Livestock Farms as Major Emission Source of Atmospheric Particles in the Netherlands: Lessons Learned and Future Perspectives

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Abstract

In the Netherlands, about 17 million people live together on a 40,000-km^2 surface area with about 4 million head of cattle, 12 million pigs, and 100 million chickens. In some rural areas, residents live in close proximity to livestock farms, exposing them to airborne particulate matter (PM) from farm emissions. To combat this problem, an extensive research programme was carried out at Wageningen University and Research from 2008 to 2013, part of which was done in a PhD project. This PhD project, among others, aimed to: (1) generate accurate and up to date concentrations and emission rates of inhalable PM (PM_{100}), PM_{10} and $PM_{2.5}$ for commonly used animal housing systems, and (2) develop PM abatement systems for use in poultry farms to reduce their PM emissions. The present conference paper briefly describes the main results from these objectives and then focusses on some lessons learned and future perspectives from the work on a meta-level. This paper highlights that the national PM emission of the livestock sector has increased considerably in the last two decades mostly due to the transition from cage housing for layers to alternative housings, in contrast to all other sectors like traffic and industry, which substantially reduced their emissions. Furthermore, an overview of the developed PM abatement systems is presented along with an economic analysis of their costs. For the long term, however, this paper proposes that new animal housing designs are needed that are able to combine both animal welfare and a low environmental impact.

Keywords: Livestock, barns, emission, particulate matter, abatement, public health, review

1. Introduction: Problem and Objectives

In many parts of the world important food products such as meat, eggs, and milk are produced by animals kept in buildings. These 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*".

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). Farmers are chronically exposed to these components during work (Figure 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 (Omland, 2002; Seifert et al., 2003; Eduard et al., 2004).

Next to the farmers, animals are chronically exposed as well (Figure 1). 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., 1966; Guarino et al., 1999; Al Homidan et al., 2003).

Since animal houses are ventilated, large amounts of PM are emitted into the atmosphere as well (Figure 1; step 2 in the lower picture). In the Netherlands, about 17 million people live together on a 40,000-km^2 surface area with about 4 million heads of cattle, 12 million pigs, and 100 million chickens. For some areas in the Netherlands, it was estimated that animal houses raise background concentrations of PM_{10} by several micrograms per cubic meter (Velders et al., 2008). Studies on urban aerosols show associations between PM_{10} concentration and respiratory and cardiovascular disease (Brunekreef and Forsberg, 2005; Pope and Dockery, 2006). For livestock PM, health effects of ambient exposure (Figure 1; step 5 through 7) are less well studied. Recent studies in the Netherlands suggest both protective effects (e.g., a lower prevalence of asthma) and adverse effects (e.g., a higher prevalence of pneumonia and more exacerbations in COPD patients) (Smit et al., 2012; Smit et al., 2014; Borlée et al., 2015).

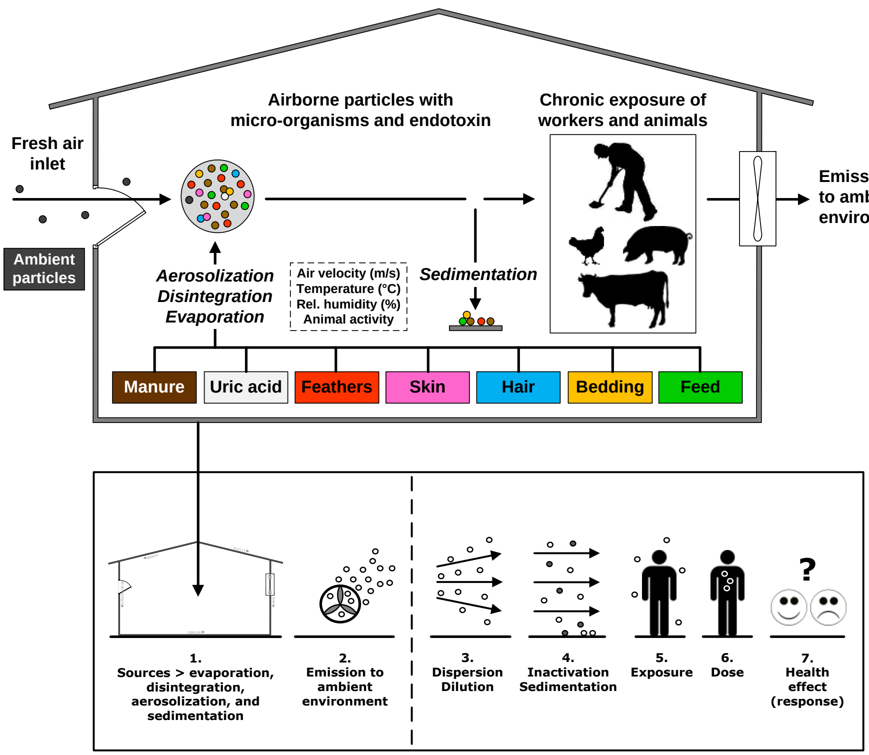

Figure 1. Infographic (Winkel, 2016) that summarizes the central problem of this paper: inside (upper picture) and outside (lower picture) the animal house.

