.* 383:174–182.

Rupprecht, Patashnick., 2004. Operating manual TEOM series 1400a. Edition: June 2004. Rupprecht & Patashnick Co., Inc.

Thermo, 2004. FH 62 I-R operating instructions. Edition: February 11, 2004. Thermo Electron Corp., Erlangen, Germany.

TSI, 2010. Operation and service manual, DustTrak aerosol monitor, model 8520. Edition: June 2010. TSI Inc., Shoreview, USA.

US-EPA, 2013. List of designated reference and equivalent methods. Edition: 27 June 2013. Available from: http://www.epa.gov/ttn/amtic/criteria.html. Environmental Protection Agency (EPA).

US-EPA., 2014. Reference method for the determination of fine particulate matter as PM2.5 in the atmosphere. Environmental Protection Agency (EPA).

Van Ransbeeck, N., Van Langenhove, H., Demeyer, P., 2013a. Indoor concentrations and emissions factors of particulate matter, ammonia and greenhouse gases for pig fattening facilities. *Biosyst. Eng.* 116:518–528.

Van Ransbeeck, N., Van Langenhove, H., Van Weyenberg, S., Maes, D., Demeyer, P., 2012. Typical indoor concentrations and emission rates of particulate matter at building level: A case study to setup a measuring strategy for pig fattening facilities. *Biosyst. Eng.* 111:280–289.

Van Ransbeeck, N., Van Weyenberg, S., Van Langenhove, H., Demeyer, P. (2013b). Indoor concentration measurements of particulate matter at a pig fattening facility: Comparison and equivalence tests with different sampling instruments and measuring techniques. *Biosystems Engineering,* 115, 453–462.

Visser, M.C., Fairchild, B., Czarick, M., Lacy, M., Worley, J., Thompson, S., Kastner, J., Ritz, C., Naeher, L.P., 2006. Fine particle measurements inside and outside tunnel-ventilated broiler houses. *J. Appl. Poult. Res.* 15: 394–405.

VSN, 2012. GenStat reference manual (release 15). Edition 15.2.0.8821. VSN-Int., Ltd, Hemel Hempstead, UK.

Winkel, A., Mosquera, J., Groot-Koerkamp, P.W.G., Ogink, N.W.M., Aarnink, A.J.A., 2015. Emissions of particulate matter from animal houses in the Netherlands. *Atmos. Environ.*111:202–212.

Zhao, Y., Aarnink, A.J.A., Hofschreuder, P., Groot Koerkamp, P.W.G., 2009. Evaluation of an impaction and a cyclone pre-separator for sampling high PM10 and PM2.5 concentrations in livestock houses. *J. Aerosol Sci* 40: 868–878.

Chapter 9

General discussion, conclusions, and recommendations for future research

INTRODUCTION

This thesis had three main objectives. The first objective was to increase our understanding and knowledge of concentration and emission levels of particulate matter in commonly applied animal housing systems in the Netherlands. This objective has been worked out in chapter 2. The second objective was to develop, test, and validate PM abatement systems so that these technologies would become available for use in poultry farms to reduce their contribution to ambient PM concentrations. These abatement systems should be effective in terms of their reduction as validated on commercial farms, be economically feasible, and be practically implementable within common housing systems and farming practices. Within chapters 3 through 7, a total of seven abatement technologies have been tested under experimental conditions and/or validated on commercial farms, namely: a fixed oil spraying system (OSF), an autonomously driving oil spraying vehicle (OSV), a negative air ionization system (NAI), a positive air ionization system (PAI), an end of pipe dry filter wall (DF), an end of pipe electrostatic precipitator (ESP), and end of pipe manure drying tunnels (MDTs). Finally, the third objective was to determine the applicability in terms of accuracy and comparability of alternative methods – i.e., alternative to the sampler developed by Hofschreuder et al. (2008) – for measurement of PM_{10} concentrations in the airflow directly upstream of animal house exhausts. This objective has been worked out in chapter 8.

This final chapter now contains three main elements. First, the main part of this chapter deals with the discussion of the main findings from chapters 2 through 8. Rather than discussing these findings on a detailed level (which has already been done in the Discussion sections of the actual chapters), this chapter discusses the findings on a meta-level, i.e., in the light of the main objectives of this thesis and within the broad context of the overall problem. Second, this chapter states the main conclusions from this thesis as a whole. Finally, this chapter identifies recommendations for future research.

DISCUSSION

1. The impact of updated PM emission figures on national PM_{10} emission estimates

Chapter 2 of this thesis describes a PM emission survey which covered 13 housing systems for poultry, pigs, and dairy cattle, and included 36 farms. This survey was needed to fill a concrete knowledge gap, namely, the lack of accurate, up to date, and housing system specific

data on emissions of PM_{10} and $PM_{2.5}$ from animal houses in the Netherlands. These data were primarily needed in the Netherlands for three reasons: (1) to estimate total national emission rates of PM, and the contribution of the livestock sector therein, (2) to allow dispersion modelling of PM, as assessment tool for permit granting to specific farms or for computing larger-scale concentration maps, and (3) to calculate the number of exceedance days of the daily PM_{10} limit value of 50 μg m^{-3} laid down in EU Directive 2008/50/EC.

Prior to the emission survey described in chapter 2, tentative emission factors (EFs) for PM_{10} and $PM_{2.5}$ were estimated by Chardon and Van der Hoek (2002) on the basis of the Northern-European emission survey by Takai et al. (1998). That survey yielded emission data from 329 animal houses in England, Denmark, Germany, and the Netherlands, collected from September 1993 to November 1995, and included the inhalable PM fraction (~PM_{100}; see Table 1 of the Introduction). PM_{10} and $PM_{2.5}$ emission figures were estimated from the inhalable PM data from animal houses in the Netherlands by conversion factors of 0.45 (PM_{10}/PM_{100}) and 0.08 ($PM_{2.5}/PM_{100}$) (Chardon and Van der Hoek, 2002; Appendix 2), which were obtained by these authors from literature (Louhelainen et al., 1987; Aarnink et al., 1999).

So far, in this thesis, the term *emission rate* has been used to refer to the mass of a pollutant emitted per unit of time, and expressed per animal present in an animal house during a measurement. In Dutch legislation on PM_{10} emissions of animal houses (Dutch Government, 2015), *emission factors* are laid down, expressed in g $year^{-1}$ animal $place^{-1}$. The EFs based on the calculations of Chardon and Van der Hoek (2002) are shown in Table 1. Table 1 also shows the updated EFs calculated from the results of chapter 2 of this thesis, and the difference between the two. For regulatory use by the Dutch Government, the emission rates in chapter 2 (in mg h^{-1} $animal^{-1}$) were converted to EFs by multiplying these with 0.001 (mg to g), 24 (hours to days), 365 (days to year), the ratio between the number of animals present and the number of animal places, and a correction factor for empty periods between production cycles when no emissions occurs (e.g., 0.90 for piglets or 0.95 for laying hens).

Table 1 clearly shows that, except for laying hens, the updated EFs based on the data of chapter 2 were considerably lower than the tentative EFs estimated by Chardon and Van der Hoek (2002). As discussed in chapter 2, two reasons can explain this. First, in retrospect, the general PM_{10}/PM_{100} conversion factor of 0.45 by Chardon and Van der Hoek (2002) for all animal types and housing systems was somewhat too high for LFH (0.40), about accurate for BRO (0.44), but clearly too high for pigs (0.32 for SIH, 0.31 for WPS, and 0.32 for FTH) and DCH (0.08). Second, the emission data of Takai et al. (1998) was mainly gathered in the second stage of the growth cycle of growing animal categories (P.W.G. Groot Koerkamp, pers. comm.)

when emission rates are high (chapter 2; Fig. 3). The updated EFs were based on measurements that were balanced over the production cycle.

Table 1
Overview of the tentative emission factors (EFs) calculated by Chardon and Van der Hoek (2002) on the basis of the data from Takai et al. (1998) and of the updated EFs calculated from the results of chapter 2 of this thesis (aplc = animal place).

Housing system [a]	PM_{10} EF			$PM_{2.5}$ EF [b]		
	Tentative (g year^{-1} aplc^{-1})	Updated (g year^{-1} aplc^{-1})	Diff. (%)	Tentative (g year^{-1} aplc^{-1})	Updated (g year^{-1} aplc^{-1})	Diff. (%)
Poultry						
LFH: laying hens in floor housing	58	84	+45	10.3	4.0	–61
LAH: laying hens in aviary housing	58	65	+12	10.3	3.9	–62
BRB: broiler breeders in floor housing	86	43	–50	15.3	3.3	–78
BRO: broilers on full litter	53	22	–58	9.4	1.6	–83
TUR: male turkeys on full litter	203	86	–58	36.0	40.2	+12
Pigs						
SIH: sows in individual housing	221	181 [c]	–18	39.2	15.5	–60
SGH: sows in group housing	221	169 [c]	–24	39.2	11.8	–70
WFS: weaners, fully slatted floor	133	56	–58	23.5	1.9	–92
WPS: weaners, partially slatted floor	133	74	–44	23.5	1.8	–92
FTH: fattening pigs in traditional housing	275	144 [d]	–48	48.4	7.0	–86
FLD: fatt. pigs, low NH_3 emission, dry feed	275	195 [d]	–29	48.4	8.3	–83
FLL: fatt. pigs, low NH_3 emission, liq. feed	275	136 [d]	–51	48.4	6.1	–87
Dairy cattle						
DCH: Dairy cattle, cubicle housing	306	148	–52	54.0	40.6	–25

[a] See chapter 2 and supplementary information 1 to that chapter for more details on housing systems.
[b] Dutch regulation does not contain EFs for $PM_{2.5}$ for animal houses: figures are shown for comparison.
[c] In Dutch regulation, one general EF for PM_{10} is used for sows of 175 g year^{-1} animal place^{-1}.
[d] In Dutch regulation, one general EF for PM_{10} is used for fattening pigs of 153 g year^{-1} animal place^{-1}.

Up to the year 2009, the tentative EFs of Chardon and Van der Hoek (2002) were used by the Institute for Public Health and the Environment (RIVM; Bilthoven, the Netherlands) to calculate national primary PM_{10} emissions in the Netherlands (reported at the website of the Pollutant Release and Transfer Register: http://www.emissieregistratie.nl). As from 2010, the updated EFs have been used in this register (J. Vonk, Centre for Environmental Studies, RIVM, Bilthoven, the Netherlands; personal comm.). Fig. 1 shows these PM_{10} emissions in the Netherlands for 1995 to 2014 for the five largest groups of sources (based on the calculation year 2014). It must be noted that this figure does not show the aforementioned drop in the emissions from Agriculture from 2005 to 2010/2012 because emissions from previous years are recalculated each year based on any relevant updates of input data: when the updated (lower) EFs were first used in 2010, the emission estimates for agriculture were recalculated and thus reduced for the previous years as well.

From Fig. 1 it is clear that the total national primary emission of PM_{10} in the Netherlands has decreased considerably, from 58,040 kTon in 1995 to 30,830 kTon in 2014. In 2014, the total emission of the agricultural sector amounted 6641 kTon; a contribution of 22%. This 6641 kTon can be further differentiated into (amongst others) 4337 kTon (or 14%) from the poultry sector, 1186 kTon (or 3.8%) from the pig sector, 407 kTon (or 1.3%) from soils and crops, and 323 kTon (or 1.0%) from the dairy sector.

The impact of using the updated EFs from chapter 2 of this thesis since 2010 can be estimated by looking at the total emission of agriculture calculated by Chardon and Van der Hoek (2002), which amounted 9322 kTon for the year 1998. The Pollutant Release and Transfer Register, however, currently (2014) contains a total emission from agriculture for the year 2000 (the year nearest to 1998) of 5199 kTon (Fig. 1). The difference between those two equals (9322 – 5199 =) 4123 kTon. This adjustment of –44% can to a large extent be attributed to the updated EFs based on chapter 2 of this thesis. The latter illustrates the importance of accurate emission rates in national PM_{10} emission calculations.

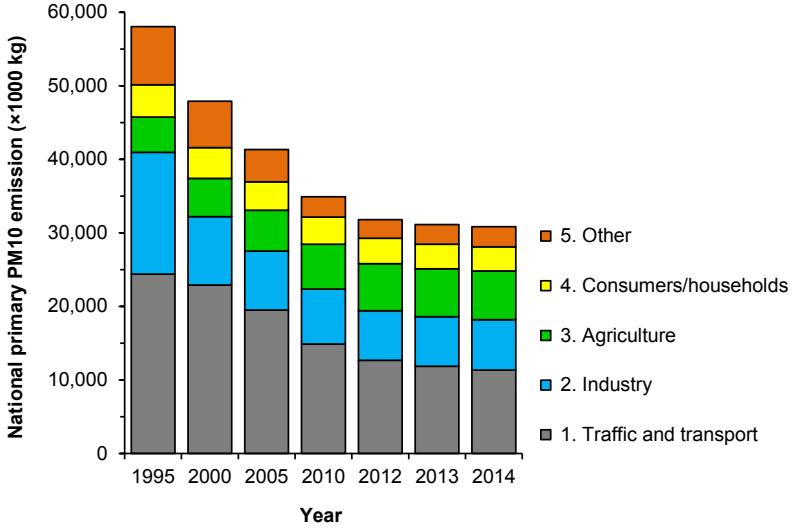


Fig. 1

National primary PM_{10} emissions (×1000 kg) in the Netherlands from 1995 to 2014. Source data: Pollutant Release and Transfer Register (RIVM, Bilthoven, the Netherlands): http://www.emissieregistratie.nl. Note that the years on the *x*-axis are not continuous.

2. The impact of updated PM emission figures in atmospheric modelling and environmental permit granting to farmers

Besides their use in nation emission calculations (section 1), the updated EFs (Table 1) have been used by the Institute for Public Health and the Environment (RIVM; Bilthoven, the Netherlands) to compute large-scale pollutant concentration maps (including PM_{10}) for the Netherlands, as reported annually by Velders et al. (2012; 2013; 2014; 2015). Third, the EFs have been used in the RIVM monitoring reports of Van Zanten et al. (2012; 2013; 2014; 2015), which annually evaluate the state of affairs of the National Air Quality Cooperation Programme in the Netherlands (Nationaal Samenwerkingsprogramma Luchtkwaliteit; NSL).

