**Comparison between light scattering and gravimetric samplers for PM10 mass concentration in poultry and pig houses**

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## Abstract

The objective of this study was to compare co-located real-time light scattering devices and equivalent gravimetric samplers in poultry and pig houses for PM10 mass concentration, and to develop animal-specific calibration factors for light scattering samplers. These results will contribute to evaluate the comparability of different sampling instruments for PM10 concentrations. Paired DustTrak light scattering device (DustTrak aerosol monitor, TSI, U.S.) and PM10 gravimetric cyclone sampler were used for measuring PM10 mass concentrations during 24 h periods (from noon to noon) inside animal houses. Sampling was conducted in 32 animal houses in the Netherlands, including broilers, broiler breeders, layers in floor and in aviary system, turkeys, piglets, growing-finishing pigs in traditional and low emission housing with dry and liquid feed, and sows in individual and group housing. A total of 119 pairs of 24 h measurements (55 for poultry and 64 for pigs) were recorded and analyzed using linear regression analysis. Deviations between samplers were calculated and dicussed. In poultry, cyclone sampler and DustTrak data fitted well to a linear regression, with a regression coefficient equal to 0.41, an intercept of 0.16 mg $m^{-3}$ and a correlation coefficient of 0.91 (excluding turkeys). In pigs, we found a regression coefficient equal to 0.61, an intercept of 0.05 mg $m^{-3}$ and a correlation coefficient of 0.84. Measured PM10 concentrations using DustTraks were clearly underestimated (approx. by a factor 2) in both poultry and pig housing systems compared with cyclone pre-separators. Absolute, relative, and random deviations increased with concentration. DustTrak light scattering devices should be self-calibrated to investigate PM10 mass concentrations accurately in animal houses. We recommend linear regression equations as animal-specific calibration factors for DustTraks instead of manufacturer calibration factors, especially in heavily dusty environments such as animal houses.

Keywords. Calibration factor, dust measurement, DustTrak, gravimetry, livestock housing.

## 1. Introduction

Appropriate samplers that can provide accurate and comparable particulate matter (PM) mass concentrations are required to ensure compliance with environmental air quality regulations regarding PM emissions from animal houses, and to assess human and animal exposure to PM. Therefore, airborne PM samplers should be able to obtain a representative sample from the original environment at the time of measurement that is consistent with the ‘true’ PM concentration and comparable between devices when tested simultaneously.

This still continues to be a challenge in certain environments where the PM under study and the environmental conditions differ from those for which samplers were designed for, especially for sampling devices different from gravimetric. In fact, PM characteristics in animal houses differ from other types of PM because concentrations are generally 10 to 100 times higher than in other indoor environments (Zhang, 2004). Concentrations also show different count and mass size distributions compared with ambient air (Lai *et al.*, 2014). In animal house environments, PM comprises heterogeneous particles of different nature, shape, size, density, and chemical composition (Cambra-López *et al.*, 2011b). Cambra-López *et al.*

(2011a) reported most particle numbers and mass in pig houses originate from manure, skin, and feed; and in poultry from manure and feathers. A minor part of the particles came from outside (ranging from 0 to 44%, both in numbers and in mass). Lai *et al.* (2014) showed remarkable differences in size of airborne PM among poultry, pig, cattle, and mink housing systems. Moreover, measurement conditions like environmental indoor temperature and relative humidity in animal houses are markedly high compared with outside.

Because animal houses' environment and PM characteristics differ considerably from ambient air, research has been conducted to find alternative samplers to the reference samplers for ambient air, to be used in animal houses. Reference samplers include gravimetric measurements prescribed in the United States federal reference method or in the European Union (EU) reference sampler for ambient air. Zhao *et al.* (2009) developed and validated specific gravimetric samplers for PM10 and PM2.5 which do not show overloading problems during time-averaged 24 h sampling periods in heavily PM loaded animal houses. The PM10 and PM2.5 size fractions mainly consist of particles smaller than 10 and 2.5 μm in diameter, respectively. These specific samplers incorporated an inlet head with a cyclone pre-separator (besides the filter holder), which used centrifugal forces to separate large particles, instead of the greased impactor pre-separator specified in the EU reference sampler and described in CEN-EN 12341 (CEN, 1998) for PM10 and in CEN-EN 14907 (CEN, 2005) for PM2.5. The developed samplers by Zhao *et al.* (2009) proved to be equivalent with the EU reference PM10 and PM2.5 samplers for low PM concentrations (< 100 μg $m^{-3}$) and for high PM10 concentrations when a correction factor was used. Their study also proved that the PM2.5 reference sampler became overloaded in the dusty environment of animal houses.

