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Dust Reduction in Broiler Houses by Spraying Rapeseed Oil

A. J. A. Aarnink, J. van Harn, T. G. van Hattum, Y. Zhao, N. W. M. Ogink

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The authors are **Andr&#65533; Aarnink, ASABE Member,** Senior Researcher Livestock Environment, **Jan van Harn,** Researcher, **Theo van Hattum,** Research Assistant, **Yang Zhao,** Researcher, and **Nico Ogink,** Senior Researcher; Wageningen UR Livestock Research, Wageningen, The Netherlands. **Corresponding author:** Andr&#65533; Aarnink, Wageningen UR Livestock Research, P.O. Box 135, 6700 AC, Wageningen, The Netherlands; phone: 31-320-293589 (directed to mobile); fax: 31-320-238094; e-mail: andre.aarnink@wur.nl.

Abstract. *The effect of spraying rapeseed oil on the reduction of dust and ammonia concentrations and emissions, and on animal parameters was investigated in a dose-response study in a broiler house during three growing periods in four (round 1) or five rooms (rounds 2 and 3). The spraying rates varied per room, from 0 (control) to 24 mL oil* m^{-2} d^{-1} *. Concentrations of* PM_{10} *and* $PM_{2.5}$ *in incoming and outgoing air were measured. Production results (growth rate, feed intake, mortality rate) and foot-pad lesions were also determined. Regression analysis showed that a spraying rate of 6 mL oil* m^{-2} d^{-1} *reduced* PM_{10} *concentrations by 44% and* PM_{10} *emissions by 48%. At 24 mL oil* m^{-2} d^{-1} *, the reduction was 82% for* PM_{10} *concentrations and 87% for* PM_{10} *emissions. For* $PM_{2.5}$ *, the lowest spraying rate of 6 mL oil* m^{-2} d^{-1} *was sufficient to reduce concentrations by 68% and emissions by 84%. The reduction achieved at higher spraying rates was not significantly greater. Emissions of* PM_{10} *and* $PM_{2.5}$ *increased exponentially with the age of the broilers. A clear diurnal pattern was observed, with lower dust concentrations during the dark periods. Production results were unaffected by the spraying rate. A high rate of 24 mL oil* m^{-2} d^{-1} *increased the number and severity of foot-pad lesions. It is concluded that spraying rapeseed oil significantly reduces dust concentrations and emissions from broiler houses. To prevent adverse effects on broilers' foot-pad quality, it is recommended that the maximum*

rate should be 16 mL oil m^{-2} d^{-1} .

Keywords. Ammonia, Broiler house, Dust reduction, Foot-pad lesions, Oil spraying.

Various publications have reported the effects of fine dust in the ambient air on human health. The health problems are related to heart and lung disorders, which cause early death (Buringh and Opperhuizen, 2002). For this reason, the EU has set standards for maximum concentrations of fine dust in the ambient air. Maximum permissible concentrations have been defined for dust particles smaller than 10 m (PM_{10}) and for particles smaller than 2.5 m ($PM_{2.5}$). These limits, especially that for PM_{10}, are exceeded in parts of the Netherlands. It is estimated that agriculture is responsible for approximately 20% of the primary fine dust emission in the Netherlands, and that most of this dust originates from poultry and pig farms (Chardon and Van der Hoek, 2002).

Livestock farmers, especially those working with poultry or pigs, are exposed to dust concentrations inside their animal houses that are 10 to 200 times higher than those in the outside air. In recent decades, much research has been done on the effects of high dust concentrations on the respiratory health of farmers. The prevalence of respiratory problems in livestock farmers is considerably higher than in other occupations (Bongers et al., 1987). It has been shown that exposure to barn dust causes disorders of the respiratory tract and the lungs (Donham et al., 1984; Dosman et al., 1997). Studies also suggest that airborne particles can have an impact on animal health, production, and welfare (Banhazi et al., 2009a; Banhazi et al., 2009b).

Over the last 15 years, much work has been done on reducing dust by spraying a mixture of oil and water. This method has proved to be very effective in reducing dust in animal houses and relatively inexpensive. The main effect of spraying oil and water is that it binds dust particles to surfaces, preventing particles from becoming airborne. With good design, total dust reductions of up to 90% have been achieved (Lemay et al., 2000; Zhang et al., 1996). Takai et al. (1995) found no adverse effect of oil spraying on animal and human health. When oil was sprayed, no change in lung function of the pigs was observed during weighing, whereas lung function in the control group clearly decreased. According to Gustafsson and Von Wachenfelt (2004), a dust reduction of 50% is achievable in poultry bedding systems by spraying water alone. The disadvantages of using only water are increased aerial humidity and damp bedding material. Little work has been done until now on testing oil spraying in animal houses with bedding, even though these houses generally have the highest dust concentrations and the highest dust emissions (Takai et al., 1998).