Fourth, the updated EFs function as inputs in a model named ISL3a (abbreviation for 'Implementatie Standaardrekenmethode Luchtkwaliteit 3' in Dutch, or 'Implementation Standard calculation method Air quality 3' in English) which was developed in the Netherlands to estimate the local dispersion of (amongst others) PM_{10} in the local vicinity of surface sources and point sources (i.e., flue gas stacks, vertical chimneys) such as industrial plants and livestock farms. Other inputs are, for instance, the number of animals housed, datasets containing 10 years of meteorological data, the terrain roughness (i.e., reflecting the amount of vegetation), but also location-specific ambient (background) concentrations of PM_{10}. The latter, in turn, originate from the large-scale pollutant concentration maps (as mentioned above). The core of the ISL3a model is equipped with a user interface and is freely available (from: www.infomil.nl). The ISL3a model is used in environmental permit granting to assess whether the settlement of a new farm, or renovation or enlargement of an existing farm, at a specific site (geographical coordinate) will result in exceedances of the PM_{10} limits of Directive 2008/50/EC at so-called receptor sites in the vicinity (i.e., immission coordinates of, for instance, houses or schools). Thus, the updated EFs based on chapter 2 of this thesis, together with the ISL3a model and the 2008/50/EC limit values, currently function as assessment framework to protect residents in the vicinity of livestock farms against exposure to excessive PM_{10} concentrations from these farms.

In the ISL3a model, the EFs for PM_{10} are included as year-averaged values, specific to the level of housing systems within animal types (e.g., aviary housing for laying hens or floor housing for broiler breeders). The appropriate EF is multiplied by the planned number of animal places in the animal house for which the model is run and a permit is requested. The model, however, does not take time variation in the emission rate into account. The results in chapter 2 suggest that this calculation method may be too simplistic, at least in growing animals where the emission rate increases exponentially (e.g., in broilers) or linearly (e.g., in fattening pigs)

throughout the growing period. The common practice in fattening pig farms in the Netherlands is to house multiple age groups of pigs at the same time. On the farm level, this practice probably flattens out any general increase in emission. In broiler farms on the other hand, the common practice is the 'all-in, all-out' system which means that all houses at a farm are occupied by birds of the same age. Therefore, the emission rate on the farm level can be expected to increase exponentially as well. Accurately modelling these time variations in the ISL3a model might be of importance to more accurately predict the occurrence of exceedance days in the vicinity of farms during time periods of high emission rates as the European limit for PM_{10} in the ambient air allows a maximum of 35 exceedances of the day-average limit concentration of 50 $\mu g\ m^{-3}$.

3. The role of animal houses in long-term PM emission trends in the Netherlands

Fig. 1 shows the national primary PM_{10} emission in the Netherlands from 1995 to 2014 for five main groups of emission sources. From this figure it is clear that PM_{10} emissions have been mitigated substantially in these years, namely by 54% from traffic/transport (24,390 kTon in 1995 to 11,330 kTon in 2014), by 59% by industries (from 16,545 kTon in 1995 to 6843 kTon in 2014), and by 25% from consumers/households (from 4370 kTon in 1995 to 3297 kTon in 2014). For the agricultural sector however, Fig. 1 shows an *increase* of PM emissions by 38% (from 4824 kTon in 1995 to 6641 kTon in 2014).

The increase for agriculture in Fig. 1 is further examined in Fig. 2. This figure shows how the national primary PM_{10} emission from agriculture can be further differentiated. From this figure, it is clear that the increase is mainly caused by laying hen houses, whereas emissions from broiler houses and dairy cattle houses remained relatively stable. The emission from pig houses decreased, presumably by the introduction and wide-spread use of air scrubbers in this sector since the 1990s (Melse et al., 2015). The increase for laying hen houses reflects the transition in this sector from cage housing to alternative housing systems in these years (i.e., aviary and floor housing systems with littered floors; in relation to the EU-wide ban on conventional cages; EU Directive 1999/74/EC). The number of hens kept in the Netherlands has remained relatively stable during this period (i.e, around 33 to 35 million).

Chapter 2 of this thesis has shown that in alternative housing systems for laying hens PM concentrations are the highest of all animal categories and housing systems studied. The data published by Takai et al. (1998) show that concentrations of inhalable PM in alternative housing systems are on average a factor 7 (range: 1.4 to 14) higher than in cage housing systems. With the information currently available, it can be concluded that, in hindsight, the transition from

cage housings to floor and (mainly) aviary housings has substantially increased PM emissions from agriculture during a period in which other main sectors were able to substantially mitigate emissions.

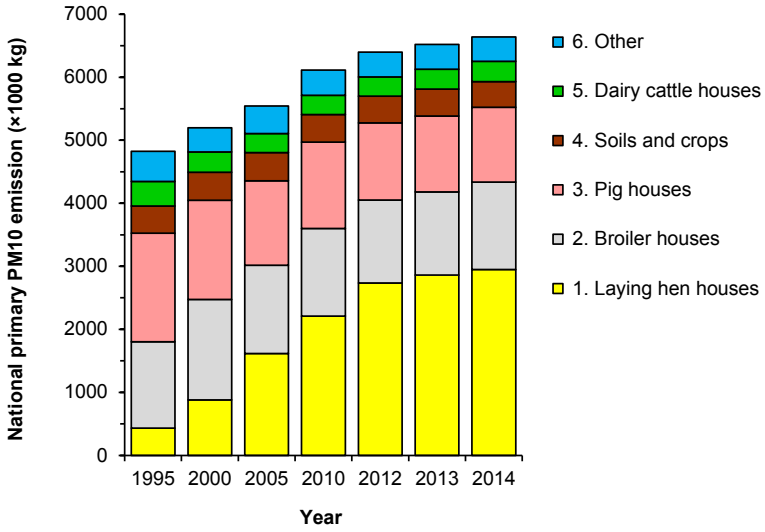


Fig. 2

National primary PM_{10} emissions (×1000 kg) in the Netherlands from 1995 to 2014 for six subgroups of sources within the main Agriculture group. Source data: Pollutant Release and Transfer Register (RIVM, Bilthoven, the Netherlands): http://www.emissieregistratie.nl. Note that the years on the *x*-axis are not continuous.

4. Potential environmental impact of PM abatement systems

In previous sections of this chapter, it was shown that poultry houses have become a major emission source of PM_{10} in the Netherlands in the last two decades, responsible for about 14% of the national annual emission of primary PM_{10} in 2014. For this reason, this thesis focused on abatement systems for this specific sector. In chapters 3 through 7 of this thesis, seven abatement systems were further developed, tested, and validated on commercial farms. The reduction performance of these systems ranged from 6% (positive air ionization system, PAI) and 15% (fixed oil spraying system in laying hen houses, OSF) to 57% (electrostatic precipitator, ESP) (see Table 2 for all systems and reduction percentages). An important question is to what extent these systems can lower ambient PM concentrations. The answer to this question requires knowledge on the origins of the mix of particles in the atmosphere and the contribution of livestock houses within this mix. Three notions are important in this respect.

First, it must be realized that about 40% of the PM_{10} in the atmosphere in the Netherlands cannot be attributed to known sources and probably originates from natural sources (such as: sea spray, dry soils, and wildfires), from yet unknown emissions processes, and from underestimated (known) emission processes. Second, from the 'attributable fraction' of about 60%, about half originates from foreign countries and is 'imported' by (uncontrollable) atmospheric air flows. However, PM from Dutch sources (or: 'domestic PM') also passes national borders, and the Netherlands is a net exporter of PM_{10} (Buijsman et al., 2005; Hendriks et al., 2013; Weijers et al., 2011). Third, PM does not only comprise primary particles from natural and anthropogenic emissions, but also secondary particles that are formed by chemical reactions in the atmosphere from precursor gasses such as ammonia. It is estimated that secondary PM contributes about 50% or more to $PM_{2.5}$ in Europe (Erisman et al., 2004). Overall, the results from the modelling study by Hendriks et al. (2013) indicate that 6% of the PM_{10} in the atmosphere in the Netherlands comes from Dutch agriculture and another 5% from foreign agriculture.

These notions suggest that reducing PM emissions from poultry farms may not reduce ambient PM levels that much. Averaged out on a national level, this may be the case, but the situation for specific areas may be very different because the origin of ambient PM differs substantially across the Netherlands (e.g. higher sea salt contributions near the shores or higher foreign contributions in border areas). Results from Hendriks et al. (2013) indicate that in the city of Rotterdam (having the largest sea port of Europe, a large harbor, and many activities related to the petro-chemical industry, cargo transshipments and transport), about two-third of the domestic PM_{10} originates from traffic and transport. In contrast to Rotterdam, little over half of the domestic PM_{10} in the Vredepeel originates from agriculture, a rural area in the south-east of the Netherlands with a high density of livestock farms. The report by Buijsman et al. (2005) illustrates in figure 1.2 on p. 14 that, on top of European, national, and regional contributions to the background concentrations, local concentration peaks occur around highways, busy city roads, and other sources. This illustration is consistent with the studies summarized in Table 3 of chapter 1 (Introduction), which show that downwind of livestock farms plumes of particles can be measured that spread out from ventilation exhausts. Concentrations in these plumes decrease with the distance travelled due to sedimentation, impaction to objects, and dilution with cleaner air. But also the results of this thesis (Fig. 1 of chapter 2) show that in the direct vicinity of poultry and pig farms concentrations of PM_{10} are often substantially higher than those measured at the nearest rural National Air Quality Monitoring (NAQM) station for the same time period. Despite that, at a certain downwind distance, PM concentrations have fallen to levels that can no longer be distinguished from upwind concentrations, part of the emitted PM will still be airborne

and contribute to the mix of background particles in that region. Furthermore, concentrations of multiple farms in a region may have overlapping areas of elevated concentrations creating a spatial plateau of elevated PM concentrations.

In conclusion, the question 'to what extent the PM abatement systems for poultry houses evaluated in this thesis can lower ambient PM concentrations' cannot be answered quantitatively based on the work in this thesis or the literature discussed. On the national scale, the reduction can be expected limited. But on a local and regional scale, i.e., in rural farming areas, the reductions may well be substantial.

5. Economic impact of PM abatement systems for poultry farms

The second objective of this thesis was to develop, test, and validate PM abatement systems for use in poultry farms to reduce their contribution to ambient PM concentrations. Such systems should, amongst others, have acceptable costs for poultry farmers. Prior to the start of the projects related to this objective (chapters 3 through 7) a literature study (Aarnink and Ellen, 2016) and a plan of action (Ogink and Aarnink, 2011) was produced, commissioned by the Dutch Ministry of Economic Affairs. In these two reports, the costs of possible options were estimated to ensure that the options included in the programme would be acceptable for farmers in the end.

Table 2 shows the costs of the systems on the basis of realistic financial figures provided by the suppliers that currently bring the systems to the market. Table 2 also includes a number of other systems for abatement of PM or ammonia. The costs are calculated for a standard laying hen house with 40,000 birds and a standard broiler farm with 2 houses with 45,000 birds each. These two situations are used as standard farms in the KWIN economic handbook for the livestock sector in the Netherlands, as published each year by Wageningen UR (Vermeij et al., 2014).

Table 2
Cost analysis of seven PM abatement systems in this thesis, and of eight other systems. Investment costs = price of the system divided by the depreciation period (10 years) + price for any construction adjustments divided by the depreciation period (20 years) + interest (4.5% yearly) + yearly maintenance costs. Exploitation costs = yearly costs for use of oil, water, and/or electricity + costs for labor associated with the system. Abbreviations: aplc = animal place(s); n.a. = system not applicable in that farm type. Source data from: Ellen et al. (2010), Ellen and Vermeij (2014), Vermeij et al. (2014), and Winkel et al. (2016).

PM abatement system	PM_{10} red. (%)	Laying hen farm, 40,000 aplc				Broiler farm, 90,000 aplc			
		a Invest. costs (€ yr^{-1} $aplc^{-1}$)	b Expl. costs (€ yr^{-1} $aplc^{-1}$)	**a + b Total costs (€ yr^{-1} $aplc^{-1}$)**	a + b Total costs (per 10% red.)	a Invest. costs (€ yr^{-1} $aplc^{-1}$)	b Expl. costs (€ yr^{-1} $aplc^{-1}$)	**a + b Total costs (€ yr^{-1} $aplc^{-1}$)**	a + b Total costs (per 10% red.)
Basic situation									
Animal house: building and inventory	-	3.00	0.35	**3.35**	-	1.20	0.50	**1.70**	-
Additional: systems in this thesis									
Fixed oil spr. syst. (OSF)	15 | 54 [a]	0.18	0.43	**0.60**	0.40	0.09	0.11	**0.20**	0.04
Oil spr. vehicle (OSV)	30	0.09	0.82	**0.91**	0.30	n.a.	n.a.	n.a.	n.a.
Neg. air ionization (NAI)	49	n.a.	n.a.	n.a.	n.a.	0.09	0.007	**0.10**	0.02
Pos. air ionization (PAI)	6	0.65	0.18	**0.83**	1.38	0.35	0.10	**0.45**	0.75
Dry filter (DF)	40	0.07	0.05	**0.12**	0.03	0.06	0.06	**0.13**	0.03
Electrost. Precip. (ESP)	57	0.34	0.001	**0.34**	0.06	0.34	0.001	**0.34**	0.06
Man. dr. tunnels (MDTs)	30 | 55 [b]	0.37	0.009 [c]	**0.38** [c]	0.13 | 0.07	n.a.	n.a.	n.a.	n.a.
Additional: other systems									
Litter scraper	25	0.08	0.005	**0.08**	0.03	n.a.	n.a.	n.a.	n.a.
Simple water scrubber	30	0.41	0.53	**0.94**	0.31	0.45	0.49	**0.95**	0.32
Acid scrubber	35	0.41	0.52	**0.93**	0.27	0.44	0.46	**0.98**	0.28
Bioscrubber	60 | 75 [d]	0.49	0.73	**1.22**	0.20 | 0.16	0.54	0.67	**1.21**	0.20 | 0.16
Multi-stage scrubber	80	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Biobed	80	0.46	0.54	**1.00**	0.12	0.52	0.61	**1.12**	0.14
Heat exchanger, type a	13	0.15	0.13	**0.28**	0.21	0.10	–0.08	**0.02**	0.01
Heat exchanger, type b	31	0.26	0.13	**0.39**	0.13	0.23	–0.11	**0.12**	0.04

[a] 15% for the OSF in laying hens, 54% for the OSF in broilers.
[b] 30% for the belt-type MDT, 55% for the plate-type MDT.
[c] Reduction of manure disposal costs not taken into account.
[d] 60 or 75% depending on the air residence time inside the scrubber.