Besides gravimetric samplers, real-time samplers, such as light scattering photometers are being widely used because they are suitable for monitoring changes in PM concentrations over a period of time where time-averaged measurements assessed gravimetrically are insufficient. Light scattering photometers measure mass concentration of particles in an air stream as a function of the light scattered by the sampled PM. The relationship between this light scattered and the PM mass concentration depends on the physics of the interaction between the light and the particle: particularly on the incident light, the geometry of the detecting optical system, and particle characteristics (refractive index, shape, density, and size) (Görner *et al.*, 1995; Vincent, 2007). The relationship between this light scattered and the PM mass concentration is usually pre-set in the factory, using a standard type of dust with known physical properties (like coal dust or ISO 12103-1 A1 test dust, Arizona Road Dust). When a light scattering sampler is used to measure PM that differs from the manufacturer's factory calibration PM, substantial sampling bias may occur. Therefore, it is essential to either re-calibrate the instrument with the PM under study, or to adjust data with a specific calibration factor, in order to obtain accurate absolute PM mass concentrations (Heal *et al.*, 2000; Kingham *et al.*, 2006).

Although light scattering samplers have been used to quantify absolutely PM concentrations and emissions in animal houses (Costa and Guarino, 2009; Roumeliotis *et al.*, 2010; Roumeliotis and Van Heyst, 2007), further research is needed to validate light scattering samplers against gravimetric methods in animal houses to obtain accurate absolute values. Yanosky *et al.* (2002) reported that light scattering samplers should be validated using co-located, well characterized methods to determine the correction equation for bias reduction, and encouraged further investigation on other influencing factors such as changes in particle characteristics. In animal environments, this should be done by comparison with the equivalent gravimetric sampler which is more suitable for animal houses, because it is less vulnerable for overloading (Zhao *et al.*, 2009). Van Ransbeeck (2013) compared a specific light scattering system among other techniques for sampling PM10 in fattening pig's house and proved equivalence compared with EU reference sampler described in CEN-EN 12341 (CEN, 1998). Similar comparison tests and investigations are encouraged in other animal housing systems in comparison with the equivalent gravimetric sampler described in Zhao *et al.* (2009).

Therefore, the objective of this study was to compare co-located real-time light scattering devices and the equivalent gravimetric sampler in poultry and pig houses for PM10 mass concentration and to develop animal-specific calibration factors for light scattering samplers. This study is part of a national field survey conducted in the Netherlands from 2008 to 2011 to obtain emissions of most relevant aerial pollutants in animal houses, including inhalable PM, PM10, PM2.5, ammonia, odor, methane and nitrous oxide. A total of 36 animal houses, covering 13 types of housings (for poultry, pigs, dairy cattle, and minks) were surveyed. An overview of the project, sampling methods and emission factors for PM is described in Winkel *et al.* (2014). Data from PM10 concentration measured using light-scattering devices and gravimetric samplers collected during this survey in poultry and pig houses is presented and analyzed in our study. These results will contribute to evaluate the comparability of different sampling instruments for PM10 concentrations.

## 2. Materials and Methods

### 2.1. Light scattering sampler

Mass concentrations of PM10 using the light scattering principle were determined with DustTraks (DustTrak aerosol monitor, model 8520, TSI, Inc., Shoreview, Minn., U.S.). DustTrak is a portable, hand-held device which uses a 90-degree light scattering to measure mass concentration of particles in an air stream that passes through an impactor at an airflow rate of 1.7 L $min^{-1}$. The PM10 inlets were used in this study. The PM10 fraction is defined as the sampling cut-off diameter of particle separators that the mass of total suspended particles have to pass, for a separation or sampling efficiency of 50%. This varies with the type of sampler and sampling efficiency. DustTraks were cleaned and zero-calibrated before each measurement. Recorded one-minute values were summarized into 24 h averages to compare with gravimetric samplers. DustTraks were factory calibrated using standard ISO 12103-1 Arizona Road Dust.