The objective of this study was to determine the effect of spraying oil in broiler houses with bedding on dust (PM_{10} and $P_{2.5}$) concentrations and emissions. Important questions within this study were:

- What is the relationship between oil dose and dust reduction?
- What effect does spraying oil have on broiler production and health?

Material and Methods

Housing and Animals

The study was conducted in four identical rooms in the first round and five identical rooms in the second and third rounds at the Spelderholt experimental station in Lelystad, The Netherlands. In each room, 2,675 one-day-old broilers (hatched) were placed. Each room

measured 8.3 × 16.0 m (133.6 m^2) and contained four feeding lines, each with seven feeders, and eight drinking lines with 180 drinking nipples in total. The rooms were heated by a central heating system with heaters on the side walls underneath the air inlets. Each room had three exhaust fans in the roof: one operated continuously, and the other two operated when needed. 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 crumb feed during the first ten days and pellet feed during the rest of the growing period. During the first two days, the rooms were continuously lit. During the rest of the growing period, an intermittent light scheme of 8 h light and 4 h dark was provided (7:45 to 15:45 light, 15:45 to 19:45 dark, 19:45 to 3:45 light, and 3:45 to 7:45 dark). Light intensity was the same for all rooms (20 lux). Between rounds, litter was removed and rooms were cleaned with a high-pressure cleaner. The rooms where oil was sprayed were pre-soaked before cleaning. One day before the broilers were introduced, 1 kg m^{-2} of wood shavings was spread in the rooms as bedding.

All rooms were heated to 33°C three 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 have been linearly interpolated). Minimum ventilation was controlled at 1 m^3 h^{-1} per kg live weight. The maximum ventilation rate in the room was 21,000 m^3 h^{-1}.

Oil Spraying System

In this study, pure rapeseed oil, which was cold-pressed, refined, and suitable to be used as bio-fuel for cars, was sprayed by full-cone nozzles (type SU26B-SSBR, Spraying Systems, Ridderkerk, The Netherlands) installed on oil tubes. 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 cover half the area of the room (8 × 8 m^2). Oil was sprayed by injecting oil and air into the nozzles at the same time, both at a pressure of 3.5 bar. This configuration gave a volume median diameter ($D_{V0.5}$) of the oil particles of 44 μm, a $D_{V0.1}$ (10% of total volume of oil particles smaller than this diameter) of 20 μm, and a $D_{V0.9}$ (90% of total volume of oil particles smaller than this diameter) of 122 μm (Aarnink and Van Hattum, 2009). 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 rooms were sequentially sprayed. 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). Figure 1 shows a schematic view and a picture of the oil spraying system inside a broiler room.

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Figure 1. Schematic and photograph of oil spraying system inside the broiler room.

Treatments

The effect of oil spraying on the different measured parameters was determined in a dose-response design. Different amounts of oil were sprayed in the rooms. The amount of oil per room was controlled by spraying time. Measurements during setup show that approximately 24 mL of oil was applied per m^2 floor area during 60 s. Oil spraying in rounds 1 and 3 started when the broilers were 12 days of age, except for room 5 in round 3, in which oil spraying started at a broiler age of 21 days. To improve inside air quality during the first two weeks, in round 2, double the daily amount of oil given in the treatment was sprayed before the broilers were placed; daily spraying started on day 5. Because of the low ventilation rate at the start of the growing period, the small particles in the oil spray remained in the air too long; therefore, it was decided to start spraying in round 3 at day 12 again, similar as in round 1. Table 1 shows the oil spraying times in the different rooms during the different rounds. The oil spraying time was randomly assigned to the different rooms, except for the control treatment in rounds 2 and 3, which was assigned to room 5 in round 2 and to room 6 in round 3, whereas the oil spraying system was installed only in rooms 1 to 4. Oil was sprayed once a day, starting in the first room at 8:00 and finishing in the last room approximately 20 min later.

Table 1. Oil spraying time (s) in each room during the three growth cycles (rounds 1 through 3). Spraying time of 60 s is equivalent to approximately 24 mL of oil per m^2 floor area.

Round	Starting Day	Room				
		1	2	3	4	5/6 [a]
1	12	60	40	20	0	--
2	5 [b]	60	15	45	30	0
3	12	20	60	40	40 [c]	0

[a] Control: room 5 was used in round 2, and room 6 was used in round 3.

[b] Before the start, a double daily dose was given.

[c] Oil spraying started on day 21.

Measurements

Oil Use

Once a week, the amount of oil sprayed was determined for each room by weighing the storage tank of the oil 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).