The yearly investment costs of the systems (Columns 'a' in Table 2), the yearly exploitation costs (Columns 'b' in Table 2), and the total of those two (Columns 'a + b' in Table 2) can be compared with those from the basic situation of the building and the inventory alone, as reported by Vermeij et al. (2014). This comparison shows that the total yearly costs of applying PM abatement systems raises the total yearly costs related to the building and the inventory with values between 4% (DF) and 27% (OSV) for the standard laying hen house, and between 6% (NAI) and 26% (PAI) for the standard broiler farm.

For laying hens, the three cheapest solutions from this thesis (in absolute € animal $place^{-1}$ $year^{-1}$) are the DF (40% PM_{10} reduction) with € 0.12, the ESP (57% PM_{10} reduction) with € 0.34, and the MDTs (30 or 55% PM_{10} reduction) with € 0.38. For broilers, the three cheapest solutions

are the NAI (49% PM_{10} reduction) with € 0.10, the DF (40% PM_{10} reduction) with € 0.13, and the OSF (54% PM_{10} reduction) with € 0.20.

If the costs are expressed per ten percentage points of PM_{10} reduction (Table 2), these figures are generally more favorable for the PM abatement systems from this thesis in comparison to the other abatement systems listed in the lower part of Table 2. Overall, the cost analysis in Table 2 indicates that the PM abatement systems from this thesis are reasonably affordable in relation to other investments for the house and the inventory. On the other hand, gross margins (i.e., revenues from eggs/meat minus variable costs for young birds, feed, energy, etcetera) are only about € 2.90 hen place^{-1} year^{-1} and € 1.30 broiler place^{-1} year^{-1} (Vermeij et al., 2014). The additional costs for a PM abatement system have to be paid from these gross margins, together with the investment and exploitation costs for the animal house, and the farmer's income. Therefore, it is still financially difficult for poultry farmers to apply PM abatement systems in their houses. In relation to this, it would be very welcome if PM abatement systems would improve bird productivity so that applying a PM abatement system would pay for itself. The experiments with spraying oil in broilers (chapter 3) and laying hens (chapter 4), and an earlier experiment with negative air ionization in broilers (Cambra-Lopez et al., 2009), however, showed no significant differences in production performances between birds in treatment (i.e., low PM) and control (i.e., high PM) groups.

To stimulate the application of PM abatement systems, several subsidy programs have been launched by the Dutch Ministry of Economic Affairs in recent years. In the latest PM subsidiary programs of 2013 and 2014, a total budget of € 15 million was available. Farmers could apply for a refund of their investment in a PM abatement system consisting of 55% of the eligible costs up to a limit of € 100,000 per farm. In 2013 and 2014, a total of 382 subsidy applications were granted (Dutch Government, 2016).

6. PM abatement by redesign of animal housing systems

Within this thesis, a total of seven systems for PM abatement have been worked out (Table 2). Each of these systems can be 'plugged in' to the totality of systems/constructions that together form the animal house: either inside the house or connected to the ventilation exhaust. The main advantage of this approach is that the systems can be used inside existing poultry farms, for instance in farms that currently cause local exceedances of the limits for PM in the ambient air. On the other hand, the addition of these systems could be regarded as compensatory measure for

shortcomings of current housing system designs that inadequately meet the key requirements of main actors involved, such as the farmer (e.g., working comfort, safety, and health), the birds (e.g., air quality), the environment (e.g., low ambient PM concentration), and the consumer (e.g., food safety). In this line of reasoning, the abatement systems from this thesis can mainly be seen as temporary add-on solutions to bridge a period in which the poultry industry and engineering science could go back to the drawing table to design, develop, and implement housing systems for poultry that better take into account indoor air quality, occupational exposure, and PM emissions.

The work described in this thesis did not aim to produce such designs. It has, however, delivered insights that might act as inspiration for such designs. Chapters 3 and 4 have shown that when particles in the litter of poultry houses are confined by applying a film of rapeseed oil droplets to the litter surface, PM concentrations and emissions can be reduced by more than 80 percent. This means that the litter floor, essentially dry and crumbly manure from the birds, is the main source of PM in litter floor housings. This finding is in agreement with the study of Cambra-Lopez et al. (2011) who identified manure as the main source of airborne particles in poultry houses. Furthermore, chapter 2 of this thesis has showed that, when lights are turned off and birds are resting/perching, PM concentrations rapidly fall by more than 90 percent: this yields very distinct light/dark patterns in continuous PM concentration data (see Chapter 2; Fig. 2). These findings show that the high PM emissions from poultry houses are caused by a combination of three aspects: (1) the presence of a layer of litter (essentially dry and crumbly manure from the birds) on the floor, (2) the behavioral activity of the birds on and in this litter layer through which particles become airborne, and (3) the ventilation air flow through poultry house that exhausts particles into the environment. These aspects are the core of the PM emission problem as illustrated in the infographic in Fig. 1 of chapter 1. Aspects (1) and (2) explain why cage housing systems for laying hens show relatively low PM concentrations and emissions: they lack a litter floor and the birds are confined to cages, unable to (fully) display their behavioral needs, such as dust bathing and scratching. Future housing design should thus focus on these three aspects.

Not offering a litter substrate, confining birds to batteries, or keeping birds in the dark, are no options in design approaches that aims to fulfill the needs of all actors involved (Bos, 2003; Bos et al., 2009; Van Weeghel et al., 2016). Light, freedom of movement, and the presence of a substrate for dustbathing and scratching are inherent elements in designs following the aforementioned approach. What can be a way forward?

Fig. 3 shows an *example* of how the presence of a litter substrate and natural bird activity could be combined in a housing design that is low in PM concentration and emission, namely, by separating the litter rooms for dustbathing and scratching from the main room of the animal house where feeding, drinking, laying and resting/perching takes place. The main room can be regarded as a 'cage-like environment' in the sense that the environment is relatively clean: the manure does not accumulate into litter layers here, but is removed frequently from this room, either by belts under the tiers of the aviary frames (in the case of hens), and/or by belts underneath slatted floors (e.g., in the case of broilers). Since a litter layer is absent in this room, and the presence of manure on belts is reduced to the minimum, concentrations of PM, ammonia, and odor can be expected to be much lower than in conventional housings.

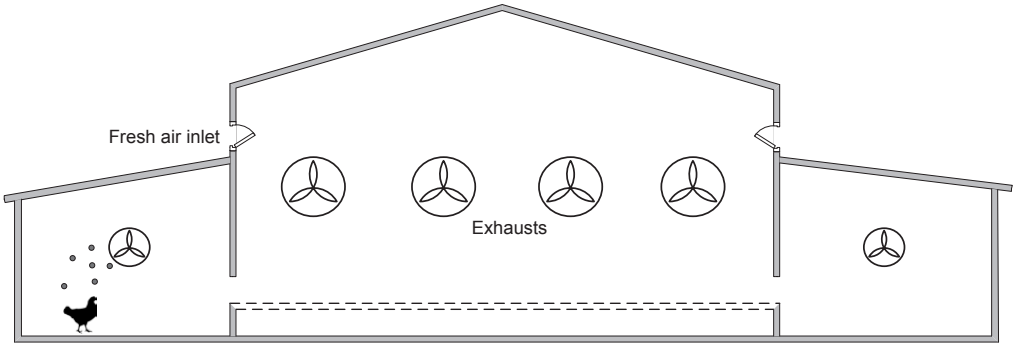


Fig. 3
Example of a housing design (cross-sectional view) for laying hens with incorporation of principles that may result in a low-emission system with regard to particulate matter (PM).

The presence of litter, and the natural behavior of the birds, can be organized in separate litter rooms (Fig. 3), which will probably be more prone to pollution than the main room. Technical solutions will be needed to prevent air from the litter rooms to flow to the main room. The litter rooms could be further designed to be as clean as possible. This could include the application of a low-dust litter substrate, keeping the litter substrate layer to a minimum required by the birds (e.g., by litter scrapers, autonomous scraping vehicles, or auger channels embedded in the floor), and/or frequent addition of fresh litter substrate (possibly followed by a cleaning step and re-use

of the substrate). These examples should prevent that the air becomes polluted with particles in the first place. In addition, a PM abatement system from this thesis could be useful to remove particles from the air in the litter rooms that are generated and aerosolized despite the design measures taken, such as an air ionization system (chapter 5). In relation to aspect (3) described above, it may be worthwhile to reduce the ventilation rate through the litter rooms to a minimum so that emission rates from these rooms are further mitigated, in addition to reducing particle concentrations in this volume. If needed, this ventilation flow may be treated further by a small-scale end of pipe system, such as an electrostatic precipitator, dry filter, or air scrubber. These end of pipe systems, however, should (on the long term) preferably be used as backup system that removes a remainder of pollutants still present in the ventilation air of future (low-emission) housing designs.

7. A retrospective view on the cyclone samplers developed and used in this thesis

This thesis established PM_{10} and $PM_{2.5}$ emission rates of animal houses (chapter 2) and determined PM reductions of abatement systems (chapters 3 through 7) using a PM measurement method that was specially developed for this task, namely the cyclone sampler (CYS) described by Hofschreuder et al. (2008). Prior to the start of the work described in this thesis (in 2007), a choice needed to be made for a measurement method that would be able to accurately quantify the mass concentrations of PM_{10} and $PM_{2.5}$ under difficult circumstances, such as high PM concentrations ($>10^4$ μg PM_{10} m^{-3}), short stacks that contain ventilators which can run at varying speeds, or no stacks at all (e.g., in the case of naturally ventilated buildings or wall ventilators).

At that time, a first decision was to adhere to measurement methods for ambient air and stay away from stack-sampling. This was decided because the air upstream of exhausts shows similarities to calm ambient air in terms of air velocity, temperature, and relative humidity, whereas isokinetic stack-sampling is complicated when air velocity varies in time during sampling. A second decision was to (initially) use straightforward filter-based systems instead of systems that are based on the principles of the oscillating micro-balance (TEOM), beta-ray attenuation, or light-scattering, since very little was known at that time about the functioning of these mechanisms when sampling animal house PM. Of the principles mentioned, the filter-based method was thought to be least sensitive to any (not yet known) sources of bias.

In essence, filter-based methods include an air sampling pump that sucks air (with airborne particles) through a filter. The filter is weighed before and after the measurement (under strict conditions and using a precise balance) to determine the mass of collected PM. The mass

concentration can then be determined by dividing the mass of collected PM by the known total flow of the pump. If a specific size fraction needs to be collected (see Table 1 of chapter 1), a pre-separator must be applied upstream of the filter which removes particles larger than the aimed cutpoint diameter from the sampling flow. As described in detail in chapter 8, the measurement method used in this thesis contained cyclone pre-separators instead of greased impactors, because of the risk of overloading the impactor plates of the latter system. An equivalence study by Zhao et al. (2009) showed that the developed CYS functioned acceptable in comparison to the European reference samplers for PM_{10} (EN 12341; CEN, 1998) and $PM_{2.5}$ (EN 14907; CEN, 2005), albeit that correction equations were needed to calibrate measured PM_{10} concentrations to the European reference sampler. The CYSs and the correction equations of Zhao et al. (2009) have been used throughout this thesis. In general, this approach has functioned satisfactory. We encountered the following drawbacks:

- in poultry houses, filters were sometimes heavily loaded making the PM layer on the filter sensitive to cracks and loss of PM. This may happen during handling and transport, but also during weighing since prior to weighing, filters have to be removed from the filter holder by thumb forceps. We therefore maximized the safety of filter handling and transportation procedures (e.g., by transporting filters in Petri-dishes and in metal containers). In future, this could be improved by reducing the sampling duration or by reducing the air flow through the filter (e.g., by using a cyclone designed for a smaller air flow rate);
- the presence of red mites (*Dermanyssus gallinae*) in laying hen houses, or insects (such as flies) in all houses, sometimes was a problem in the sense that incidentally, an insect was found on the filter which had disturbed the PM layer by movements of wings/feet. Such filter weights were excluded from datasets. When DustTrak samplers were used in laying hen houses, they would sometimes contain red mites crawling behind the glass of displays or inside the device. Because of the presence of insects, high PM concentrations, and the risk of spreading parasites/pathogens from one farm to the next, we spent much time and effort on cleaning, disinfection, inspection, maintenance, and calibration.
- with regard to the CYS itself, drawbacks of the method are that it only yields time-averaged mass concentrations (e.g., over 24 hours) instead of time-resolved concentrations (e.g., hourly values). Furthermore, the method requires manual filter weighing, which is time-consuming and requires a special weighing lab that is able to keep climate conditions within very strict margins. Third, the method is not battery-powered. It requires the presence of electricity sockets that can supply about 2 to 3 A for one unit.

8. Other samplers to be used for PM measurement in animal houses

As described above, the developed CYS also has drawbacks. Therefore, the third objective of this thesis was to determine the applicability (in terms of acceptable accuracy and comparability) of alternative PM_{10} measurement methods – i.e., alternative to the CYS – to be applied in future, so that PM_{10} measurement methods can be harmonized across institutes and more types of samplers could become available for PM_{10} measurement in animal houses. This objective has been worked out in chapter 8 as equivalence study between the European reference sampler for PM_{10} (RES; described in EN 12341) and five different candidate samplers: the CYS, FH-62-IR beta-ray attenuation sampler (BAS), TEOM 1400ab, DustTrak model 8520 light-scattering device (DT), and Portable aerosol spectrometer model 1.109 (PAS). The main findings from chapter 8 were that all methods showed a systematic deviation from 'true' values obtained by the RES, that between-device variation was relatively high, and that these methods started to dysfunction after about 432 to 500 h of operation (since the last full service).