The detection range of DustTraks was from 0.001 to 100 mg $m^{-3}$ for particles from 0.1 to 10 µm in diameter, with a resolution of ±0.1% of reading or ±0.001 mg $m^{-3}$, whichever is greater (TSI, 2002).

### 2.2. Gravimetric sampler

Concentrations of PM10 were measured simultaneously and gravimetrically with two cyclone samplers (URG Corp., Chapel Hill, N.C., U.S.) for PM10 following CEN-EN 12341 (CEN, 1998). Samplers included the EU reference inlet in combination with a cyclone pre-separator. A detailed description of samplers can be found in Zhao *et al.* (2009). After pre-separation inside the cyclone, PM samples were collected on glass fibre filters (47 mm diameter, type GF-3, Macherey-Nagel, Duren, Germany). Sampled air was drawn into the sampler at an airflow rate of 16.7 L $min^{-1}$ using stationary pumps (Charlie HV, Ravebo Supply B.V., Brielle, the Netherlands). The pumps were able to keep a constant airflow using a temperature sensor at the same position as the inlet of the cyclone PM collector. The volume of air passing through the cyclones was measured by a gas meter within the pump and corrected for the temperature measured at the sampling point.

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; resolution: 10 µg), following CEN-EN 14907 (CEN, 2005). The average value was calculated as the filter weight. For the loaded filters, the same weighing procedure was adopted. The weight difference between loaded and unloaded filters equaled the amount of collected PM. The PM concentrations were calculated as the mass of collected PM divided by the volume of air drawn through the filter. Average of duplicate cyclone measurements was used for calculations.

### 2.3. Sampling sites

Sampling was conducted in 32 animal houses in the Netherlands: 16 houses for poultry including broilers, broiler breeders, layers in floor and in aviary systems, and turkeys; and 16 houses for pigs, including piglets, growing-finishing pigs in traditional and low emission housing with dry and liquid feed, and sows in individual and group housing. Table 1 describes the sampling sites. Co-located sampling instruments (one DustTrak and two cyclone samplers) in each animal house were positioned with the inlets of both instruments at a horizontal distance of 0.5 m from the border of the exhaust opening and at a vertical distance of 0.10 m underneath the exhaust opening (in buildings with room ventilators); and in front of the ventilators at a horizontal distance of approximately 2–3 m (air velocity $<2$ m $s^{-1}$; allowing non-isokinetic PM sampling) (in buildings with tunnel ventilation). Sampling duration was 24 h (from noon to noon). During measurements, environmental indoor temperature and relative humidity were registered. More details of sampling sites, position, and measurement methods are described in Winkel *et al.* (2014).

Table 1. Description of sampling sites and number of samples.

| Animal species | Housing system | | Number of houses | Number of samples | Ventilation system | Number of animals per house |
|---|---|---|---|---|---|---|
| Poultry | Broilers | Litter floor | 4 | 13 | Tunnel | 19,000-52,000 |
| | Broiler breeders | Litter and slatted floor | 2 | 8 | Tunnel | 8,121-10,253 |
| | Laying hens - floor | Litter and slatted floor | 4 | 14 | Tunnel or roof (2 houses each) | 4,300-17,500 |
| | Laying hens - aviary | Litter and aviaries | 4 | 13 | Tunnel | 10,900-36,900 |
| | Turkeys | Litter floor | 2 | 7 | Tunnel | 4,500-5,000 |
| Pigs | Piglets | Fully or partially slatted floor (2 houses each) | 4 | 17 | Ceiling fans | 75-130 |
| | Growing-finishing pigs - traditional | Partially slatted floor | 4 | 13 | Ceiling fans | 55-120 |
| | Growing-finishing pigs - low emission, dry feed | Partially slatted floor, pit with slanted walls and sewage pipe | 2 | 9 | Ceiling fans | 132-144 |
| | Growing-finishing pigs - low emission, liquid feed | Partially slatted floor, pit with slanted walls and sewage pipe | 2 | 9 | Ceiling fans | 144-156 |
| | Dry and pregnant sows - individual housing | Confined gestation stalls (solid and slatted floor) | 2 | 10 | Ceiling fans | 32-135 |
| | Dry and pregnant sows - group housing | Free access to gestation stalls (solid and slatted floor) | 2 | 6 | Ceiling fans | 39-44 |