Dust Concentrations

Measurements of PM_{10} and $PM_{2.5}$ concentrations are labor-intensive and were therefore only done on certain days spread over the growing period after oil spraying had started. In round 3, measurements started before oil spraying to get a full dust concentration and emission pattern during the whole growing period. PM_{10} and $PM_{2.5}$ concentrations of the incoming and exhaust air were measured on the following days:

- Round 1: days 20 and 33.
- Round 2: days 8, 22, 26, and 33.
- Round 3: days 1, 8, 15, 22, 29, and 32.

The inlets of the dust samplers for sampling exhaust air were placed 0.5 m horizontally from the border of the exhaust opening and 0.10 m vertically below the exhaust opening. Incoming air was sampled just outside the animal house. Dust was sampled for 22 h (from 10:00 to 8:00). To protect the equipment, no dust was sampled around the oil spraying period (from 8:00 to 10:00). Particles larger than required were pre-separated with cyclones (URG Corp., Chapel Hill, N.C.). The airflow through the samplers was 1 $m^3 h^{-1}$ and was drawn with a constant-flow pump (Charlie HV, Ravebo Supply, Brielle, The Netherlands). Dust was collected on glass-fiber filters with a diameter of 47 mm (type GF-3, Macherey-Nagel, D�ren, Germany). The unloaded filters were stabilized for 48 h under standard conditions (20�C � 1�C temperature and 50% � 5% relative humidity). Each filter was then weighed four times using a precise balance (AT261 DeltaRange, Mettler, Greifensee, Switzerland) with resolution of 10 � g. The average value was calculated as the filter weight. The loaded filters were weighed the same way. To calculate the amount of dust collected, the weight of the unloaded filters was subtracted from the weight of the loaded filters. For more details on the sampling procedure, see Zhao et al. (2009).

Twice during the third round (days 17 and 33), the PM_{10} and $PM_{2.5}$ concentrations were measured according to the procedure described above at around oil spraying time (from 8:00 to 9:00) in the rooms with spraying times of 0 s, 20 s, 40 s (only the room in which spraying started on day 12), and 60 s. The concentrations were measured at 3.0 m distance from the nozzles at 1.0 m from the floor.

Whenever the gravimetric measurements were conducted and at the same location near the exhaust fan, the PM_{10} concentrations were measured continuously with a light-scattering system (DustTrak, TSI, Shoreview, Minn.). This system was also used in the first round to take continuous measurements during oil spraying. Personal dust exposure was determined twice during the second round (days 26 and 34) and the third round (days 17 and 31) using the DustTrak. To measure the PM_{10} concentration near the human breathing zone, the DustTrak was attached to the stock handler's lapel, at a height of approximately 1.5 m, with the PM_{10} sampling inlet facing upward. PM_{10} concentration was measured for at least 8 min per room. One-minute values were stored so that average PM_{10} concentrations could be calculated (in mg m^{-3}).

Ammonia Concentration

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 by a converter at 775�C. Exhaust air was sampled inside the shaft of the ventilator that was continuously running. The monitor was calibrated weekly. Hourly means

were stored in a data logging system.

Animal Data

Broilers were weighed per room on day 1 and day 35. The total amount of feed delivered to each room per day was determined by weighing. Mortality rate was registered per room. Foot-pad lesions were assessed by eye and scored according to the protocol of Berg (1998) for 50 female and 50 male birds per room just before delivery of the birds (day 35). Within this protocol, the foot-pads of the broilers are scored as follows: 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.

Ventilation Rate

The ventilation rate in all three ventilation shafts was measured with calibrated anemometers (Fancom, Panningen, The Netherlands) of the same diameter as the ventilation shafts. Hourly means were stored in a data logger.

Environmental Parameters

Temperature and relative humidity (RH) outside and in each room, near the outlet 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.

Data Analysis

Dust and ammonia emissions were calculated as follows:

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where

Emission = dust or ammonia emission (mg h^{-1})

C exhaust = exhaust air concentration (mg m^{-3})

C inlet = inlet air concentration (mg m^{-3})

Q = ventilation rate (m^3 h^{-1}).

Linear dose-response relationships were determined for the different dependent variables. These variables were calculated relative to the value of the control treatment (no oil) within the same round. Rooms within rounds were the experimental units, so the values measured on different days within a growing period within a certain room were first averaged before statistical analysis. Comparisons between treatment groups on one side and control groups on the other side were tested with one-tailed t-tests. All statistical analyses were done with Genstat software (Genstat Committee, 2010).

Results

Ventilation, Temperat ure, and Humidity

Table 2 gives the mean ventilation rate, inside and outside temperatures, and relative humidity of different rooms in the different rounds. The data in this table show that the ventilation rates, temperatures, and relative humidity in the rooms were very similar. Between rounds there were differences, especially in ventilation rate.

Table 2. Ventilation rate, indoor and outside temperatures, and relative humidity (RH) in the different rooms and growth cycles. Rooms 5 and 6 were not used in the first growth cycle.

