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SOURCE IDENTIFICATION AND QUANTIFICATION OF PARTICULATE MATTER EMITTED FROM LIVESTOCK HOUSES

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ABSTRACT

It is necessary to accurately identify and quantify sources which contribute to particulate matter (PM) emissions from livestock houses to develop adequate reduction strategies. To identify and quantify the contribution of different sources to fine (PM2.5) and coarse (PM10-2.5) PM emissions from poultry and pig houses, we compared the chemical and morphological characteristics of fine and coarse PM from known sources collected from livestock houses with the characteristics of on-farm fine and coarse airborne PM. Two methods were used to estimate source contributions: classification rules based on decision trees and multiple linear regression. Results showed that in poultry houses, most on-farm airborne PM originates from feathers (ranging from 4 to 43% in fine and from 6 to 35% in coarse PM) and manure (ranging from 9 to 85% in fine and from 30 to 94% in coarse PM). In broilers and turkeys, wood shavings contribute less than 34% of particle numbers. In pigs, most on-farm airborne PM originates from manure (ranging from 70 to 98% in fine and from 41 to 94% in coarse PM). The contributions of wood shavings in poultry and skin in pigs were less than 34%, varying with livestock categories. The contribution of manure to on-farm airborne PM was higher in coarse PM in poultry, but higher in fine PM in pigs. Feed had a negligible contribution to on-farm airborne PM compared with the rest of the sources. Results presented in this study improve the understanding of where PM comes from in different livestock housing systems. This can be valuable to choose the optimal dust reduction methods.

KEYWORDS. Animal housing, Dust, Emissions, Source apportionment.

INTRODUCTION

Large amounts of particulate matter (PM) are emitted from livestock houses. High concentrations of PM can threaten the environment, as well as animals' and humans' respiratory health (Donham, 2000; Radon *et al.*, 2001; Zuskin *et al.*, 1995). To develop technically feasible and economically viable solutions to reduce these emissions, it is necessary to accurately identify and quantify sources which contribute to PM in livestock houses.

The formation of PM in livestock houses, its concentrations, and emissions depend on many physical and biological factors such as kind of housing and feeding, animal type, and environmental factors (Takai *et al.*, 1998). An extended review of these issues is described in

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Cambra-López *et al.* (2010a). Generated PM in livestock houses mainly originates from feed, manure, bedding, and animal's skin, and feathers (Aarnink *et al.*, 1999; Donham *et al.*, 1986; Feddes *et al.*, 1992; Heber *et al.*, 1988; Qi *et al.*, 1992). Attempts to identify and quantify sources of PM in livestock houses have been made in pigs and poultry (Aarnink *et al.*, 1999; Aarnink *et al.*, 2004; Feddes *et al.*, 1992; Heber *et al.*, 1988; Honey and McQuitty, 1979; Qi *et al.*, 1992), but the individual contribution of each source in size-fractioned PM in different housing systems is still unknown.

Source apportionment models based on multivariate linear regression techniques can be used to apportion PM to sources by relating chemical and physical properties of the source, to the properties measured at the receptor site (Watson *et al.*, 2002). Furthermore, expert systems based on supervised methods such as classification rules based on the decision tree approach can be used (Kim and Hopke, 1988).

The objective of this study was to identify and quantify the contribution of different sources to fine (PM2.5) and coarse (PM10-2.5) PM emissions from poultry and pig houses based on chemical and morphological characteristics of particles. The contribution from each source was estimated by comparing the chemical and morphological characteristics of fine and coarse PM from known sources collected from livestock houses, with the characteristics of on-farm fine and coarse airborne PM. Two methods were used to estimate source contributions: classification rules based on decision trees and multiple linear regression. This study will provide a better understanding of PM origin, essential to better understand potential health and environmental hazards of PM, and to improve actual reduction programs applicable to livestock houses.

MATERIALS AND METHODS

Housing and animals

Table 1 describes surveyed livestock houses and housing systems. Two different locations were sampled once for each livestock housing system. All surveyed livestock houses used automatically distributed feeding systems with crumbles or pelleted feed.

Table 1. Description of surveyed livestock houses.