In view of this problem, an extensive research programme was carried at Wageningen University and Research between 2008 and 2013. Part of this work was done in a PhD project (Winkel, 2016) which, among others, included the following two objectives:

1. to generate accurate and up to date concentrations and emission rates of inhalable PM (PM_{100}), PM_{10} and $PM_{2.5}$ for commonly used animal housing systems, under representative inside and outside climate conditions and ventilation rates;
2. to develop, test, and validate PM abatement systems for use in poultry farms to reduce their contribution to ambient PM concentrations.

The present conference paper briefly describes the main results related to these objectives and then focusses on some lessons learned and future perspectives from the work on a meta-level.

2. Emissions of Animal Houses and their Contribution to National PM_{10} Emissions

With regard to objective 1 from the PhD thesis of Winkel (2016), a PM emission survey was carried out. This survey produced emission rates for 13 housing systems for poultry, pigs, and dairy cattle, and included 36 farms (Winkel et al., 2015b). 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 mean emission rate of PM_{10} ranged from 2.2 to 12.0 mg h^{-1} $animal^{-1}$ in poultry, ranged from 7.3 to 22.5 mg h^{-1} $animal^{-1}$ in pigs, and amounted 8.5 mg h^{-1} $animal^{-1}$ in dairy cattle. 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 and report 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.

Based on the emission rates from the survey, the national yearly emissions from animal houses have been estimated. Figure 2A shows the national primary PM_{10} emission in the Netherlands from 1990 to 2015 for five main groups of emission sources, including agriculture, which is further specified in Figure 2B. From this figure it is clear that PM_{10} emissions have been mitigated substantially in these years in all groups, except for agriculture, which shows in *increase* in emission. This increase is mainly caused by laying hen houses (Figure 2B), whereas emissions from broiler houses and dairy cattle houses remained relatively stable. The emission from pig houses decreased, presumably by the wide-spread use of air scrubbers in this sector since the 1990s. 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).

The survey (Winkel et al., 2015b) 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. Thus, it can be argued that with the transition from cage housings to alternative housings, an animal welfare problem has not so much been truly solved, but rather swapped for an air quality problem.

3. Overview of Developed PM Abatement Systems

With regard to objective 2 from the PhD thesis of Winkel (2016), a total of seven PM abatement systems were worked out, some tested experimentally, but all validated at commercial farms under field conditions. Table 1 provides an overview of the systems, their names (abbreviations), working principle, PM_{10} emission reduction, and references to underlying journal papers. Based on this work, official PM_{10} emission reduction percentages for the OSF, OSV, NAI, DF, ESP, and MDTs have been adopted in Dutch legislation. When poultry farmers want to build or enlarge a poultry house, choosing and installing one of these systems allows them to mitigate PM emissions and receive an environmental permit from the local government.