Variable	Round	Outside	Room				
			1	2	3	4	5/6
Ventilation	1	--	7776	7654	7231	7381	--
($m^3 h^{-1}$)	2	--	4863	4808	4537	4702	4604
	3	--	1755	1776	1775	1818	1767
Temperature	1	15.8	25.6	25.6	25.7	25.6	--
(°C)	2	19.3	26.1	26.1	26.2	26.3	25.6
	3	7.1	25.3	25.7	25.9	25.8	26.4
RH	1	62.0	58.4	57.5	59.0	57.1	--
(%)	2	71.5	66.2	65.6	65.7	65.0	68.0
	3	91.2	54.4	55.4	53.8	53.0	50.9

Functioning of Oil Spraying System

The oil spraying system functioned very well throughout the study. The only problem was that some nozzles leaked a bit of oil after spraying had ceased. This was solved by hanging a small bucket underneath each leaking nozzle. This amount was insignificant compared to the total amount of oil sprayed per room. Between the second and third rounds, the oil spraying system was idle for four months, but it was subsequently restarted without any problems. Figure 2 shows the linear relationship between the spraying time and the amount of oil that was sprayed ($p < 0.001$). From this regression line it can be estimated that 24 mL of oil was

sprayed during 60 s. The amounts of oil sprayed within the other treatments can also be calculated easily. We observed that the oil was sprayed over the whole area of the rooms but that the distribution of the oil was not uniform. Less oil was deposited on the bedding underneath the oil lines and near the side walls of the broiler house.

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Figure 2. Relationship between spraying time (s) and oil application rate (mL m^{-2} d^{-1}).

Dust Concentrations and Emissions

Table 3 shows the mean PM_{10} and $PM_{2.5}$ concentrations, when oil application in the room had started, within the three rounds for the different oil application rates. From the PM_{10} data it is clear that oil application reduced dust concentrations inside the broiler house and that the reduction increased with the application rate. Regression analyses showed that spraying rate significantly affected PM_{10} concentrations (relative to control; $p < 0.01$). Calculated reductions varied between 44% at the lowest rate (6 mL oil m^{-2} d^{-1}) to 82% at the highest rate (24 mL oil m^{-2} d^{-1}). The $PM_{2.5}$ data in table 3 show that $PM_{2.5}$ concentrations decreased greatly at the lowest spraying rate and then did not decrease further at higher rates. Regression analyses showed no effect of spraying rate on $PM_{2.5}$ concentrations (relative to control). Calculated reductions in $PM_{2.5}$ concentrations varied from 68% at the lowest rate (6 mL oil m^{-2} d^{-1}) to 74% at the highest rate (24 mL oil m^{-2} d^{-1}). A one-tailed t-test of all the oil treatments showed that the $PM_{2.5}$ concentrations were significantly different from the control treatment ($p < 0.001$).

Table 3. Mean PM_{10} and $PM_{2.5}$ concentrations and emissions on different measuring days at different oil spraying rates in the three growth cycles. Only measuring days on which oil spraying had already been started are included. Standard deviations between measuring days are shown in parentheses.

Oil (mL m^{-2} d^{-1})	Concentration (mg m^{-3})		Emission (mg h^{-1})	
	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$
Round 1 (measuring days 20 and 33) [a]				
0	2.1 (0.9)	0.13 (0.13)	6.8 (5.5)	0.43 (0.54)
8	1.5 (1.4)	0.04 (0.03)	4.5 (5.2)	0.08 (0.11)
16	0.6 (0.5)	0.02 (0.01)	2.0 (2.2)	0.03 (0.04)
24	0.2 (0.2)	0.02 (0.01)	0.6 (0.7)	0.01 (0.02)

Round 2 (measuring days 8, 22, 26, and 33) [a]				
0	1.6 (0.8)	0.11 (0.07)	4.4 (3.9)	0.26 (0.28)
6	0.8 (0.5)	0.03 (0.02)	2.2 (2.2)	0.03 (0.05)
12	0.5 (0.4)	0.03 (0.01)	1.4 (1.5)	0.02 (0.02)
18	0.4 (0.2)	0.05 (0.04)	1.0 (0.9)	0.12 (0.15)
24	0.4 (0.2)	0.03 (0.02)	1.1 (1.0)	0.07 (0.09)
Round 3 (measuring days 15, 22, 29, and 33) [a]				
0	3.3 (1.8)	0.12 (0.10)	3.5 (2.8)	0.14 (0.15)
8	1.3 (0.8)	0.04 (0.02)	1.4 (1.3)	0.03 (0.04)
16	1.0 (1.1)	0.04 (0.02)	1.2 (1.5)	0.03 (0.03)
16	0.7 (0.6)	0.03 (0.01)	0.8 (0.7)	0.02 (0.01)
24	0.4 (0.3)	0.04 (0.03)	0.5 (0.5)	0.03 (0.05)

[a] Measuring days are given in days after start of growing period.