Livestock species	Housing system	Farm location	Ventilation	Number of animals	Age (weeks)
Poultry	Broilers - bedding	1	Tunnel	50,400	4
		2	Roof	2675	3
	Laying hens - floor	1	Tunnel	3850	71
		2	Tunnel	16,500	22
	Laying hens - aviary	1	Tunnel	24,712	71
		2	Tunnel	35,000	50
	Turkeys - bedding	1	Ridge	5000	12
		2	Ridge	4040	10
Pigs	Piglets- slatted floor	1	Roof	125	8
		2	Roof	75	9
	Growing-finishing pigs - partially slatted floor	1	Roof	120	16
		2	Roof	60	20
	Dry and pregnant sows - group housing	1	Roof	39	Diverse
		2	Roof	46	Diverse

On-farm airborne and source samples

Duplicate virtual cascade impactors (RespiCon, Wetzlar, Germany) were used in each farm to sample simultaneously airborne fine and coarse PM onto separate polycarbonate filters (37 mm Ø, 5 µm pore size). Portable pumps (Genie VSS5, Buck Inc, U.S.) were used to suck air through each impactor at a constant flow of 3.11 L/min. Sampling was conducted during morning (from 09:00 to 12:00) at each livestock house. Samples were taken near the exhaust in each farm. Sampling time varied from 5 to 60 min, adjusted to obtain particle loads of 5 to 20 µg particles/cm^2 filter, to minimize particle overlap (Willis *et al.*, 2002). Background (outside) samples were taken upwind of livestock houses in the same way as indoor samples in all farms. Sampling time outside varied from 30 to 60 min.

Additionally, a light scattering system (DustTrak TM Aerosol Monitor, model 8520, TSI Incorporated, Shoreview, U.S.) was used for on-line continuous airborne PM10 concentration measurement inside and outside livestock houses. Sampling time was 30 to 60 min. One-minute values were recorded and stored.

On each farm, we collected 200 to 500 grams of a representative sample of concentrate feed (all farms), manure (fresh excreta in poultry, and fresh feces in pigs), wood shavings used as bedding material (present only in broilers and turkeys), and feathers in poultry (10 to 50 grams). We also collected skin samples in pig houses, but only from sows because it was impractical to collect such source from younger animals (piglets and growing-finishing pigs). Each sample was dried for 12 h at 70ºC. Dried samples were crushed in a ball mill during 1.5 min at 250 rpm. A varying quantity of milled source was used in a laboratory stainless steel dust generator to collect airborne fine and coarse PM samples from each source through agitation at 200 rpm (Cambra-López *et al.*, 2010b). The generated PM was collected using a virtual cascade impactor (RespiCon, Wetzlar, Germany) and portable pump using polycarbonate filters, same as for on-farm sampling. Sampling time varied from 1 min to 7 h, aiming at particle loads of 5 to 20 µg particles/cm^2 filter (Willis *et al.*, 2002). Filter samples were stored in sealed filter cassettes at room temperature (20-25ºC) before analysis.

<u>Morpho-chemical analysis of airborne and source samples</u>

High-resolution Scanning Electron Microscopy (SEM) (JEOL, JSM-5410) combined with energy-dispersive X-ray analysis (EDX) (Link Tetra Oxford Analyzer) was used to obtain particle-by-particle chemical and morphological data from source samples, as well as from on-farm airborne fine and coarse PM samples. At least three fields of view (spots) per filter sample were analyzed. On each analyzed field, both an image (photomicrograph at 1000x for coarse PM, or 1800x for fine PM) and single particle X-ray spectra of every particle found in that field were obtained and stored. Detection of elements with atomic number ≥ 6 (carbon) was obtained from elemental x-ray spectra. All spectra were confirmed, and checked manually to correct for the contribution of the filter material (C and O).

The stored images (SEM photomicrographs of each field of view) were analyzed using the Object Based Image Analysis (OBIA) approach (Blaschke, 2010) using FETEX 2.0 Software (Ruiz *et al.*, 2010). The OBIA software extracted spectral, texture, and morphological features. Based on chemical, spectral, texture, and morphological characteristics, each particle was exhaustively characterized by 48 variables.

<u>Source apportionment methods</u>

Single particle chemical and morphological characteristics from fine and coarse source samples, as well as from on-farm airborne fine and coarse PM samples obtained using SEM-EDX, were used as data sources in source apportionment. The contribution of sources to on-farm airborne PM was calculated in particle numbers, using classification rules based on decision trees and using multiple linear regression.

Classification rules based on decision trees

Decision trees were used to develop a set of rules for each source from each livestock house. Both single particle chemical and morphological characteristics were joined in a combined database and used in this process. Decision trees were built using See 5 Software which uses the C5.0 classification algorithm, which is the latest version of the algorithms ID3 and C4.5 developed by Quinlan (1993). Decision trees were created following the boosting multi-classifier method (Freund, 1995). The rule-generator program searched the features that best separated one source from the other by dividing data using mutually exclusive conditions until the newly generated subgroups were homogeneous. The rules developed using the known sources were then applied to classify airborne on-farm samples into one of the known sources based on their chemical and morphological characteristics. Accuracy of this method was tested through cross-validation, applying the rules to the known source samples and comparing the source assigned to each particle using rules with its reference source. Overall measure of prediction accuracy was obtained by dividing the total correct validations in each source by the total number of classified particles.