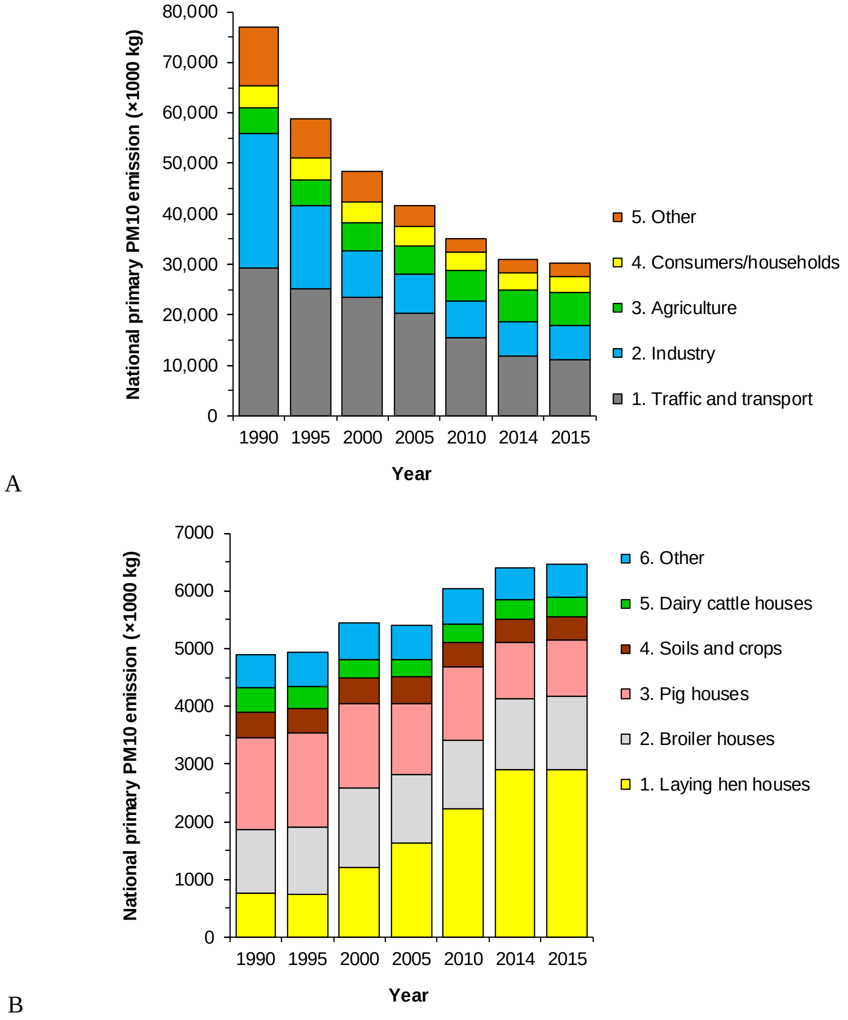

Figure 2. A: national primary PM_{10} emissions (×1000 kg) in the Netherlands from 1990 to 2015. B: the same figures within the main Agriculture group. Source data: Pollutant Release and Transfer Register (RIVM, Bilthoven, The Netherlands): http://www.emissieregistratie.nl. Note that the years on the x-axis are not continuous.

4. Economic Impact of PM Abatement Systems

The systems listed in Table 1 were worked out based on a number of criteria, including that, in the end, they must have acceptable costs for poultry farmers. Table 2 shows the costs of the systems based on realistic financial figures provided by the suppliers that currently bring the systems to the market. The costs are calculated for a standard laying hen house with 40,000 birds and a standard broiler farm with two houses with 45,000 birds each.

Table 1. Overview of PM abatement systems from Winkel (2016).

System	Working principle	PM_{10} reduction	References
Fixed oil spraying system (OSF)	Rapeseed oil droplets confine particles in litter	54% (broilers); 21% (layers)	Aarnink et al. (2011); Winkel et al. (2014); Winkel et al. (2016a)
Oil spraying vehicle (OSV)	Idem	32% (layers)	Winkel et al. (2016b); Winkel et al. (2016a)
Negative air ionization (NAI)	Ionization and removal of particles from inside air	49% (broilers)	Cambra-López et al. (2009); Winkel et al. (2016a)
Positive air ionization (PAI)	Ionization and removal of particles from inside air	6% (layers)	Winkel et al. (2016a)
Dry filter (DF)	Inertial impaction of particles in a filter wall (end of pipe)	40% (all)	(Winkel et al., 2015a)
Electrostatic precipitator (ESP)	Ionization (end of pipe)	57% (all)	(Winkel et al., 2015a)
Manure drying tunnels (MDTs)	Filtration of particles inside manure layer (end of pipe)	30/55% (layers)	(Winkel et al., 2017)

Table 2. Cost analysis of PM abatement systems from Winkel (2016).

System	*Laying hen farm; 40,000 animal places* Investment costs / Exploitation costs / Total costs (€ yr^{-1} $aplc^{-1}$)	*Broiler farm; 90,000 animal places* Investment costs / Exploitation costs / Total costs (€ yr^{-1} $aplc^{-1}$)
Basic situation: barn + inventory	3.00 / 0.35 / 3.35	1.20 / 0.50 / 1.70
Fixed oil spraying system (OSF)	0.18 / 0.43 / 0.60	0.09 / 0.11 / 0.20
Oil spraying vehicle (OSV)	0.09 / 0.82 / 0.91	---
Negative air ionization (NAI)	---	0.09 / 0.007 / 0.10
Positive air ionization (PAI)	0.65 / 0.18 / 0.83	0.35 / 0.10 / 0.45
Dry filter (DF)	0.07 / 0.05 / 0.12	0.06 / 0.06 / 0.13
Electrostatic precipitator (ESP)	0.34 / 0.001 / 0.34	0.34 / 0.001 / 0.34
Manure drying tunnels (MDTs)	0.37 / 0.009 / 0.38	---