The conclusion from chapter 8 was that some of the samplers tested could be regarded acceptable when appropriate measures (such as duplicate sampling, correction factors, and more frequent servicing) are applied. More concrete, acceptable methods could be the CYS, TEOM, and DT. Chapter 8 shows that these three methods best meet the EN 12341 criteria on accuracy and comparability between instruments. These methods could be chosen, provided that they are used in duplicate (to be combined in one mean value), their systematic error is calibrated to 'true' concentrations (for instance by using the correction equations in Table 6 of chapter 8), and they are serviced frequently (for instance within the maximum operating time reported in Table 7 in chapter 8). Thus, chapter 8 contributed to the availability of more samplers being applicable for PM_{10} measurement in animal houses.

Chapter 8 also aimed to contribute to the harmonization of measurement methods across institutes. In chapter 8, we determined systematic errors of methods to 'true' values as produced by the European reference sampler for ambient sampling described in EN 12341. We also followed the procedures and statistical tests of this standard because a standard on how to assess equivalence within the context of animal house measurements is lacking. Chapter 8 has shown at least that, in order for data on PM emissions to be compatible between institutes and countries, there is an urgent need for institutes to relate their methods to a (shared) reference. We have chosen to relate to the reference sampler for ambient PM_{10} so that PM_{10} concentrations measured upstream of animal house exhaust are as compatible as possible with PM_{10} concentrations measured elsewhere, such as at National Air Quality Monitoring Stations. Ideally, institutes

within (for instance) Europe should all relate their methods to one common standard. Chapter 8 not only shows the need for that, but also provides a knowledge basis to start the development of such a standard.

GENERAL CONCLUSIONS

The main important conclusions from chapters 2 through 8 can be summarized as follows:

- **Chapter 2:** PM emission rates increase exponentially with increasing age in broilers and turkeys and increase linearly with increasing age in weaners and fatteners. In laying hens, broiler breeders, sows, and dairy cattle, emission levels are variable throughout the year. The mean emission rate of PM_{10} ranges from 2.2 to 12.0 mg h^{-1} $animal^{-1}$ in poultry, ranges from 7.3 to 22.5 mg h^{-1} $animal^{-1}$ in pigs, and amounts 8.5 mg h^{-1} $animal^{-1}$ in dairy cattle. Mean emission rate of $PM_{2.5}$ ranges from 0.11 to 2.41 mg h^{-1} $animal^{-1}$ in poultry, ranges from 0.21 to 1.56 mg h^{-1} $animal^{-1}$ in pigs, and amounts 1.65 mg h^{-1} $animal^{-1}$ in dairy cattle.
- **Chapter 3:** oil spraying for PM abatement in broiler houses should be done by daily application of 16 mL m^{-2} or less starting from day 21 of the growth cycle. This can reduce PM emission rates from the last 3 weeks of the growing cycle up to 70% without effects on ammonia emission, odor emission, bird performance, birds' exterior quality, and litter dry matter content.
- **Chapter 4:** oil spraying for PM abatement in aviary housings for laying hens at application rates of 15, 30, or 45 mL m^{-2} day^{-1} reduces emission rates of PM_{10} by 27, 62, and 82%, and emission rates of $PM_{2.5}$ by 71, 83, and 94%, respectively. It is advised to use application rates of 15 to 30 mL m^{-2} day^{-1} at which no or minor side effects are found in terms of mortality, egg production, dust bathing behavior, scratching behavior, plumage soiling, DM content of the litter, or friability of the litter.
- **Chapter 5:** the PM_{10} and $PM_{2.5}$ emission reductions of the four PM abatement systems evaluated are: 60% and 53% for the fixed oil spraying system in broilers (at 12 mL m^{-2} day^{-1}), 21% and 31% for the fixed oil spraying system in laying hens (at 15 mL m^{-2} day^{-1}), 32% and 38% for the autonomously driving oil spraying vehicle in laying hens (at 30 mL m^{-2} day^{-1}), 49% and 68% for the negative air ionization system in broilers, and 6% and zero for the positive air ionization system in laying hens. None of the systems reduces odor or

ammonia emission. On the basis of this work, emission reduction factors of the OSF, OSV, and NAI were adopted in Dutch regulations.

- **Chapter 6:** the PM removal efficiency of the dry filter increases with increasing particle diameter. It can reduce PM_{10} by 40%, but does not remove $PM_{2.5}$ from the exhaust air. The removal efficiency of the electrostatic precipitator amounts 57% for PM_{10} and 45% for $PM_{2.5}$. The performance of both systems can be further improved. On the basis of this work, emission reduction factors of both systems were adopted in Dutch regulations.
- **Chapter 7:** manure drying tunnels can act as dust filters: they are able to filter out PM from the drying air flow when it passes the manure layer in these tunnels. The PM_{10} removal efficiency increases linearly with increasing manure layer thickness: from approximately 35% at 4 cm to approximately 84% at 17 cm. This PM reduction is accompanied by extra emissions of ammonia and odor from the drying manure. Intensive pre-drying inside the house or shortening manure accumulation time in the house to 24 h (without pre-drying) can only partly prevent extra ammonia emission from the manure drying tunnel later on. Even shorter manure accumulation times (e.g., 18, 12, or 6 h) may be needed to further reduce the ammonia emission from manure drying tunnels.
- **Chapter 8:** the five PM_{10} samplers tested show systematic deviations from the European reference sampler. Furthermore, their between-device variation is relatively high, and they start to dysfunction after 432 to 500 h of operation (since the last full service). Duplicate sampling, application of correction factors, and an adequate frequency of servicing are necessary measures when using these samplers to determine PM_{10} concentrations in animal houses.

Further conclusions from the discussion of these main findings on a meta-level are:

- **Societal impact of PM emission rates**: since 2010, the emission rates from chapter 2 play an important role in dealing with the problem of particulate air pollution in the Netherlands. They: (1) have been adopted as emission factors in Dutch regulation on PM emissions from livestock houses; (2) substantially altered the national PM_{10} emission estimates of the livestock sector since 2010, and herewith the contribution of the livestock sector to the total national PM_{10} emissions; (3) are used to compute large-scale pollutant concentration maps (including PM_{10}) for the Netherlands; (4) are used in annual evaluations of the state of affairs of the National Air Quality Cooperation Programme in the Netherlands; and (5) are

used in the ISL3a dispersion model which is used in the environmental permit granting procedure in the Netherlands to protect residents in the vicinity of livestock farms against exposure to excessive PM_{10} concentrations from farm emissions.

- **Environmental impact of PM abatement systems:** despite the fact that PM abatement systems for poultry houses as evaluated in this thesis may contribute only little to the reduction of ambient PM concentrations on the national scale, their contribution on a local and regional scale (i.e., in rural farming areas) is likely to be significant.
- **Economic impact of PM abatement systems:** the PM abatement systems evaluated in this thesis have yearly costs that are generally affordable for laying hen and broiler farms in comparison to other investments for the house and inventory. Gross margins in these sectors are, however, small, and the systems probably do not increase bird performance and revenues.
- **Design of low-PM housing systems for poultry:** the substantial increase in the national emission of PM_{10} from agriculture due to the transition from cage housings to alternative housings for laying hens could on the long term be reduced again by new housing designs that more adequately meet the requirements of the farmer, the animal, the consumer, and the environment.

SUGGESTIONS FOR FUTURE RESEARCH

On the basis of this thesis, the following recommendations are given for future research:

- Chapter 2 of this thesis presents separate emission rates for different housing categories within an animal category (e.g., laying hens in aviary housing versus laying hens in floor housing). The question is whether the emission rates from those housing systems are truly different. Statistically, the dataset of chapter 2 (with two or four houses per housing system) was insufficient with respect to the number of observations to determine the significance of such differences. Merging the dataset from chapter 2 with emission data from control houses in this thesis (i.e., chapters 5 through 7), and other projects carried out at our institute in recent years, can result in a dataset two or three times the original size. Such a dataset can improve the accuracy of the emission estimates of housing systems and allows determination of significant differences between housing systems. If there is no statistical

basis for maintaining separate emission factors for housing systems within animal categories, emission factors could be harmonized into one figure.

- A dataset as mentioned above could further be used to determine the contribution of variance components (i.e., between sampler variation within duplicates, within-house variation in time, and between-house variation) to the total variance of an emission estimate for a housing system. Such analysis can give important insights that may further shape the measurement strategy (e.g., number of houses and number of measurements per house to be performed) for accurate determination of PM emission factors of housing systems. Furthermore, information on within-house variation in time, combined with identification of systematic time-patterns could improve the accuracy of percentile-estimates from dispersion modelling of PM_{10}. Inclusion of this information in the current model used in license procedures (ISL3a) could avoid the risk of bias in estimated percentiles.
- In this thesis, we found similar production performances between birds in treatment (i.e., low PM) and control (i.e., high PM) groups in semi-practical housings. The literature is inconclusive about the extent to which the poor air quality reported in chapter 2 leads to adverse effects on the health, wellbeing and production performance of animals. More scientific information is needed on this matter, because clean air may well improve both the living conditions for the animals and their production performance.
- To facilitate the design of low-PM housing systems for poultry, more insight is needed in the efficacy of key design elements for the prevention of high PM concentrations, such as litter substrates, frequent replacement of litter, or the separation of behaviors in different parts of the building.
- In chapter 8 of this thesis, we found that the cyclone sampler for PM_{10} as used throughout the work in this thesis, was equivalent to the European reference sampler (described in EN 12341) in pigs and layers, but overestimated 'true' concentrations in broilers. An earlier equivalence study by Zhao et al. (2009) found more pronounced overestimations. In chapter 8, we discussed that this might be due to between-farm variation in the cyclone/reference sampler relationship. A future study with side by side measurements of PM_{10} with both samplers in multiple farms is needed to clarify this between-farm variation. Based on the study of Zhao et al. (2009), we used a correction equation of 0.83 (and an intercept of 223 $\mu g\ m^{-3}$) to all PM_{10} concentrations. The recommended study can clarify whether emission data should be corrected with factors closer to 1.

REFERENCES

Aarnink, A.J.A., Ellen, H.H., 2006. Processen en factoren bij fijn stofemissie in de veehouderij [Processes and factors influencing fine dust emissions from livestock production; in Dutch, with English summary]. Report 11. Wageningen University and Research Centre, Animal Sciences Group, Lelystad, the Netherlands.

Aarnink, A.J.A., Roelofs, P.F.M.M., Ellen, H.H., Gunnink, H., 1999. Dust sources in animal houses. In: International Symposium on Dust Control in Animal Production Facilities. Danish Institute of Animal Science Aarhus, Denmark, pp. 34–40.

Bos, A.P., Groot Koerkamp, P.W.G., Gosselink, J.M.J., Bokma, S., 2009. Reflexive interactive design and its application in a project on sustainable dairy husbandry systems. *Outlook Agric.* 38:137–145.

Bos, A.P., Groot Koerkamp, P.W. G., Groenestein, K., 2003. A novel design approach based on recursive control. *Livest. Prod. Sci.* 84:157–170.

Buijsman, E., Beck, J.P., Cassee, F.R., Koelemeijer, R.B.A., Matthijsen, J., Thomas, R., Wieringa, K., 2005. Fijn stof nader bekeken – De stand van zaken in het dossier fijn stof [A closer look on particulate matter – The state of affairs in the particulate matter dossier; in Dutch]. Milieu- en Natuurplanbureau Rapport 500037008. Milieu- en Natuurplanureau en sector Milieu en Veiligheid, National Institute for Pulic Health and the Environment, Bilthoven, the Netherlands.

Cambra-López, M., Hermosilla, T., Lai, H.T.L., Aarnink, A.J.A., Ogink, N.W.M., 2011. Particulate matter emitted from poultry and pig houses: Source identification and quantification. *Trans. ASABE* 54: 629–642.

Chardon, W.J., Van der Hoek, K.W., 2002. Berekeningsmethode voor de emissie van fijn stof vanuit de landbouw [Calculation method for emission of fine dust from agriculture; in Dutch]. Alterra-report 682 / RIVM-report 773004014. Wageningen University and Research Centre, Alterra and the National Institute for Public Health and the Environment (RIVM), Wageningen, the Netherlands.

Ellen, H., Vermeij, I., 2014. Update berekening van kosten voor fijnstofreductiesystemen [Update of cost estimates of particulate matter reduction systems]. Unpublished data. Wageningen University and Research Centre, Livestock Research.

Ellen, H., Vermeij, I., Winkel, A., van Emous, R., 2011. BBT fijn stof: beschrijving systemen en kosten [Best available techniques for particulate matter: description of systems and costs; in Dutch]. Report 476. Wageningen University and Research Centre, Livestock Research, Lelystad, the Netherlands.

Erisman, J.W., Schaap, M., 2004. The need for ammonia abatement with respect to secondary PM reductions in Europe. *Environ. Pollut.* 129:159–163.

Hendriks, C., Kranenburg, R., Kuenen, J., van Gijlswijk, R., Wichink Kruit, R., Segers, A., Denier van der Gon, H., Schaap, M., 2013. The origin of ambient particulate matter concentrations in the Netherlands. *Atmos. Environ.* 69:289–303.

Louhelainen, K., Vilhunen, P., Kangas, J., Terho, E.O., 1987. Dust exposure in piggeries. European Journal of *Respirat. Dis.* 71:80–90.

Melse, R.W., Schalk, J.A.C., Bartels, A.A., 2015. Onderzoek naar aanwezigheid van legionella in biologische luchtwassers bij stallen [Research into the presence of Legionella in bioscrubbers at livestock farms; in Dutch, with English summary]. Report 891. Wageningen University and Research Centre, Livestock Research, Wageningen, the Netherlands.

Ogink, N.W.M., Aarnink, A.J.A., 2011. Plan van aanpak bedrijfsoplossingen voor fijnstofreductie in de pluimveehouderij [Plan of action for particulate matter mitigation solutions in poultry; in Dutch, with English summary]. Report 113. Animal Sciences Group, Wageningen University and Research Centre, Lelystad, the Netherlands.