Multiple linear regression

Average particle chemical composition data were used in multiple linear regression to apportion airborne PM sampled on the farms to the known sources. The average PM concentration of elements in fine and coarse airborne on-farm samples were used as dependent variables and the average fine and coarse PM concentrations of elements in each known source were used as independent variables. All elements were included at once in the model following equation 1:

$$Y_{im} = \sum_{k=1}^{n} \left(f_{ikm} \times F_{ikm} \right) \qquad (1)$$

where: Y_{im}= relative concentration of the i^{th} element in collected airborne fine or coarse PM in the m^{th} farm (average of duplicate samples); f_{ikm}= number contribution of the i^{th} element of the k^{th} source to airborne fine or coarse PM in the m^{th} farm. The sum of the fractions was set to 1; F_{ikm}= average relative concentration of the i^{th} element in the k^{th} source in the m^{th} farm.

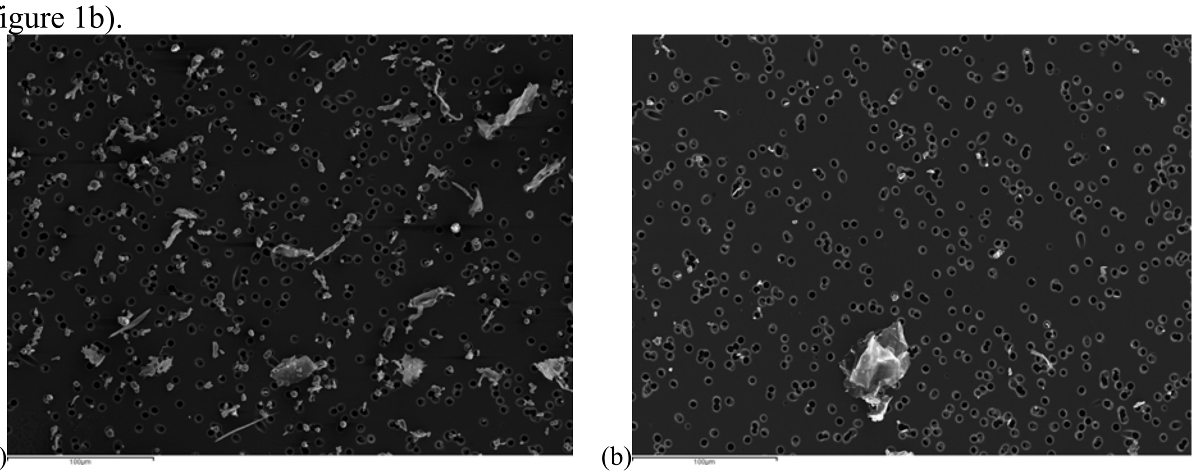
RESULTS

On-farm PM airborne measurements

Average PM10 concentrations measured on-farm were the lowest in dry and pregnant sow houses (0.39±0.01 mg/m^3) and the highest in laying hens floor housing (3.94±0.69 mg/m^3), followed by laying hens in aviary system (3.06±1.54 mg/m^3). The rest of sampled livestock houses showed average PM10 concentrations inside varying from 1.27 to 2.32 mg/m^3. Outdoor PM10 concentrations were very similar amongst all sampled livestock houses, varying from 0.03 to 0.08 mg/m^3.

Source identification

Some particle types from different livestock housing systems are shown in Figure 1. Different morphological types could be identified in poultry and pigs. For example, in broilers, a mixture of particles showing "fluffy" appearance probably from feathers, sharp-edged particles from wood shavings, and spherical particles from poultry excreta (uric acid crystals) were dominant (figure 1a). In sows, most particles were small, but also showed flattened, folded skin particles (figure 1b).



(a) (b)

Figure 1. Examples of SEM images from on-farm airborne PM samples collected on polycarbonate filters (note 5 µm diameter filter pores shown as round dark holes). (a) Mixture of particles showing "fluffy" appearance, sharp-edged particles, and spherical particles collected from broiler houses. (b) Scarce, small particles and flattened, folded, and big skin particle collected from dry and pregnant sow houses. Scale bar 100 µm.

Source quantification

Because each method used different particle characteristics and after EDX spectra and OBIA acquisition correction, a total of 912 individual particles were apportioned in fine and 1071 in coarse PM using classification rules based on decision trees, and an average from 1546 individual particles were apportioned in fine and 1670 in coarse PM using multiple linear regression. Results are presented as percentage contributions of sources to on-farm airborne PM expressed in particle numbers.