For laying hens, the three cheapest solutions are the DF (€ 0.12), the ESP (€ 0.34), and the MDTs (€ 0.38). For broilers, the three cheapest solutions are the NAI (€ 0.10), the DF (€ 0.13), and the OSF (€ 0.20). The gross margins (i.e., revenues from eggs/meat minus variable costs for young birds, feed, energy, and etcetera) in the Netherlands are about € 2.90 hen $place^{-1}$ $year^{-1}$ and € 1.30 broiler $place^{-1}$ $year^{-1}$. The additional costs for a PM abatement system have to be paid from those gross margins, together with the investment and exploitation costs for the animal house, and the farmer's income. Therefore, it is still financially challenging poultry farmers to apply PM abatement systems in their houses. In relation to this, it would be welcome if PM abatement systems would improve bird productivity so that applying a PM abatement system would pay for itself. The experimental work from Table 1 however, did not show significant differences in production performances between birds in treatment (i.e., low PM) and control (i.e., high PM) groups.

5. PM Abatement by Redesign of Animal Housing Systems

The PM abatement systems listed in Tables 1 and 2 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 EU Directive 2008/50/EC limits for PM_{10} in 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 the PhD thesis of Winkel (2016) 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 Winkel (2016) did not aim to produce such designs. It has, however, delivered insights that might act as inspiration for such designs. The work clearly showed 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 Figure 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. 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? Figure 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. The presence of litter, and the natural behavior of the birds, can be organized in separate litter rooms. 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, and/or frequent addition of fresh litter substrate. These examples should prevent that the air becomes polluted with particles in the first place. In addition, a PM abatement system from Tables 1 and 2 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. If needed, the ventilation flow through litter rooms 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.

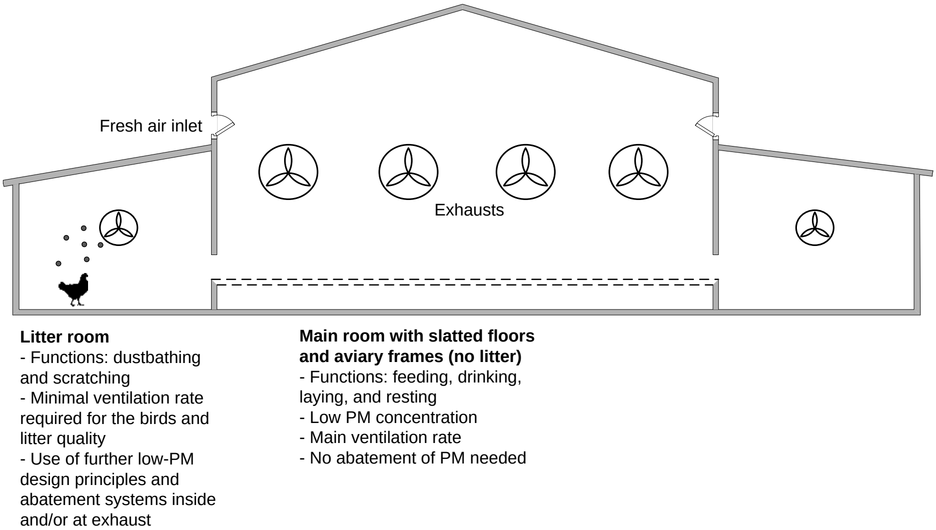

Figure 3. Example of a housing design (cross-sectional view) for laying hens with incorporation of principles that may result in a low-emission system with regard to particulate matter (PM).

6. Summary and Conclusions

The present conference paper provided a brief overview of the main findings of a recent PhD project on PM emission and emission abatement and focused on some lessons learned and future perspectives from the work on a meta-level. The PM emission data from the project has shown that in the last two decades, PM emissions of the livestock sector in the Netherlands has increased substantially where all other main sectors like traffic and industry reduced emissions. This increase is mainly attributable to the transition from low-dust cage housing of laying hens to extremely dusty alternative housing systems: a development that has swapped an animal welfare problem for an air quality problem. For the short term, the work has yielded several PM abatement systems, which can be added to existing poultry houses to mitigate emissions and reduce ambient PM concentrations for the general population. However, their implementation remains a challenge from an economic point of view because gross margins in the poultry sector are limited and systems do not seem to improve animal productivity. For the long term, housing designs that have inherently low PM emissions are needed to combine both animal welfare and a low environmental impact. Separating PM-generating behavior in separate rooms and removing manure from the housing system might be a promising principle to achieve such designs.

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