Dutch Government, 2015. Emissiefactoren fijn stof voor veehouderij 2015 [Fine dust emission factors for the livestock sector 2015]. Ministry of Infrastructure and the Environment, Den Haag, the Netherlands.

Dutch Government, 2016. Fijnstofmaatregelen 2015 [Fine dust measures 2014]. http://www.rvo.nl/subsidies-regelingen/fijnstofmaatregelen-2013. Accessed: June 2016. Ministry of Infrastructure and the Environment, Den Haag, the Netherlands.

Takai, H., Pedersen, S., Johnsen, J.O., Metz, J.H.M., Groot Koerkamp, P.W.G., Uenk, G.H., Phillips, V.R., Holden, M.R., Sneath, R.W., Short, J.L., White, R.P., Hartung, J., Seedorf, J., Schröder, M., Linkert, K.H., Wathes, C.M., 1998. Concentrations and emissions of airborne dust in livestock buildings in Northern Europe. *J. Agric. Eng. Res.* 70:59–77.

Van Weeghel, H.J., Bos, A.P., Spoelstra, S.F., Groot Koerkamp. P.W.G., 2016. Involving the animal as a contributor in design to overcome animal welfare related trade-offs: The dust bath unit as an example. *Biosyst. Eng.* 145:76–92.

Van Zanten, M.C., Berkhout, J.P.J., Wesseling, J., Mooibroek, D., Nguyen, P.L., Groot Wassink, H., Sanders, A., 2015. Monitoringsrapportage NSL 2015 [State of affairs of the National Air Quality Cooperation Programme

2015, in Dutch, with English summary]. Report 2015-0166. National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands.

Van Zanten, M.C., Van Alphen, A., Wesseling, J., Mooibroek, D., Nguyen, P.L., Groot Wassink, H., Verbeek, C., 2012. Monitoringsrapportage NSL 2012 [State of affairs of the National Air Quality Cooperation Programme 2012, in Dutch, with English summary]. Report 680712004/2012. National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands.

Van Zanten, M.C., Van Alphen, A., Wesseling, J., Mooibroek, D., Nguyen, P.L., Groot Wassink, H., Verbeek, C., 2013. Monitoringsrapportage NSL 2013 [State of affairs of the National Air Quality Cooperation Programme 2013, in Dutch, with English summary]. Report 680712005/2013. National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands.

Van Zanten, M.C., Van Alphen, A., Wesseling, J., Mooibroek, D., Nguyen, P.L., Groot Wassink, H., Verbeek, C., 2014. Monitoringsrapportage NSL 2014 [State of affairs of the National Air Quality Cooperation Programme 2014, in Dutch, with English summary]. Report 2014-0092. National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands.

Velders, G.J.M., Aben, J.M.M., Geilenkirchen, G.P., Den Hollander, H.A., Jimmink, B.A., Van der Swaluw, E., De Vries, W.J., Wesseling, J., Van Zanten, M.C., 2013. Grootschalige concentratie- en depositiekaarten Nederland 2013 [Large-scale concentration and deposition maps for the Netherlands 2013; in Dutch]. Report 680362003/2013. National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands.

Velders, G.J.M., Aben, J.M.M., Geilenkirchen, G.P., Den Hollander, H.A., Noordijk, H., Van der Swaluw, E., De Vries, W.J., Wesseling, J., Van Zanten, M.C., 2014. Grootschalige concentratie- en depositiekaarten Nederland 2014 [Large-scale concentration and deposition maps for the Netherlands 2014; in Dutch]. Report 680363002/2014. National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands.

Velders, G.J.M., Aben, J.M.M., Geilenkirchen, G.P., Den Hollander, H.A., Van der Swaluw, E., De Vries, W.J., Van Zanten, M.C., 2015. Grootschalige concentratie- en depositiekaarten Nederland 2015 [Large-scale concentration and deposition maps for the Netherlands 2015; in Dutch]. Report 2015-119. National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands.

Velders, G.J.M., Aben, J.M.M., Jimmink, B.A., Geilenkirchen, G.P., Van der Swaluw, E., De Vries, W.J., Wesseling, J., Van Zanten, M.C., 2012. Grootschalige concentratie- en depositiekaarten Nederland 2012 [Large-scale concentration and deposition maps for the Netherlands 2012; in Dutch]. Report 680362002/2012. National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands.

Vermij, I. (editor), 2014. Kwantitatieve Informatie Veehouderij (KWIN) 2014-2015 [Quantitative information about the livestock sector 2014-2015]. Handbook 28. Wageningen University and Research Centre, Livestock Research, Wageningen, the Netherlands.

Weijers, E.P., Schaap, M., Nguyen, L., Matthijsen, J., Denier Van Der Gon, H.A.C., Ten Brink, H.M., Hoogerbrugge, R., 2011. Anthropogenic and natural constituents in particulate matter in the Netherlands. *Atmos. Chem. Phys.* 11:2281–2294.

Winkel, A., Wouters, I.M. (editors), 2016. Additionele maatregelen ter vermindering van emissies van bioaerosolen uit stallen: verkenning van opties, kosten en effecten op de gezondheidslast van omwonenden. [Additional measures to reduce emissions of bioaerosols from animal houses: exploration of options, costs, and effects on health of neighboring residents; in Dutch]. Report 949 (in press), Institute for Risk Assessment Sciences (IRAS), Utrecht University (authors: Wouters, I.M., Heederik, D.J.J.), Wageningen UR, Central Veterinary Institute (author: Hagenaars, T.J.), Wageningen UR Livestock Research (Ogink, N.W.M., Vermeij, I., Winkel, A.), Wageningen, the Netherlands.

Summary

In many parts of the world important food products such as meat, eggs, and milk are produced by animals kept in specialized houses equipped with mechanical and computerized systems, such as feeding systems and ventilation systems. These animal houses are extremely dusty environments. The term 'dust' is often used in popular language, whereas this thesis uses the term *particulate matter* (PM) to refer to 'fine solid or liquid particles suspended in a gaseous medium'. PM inside animal houses mainly originates from manure, feathers, skin flakes, hair, bedding material, and feed. These sources dry, deteriorate into small particles, and become aerosolized by the activity of the animals or by ventilation air flows. Due to its organic nature, animal house PM contains high levels of endotoxins (i.e., pro-inflammatory compounds from the outer membrane of Gram-negative bacteria) and micro-organisms. Farmers are chronically exposed to high concentrations of PM which negatively impacts their respiratory health. Adverse effects of PM have also been found on the health and productivity of the animals. Since animal houses are ventilated, large amounts of PM are emitted into the atmosphere, contributing to local and regional ambient PM concentrations. In many livestock farming areas, PM_{10} concentrations are only just below the limits laid down in European directive 2008/50/EC to protect its residents against air pollution, and in several other regions these limits are exceeded. Studies on urban aerosols show associations between PM_{10} concentration and respiratory and cardiovascular disease, but health effects of livestock PM have are less well studied. Recent studies suggest both protective effects (e.g., a lower prevalence of asthma) and adverse effects (e.g., a higher prevalence of pneumonia). Thus, livestock PM poses a threat to the farmer, the animals, and residents living in livestock farming areas, but the primary focus of this thesis is on the cause of the latter **problem**, namely on *emissions of PM from livestock houses*.

In relation to this problem, the **objectives** of this thesis were threefold. The first objective was to increase our understanding and knowledge of concentrations and emission rates of particulate matter in commonly applied animal housing systems. This can be used to develop abatement solutions, to adopt emission factors in legislation, to estimate national emissions, ambient PM concentrations and exceedances, to facilitate policy making, and to allow environmental permit granting to farmers. The second objective was to develop, test, and validate technologies to mitigate PM concentrations and emissions such that these systems will become available for use in poultry farms, and ultimately contribute to cleaner outdoor air. The third objective was to determine the applicability (in terms of acceptable accuracy and comparability) of alternative PM_{10} measurement methods to the method used in chapters 2 through 7 of this thesis. This can be used to harmonize PM_{10} measurement methods across institutes and to further increase the availability of samplers for the measurement of PM_{10} in animal production.

In relation to the first objective, **chapter 2** presents a national emission survey into the concentrations and emissions of particulate matter from animal houses in the Netherlands. This survey covered 13 housing systems for poultry, pigs, and dairy cattle, and included 36 farms. In total, 202 24-h measurements were carried out, which included concentrations of inhalable PM, PM_{10}, $PM_{2.5}$, and CO_2, ventilation rate, temperature, and relative humidity. On an animal basis, geometric mean emission rates of PM_{10} ranged from 2.2 to 12.0 mg h^{-1} in poultry and from 7.3 to 22.5 mg h^{-1} in pigs. The mean PM_{10} emission rate in dairy cattle was 8.5 mg h^{-1}. Geometric mean emission rates of $PM_{2.5}$ ranged from 0.11 to 2.41 mg h^{-1} in poultry and from 0.21 to 1.56 mg h^{-1} in pigs. The mean $PM_{2.5}$ emission rate in dairy cattle was 1.65 mg h^{-1}. Emissions are also reported per Livestock Unit and Heat Production Unit. PM emission rates increased exponentially with increasing age in broilers and turkeys and increased linearly with increasing age in weaners and fatteners. In laying hens, broiler breeders, sows, and dairy cattle, emission levels were variable throughout the year.

In relation to the second objective, **chapter 3** presents an experiment into the application of a thin film of rapeseed oil onto the litter of broiler houses, which prevents particles in the litter from becoming airborne. Effects were investigated of two rapeseed oil application rates (8 or 16 mL m^{-2} d^{-1}) in combination with two spraying frequencies (daily or every other day) in four oil treatments: 8 mL m^{-2} (24 h)$^{-1}$, 16 mL m^{-2} (48 h)$^{-1}$, 16 mL m^{-2} (24 h)$^{-1}$, and 32 mL m^{-2} (48 h)$^{-1}$ during two growth cycles of broilers. Oil treatments were randomly assigned to four rooms, whereas two rooms served as control (0 mL m^{-2}). Oil spraying started on day 21. Prior to the second growth cycle, the spraying system was optimized to improve the distribution of oil and reduce the generation of small oil particles. We measured concentrations of PM_{10}, $PM_{2.5}$, ammonia, and odor, and ventilation rate. Furthermore, we recorded bird performance and birds' exterior quality. PM_{10} emission was significantly reduced by 59% at 8 mL m^{-2} d^{-1} and by 64% at 16 mL m^{-2} d^{-1}. For $PM_{2.5}$, these values were 81% and 74% respectively. In the two 'every other day' treatments, PM_{10} emission was 44% higher on days after spraying than on spraying days. No significant effect of oil spraying was found on ammonia emission, odor emission, bird performance, and birds' exterior quality. The latter confirms results from an earlier experiment that at an application rate of 16 mL m^{-2} d^{-1} the incidence of foot-pad lesions is not increased. It is recommended to validate the effects of oil spraying inside full-scale commercial broiler houses at a daily application of 16 mL m^{-2} or less.

In relation to the second objective, **chapter 4** presents an experiment into dose-response effects of oil spraying in aviaries for laying hens on concentrations and emission rates of PM_{10} and $PM_{2.5}$, on stockmen's exposure to PM_{10}, on egg production, exterior quality and behavior of

the hens, and on the litter. The experiment was carried out with 4 treatments: 0 (control), 15, 30, and 45 mL/m^2 per day (oil treatments). Each treatment was applied in 2 rooms with different aviary systems (8 rooms in total). The experiment was repeated during a second period, both lasting 35 d. From day 11 to day 35, oil was applied daily using a spraying gun. Applying 15, 30, or 45 mL/m^2 per day significantly reduced emission rates of PM_{10} by 27, 62, and 82%, and emission rates of $PM_{2.5}$ by 71, 83, and 94% respectively. No significant effects of oil spraying were found on mortality, egg production, dust bathing behavior, scratching behavior, plumage soiling, DM content of the litter, or friability of the litter. A significant worsening of the plumage condition was only found for the body spot back/wings/tail (not for: throat/neck, chest/breast, or legs) in the 45 mL/m^2 per day treatment. Egg quality shifted significantly towards more second class eggs in the oil treatments (1.9% versus 1.4). Remarkably, foot soiling decreased with increasing oil application. It was concluded that PM concentrations and emission rates in aviaries can be effectively reduced by spraying 15 to 30 mL/m^2 per day with minor side effects within a 25 day application period.

In relation to the second objective, **chapter 5** presents a field evaluation of the performance of four systems for abatement of particulate matter (PM) emission inside full-scaled commercial poultry houses: a fixed oil spraying system (OSF) inside two broiler farms and one laying hen house), an autonomously driving oil spraying vehicle (OSV) in one laying hen house, a negative air ionization system (NAI) inside two broiler farms, and a positive air ionization system (PAI) inside two laying hen houses. The systems were evaluated using case-control approaches. At each farm, six 24-h measurements were scheduled of PM_{10}, $PM_{2.5}$, ammonia, odor, and carbon dioxide concentrations (the latter for estimation of the ventilation rate and herewith emissions). This chapter presents the layout of the systems, compares their performance in practice with that under experimental conditions, discusses improvement possibilities, reports the baseline emission rates of the poultry houses, and discusses the validity of the case-control approaches. The emission reductions of PM_{10} and $PM_{2.5}$ were: 60% and 53% for the OSF in broilers (at 12 mL m^{-2} d^{-1}), 21% and 31% for the OSF in laying hens (at 15 mL m^{-2} d^{-1}), 32% and 38% for the OSV in laying hens (at 30 mL m^{-2} d^{-1}), 49% and 68% for the NAI in broilers, and 6% and zero for the PAI in laying hens. None of the systems significantly reduced the emission rate of odor or ammonia. On the basis of this work, emission reduction factors of the OSF, OSV, and NAI have been adopted in Dutch regulations.