**2.4. Data analyses**

A total of 119 pairs of 24 h measurements (55 for poultry and 64 for pigs) were recorded and analyzed using linear regression analysis. Linear regression was conducted separately for each animal species (poultry and pigs). In all cases, the PM10 concentration measured during 24 h using cyclone samplers was used as independent variable, whereas the PM10 concentration measured using the DustTrak was used as the dependent variable following equation 1.

$$y = \beta_1 x + \beta_0 \quad \text{Equation 1}$$

where: $\beta_1$is the slope and $\beta_0$ is the intercept. A significance level of 0.05 was used for all statistical tests. According to Cheng (2008), regression intercepts significantly different from zero were considered to indicate systematic bias of PM concentrations between samplers. Regression slopes significantly different from one were considered to indicate proportional bias of PM concentrations between samplers. The coefficient of determination ($R^2$) was used to describe the correlation of measured PM concentrations between samplers. Data were analyzed using SAS Software (SAS, 2001).

We also analyzed absolute and relative deviations associated with these samplers. The absolute deviation between the DustTrak and cyclone sampler was calculated for poultry and pig dataset following equation 2, as the difference between both samplers. The relative deviation between the DustTrak and cyclone sampler was calculated for poultry and pig dataset following equation 3. This deviation was multiplied by 100, to express it in percentage, varying from -100% to 100%. Besides these deviations, random deviations independent from systematic and proportional bias were calculated as the difference between the reference cyclone PM10 concentration and the modeled PM10 concentration calculated from applying each regression equation to poultry and pig data separately following equation 4. Random deviations were calculated independent from the fact that reference samplers could also attribute by their own random deviations to this term.

$$Absolute\ deviation = Cyclone\ PM10\ concentration - DustTrak\ PM10\ concentration \quad \text{Equation 2}$$

$$\text{Relative deviation (\%)} = \left( \frac{\text{Absolute deviation}}{\text{Cyclone PM10 concentration}} \right) \times 100 \qquad \text{Equation 3}$$

*Random deviation= DusTrak observed PM10 concentration – Modeled DustTrak PM10 concentration*

Equation 4

## 3. Results

### 3.1. Environmental conditions and PM10 concentrations

During measurements, PM10 concentrations inside animal houses, measured with cyclone samplers, were higher in poultry than in pig houses. In poultry houses, indoor PM10 concentrations ranged from 0.47 to 8.45 mg $m^{-3}$ (average 2.52 mg $m^{-3}$); whereas in pig houses, indoor PM10 concentrations ranged from 0.18 to 1.88 mg $m^{-3}$ (average 0.76 mg $m^{-3}$).

Indoor temperature and relative humidity in the animal houses during the measurements are shown in Table 2. Further details of environmental conditions during sampling (indoor inhalable and PM2.5 concentration, outdoor temperature and relative humidity and ventilation rates) can be found in Winkel *et al.* (2014).

Table 2. Average indoor temperature (ºC) and relative humidity (%) and range in brackets, during measurements.

| Animal species and housing system | Temperature | Relative humidity |
|---|---|---|
| Broilers | 22.8 (18.0-29.1) | 69.5 (55.7-86.4) |
| Broiler breeders | 21.7 (20.2-22.3) | 72.8 (65.1-90.3) |
| Laying hens - floor | 19.9 (16.2-24.0) | 67.4 (58.0-74.4) |
| Laying hens - aviary | 21.5 (19.2-25.6) | 62.5 (51.4-92.9) |
| Turkeys | 21.6 (20.1-23.6) | 68.4 (65.3-73.4) |
| Piglets | 26.4 (24.4-29.4) | 54.6 (41.2-69.1) |
| Growing-finishing pigs - traditional | 24.8 (20.1-28.0) | 56.5 (41.0-73.8). |
| Growing-finishing pigs - low emission, dry feed | 25.2 (23.2-27.9) | 54.8 (44.0-78.0) |
| Growing-finishing pigs - low emission, liquid feed | 24.9 (22.3-26.1) | 55.6 (45.1-69.3) |
| Dry and pregnant sows - individual housing | 21.2 (18.1-24.0) | 59.8 (43.3-74.3) |
| Dry and pregnant sows - group housing | 22.0 (19.4-24.8) | 67.9 (56.5-84.0) |

## 3.2. Comparison between samplers

The linear response of DustTrak to PM10 concentrations measured with cyclone samplers showed a clear proportional and systematic bias which varied slightly among animal species. In poultry, cyclone and DustTrak data fitted well to a linear regression line (P<0.0001), with a regression coefficient equal to 0.41 (P=0.008; test for difference from 1), an intercept of 0.16 mg $m^{-3}$ (P<0.0001; test for difference from 0) and a correlation coefficient of 0.91 (excluding turkeys) (Figure 1). Results in turkeys showed a different trend, with a regression coefficient equal to 1.1 (P=0.49), an intercept of 0.06 mg $m^{-3}$ (P<0.0001) and a correlation coefficient of 0.98.