Figure 3 shows strong increases of PM_{10} and $PM_{2.5}$ concentrations at increasing age of the broilers in the third round; for the control room, PM_{10} concentrations increased from 0.2 to 5.5 mg m^{-3}, and $PM_{2.5}$ concentrations increased from 0.03 to 0.25 mg m^{-3}. Figure 3 also shows that PM_{10} and $PM_{2.5}$ concentrations were instantly reduced when oil was applied. This can be seen from the results at day 15, after oil spraying started in three of the four oil treatments on day 12, and from the results at day 22, after oil spraying started in one of the oil treatments (16, 3w) on day 21.

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Figure 3. Concentrations of (a) PM_{10} and (b) $PM_{2.5}$ during the growing period at different oil spraying rates (in mL m^{-2} d^{-1}) in round 3. Oil spraying started on day 12, except for treatment 16, 3w, when oil spraying started on day 21. Asterisk (*) indicates missing data.

Mean PM_{10} emissions for 22 h per broiler during the measuring days in the control rooms were 6.8 mg h^{-1} in round 1, 4.4 mg h^{-1} in round 2, and 3.5 mg h^{-1} in round 3 (table 3). Oil application caused reductions in dust emissions similar to those achieved for dust concentrations because the ventilation rates in the different rooms were similar (table 2). Figure 4a gives the regression line of mean emission reductions (relative to the control treatment) in relation to oil application rate. Calculated reductions (with the regression line) varied between 48% at the lowest rate (6 mL oil m^{-2} d^{-1}) to 87% at the highest rate (24 mL oil m^{-2} d^{-1}). Mean $PM_{2.5}$ emissions per broiler during the measuring days in the control rooms were 0.43 mg h^{-1} in round 1, 0.26 mg h^{-1} in round 2, and 0.14 mg h^{-1} in round 3 (table 3). The regression line of mean $PM_{2.5}$ emission reductions (relative to the control treatment) in relation to oil application rate is given in figure 4b. The calculated 84% reduction in $PM_{2.5}$ achieved at a rate of 6 mL oil m^{-2} d^{-1} was much greater than that achieved for PM_{10}, but $PM_{2.5}$ did not decrease further at higher spraying rates. Regression analyses showed a significant effect of spraying rate on PM_{10} emissions (relative to control; $p < 0.001$); however, for $PM_{2.5}$, no relation with spraying rate was found ($p = 0.70$). A one-tailed t-test showed that $PM_{2.5}$ emission in the oil treatments differed significantly from the control treatment ($p < 0.001$).

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Figure 4. Linear regression of (a) PM_{10} and (b) $PM_{2.5}$ emission reductions (relative to the control treatment) on oil application rates in the three growing cycles.

Figure 5a gives the pattern of PM_{10} emission in the control room during the third round. Dust emission increased exponentially during the growing period of the birds. The fitted curve in the figure is an exact match with the measured data. It was used to calculate the cumulative PM_{10} emission (fig. 5b). The curve shows that most dust (88% of the total PM_{10} emission) was emitted during the last two weeks of the five-week growing period. A similar curve was fitted for $PM_{2.5}$ ($Y = 0.0038 + 0.00011 \cdot (1.29)^{X}$; $R^2 = 1.00$), and from these calculations it was shown that 95% of $PM_{2.5}$ was emitted during the last two weeks of the five-week growing period.

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Figure 5. Emission of PM_{10} during round 3 in the control room: (a) measured PM_{10} emission in mg h^{-1} per broiler and the fitted curve, and (b) cumulative PM_{10} emission as percentage of total emission in the whole growing cycle.

Figure 6 shows the effect of oil dose on PM_{10} concentration in the breathing zone of the poultry farmer, measured in rounds 2 and 3. This graph shows that the dust load to the poultry farmer can be reduced by approximately 60% at an application rate of 6 mL oil m^{-2} d^{-1}. This reduction increased to more than 80% at a rate of 24 mL oil m^{-2} d^{-1}. Because of the high variation, the linear relationship between spraying rate and personal PM_{10} load was not statistically significant ($p = 0.14$).

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Figure 6. Effect of oil dose per day on reduction of PM_{10} concentration during stock handler's presence inside the broiler rooms.

Figure 7 shows a typical pattern of PM_{10} concentrations during the day (day 23/24, round 1). The patterns from the control room and from the room sprayed at a rate of 24 mL oil m^{-2} d^{-1}

are shown. The light and dark periods coincide with low PM_{10} concentrations. Just after 8:00, when oil was sprayed, a high PM_{10} peak for the 24 mL treatment was observed.

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Figure 7. PM_{10} concentration pattern during the day (day 23/24, round 1) for the control room and the room with an oil application rate of 24 mL m^{-2} d^{-1}.