Using classification rules based on decision trees

Results using classification rules based on decision trees are shown in Table 2 (fine PM) and Table 3 (coarse PM), together with method accuracies.

Table 2. Average (Avg) percentage number contribution of the different PM sources to airborne fine PM (PM2.5) from different livestock housing systems and accuracy of the classification. Standard error (SE) represents variation in the contribution between livestock houses for the same housing system.

Sources	Broilers		Laying hens- floor		Laying hens- aviary		Turkeys		Piglets		Growing-finishing pigs		Dry and pregnant sows	
	Avg	SE	Avg	SE	Avg	SE	Avg	SE	Avg	SE	Avg	SE	Avg	SE
Feathers	30.1	20.7	38.4	22.9	10.5	5.8	27.3	19.1	-	-	-	-	-	-
Feed	8.1	8.1	3.0	1.8	2.4	2.4	1.7	1.7	15.9	5.1	3.7	1.5	14.5	2.2
Manure	14.0	7.3	49.5	22.0	84.7	1.0	8.9	8.9	73.9	1.6	88.8	1.3	69.8	2.4
Outside	28.8	9.1	9.2	0.8	2.4	2.4	44.3	37.1	7.0	5.3	5.4	0.1	4.1	4.1
Skin	-	-	-	-	-	-	-	-	3.2	1.4	2.1	0.1	11.7	0.6
Wood shavings	19.0	10.8	-	-	-	-	17.8	10.8	-	-	-	-	-	-
Accuracy (%)	73 - 86		73 - 74		52 - 75		67 - 83		57 - 79		78 - 84		74 - 75	

Table 3. Average (Avg) percentage number contribution of the different PM sources to airborne coarse PM (PM10-2.5) from different livestock housing systems and accuracy of the classification. Standard error (SE) represents variation in the contribution between livestock houses for the same housing system.

Sources	Broilers		Laying hens-floor		Laying hens-aviary		Turkeys		Piglets		Growing-finishing pigs		Dry and pregnant sows	
	Avg	SE	Avg	SE	Avg	SE	Avg	SE	Avg	SE	Avg	SE	Avg	SE*
Feathers	35.1	13.1	12.8	1.9	8.9	2.7	32.4	17.6	-	-	-	-	-	-
Feed	8.2	1.8	2.5	1.5	2.5	0.0	3.7	1.7	14.1	7.0	5.0	0.7	6.3	-
Manure	29.8	7.2	83.6	1.5	86.7	4.7	40.7	8.0	41.3	34.1	71.0	0.4	84.1	-
Outside	16.5	4.5	1.0	0.0	1.9	1.9	13.7	7.9	11.6	9.8	10.8	6.6	1.6	-
Skin	-	-	-	-	-	-	-	-	33.0	31.3	13.1	5.5	7.9	-
Wood shavings	10.3	0.3	-	-	-	-	9.5	0.1	-	-	-	-	-	-
Accuracy (%)	76 - 85		78 - 88		75 - 84		62 - 76		74 - 79		78 - 81		63	

*No standard error because missing values for one farm.

Using multiple linear regression

Results using multiple linear regression are shown in Table 4 (fine PM) and Table 5 (coarse PM), together with the variance explained by the regression model.

Table 4. Average (Avg) percentage number contribution of the different PM sources to airborne fine PM (PM2.5) from different livestock housing systems and variance explained by the model (R^2). Standard error (SE) represents variation in the contribution between livestock houses for the same housing system.

Sources	Broilers		Laying hens- floor		Laying hens- aviary		Turkeys		Piglets		Growing-finishing pigs		Dry and pregnant sows	
	Avg	SE	Avg	SE	Avg	SE	Avg	SE	Avg	SE	Avg	SE	Avg	SE
Feathers	28.4	21.5	4.4	1.1	16.0	8.7	43.2	15.3	-	-	-	-	-	-
Feed	0.0	0.0	9.6	9.6	0.0	0.0	0.0	0.0	2.4	2.4	0.4	0.4	0.7	0.7
Manure	67.7	18.2	74.2	1.8	84.0	8.7	22.9	12.8	91.2	4.0	98.3	1.7	78.9	4.1
Outside	0.3	0.3	11.8	8.9	0.0	0.0	0.2	0.2	6.4	6.4	1.0	1.0	0.4	0.4
Skin	-	-	-	-	-	-	-	-	0.0	0.0	0.4	0.4	20.0	4.4
Wood shavings	3.5	3.5		-	-	-	33.7	2.7	-	-	-	-	-	-
R^2	79 - 82		49 - 87		94 - 96		88 - 97		43 - 74		78 - 96		71 - 78	

Table 5. Average (Avg) percentage number contribution of the different PM sources to airborne coarse PM (PM10-2.5) from different livestock housing systems, and variance explained by the model (R^2). Standard error (SE) represents variation in the contribution between livestock houses for the same housing system.