In pigs, cyclone and DustTrak data also fitted well to a linear regression line (P<0.0001), with a regression coefficient equal to 0.61 (p=0.07), an intercept of 0.05 mg $m^{-3}$ (P<0.0001) and a correlation coefficient of 0.84 (Figure 2).

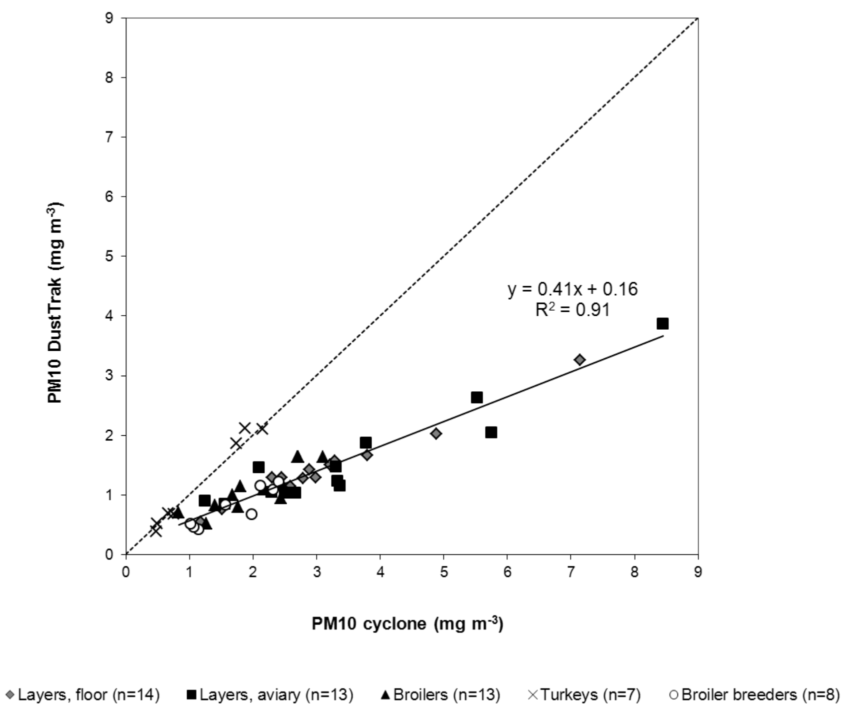

Figure 1. Relationship between light scattering DustTrak and cyclone sampler for PM10 concentrations in poultry houses. The dashed line represents y=x.