Figure 8 shows continuous PM_{10} concentration measurements around oil spraying (day 23/24, round 1). From this figure it is clear that oil spraying itself produces small particles, too. PM_{10} concentrations remained elevated for 15 to 30 min. Figure 9 gives the gravimetric measurements of PM_{10} and $PM_{2.5}$ during 1 h around oil spraying (8:00 to 9:00). This figure shows that PM_{10} and $PM_{2.5}$ concentrations in the hour around spraying increased linearly with oil dose due to the small oil particles in the air directly after spraying. The increase was smaller on day 33 than on day 17.

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Figure 8. PM_{10} concentration pattern around oil spraying (day 23/24, round 1) for the different oil application rates (in mL m^{-2} d^{-1}). Oil was sprayed just after 8:00.

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Figure 9. Mean (a) PM_{10} and (b) $PM_{2.5}$ concentrations around oil spraying (from 8:00 to 9:00) on days 17 and 33 in round 3.

Ammonia Emission

Mean ammonia emissions per broiler in the control room were 6.54 mg h^{-1} in round 1, 6.53 mg h^{-1} in round 2, and 4.66 mg h^{-1} in round 3. Figure 10 shows a representative pattern of ammonia emission during the growing period of the broilers (round 2). The estimated regression line of mean ammonia emissions per round per treatment relative to the control treatment on oil dose was: $Y = -0.0024\ X + 1.01$ ($R^2 = 0.00$), which indicates that oil had no effect on ammonia emission from the broiler rooms.

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Figure 10. Pattern of ammonia emissions from the rooms with different oil application rates (in mL m^{-2} d^{-1}) in round 2.

Animal Parameters

Animal growth rate was not significantly influenced by oil application rate. Mean broiler growth rates in the control room were 59.9 g d^{-1} in round 1, 56.5 g d^{-1} in round 2, and 57.4 g d^{-1} in round 3. The estimated regression line of growth rate relative to the control treatment within rounds on oil spraying rate was: $Y = 0.00061\ X + 0.98$ ($R^2 = 0.00$). Daily feed intake was not significantly influenced by oil application rate. Mean feed intake in the control room was 94.3 g d^{-1} in round 1, 88.2 g d^{-1} in round 2, and 92.2 g d^{-1} in round 3. The estimated regression line of feed intake relative to the control treatment within rounds on oil dose was: $Y = 0.00040\ X + 0.995$ ($R^2 = 0.00$). Mortality rate was not influenced by oil application rate. Mortality rate in the control room was 2.0% in round 1, 3.0% in round 2, and 2.4% in round

3. The estimated regression line of mortality rate relative to the control treatment within rounds on oil application rate was: $Y = 0.0078\ X + 0.948$ ($R^2 = 0.00$). Mean foot-pad scores in the control room were 34 in round 1, 72 in round 2, and 31 in round 3. Figure 11 shows the foot-pad scores of the broilers relative to the control treatment within rounds, in relation to oil application rate. Statistical analyses showed no significant linear effect ($p = 0.20$). When the oil treatments were divided into three groups (low rate: 6 to 12 mL oil $m^{-2}\ d^{-1}$; medium rate: 16 to 18 mL oil $m^{-2}\ d^{-1}$; high rate: 24 mL oil $m^{-2}\ d^{-1}$), the means per group (relative to the control treatment) were 1.42 (s.e. 0.23) for the low rate, 1.47 (s.e. 0.23) for the medium rate, and 1.88 (s.e. 0.26) for the high rate. Only foot-pad score of the high oil rate differed significantly from the control group ($p < 0.05$).

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Figure 11. Effect of oil dose on foot-pad score of broilers (relative to the control treatment within rounds) in the different rounds.

Discussion

The oil spraying system functioned very well throughout the study, except for some nozzles leaking drops of oil after spraying. This could be solved by placing receptacles under the nozzles to catch the oil or by fitting anti-drip valves on every nozzle; the latter solution is costly, however. Takai et al. (1995) encountered some problems with spraying nozzles becoming clogged by the emulsion of oil in water. In this study, we chose to spray pure oil to avoid clogging of nozzles and potential problems with mixing of oil in water. When spraying pure oil, the oil needs to be aerosolized in the nozzle with pressurized air.