In relation to the second objective, **chapter 6** presents a field evaluation of the removal performance of two exhaust air cleaning systems for abatement of PM emission in poultry houses: a commercially available dry filter (DF) and a full-scale prototype electrostatic

precipitator (ESP). Each system was connected to two commercial, non-cage laying hen houses: one with aviary housing, the other with floor housing. At each house, six to nine 24-h measurements were carried out, spread over the year and the laying cycle. Upstream and downstream of the systems, we measured PM_{10}, $PM_{2.5}$, and carbon dioxide concentrations, temperature, and relative humidity. Additional measurements of particle size distribution only were carried out at the DF of another poultry house. The latter showed that removal of PM by the DF increased with increasing particle diameter. Mean removal efficiency of the DF for PM_{10} was 40.1%, whereas $PM_{2.5}$ was not significantly removed. The ESP reduced concentrations of PM_{10} by an average of 57.0% and concentrations of $PM_{2.5}$ by an average of 45.3%. For neither of the two systems an effect of upstream PM concentration on removal performance was found. Results of this study are compared with the available literature and possibilities to improve removal performance are discussed. The mean (SD between houses) untreated emissions rate from the non-cage layer houses was 7.81 (4.12) mg PM_{10} h^{-1} $bird^{-1}$ and 0.44 (0.28) mg $PM_{2.5}$ h^{-1} $bird^{-1}$. On the basis of this work, emission reduction factors of the DF and ESP have been adopted in Dutch regulations.

In relation to the second objective, **chapter 7** presents a study on the efficacy of manure drying tunnels (MDTs) to serve as 'end of pipe' PM filters, and on possible additional emissions of ammonia and odor from these MDTs. This study aimed to determine the PM abatement potential of the MDTs, their additional emissions of ammonia and odor, and the perspective of two strategies to reduce additional emissions: (1) by pre-drying the manure on the belts inside the house, and (2) by reducing manure accumulation time (MAT) in the house to 24-h followed by rapid drying inside the MDT. This study was set up as an emission survey at 16 laying hen farms with a MDT. The results showed that PM_{10} removal efficiency of the MDTs increases linearly with manure layer thickness: from about 35% at 4 cm to 84% at 17 cm. Ammonia and odor concentrations in the drying air increased substantially upon passing the manure layers, from on average 5.5 to 13.9 ppm ammonia and from 822 to 1178 OU_E m^{-3}. With regard to strategy (1), ammonia emission decreased with increasing DM content of the manure, but even at DM content levels beyond 50%, substantial ammonia emission remained. With regard to strategy (2), the emission rates of houses and MDTs together were 44% lower for PM_{10}, 20% higher for ammonia, and 40% higher for odor compared with the theoretical situation of the houses without MDT. From this chapter it is concluded that the strategies are not sufficient in preventing the additional emissions. Further shortening MAT to 18, 12, or 6 h might be needed to reduce emissions from MDTs.

In relation to the third objective, **chapter 8** presents an equivalence study on the accuracy and comparability of samplers available for measuring the high PM_{10} concentrations (>100 μg m^{-3}) in the inside air directly upstream of the ventilation exhausts. This chapter provides insight into this matter for five candidate samplers: a filter-based cyclone sampler (CYS), the Thermo Scientific FH 62 I-R beta-attenuation sampler (BAS), the Thermo Scientific Tapered Element Oscillating Microbalance, model 1400ab (TEOM), the TSI DustTrak model 8520 (DT), and the GRIMM Portable Aerosol Spectrometer model 1.109 (PAS). Equivalence tests were carried out following European Standard EN 12341 using two devices for each candidate sampler (CAS) and four filter-based low-volume reference samplers (RES). Measurements were performed inside three major animal housings (a fattening pig house, a laying hen house, and a broiler house) and inside an office room. The key results and conclusions are: (1) neither one of the five CASs, nor the RES itself, met the EN 12341 requirement for comparability between devices of the same sampler type. Using a less strict boundary for this aspect – in concert with performing duplicate sampling – may be appropriate. (2) The CYS met the EN 12341 accuracy requirements in pigs and layers, but overestimated the RES concentration in broilers. The BAS, TEOM, and DT underestimated, and the PAS overestimated, RES concentrations in a systematic manner. The use of correction factors seems to be a promising method to calibrate measured values to RES concentrations. (3) The BAS, TEOM, DT, and PAS started to show scattered regression after 432–500 h of sampling, which stresses the need for shortened time intervals between full services. In conclusion, some of the samplers tested could be regarded acceptable when appropriate measures (such as duplicate sampling, correction factors, and more frequent servicing) are applied.

In **chapter 9**, the main findings from chapters 2 through 8 are discussed on a meta-level, i.e., in the light of the main objectives of this thesis and within the broad context of the overall problem. This chapter shows that the emission rates from chapter 2 currently play an important role in dealing with the problem of particulate air pollution in the Netherlands. They (1) have been adopted as emission factors in Dutch regulation on PM emissions from livestock houses; (2) substantially altered the national PM_{10} emission estimates of the livestock sector since 2010, and herewith the contribution of the livestock sector to the total national PM_{10} emissions; (3) are used to compute large-scale pollutant concentration maps (including PM_{10}) for the Netherlands; (4) are used in annual evaluations of the state of affairs of the National Air Quality Cooperation Programme in the Netherlands; and (5) are used in the ISL3a dispersion model which is used in the environmental permit granting procedure in the Netherlands to protect residents in the vicinity of livestock farms against exposure to excessive PM_{10} concentrations from farm

emissions. With regard to the abatement systems, the discussion shows that, despite that they may contribute only little to the reduction of ambient PM concentrations on the national scale, their contribution on a local and regional scale (i.e., in rural farming areas) is likely to be significant. The PM abatement systems evaluated in this thesis have yearly costs that are generally affordable for laying hen and broiler farms in comparison to other investments for the house and inventory. Gross margins in these sectors are, however, small, and these systems probably do not increase bird performance and revenues. This chapter furthermore illustrates that the national emission of PM_{10} from agriculture due to the transition from cage housings to alternative housings for laying hens could on the long term be reduced again by new housing designs that more adequately meet the requirements of the farmer, the animal, the consumer, and the environment. Finally, this chapter gives recommendations for future research.

Epilogue

This PhD adventure started in the summer of 2008. After an open application and two job interviews, I was offered a position as junior researcher and project leader with a focus on 'particulate matter emission from livestock houses'. In previous years, livestock houses had been identified as an important source of airborne particulate matter in some regions in the Netherlands and much work needed to be done to increase our understanding of this subject. Initially, it was not my intention to start a PhD project. I knew little about the subject, so my focus was on gaining expertise, setting up and leading projects, and getting all the work done; not so much on obtaining a degree of doctor based on that work. It was **Peter Groot Koerkamp** who first came up to me and raised the idea to use completed and running projects to write a series of papers within a PhD setting. This idea gradually developed and about four years ago, a committee was set up with Peter Groot Koerkamp as promotor and **Nico Ogink** and **André Aarnink** as co-promotors. From then on, things accelerated. Our ideas were transformed into a concrete PhD plan and a Training and Supervision Plan, all formal arrangements were made, I started re-analyzing datasets from completed projects that had been published in research reports, and started writing English manuscripts for scientific journals. Thanks to a pile of available research results and great supervisors, everything went rather smoothly and I never really had to doubt whether the PhD project would succeed. Peter, Nico, and André; it was a pleasure to be supervised by you during this process. Our meetings, conversations, and discussions, and your often raiser-sharp comments to drafts, felt like intellectual training sessions which allowed me to grow in knowledge, insight, and competence. Thanks for your ongoing collegiality, humor, and energy! My thanks also goes to **Nico Verdoes** for putting trust in me during the first years of my job, for offering me a permanent position thereafter, and for stimulating me to start this PhD project. **Bastiaan Meerburg**, as Nico's successor you always stimulated me to further this PhD project and helped in any way you could. Your no-nonsense, constructive and energetic attitude created the right setting for me to prosper in.

Chapters 2, 5, 6, 7, and 8 of this thesis are based on data obtained from measurements at about 60 commercial farms. It is thanks to the hospitality of each of these **dairy, pig, and poultry farmers** that these chapters could be written. I have refrained from writing down each of their names because it would probably cover half a page, but it can't be emphasized enough how important their voluntary and kind assistance has been for this thesis. My thanks also goes to **Johan Pikstra**, **Hans Kooijman**, **Fred Pouls**, and **Gerrit Vunderink**, animal caretakers at the former poultry research center 'Het Spelderholt' in Lelystad. Their practical but professionally conducted work underlies chapters 3 and 4 of this thesis.

The data in this thesis were mainly gathered by our research assistants and lab technicians. **Klaas Blanken, Freerk Dousma, Theo van Hattum**, **Jos Huis in't Veld, Annemieke Hol, Renske Kwikkel, Guus Nijboer**, and **Henk Schilder** carried out most of the practical field work, **Eef Lovink** and **Johan Ploegaert** meticulously nourished all measurement instruments, and **Geert Kupers** and **Jean Slangen** weighed hundreds and hundreds of dust filters, next to all other lab analyses. The expression 'Measuring is knowing' sounds so simple, but you all know it is far from that. Thanks guys!

An important 'partner in crime' during my first dust projects has been **Julio Mosquera Losada**, who introduced me into efficient data processing, sophisticated Excel formulas (that took ages to grasp ;-), and straightforward report writing. Thanks for your hard work and collegiality. Your co-authorship of several chapters in this thesis is definitely not without reason. **Johan van Riel**, we have spent many hours on statistical modelling which furthered my knowledge on statistics and GenStat programming. Your expertise as both animal scientist and mathematician has been very valuable and resulted in a co-authorship of chapter 4.

Since air pollution by particulate matter is an important issue in especially the poultry sector, colleagues **Hilko Ellen**, **Rick van Emous**, and **Jan van Harn** introduced me into the world of poultry farming. Aware of my passion for the mysterious homing pigeon, you successfully set the trap and got me interested in this other feathered species too.

María Cambra-López, as former PhD student on the same subject, you and I worked together in three settings which resulted in an equal number of scientific papers. Thanks for your kindness and the warm connection with Valencia. Both you and **Yang Zhao** critically reviewed my PhD plan and helped to shape my ideas for the Discussion chapter. **Jorge Llorens Rubio**, the field work within your MSc thesis was an important contribution to chapter 8. I much enjoyed it supervising your work. **Jan Vonk**, thanks to you, we could successfully include the TEOM and beta-attenuation instruments of the RIVM institute in the study of chapter 8. Thanks for sharing your expertise on measuring airborne particulate matter in ambient air.

I want to thank my **family** and **friends** for regularly showing interest into my PhD project and for their mental support. From now on, there is no more need to refer to me as 'doctorandus fine dust', demonstratively cough when I enter a room, or give me a pack of dust masks as Santa-Claus surprise. The dust era is over ;-).

Dear **Marjon**, thanks for your ongoing love, support and encouragement in so many ways. We did it.

Last but not least, my gratitude goes to God who has inspired me most to try and make this scientific team work flourish.

About the author

Curriculum vitae

List of publications

Training and Supervision Plan

CURRICULUM VITAE

Albert Winkel was born on 12 March 1980 in Leeuwarden, the Netherlands. After graduating from high school Gomarus College in Groningen in 1997, he started a Bachelor study in Agriculture at the Van Hall Larenstein University of Applied Sciences in Leeuwarden (specialization: animal health care and food chain management). In 2001, he completed his graduation thesis on effects of light on the performance, physiology, and behavior of cows, which received a mark 9 and was later issued as research report by Wageningen UR. Subsequently, he moved to Wageningen to start an MSc study in Animal Sciences at Wageningen University. He completed his curriculum with a major thesis at the Adaptation Physiology Group and a minor thesis at the Cell Biology and Immunology Group. In both theses, he studied whether antigen presenting immune cells of chickens can be skewed *in vitro* towards specific immune responses by administering (probiotic) bacteria or bacterial compounds. After his graduation, he found a first job as project officer at the former Ministry of Agriculture, Nature and Food Quality. In 2008, he became researcher/project leader at the Livestock Research institute of Wageningen UR. In the following years, he mainly worked on two extensive research programs on the measurement of particulate matter emissions from livestock houses and the development of abatement technologies. It is a selection of projects from these programs that now form chapters two to eight of this doctoral thesis. Besides his work, he is passionate admirer of the homing pigeon (*Columba livia*) and its puzzling ability to navigate to its home from distant and unfamiliar release sites. Since 2001, he is a member of the scientific advisory committee on animal welfare of the NPO, the Dutch association for about 20,000 pigeon keepers. Since 2012, he frequently combines his work as researcher with that of lecturer at the Van Hall Larenstein University of Applied Sciences and the Farm Technology Group of Wageningen University. His main position to date, still is that of researcher/project leader at Wageningen UR Livestock Research.

LIST OF PUBLICATIONS

Scientific articles in peer-reviewed journals

(in chronological order)

Cambra-López, M., **Winkel, A.**, Van Harn, J., Ogink, N.W.M., Aarnink, A.J.A., 2009. Ionization for reducing particulate matter emissions from poultry houses. *Trans. ASABE* 52:1757–1771.

Winkel, A., Cambra-López, M., Groot Koerkamp, P.W.G., Ogink, N.W.M., Aarnink, A.J.A., 2014. Abatement of particulate matter emission from experimental broiler housings using an optimized oil spraying method. *Trans. ASABE* 57:1853–1864.

Cambra-López, M., **Winkel, A.**, Mosquera, J., Ogink, N.W.M., Aarnink, A.J.A., 2015. Comparison between light scattering and gravimetric samplers for PM10 mass concentration in poultry and pig houses. *Atmos. Environ.* 111:20–27.

Winkel, A., Mosquera, J., Groot Koerkamp, P.W.G., Ogink, N.W.M., Aarnink, A.J.A., 2015. Emissions of particulate matter from animal houses in the Netherlands. *Atmos. Environ.* 111:202–212.

Winkel, A., Llorens Rubio, J., Huis in't Veld, J.W.H., Vonk, J., Ogink, N.W.M., 2015. Equivalence testing of filter-based, beta-attenuation, TEOM, and light-scattering devices for measurement of PM_{10} concentration in animal houses. *J. Aerosol Sci.* 80:11–26.

Winkel, A., Mosquera, J., Aarnink, A.J.A., Groot Koerkamp, P.W.G., Ogink, N.W.M., 2015. Evaluation of a dry filter and an electrostatic precipitator for exhaust air cleaning at commercial non-cage laying hen houses. *Biosyst. Eng.* 129:212–225.