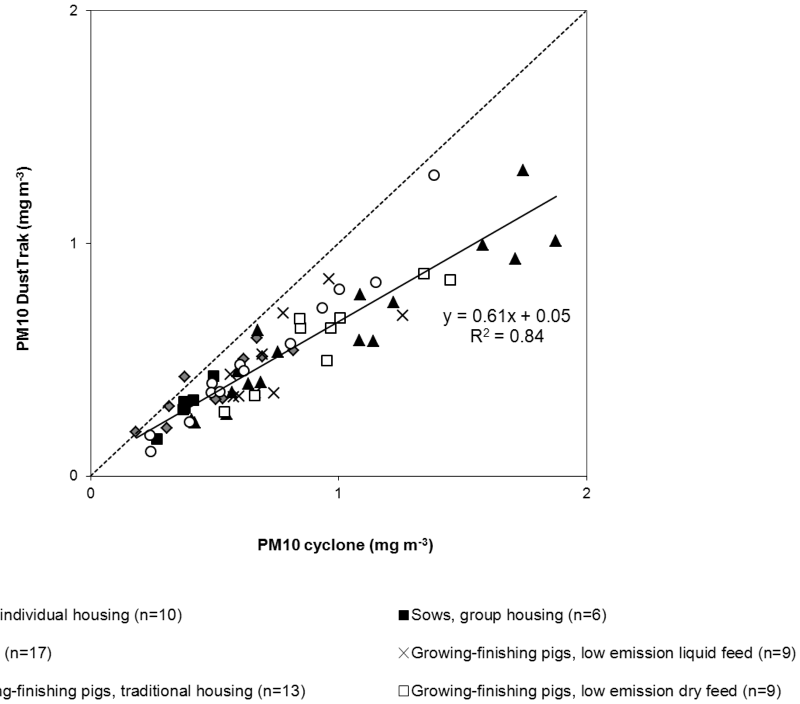


Figure 2. Relationship between light scattering DustTrak and cyclone sampler for PM10 concentrations in pig houses. The dashed line represents y=x.

**3.3. Deviations between samplers**

Figure 3 shows the distribution of absolute deviations within the whole data set (excluding turkeys). Absolute deviations varied from -0.05 to 4.57 mg $m^{-3}$ and increased linearly with PM10 concentration. Average absolute deviation equaled 0.75 mg $m^{-3}$.

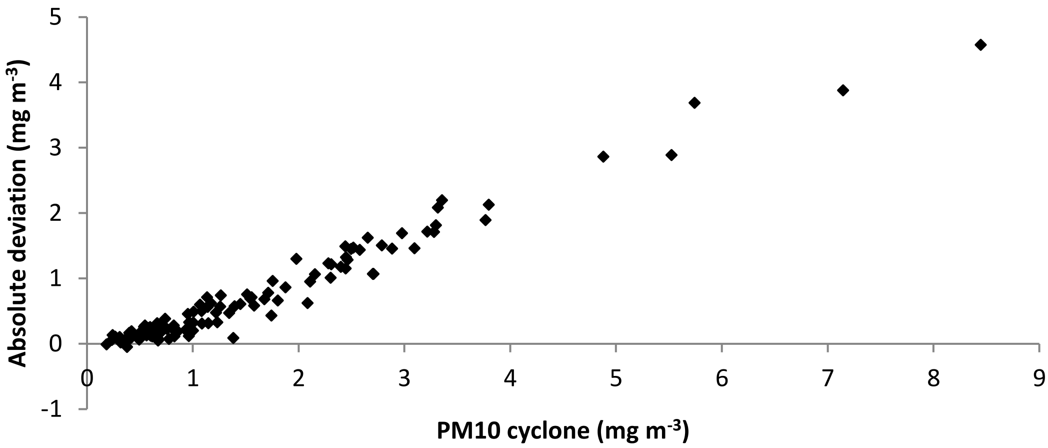


Figure 3. Absolute deviation (mg m$^{-3}$) between DustTrak and cyclone sampler for poultry and pig dataset (n= 112, excluding turkeys), as a function of PM10 concentrations measured with cyclone sampler.

As regards relative deviations, Figure 4 shows the distribution of relative deviations for poultry and pig dataset (excluding turkeys). Relative deviation varied from -12 to 66%, being on average 39%. Relative deviation increased with PM10 concentration. The distribution of this deviation resembled a logarithmic curve. It showed a wide variation in the lowest concentrations ranges (below 2 mg m$^{-3}$) and was closer or exceeded the average relative deviation of 39% over 2 mg m$^{-3}$.

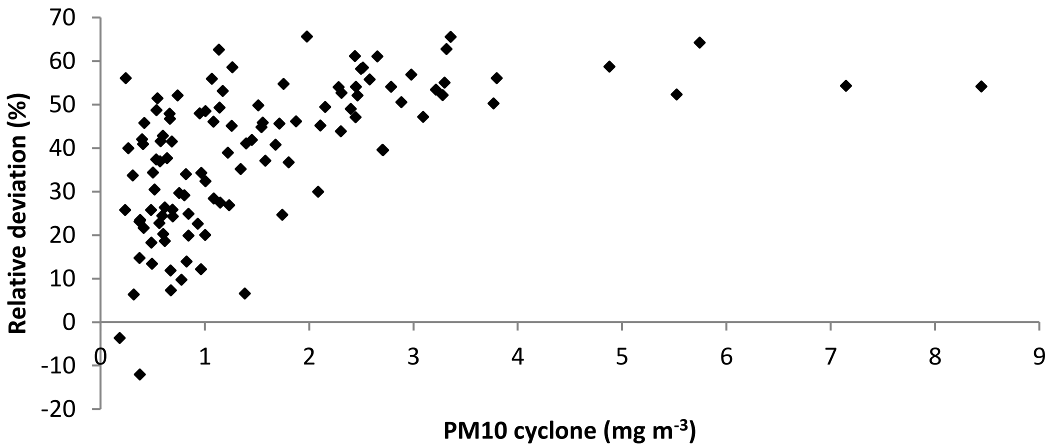

Figure 4. Relative deviation in percentage for poultry and pig dataset (n= 112, excluding turkeys) between DustTrak and cyclone sampler as a function of PM10 concentrations measured with cyclone sampler.