In this study, we found that PM_{10} concentrations and emissions were reduced by 44% to 48% at an application rate of 6 mL oil $m^{-2}\ d^{-1}$ and by as much as 82% to 87% at a rate of 24 mL oil $m^{-2}\ d^{-1}$. This range is similar to that reported by Takai (2007) in a literature review of dust reduction by oil spraying in pig houses. In the studies Takai cited, however, it was not PM_{10} or $PM_{2.5}$ but total or inhalable dust and/or respirable dust that was measured. Total or inhalable dust particles are not well defined because this fraction does not have a sharp cutoff diameter of sampled particles, but the sampled particles are generally smaller than 50 to 100 μm; respirable dust particles have a cutoff diameter of 4 μm (Cambra-López et al., 2010). Remarkably, we found no relationship between oil application rate and $PM_{2.5}$ reduction. We found significant reductions in $PM_{2.5}$ concentrations (68%) and emissions (84%) even at the lowest rate of 6 mL oil $m^{-2}\ d^{-1}$. At higher oil application rates, the $PM_{2.5}$ concentrations and emissions were not decreased further. A possible reason for this could be that one of the dust sources was unaffected by the oil spraying, causing a maximum reduction of approximately 80%. However, this is unlikely because the oil was sprayed from the ceiling; therefore, the whole room, including the birds, became covered with a thin layer of oil. A more plausible reason might be that there were still some small oil particles in the air during the dust sampling period. As the $PM_{2.5}$ concentrations in the broiler rooms are relatively low, the concentration can easily be influenced by small oil particles. Although we did not sample the air during 2 h around oil application (from 8:00 to 10:00) to determine PM_{10} and $PM_{2.5}$ concentrations, some of the oil particles might still have been in the air during the time of sampling (from 10:00-08:00), and they may have cancelled out any extra reduction in $PM_{2.5}$. The relative contribution of the oil particles to concentrations of PM_{10} particles was low; moreover, PM_{10} particles settle faster than $PM_{2.5}$ particles.

From the fitted curves for PM_{10} and $PM_{2.5}$ emissions during round 3, the total PM_{10} and

PM $_{2.5}$ emissions per market broiler can be estimated: 2.12 g for PM $_{10}$ and 0.084 g for PM $_{2.5}$. By fitting the curves on the values measured in rounds 1 and 2, the calculated PM $_{10}$ emissions per market broiler were 2.76 g in round 1 and 2.57 g in round 2; for PM $_{2.5}$ these values were 0.141 g in round 1 and 0.144 g in round 2. In the U.S., Burns et al. (2008) found emissions per market broiler of 2.52 g for PM $_{10}$ and 0.25 g for PM $_{2.5}$ (our calculations). The reported growing period of the broilers lasted 52 days, compared with 35 days in this study. While dust emissions increase during the growing period, the PM $_{10}$ emission values of their study are relatively low compared with our study. When using the fitted curves, their results showed PM $_{10}$ and PM $_{2.5}$ emissions after a 35 day growing period of 0.94 and 0.07 g per broiler, respectively. In Canada, Modini et al. (2010) found even lower emissions per market broiler during a 56-day growing period: 1.42 g PM $_{10}$ and 0.33 PM $_{2.5}$ (our calculations). The lower PM $_{10}$ emissions in the U.S. and Canada might be attributable to differences in bedding material and litter quality (damper).

From the measurements it can be calculated that on average the proportion of PM $_{2.5}$ particles in the control rooms was 5.4% of the PM $_{10}$ fraction. This is lower than reported in the studies by Burns et al. (2008) (10%) and Modini et al. (2010) (23%) and much lower than the proportions of over 50% found in the ambient air in big cities (Das et al., 2006; Kan et al., 2007).

The instant fall in PM $_{10}$ and PM $_{2.5}$ concentrations after oil application (fig. 3) suggests that the oil mainly affected the upper layer of the litter. It seems that the oil forms a film on top of the litter that prevents dust becoming airborne. Measurements show an exponential increase of PM $_{10}$ and PM $_{2.5}$ emissions during the growing period of the broilers (fig. 5). This means that the contribution to dust emissions (per market broiler) during the first weeks of the growing period is very small. During the first three weeks of the growing period, the amount of PM $_{10}$ emitted is only 12% of the total PM $_{10}$ emissions per market broiler, and the amount of PM $_{2.5}$ emitted is only 5% of total PM $_{2.5}$ emissions. Starting spraying at three weeks instead of on day 5 (round 2) or day 12 (rounds 1 and 3) will have little effect on dust reduction but will reduce the amount of oil needed by 53% and 39%, respectively, and may also benefit the health of the broilers by resulting in fewer foot-pad lesions or potential problems with temperature regulation (McGovern et al., 2000).