Winkel, A., Mosquera, J., Aarnink, A.J.A., Groot Koerkamp, P.W.G., Ogink, N.W.M., 2016. Evaluation of oil spraying systems and air ionisation systems for abatement of particulate matter emission in commercial poultry houses. *Biosyst. Eng.* 150:104–122.

Winkel, A., Van Riel, J.W., Van Emous, R.A., Aarnink, A.J.A., Groot Koerkamp, P.W.G., Ogink, N.W.M., 2016. Abatement of particulate matter emission from experimental aviary housings for laying hens by spraying rapeseed oil. *Poult. Sci.*, in press.

Winkel, A., Mosquera, J., Aarnink, A.J.A., Groot Koerkamp, P.W.G., Ogink, N.W.M., 2016. Evaluation of manure drying tunnels to serve as dust filters in the exhaust of laying hen houses: emissions of particulate matter, ammonia, and odour. Manuscript submitted to: *Biosystems Engineering.*

Articles and abstracts presented at conferences

(in chronological order)

Aarnink, A.J.A., Harn, J. van, **Winkel, A.**, de Buisonjé, F.E., van Hattum, T.G., Ogink, N.W.M., 2009. Dust reduction in poultry houses by spraying rapeseed oil. In: Joint International Agricultural Conference (JIAC 2009), July 6–8, 2009, Wageningen Academic Publishers, Wageningen, the Netherlands, pp. 73–79.

Aarnink, A.J.A., Mosquera, J., **Winkel, A.**, Cambra-López, M., van Harn, J., de Buisonjé, F.E., Ogink, N.W.M., 2009. Options for dust reduction from poultry houses. In: CIGR International Symposium on 'Agricultural Technologies in a Changing Climate', September 13–16, 2009, International Commission of Agricultural and Biosystems Engineering (CIGR), Brisbane, Australia.

Ogink, N.W.M., Aarnink, A.J.A., Mosquera, J., **Winkel, A.**, 2010. Development and testing of technical measures for the abatement of PM_{10} emissions from poultry housings. In: XVIIth World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR), June 13–17, 2010, Canadian Society for Bioengineering (CSBE/SCGAB), Québec City, Canada.

Ellen, H.H., Aarnink, A.J.A., Mosquera Losada, J., **Winkel, A.**, Cambra-Lopez, M., van Harn, J., Ogink, N.W.M., 2010. Dust reduction options for poultry houses. In: XIIIth European Poultry Conference, August 23–27, 2010, French Branch of the World's Poultry Science Association (WPSA), Tours, France, pp. 282-282.

Aarnink, A.J.A., **Winkel, A.**, Mosquera Losada, J., Ogink, N.W.M., 2010. Emissions of aerial pollutants from poultry houses. In: International Symposium on Air Quality and Manure Management for Agriculture, September 13–16, 2010, American Society of Agricultural and Biological Engineers (ASABE), Dallas, Texas USA.

Winkel, A., Van Emous, R.A., van Hattum, T.G., Ogink, N.W.M., Aarnink, A.J.A., 2010. Dust reduction from aviary housing for laying hens by ionization and oil spraying. In: International Conference on Agricultural Engineering (AgEng 2010), September 6–8, 2010, European Society of Agricultural Engineers (EurAgEng), Clermont-Ferrand, France.

Winkel, A., Mosquera Losada, J., Ogink, N.W.M., 2011. Removal efficiency of a dry filter for abatement of particulate matter emissions from poultry houses. In: AAAR 30th Annual Conference, October 3–7, 2011, American Association for Aerosol Research (AAAR), Orlando, Florida, USA.

Winkel, A., Mosquera Losada, J., Ellen, H.H., Aarnink, A.J.A., Ogink, N.W.M., 2012. Dust filtering properties and ammonia emission of on-farm drying systems for poultry manure. In: International Symposium on Emissions of Gas and Dust from Livestock (EmiLi 2012), June 10–13, 2012, Saint-Malo, France.

Winkel, A., Mosquera, J., Ogink, N.W.M., 2012. Removal efficiency of a wire-to-plate . In: Ninth International Livestock Environment Symposium (ILES IX), July 8–12, 2012, American Society of Agricultural and Biological Engineers (ASABE), Valancia, Spain.

Cambra-Lopez, M., **Winkel, A.**, Mosquera, J., Ogink, N.W.M., Aarnink, A.J.A., 2012. Comparison between light scattering and gravimetric devices for sampling PM_{10} mass concentration in livestock houses. In: Ninth International Livestock Environment Symposium (ILES IX), July 8–12, 2012, American Society of Agricultural and Biological Engineers (ASABE), Valancia, Spain.

Winkel, A., Vermeij, I., Ellen, H.H., 2014. Testing of various techniques for dust reduction in an experimental pig house. In: International Conference of Agricultural Engineering (AgEng), Zurich, July 6–10, 2014, European Society of Agricultural Engineers (EurAgEng), Zurich, Switzerland.

Research reports

(listed per year and alphabetic order of the authors)

2003

Biewenga, G., **Winkel, A.**, 2003. Licht nader belicht: effecten van licht op dierprestaties en gedrag van melkvee [Shedding more light on light: the effects of light on the performance and behaviour of dairy cows; in Dutch, with English summary]. Praktijkrapport Rundvee 34, Animal Sciences Group, Wageningen UR, Lelystad, the Netherlands.

2009

Cambra-López, M., **Winkel, A.**, van Harn, J., Hannink, N., Aarnink, A.J.A., 2009. Measures to reduce fine dust emission from poultry houses: reduction from broiler houses by ionization. Report 215, Animal Sciences Group, Wageningen UR, Lelystad, the Netherlands.

Mosquera, J., van Emous, R.A., **Winkel, A.**, Dousma, F., Lovink, E., Ogink, N.W.M., Aarnink, A.J.A., 2009. Fijnstofemissie uit stallen: (groot)ouderdieren van vleeskuikens [Dust emission

from animal houses: broiler breeders; in Dutch, with English summary]. Report 276, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Mosquera, J., **Winkel, A.**, Dousma, F., Lovink, E., Ogink, N.W.M., Aarnink, A.J.A., 2009. Fijnstofemissie uit stallen: leghennen in scharrelhuisvesting [Dust emission from animal houses: layer hens in floor housing; in Dutch, with English summary]. Report 279, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Mosquera, J., **Winkel, A.**, Kwikkel, R.K., Gerrits, F.A., Ogink, N.W.M., Aarnink, A.J.A., 2009. Fijnstofemissie uit stallen: vleeskalkoenen [Dust emission from animal houses: turkeys; in Dutch, with English summary]. Report 277, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Ogink, N.W.M., van Hattum, T.G., **Winkel, A.**, 2009. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij: indicatieve evaluatie van het droogfiltersysteem StuffNix van Big Dutchman [Measures to reduce fine dust emission from poultry facilities: indicative evaluation of the Stuffnix system of Big Dutchman; in Dutch, with English summary]. Report 203, Animal Sciences Group, Wageningen UR, Lelystad, the Netherlands.

Van Emous, R.A., **Winkel, A.**, Ogink, N.W.M., 2009. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij: indicatieve evaluatie van het scharrelsysteem met gescheiden strooiselruimte [Measures to reduce fine dust emission from poultry houses: indicative evaluation of the housing system with separated floor bedding; in Dutch, with English summary]. Report 298, Animal Sciences Group, Wageningen UR, Lelystad, the Netherlands.

Winkel, A., Aarnink, A.J.A., 2009. Blootstelling aan fijnstof in de biologische varkenshouderij [Exposure to fine dust in organic pig farming; in Dutch, with English summary]. Report 284, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., Cambra-López, M., van Harn, J., van Hattum, T.G., Aarnink, A.J.A., 2009. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij: optimalisatie van een oliefilmsysteem bij vleeskuikens [Measures to reduce fine dust emission from poultry: optimization of an oil spraying system for broilers; in Dutch, with English summary]. Report 204, Animal Sciences Group, Wageningen UR, Lelystad, the Netherlands.

Winkel, A., Mosquera, J., Hol, J.M.G., Nijeboer, G.M., Ogink, N.W.M., Aarnink, A.J.A., 2009. Fijnstofemissie uit stallen: leghennen in volièrehuisvesting [Dust emission from animal houses: layer hens in aviary systems; in Dutch, with English summary]. Report 278, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., Mosquera, J., Kwikkel, R.K., Gerrits, F.A., Ogink, N.W.M., Aarnink, A.J.A., 2009. Fijnstofemissie uit stallen: vleeskuikens [Dust emission from animal houses: broilers; in Dutch, with English summary]. Report 275, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., van Emous, R.A., Kwikkel, R.K., Ogink, N.W.M., Aarnink, A.J.A., 2009. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij: ionisatie bij leghennen in volièrehuisvesting [Measures to reduce fine dust emission from poultry houses: ionization in aviary housing for layers; in Dutch, with English summary]. Report 285,Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., van Hattum, T.G., Aarnink, A.J.A., 2009. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij: ontwikkeling van een oliefilmsysteem voor leghennen in volièrehuisvesting [Measures to reduce fine dust emission from poultry houses: development of an oil spraying system for layers in aviary housing; in Dutch, with English summary]. Report 286, Wageningen UR Livestock Research, Lelystad, the Netherlands.

2010

De Vries, J.W., Radersma, S., **Winkel, A.**, de Buisonjé, F.E., 2010. Verkenning van milieuemissies en verbruiken van schaarse hulpbronnen in de sectoren: konijnen, vleeskalveren, eenden en kalkoenen [Exploring environmental emissions and depletion of resources of rabbit, veal calf, duck, and turkey production chains in the Netherlands; in Dutch, with English summary]. Report 383, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Mosquera, J., Hol, J.M.G., **Winkel, A.**, Huis, in't Veld, J.W.H., Gerrits, F.A., Ogink, N.W.M., Aarnink, A.J.A., 2010. Fijnstofemissie uit stallen: melkvee [Dust emission from animal houses: dairy cattle; in Dutch, with English summary]. Report 296, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Mosquera, J., Hol, J.M.G., **Winkel, A.**, Lovink, E., Ogink, N.W.M., Aarnink, A.J.A., 2010. Fijnstofemissie uit stallen: vleesvarkens [Dust emission from animal houses: growing and finishing pigs; in Dutch, with English summary]. Report 292, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Mosquera, J., Hol, J.M.G., **Winkel, A.**, Nijeboer, G.M., Ogink, N.W.M., Aarnink, A.J.A., 2010. Fijnstofemissie uit stallen: dragende zeugen [Dust emission from animal houses: pregnant

sows; in Dutch, with English summary]. Report 294, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Van Emous, R.A., Ogink, N.W.M., **Winkel, A.**, 2010. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij: gescheiden bedekte strooiselruimten bij legkippen [Measures to reduce fine dust emission from poultry houses: separated covered floor bedding for laying hens; in Dutch, with English summary]. Report 299, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., Blanken, K., Bokma, S., 2010. Beoordeling van de FSC 2000 als vervanger van de Leroux-meter voor het bepalen van de stroefheid van betonnen stalvloeren [Evaluation of the FSC 2000 as substitute for the Leroux apparatus for determination of skid resistance of concrete floors of animal houses; in Dutch, with English summary]. Report 315, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., Hol, J.M.G., Ogink, N.W.M., 2010. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij: indicatieve evaluatie van biofiltratie als potentiële fijnstofreductietechniek [Measures to reduce fine dust emission from poultry: indicative evaluation of biofiltration as potential fine dust reduction technique; in Dutch, with English summary]. Report 313, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., Mosquera, J., Hol, J.M.G., van Hattum, T.G., Lovink, E., Ogink, N.W.M., Aarnink, A.J.A., 2010. Fijnstofemissie uit stallen: biggen [Dust emission from animal houses: piglets; in Dutch, with English summary]. Report 293, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., Ogink, N.W.M., 2010. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij: indicatieve evaluatie van positieve ionisatie van uitgaande ventilatielucht [Measures to reduce fine dust emission from poultry: indicative evaluation of positive ionization of exhaust air; in Dutch, with English summary]. Report 314, Wageningen UR Livestock Research, Lelystad, the Netherlands.

2011

Ellen, H., Vermeij, I., **Winkel, A.**, van Emous, R., 2011. BBT fijn stof: beschrijving systemen en kosten [Best available techniques for particulate matter: description of systems and costs; in Dutch]. Report 476, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Mosquera, J., Hol, J.M.G., Melse, R.W., **Winkel, A.**, Nijeboer, G.M., Ploegaert, J.P.M., Ogink, N.W.M., Aarnink, A.J.A., 2011. Fijnstofemissie uit stallen: luchtwassers [Dust emission from

animal houses: air scrubbing techniques; in Dutch, with English summary]. Report 295, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Mosquera, J., Hol, J.M.G., **Winkel, A.**, Huis in 't Veld, J.W.H., Dousma, F., Ogink, N.W.M., Groenestein, C.M., 2011. Fijnstofemissie uit stallen: nertsen [Dust emission from animal houses: minks; in Dutch, with English summary]. Report 340, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Van Emous, R.A., **Winkel, A.**, Ellen, H.H., Ogink, N.W.M., 2011. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij: ontwerp van stallen met integratie van fijnstofarme technieken en nieuwe inrichtingsconcepten [Measures to reduce fine dust emission from poultry facilities: design of poultry houses with integration of fine dust measurements and new layout concepts; in Dutch, with English summary]. Report 444, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Van Emous, R.A., **Winkel, A.**, Ogink, N.W.M., 2011. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij: indicatieve evaluatie van een recirculatiesysteem met ionisatiefilter [Measures to reduce fine dust emission from poultry facilities: indicative evaluation of a recirculation system with ionization filter; in Dutch, with English summary]. Report 504, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., 2011. Lichtbehoeften van koe en melkveehouder [Lighting needs of cow and dairy farmer; in Dutch]. In: Adviesdocument voor agrariërs en overheid: optimale verlichting van melkveestallen (bijlage 2), LTO Noord, Drachten, the Netherlands, p. 23–26.