Figure 5 shows the distribution of random deviations for poultry and pig dataset (excluding turkeys) based on the modeled DustTrak concentrations. Random deviations varied from -0.46 to 0.45 mg m$^{-3}$, being on average 0.01 mg m$^{-3}$. Most frequent values were found between -0.2 and 0.2 mg m$^{-3}$. Random deviations increased with PM10 concentration, especially above 1 mg m$^{-3}$.

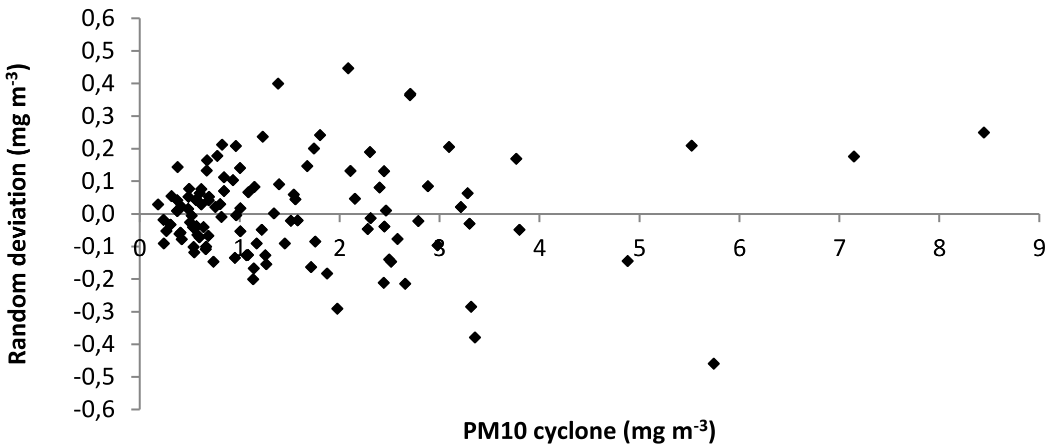


Figure 5. Random deviation for poultry and pig dataset between observed and modeled DustTrak PM10 concentration as a function of PM10 concentrations measured with cyclone sampler.

**Discussion**

In the present comparative study, light-scattering devices showed a linear response to PM from different animal housing systems. Our results indicate that DustTraks systematically underestimate PM10 concentrations in pig and poultry houses by a factor of *circa.* 2 as determined by cyclone samplers. This underestimation is probably caused by different particle's properties of animal PM as compared to standard ISO 12103-1 Arizona Road Dust (for which DustTraks are factory calibrated). Heal *et al.* (2000) determined that differences in particle size distribution, shape and reflectance properties from the factory pre-set calibration and the sampled airborne PM can produce different scattering responses for identical masses of PM passing through the instrument. Light-scattering devices show high sensitivity and time resolution, but scattering per unit mass is a strong function of particle size and refractive index (Görner *et al.*, 1995). An explanation for this can be found in the measurement principle of light-scattering devices, which is based on light scattering by airborne particles inside an optical sensing volume. This depends on the Mie theory of light scattering and the built-in optical parameters of such light-scattering photometers (Görner *et al.*, 1995).

Chung *et al.* (2001) reported that DustTraks are not calibrated to measure submicron particles, but are calibrated with particles larger than 1 micrometer. The DustTrak cannot detect particles with sized diameter smaller than 0.1 µm, and the amount of light scattered by particles with diameter smaller than 0.25 µm is proportional to particle diameter raised to the sixth power ($Dp^6$). These effects can cause the DustTrak measurements to differ from gravimetric measurements of airborne particulate matter when the size distribution of the airborne particles differs significantly from the size distribution of the test aerosol (Chung *et al.*, 2001).