Sources	Broilers		Laying hens- floor		Laying hens- aviary		Turkeys		Piglets		Growing-finishing pigs		Dry and pregnant sows	
	Avg	SE	Avg	SE	Avg	SE	Avg	SE	Avg	SE	Avg	SE	Avg	SE*
Feathers	17.2	6.8	6.3	6.3	10.2	9.9	31.7	3.2	-	-	-	-	-	-
Feed	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.0	6.0	4.2	4.2	-	-
Manure	82.8	6.8	93.7	6.3	87.7	7.8	35.8	1.5	94.0	6.0	84.5	1.8	85.4	-
Outside	0.0	0.0	0.0	0.0	2.2	2.2	0.0	0.0	0.0	0.0	0.0	0.0	-	-
Skin	-	-	-	-	-	-	-	-	0.0	0.0	11.3	2.4	14.6	-
Wood shavings	0.0	0.0	-	-	-	-	32.5	1.7	-	-	-	-	-	-
R^2	86 - 97		88 - 88		95 - 96		86 - 94		44 - 61		76 - 88		85	

*No standard error because missing values for one farm.

DISCUSSION

Results indicated that in poultry, most of the PM originated from feathers (ranging from 4 to 43% in fine and from 6 to 35% in coarse PM) and manure. Contribution of manure was generally higher in coarse PM (ranging from 30 to 94%) compared with fine PM (ranging from 9 to 85%). Manure contribution was higher in laying hen houses compared with broilers and turkeys; whereas feather contribution was higher in broilers and turkeys compared with laying hens. Where present, wood shavings contributed less than 34% of particle numbers. In poultry, Aarnink *et al.* (1999) identified down feathers and urine components as the most abundant sources of PM in broilers. Feddes *et al.* (1992) also found high fecal contribution and spherical uric acid crystals as the main constituent of PM in turkey houses.

In pigs, most of the PM originated from manure. The contribution of manure was higher in fine PM (ranging from 70 to 98%) compared with coarse PM (ranging from 41 to 94%) for all pig categories. Donham *et al.* (1986) reported similar findings. Contribution of skin ranged from 8 to 33%, varying amongst pig categories. Contribution of feed was below 16% for all livestock categories, being the highest in pigs compared with poultry. Feed processing could play a role, as poultry feed has generally coarser particles than pig feed. The contribution of feed to PM in livestock houses has been generally reported in higher ranges than those presented in this study (Aarnink *et al.*, 1999; Heber *et al.*, 1988). Fecal particles can resemble feed particles, furthermore, undigested feed components could be found in manure particles. The higher proportion of feed particles found in other studies, mainly starch in pig houses, could be attributable to the use of only light microscopy to distinguish between particles, and the higher content of starch that can be found in pig's feces compared with poultry (Feddes *et al.*, 1992). Outside particles had a relevant contribution in broilers and turkeys, especially in fine PM.

Results using multiple linear regression showed higher contributions of manure to fine and coarse PM, and mostly lower contributions of feed and outside PM, compared with using classification rules based on decision trees. Overall method accuracies varied from 52 to 88%. The variation explained by multiple linear regression model was generally above 80%. The large differences in source contributions for a given housing system expressed as high standard errors could be part of the variation in the method used, because source apportionment models usually show high variations. Moreover, this could have been caused by the different housing conditions during samplings, together with the short sampling times used.

CONCLUSIONS

1. Results presented in this study improve the understanding of where PM comes from in different livestock housing systems. This can be valuable to choose the optimal dust reduction methods.
2. Based on particle numbers, in poultry houses, most on-farm airborne PM originates from feathers (ranging from 4 to 43% in fine and from 6 to 35% in coarse PM) and manure (ranging from 9 to 85% in fine and from 30 to 94% in coarse PM). In broilers and turkeys, wood shavings contribute less than 34% of particle numbers.
3. Based on particle numbers, in pigs, most on-farm airborne PM originates from manure (ranging from 70 to 98% in fine and from 41 to 94% in coarse PM). Contribution of skin is below 33%, varying amongst pig categories.
4. The contribution of manure to on-farm airborne PM is higher in coarse PM in poultry, but higher in fine PM in pigs.
5. Feed has a negligible contribution to on-farm airborne PM compared with the rest of the sources. Its contribution, however, is higher in pigs compared with poultry.

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