Winkel, A., Mosquera, J., Ellen, H.H., Van Emous, R.A., Hol, J.M.G., Nijeboer, G.M., Ogink, N.W.M., Aarnink, A.J.A., 2011. Fijnstofemissie uit stallen: leghennen in stallen met een droogtunnel [Dust emission from animal houses: laying hens in houses with a tunnel drying system; in Dutch, with English summary]. Report 280, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., Mosquera, J., Huis in't Veld, J.W.H., Nijeboer, G.M., Ogink, N.W.M., 2011. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij: validatie van een droogfilterwand op leghennenbedrijven [Measures to reduce fine dust emission from poultry houses: validation of a dry filter wall on layer farms; in Dutch, with English summary]. Report 394, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., Mosquera, J., Huis in't Veld, J.W.H., Ogink, N.W.M., Aarnink, A.J.A., 2011. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij: validatie van een ionisatiesysteem op vleeskuikenbedrijven [Measures to reduce fine dust emission from

poultry: validation of an ionization system on broiler farms; in Dutch, with English summary]. Report 462, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., Mosquera, J., van Harn, J., Nijeboer, G.M., Ogink, N.W.M., Aarnink, A.J.A., 2011. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij: validatie van een oliefilmsysteem op vleeskuikenbedrijven [Measures to reduce fine dust emission from poultry houses: validation of an oil spraying system on broiler farms; in Dutch, with English summary]. Report 392, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., Smolders, M.M.A.H.H., Aarnink, A.J.A., Ogink, N.W.M., 2011. Plan van aanpak voor ontwikkeling van fijnstofreductiemethoden in varkensstallen [Plan of action for development of dust reduction principles inside pig houses; in Dutch, with English summary]. Report 395, Wageningen UR Livestock Research, Lelystad, the Netherlands.

2012

Van Dooren, H.J.C., Sleurink, D., Biewenga, G., Kasper, G.J., **Winkel, A.**, Blanken, K., Wemmenhove, H., Meerburg, B.G., Sapounas, A., Overbeek, J., Elling, G., Sloff, J., Versluis, H., 2012. Dakmagazine: meer licht, lucht en ruimte, voor minder [Roof magazine: more light, air, and space, for less; in Dutch]. Report, AgriMedia, Wageningen, the Netherlands.

Van Oosterhout, F., Biewenga, G., **Winkel, A.**, Ouweltjes, W., Meijer, J.H., 2012. Het effect van lichtkleur en lichtduur op melkproductie en gedrag van melkvee [The effect of light colour and photoperiod on milk production and behaviour of dairy cows; in Dutch]. Report, Leiden University Medical Center and Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., Belgers, J.D.M., Peters, B., Vermeij, I., Ellen, H.H., 2012. Ontwikkeling en evaluatie van technieken ter verlaging van stofconcentraties in varkensstallen [Development and evaluation of techniques to mitigate dust concentrations in pig houses; in Dutch, with English summary]. Report 654, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., Mosquera, J., van Hattum, T.G., Huis in't Veld, J.W.H., Nijeboer, G.M., Ogink, N.W.M., 2012. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij: validatie van een ionisatiefilter op leghennenbedrijven [Measures to reduce fine dust emission from poultry houses: validation of an ionisation filter on layer farms houses; in Dutch, with English summary]. Report 440, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., van Emous, R.A., Mosquera Losada, J., Nijeboer, G.M., van Hattum, T.G., van Riel, J.W., Aarnink, A.J.A., Ogink, N.W.M., 2012. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij: optimalisatie aanbrengen oliefilm op strooisel bij leghennen in volièrehuisvesting [Measures to reduce fine dust emission from poultry: optimization of oil application on litter of aviary housing for layers houses; in Dutch, with English summary]. Report 597, Wageningen UR Livestock Research, Lelystad, the Netherlands.

2013

Mosquera, J., Groenestein, C.M., Timmerman, M., Aarnink, A.J.A., **Winkel, A.**, Ploegaert, J.P.M., Ogink, N.W.M., 2013. Deskstudie naar maatregelen ter vermindering van broeikasgasemissies uit varkens- en pluimveestallen [Desk study on measures to reduce greenhouse gas emissions from pig and poultry houses; in Dutch]. Report 750, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., Huis in't Veld, J.W.H., Nijeboer, G.M., Blanken, K., Schilder, H., van Hattum, T.G., Ogink, N.W.M., 2013. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij: validatie van een oliefilmrobot op een leghennenbedrijf [Measures to reduce fine dust emission from poultry: validation of an oil spraying robot on a layer farm; in Dutch, with English summary]. Report 686, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., Nijeboer, G.M., Huis in't Veld, J.W.H., Ogink, N.W.M., 2013. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij: validatie van een ionisatiesysteem op leghennenbedrijven [Measures to reduce fine dust emission from poultry houses: validation of an ionisation system on layer farms; in Dutch, with English summary]. Report 685, Wageningen UR Livestock Research, Lelystad, the Netherlands.

2014

Winkel, A., Blanken, K., Ellen, H.H., Ogink, N.W.M., 2014. Ammoniakvorming in mestdroogsystemen op legpluimveebedrijven met mestbandbeluchting [Ammonia production in manure drying systems at layer farms with manure belt aeration; in Dutch, with English summary]. Report 730, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., Demeyer, P., Feilberg, A., Jørgensen, M., Puterflam, J., Engel, P., 2014. Measurement of particulate matter: recommendations for the VERA test protocol on air cleaning technologies. Report 797 (produced under an ICT-AGRI project by: Wageningen University and Research Centre, Aarhus University, Danish Pig Research Centre, Institute for Agricultural and Fisheries Research (ILVO), the Technical Institute for Poultry Research (ITAVI), and the VERA Secretariat), Wageningen UR Livestock Research, Wageningen, the Netherlands.

Winkel, A., Ellen, H.H., Ogink, N.W.M., 2014. Mogelijkheden voor het vaststellen van emissies van leghennenstallen met een nageschakeld mestdroogsysteem [Possibilities for determining emissions of laying hen houses connected to a manure drying system; in Dutch, with English summary]. Report 803, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., Huis in't Veld, J.W.H., Nijeboer, G.M., Ogink, N.W.M., 2014. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij: validatie van een oliefilmsysteem op een leghennenbedrijf [Measures to reduce fine dust emission from poultry houses: validation of an oil spraying system on a layer farm; in Dutch, with English summary]. Report 801, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., Huis in't Veld, J.W.H., Nijeboer, G.M., Schilder, H., van Hattum, T.G., Ellen, H.H., Ogink, N.W.M., 2014. Emissies uit mestdroogsystemen op leghennenbedrijven bij dagontmesting en versneld drogen [Emissions from manure drying systems on layer farms using 24-h manure removal and rapid drying; in Dutch, with English summary]. Report 731, Wageningen UR Livestock Research, Lelystad, the Netherlands.

Winkel, A., Wouters, I.M., Aarnink, A.J.A., Heederik, D.J.J., Ogink, N.W.M., 2014. Emissies van endotoxinen uit de veehouderij: een literatuurstudie voor ontwikkeling van een toetsingskader [Emissions of endotoxins from animal production: a literature survey for development of an assessment framework; in Dutch, with English summary]. Report 773, Institute for Risk Assessment Sciences, Utrecht University and Wageningen UR Livestock Research, Wageningen, the Netherlands.

2015

Van Niekerk, T.G.C.M., Ellen, H.H., **Winkel, A.**, 2015. Licht en verlichting in de pluimveehouderij in relatie tot beschadigend pikgedrag [Light and lighting in the poultry industry in relation to damaging pecking behaviour; in Dutch]. Report 992, Wageningen UR Livestock Research, Wageningen, the Netherlands.

2016

Ogink, N.W.M., Erbrink, H. (editors), 2016. Emissies van endotoxinen uit de veehouderij: emissiemetingen en verspreidingsmodellering [Emissions of endotoxins from animal production: emission measurements and dispersion modelling; in Dutch, with English summary]. Report 959, Institute for Risk Assessment Sciences (IRAS), Utrecht University (authors: Wouters, I.M., Heederik, D.J.J.), Erbrink Stacks Consult (author: Erbrink, H.), Wageningen UR Livestock Research (Ogink, N.W.M., **Winkel, A.**), Wageningen, the Netherlands.

Winkel, A., Wouters, I.M. (editors), 2016. Additionele maatregelen ter vermindering van emissies van bioaerosolen uit stallen: verkenning van opties, kosten en effecten op de gezondheidslast van omwonenden. [Additional measures to reduce emissions of bioaerosols from animal houses: exploration of options, costs, and effects on health of neighboring residents; in Dutch]. Report 949, Institute for Risk Assessment Sciences (IRAS), Utrecht University (authors: Wouters, I.M., Heederik, D.J.J.), Wageningen UR, Central Veterinary Institute (author: Hagenaars, T.J.), Wageningen UR Livestock Research (Ogink, N.W.M., Vermeij, I., Winkel, A.), Wageningen, the Netherlands.

Articles in magazines aimed at a professional audience

(in chronological order)

Biewenga, G., **Winkel, A.**, 2003. Melken van licht: belang van goed lichtregime op productie 'onderbelicht'. *Veeteelt* 20(4), februari-2 2003, p. 71.

Biewenga, G., **Winkel, A.**, 2003. Betere verlichting geen sprong in het duister. *PraktijkKompas Rundvee* 17(1), februari 2003, p. 4–5.

Biewenga, G., **Winkel, A.**, 2005. Melkkoeien goed belicht? *AgriConstruct* 8(3), p. 6–7.

Biewenga, G., **Winkel, A.**, 2008. Voldoende licht voor een productieve en weerbare koe. *Veehouder & Dierenarts* 22(1), januari 2008, p. 21–22.

Winkel, A., Aarnink, A.J.A., 2009. Stofniveau biologische varkensstal onveilig hoog. *V-focus*, december 2009, p. 34–36.

Winkel, A., Van Dooren, H.J.C., 2010. Innovatieve en goedkope daken voor melkveestallen. *V-focus*, februari 2010, p. 20–21.

Winkel, A., 2010. Bescherm je longen tegen stof. BioKennisbericht Varkensvlees nr. 12, maart 2010, Wageningen UR, Communication Services, Wageningen, the Netherlands, 4 pp.

Van Harn, J., Aarnink, A.J.A., **Winkel, A.**, 2010. Slim Plakwerk. *De Pluimveehouderij* 40(4), maart 2010, p. 54–55.

Winkel, A., Bokma, S., 2011. Adviezen voor daglicht in varkensstallen. *V-focus*, juni 2011, p. 36–37.

Van Weeghel, H.J.E., Groot Koerkamp, P.W.G., **Winkel, A.**, 2011. Stofbad van hennen doet stof opwaaien. *V-focus*, oktober 2011, p. 44–45.

Winkel, A., Swinkels, G.L.A.M., Biewenga, G., Van Oosterhout, F., 2011. Mag het licht uit? Koe en omgeving willen 's nachts duisternis. *V-focus*, december 2011, p. 24–25.

Winkel, A., 2012. Negative air ionisation strongly decrease fine dust. *World Poultry* 28, March 2012, p. 24–25.

Winkel, A., Ellen, H.H., Swinkels, G.L.A.M., 2014. Energiebesparende verlichting in de stal. *V-focus*, februari 2014, p. 32–33.

Winkel, A., Ellen, H.H., Swinkels, G.L.A.M., 2014. Nieuwe waardering voor daglicht in de stal. *V-focus*, april 2014, p. 36–37.

TRAINING AND SUPERVISION PLAN (TSP)

The basic package (0 credits)	
WIAS Introduction day	Exemption
Ethics and Philosophy in Life Sciences	Exemption
Disciplinary Competences (8 credits)	
Course Introduction to GenStat, Biometris, Wageningen, the Netherlands	2010
Course Measurement of aerial emissions, VVM, Amersfoort, the Netherlands	2010
Course Measurement of nanoparticles, Ravebo, Brielle, the Netherlands	2011
Course Introduction to aerosol mechanics I and II, AAAR, Orlando, USA	2014
Member int. working group on 'Harmonization of the measurement of particulate matter in animal houses', VERA, Copenhagen, Denmark	2014
Writing of PhD research proposal	2014
Professional Competences (13 credits)	
Personal profile assessment, Discovery Insights, Wageningen, the Netherlands	2009
Course Project management, P^2 Managers, Lelystad, the Netherlands	2009
Course Writing for academic publication, McPhee Consulting, Lelystad, the Netherlands	2012
Course Expert in sales I and II, Kenneth Smith Training, Lelystad, the Netherlands	2012
Talents and Topics training programme 2012, WIAS, Wageningen, the Netherlands	2012
Presentation skills (4 credits)	
EurAgEng, Clermont-Ferrand, France, September 6–8 (paper + oral presentation)	2010
AAAR 30th Annual Conference, Orlando, USA, Oct. 3–7 (abstract + oral present.)	2011
CIGR-EurAgEng, Valencia, Spain, July 8–12 (paper + oral presentation)	2012
EmiLi 2012 conference, St. Malo, France, June 10–13 (paper + oral presentation)	2012
EurAgEng, Zürich, Switzerland, June 6–10 (paper + oral presentation)	2014
Teaching competences (6 credits)	
Lectures course Livestock Technology (FTE-30306), Wageningen University	‘12–‘16
Lectures course Quant. Anal. of Innov. Biosystems (FTE-34306), Wageningen University	‘14–‘16
Lectures course Research Methods Biosyst. Eng. (FTE-25806), Wageningen University	‘14–‘16
Supervising MSc student Jorge Llorens Rubio (12 months), Wageningen University	‘13–‘14

Total: 31 credits (one ECTS credit equals a study load of approximately 28 hours)

COLOPHON

Funding
The research described in this thesis was funded by:
Ministry of Economic Affairs
Ministry of Infrastructure and the Environment
Province of Gelderland
Province of Noord-Brabant

Cover design
Ferdinand van Nispen tot Pannerden (www.citroenvlinder-dtp.nl)
Petra Siebelink (Wageningen UR, Communication Services)
Albert Winkel

Layout
Albert Winkel

Printing
GVO drukkers & vormgevers, Ede, the Netherlands