The main problem noted in this study is that the oil system produced a large number of small particles, causing peak concentrations of PM $_{10}$ and PM $_{2.5}$ around spraying period. The amount of airborne oil particles within these size fractions can be calculated by calculating the increase of PM $_{10}$ and PM $_{2.5}$ concentrations relative to the concentration within the control room during the time around spraying, and then multiplying this by the airflow rate and dividing by the density of the oil (0.91 g mL $^{-1}$). The calculations show that, in terms of the total amount of oil sprayed in the room, airborne oil particles in the PM $_{10}$ size range represented 1.2% (s.e. 0.13) and the airborne particles in the PM $_{2.5}$ size range were 0.36% (s.e. 0.03). To prevent high peak concentrations of PM $_{10}$ and PM $_{2.5}$ around spraying, smaller amounts should be sprayed at the same time. Reducing the spraying rate from 24 to 8 mL oil m $^{-2}$ reduced peak PM $_{10}$ concentrations from 93 to 6 mg m $^{-3}$. To achieve a certain desired reduction in PM emissions, it could be worthwhile to spray more than once per day. Another option could be to lower the air pressure for spraying. In this study, both the oil and air pressures were set at 3.5 bar. In a laboratory study testing oil particle sizes at different oil and air pressures, it was shown that oil particle sizes could be increased by decreasing the air pressure, e.g., from 3.5 to 2.5 or 3.0 bar (Aarnink and Van Hattum, 2009). The lower the air pressure, however, the smaller the area sprayed and therefore the greater the number of spraying nozzles needed, which adds to the costs. Furthermore, bigger droplets decrease the distribution of the droplets over the total floor area. However, the broilers might help spread the oil droplets. A follow-up study should be done to find the optimum balance between

droplet size and number of spraying nozzles.

The diurnal PM_{10} concentration pattern (fig. 7) shows that dust concentrations (and emissions) are considerably influenced by the light scheme: PM concentrations were high during the light periods and low during the dark periods, as was also found in the study by Cambra-L&#65533;pez et al. (2009). This pattern seems to be mainly caused by differences in the birds' activity. Strong relationships between animal activity and dust concentrations have been shown in previous studies (Pedersen, 1993; Pedersen and Takai, 1999).

Ammonia emission increased considerably during the growing period of the broilers, with emissions being negligible during the first week and increasing linearly thereafter (fig. 10). Similar results were found by Lacey et al. (2003) and Wheeler et al. (2006). The results show that there was no effect of oil application rate on ammonia emission. The ammonia emission patterns of the treatment rooms and the control room were also very similar. Mean ammonia emission in the control rooms during the three growing periods was 5.9 mg h^{-1}, equivalent to 5.0 g per market broiler (35-day growing period). This is considerably lower than the emission estimated by Gates et al. (2008) for U.S. broiler houses of 17.6 g per market bird. In that study, the growing period lasted 40 days, but that cannot on its own explain this large difference. Another reason could be differences in litter quality. Groot Koerkamp et al. (1995) found a strong relationship between moister content of the litter and ammonia emission.

The oil treatments had no effect on animal parameters (growth rate, feed intake, mortality rate). Only the high oil application rate of 24 mL oil m^{-2} d^{-1} significantly increased foot-pad score. It is therefore advised to reduce oil application rate to a maximum of 16 mL oil m^{-2} d^{-1}. At this rate, no significant increase in food-pad score was found, but dust emissions were greatly reduced. The effect of high oil application rate on foot-pad lesions might be attributable to the litter becoming sticky and adhering to the foot-pads of the broilers, causing irritation and lesions. The higher foot-pad score in round 2 might be explained by the higher relative humidity measured inside the rooms (table 2), which would have resulted in damper litter (Ekstrand et al., 1997; Hester, 1994).

Conclusions

From this study, it is concluded that:

- Application of rapeseed oil in broiler houses produced significant reductions of PM_{10} and $PM_{2.5}$ concentrations and emissions.
- The degree of dust reduction depends on the oil application rate and the particle size. At an application rate of 6 mL oil m^{-2} d^{-1}, PM_{10} concentrations were reduced by 44% and PM_{10} emissions were reduced by 48%. This compares with up to 82% concentration reduction and 87% emission reduction at an oil dose of 24 mL m^{-2} d^{-1}. For $PM_{2.5}$, concentrations and emissions were already drastically reduced (by 68% and 84%, respectively) at the lowest oil dose of 6 mL m^{-2} d^{-1}. At higher oil doses, the reduction did not increase further.
- PM_{10} and $PM_{2.5}$ emissions increased exponentially with the age of the broilers. During the first three weeks of the growing period, only 12% of PM_{10} and 5% of $PM_{2.5}$ of the total emissions per market broiler were emitted.
- The oil spraying system in this study, with oil and air pressures of 3.5 bar, produced too many oil particles in the small size range, causing high peaks of PM_{10} and $PM_{2.5}$

concentrations immediately after spraying.

- The diurnal PM_{10} concentration pattern was mainly influenced by the light scheme, with high concentrations during light periods and low concentrations during dark periods.
- No effects of oil spraying were found on ammonia emission and on production results of the broilers (growth rate, feed intake, mortality rate).
- A high application rate of 24 mL oil m^{-2} d^{-1} increased the number and severity of foot-pad lesions. Therefore, it is advised not to exceed a maximum rate of 16 mL oil m^{-2} d^{-1}.

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