As opposed to the other poultry categories, no evident underestimation was found for turkeys. Cambra-López *et al.* (2011a) reported that in turkey houses with ridge ventilation, PM could partially originate from ambient air (outside source), whereas manure and feathers are the most relevant sources of PM in broilers and hens, and manure and skin flakes the most relevant sources in pigs. Ambient PM differs from PM found inside animal houses both in morphology (smaller in size), chemical composition and size distribution (Cambra-López *et al.*, 2011b), which may explain why DustTraks and cyclone samplers are in good agreement for turkeys.

Conversely to our results, DustTraks tend to overestimate ambient PM concentrations compared with gravimetric samplers by a factor of 1.4 to 3.0 (Cheng, 2008; Jenkins *et al.*, 2004). Cheng (2008) reported lower overestimations of DustTrak as particle size increased. DustTrak provided a lower overestimation of PM10 compared with PM2.5 (Cheng, 2008).

Lehocky and Williams (1996) suggested that at or below 1.1 mg/m$^3$, DustTraks provided higher values than gravimetric samplers, and this difference decreased as concentrations exceeded 1.1 mg/m$^3$, for coal dust. Differences in correlation or coefficient slopes might be attributable to lower concentration range and PM composition (Yanosky *et al.*, 2002).

Liu *et al.* (2002) determined how PM sources related with cooking/frying activities within households influenced the response of instruments. They also observed different responses with high/low PM concentrations, concluding that their performance depends on the nature of PM emissions. Thorpe and Walsh (2002) reported differences between flour dust (higher variations in size) compared with pine or stone dust. These authors tested effects of dust concentrations, dust composition, particle size, air velocity, monitor orientation and monitor maintenance and cleaning. Contamination of the optics with dust often resulted in an increase in monitor's response which decreased after cleaning. Among other factors influencing DustTrak's response, Liu *et al.* (2002) identified that relative humidity played an important role in particle volume and its light scattering properties. Moreover, further research on how inherent particle properties and ambient relative humidity can influence light-scattering properties of PM10 in animal environments should be conducted.

An increase in DustTraks response with PM10 concentration was observed in our study. Absolute, relative, and random deviations increased with concentration. According to Kingham *et al.* (2006), over-reading with DustTraks is probable, and these over-recording is usually higher with increasing PM10 concentrations. Van Ransbeeck (2013) reported increasing differences between real-time photometers and gravimetric sampler for PM10 concentrations (in the range between 0.02 to 2.29 mg m$^{-3}$). Optical light scattering instruments are more sensitive at low concentrations. This is because it is easier to detect a change in a small light intensity than in an intensity which is already very bright (VINCENT, 2007). On the other hand, smaller particles usually scatter more light and so the response of DustTraks might increase with decreasing particle size (Visser *et al.*, 2006).

The lack of adequately standardized monitoring devices for PM sampling has biased PM quantification in animal houses. If true mass has to be measured using light-scattering photometers, animal-specific calibration factors are necessary and measured PM concentrations need to be corrected. Therefore, it is essential to firstly, calibrate these devices to obtain reliable calibration factors, and secondly, to correct data by applying these calibration factors. Jenkins *et al.* (2004) identified two calibration options: in the laboratory with equivalent aerosol or on-field. On-field calibration was conducted in our study to obtain linear regression calibration equations per animal species.

The DustTrak's manual, however, recommends using custom calibration factors to correct real-time PM10 mass concentrations. Custom calibrations factors can be calculated by simply dividing reference PM10 concentration measured with the cyclone sampler by the PM10 concentration measured with the DustTrak sampler following equation 5.

$$Calibration\ factor = \frac{Cyclone\ PM10\ concentration}{DustTrak\ PM10\ concentration} \qquad \text{Equation 5}$$

An example of custom calibration factors for DustTrak calculated following equation 5, for our dataset is presented in Table 3. These values resulted in lower calibration factors for pigs compared with poultry, being on average equal to 2.1 for poultry and 1.5 in pigs (Table 3). In turkeys, calibration factor equaled 1.0.

Table 3. DustTrak calibration factors for each studied animal species and housing systems.

| Animal species and housing system | Calibration factor |
|---|---|
| Broilers | 1.9 |
| Broiler breeders | 2.2 |
| Laying hens - floor | 2.1 |
| Laying hens - aviary | 2.2 |
| Turkeys | 1.0 |
| Average poultry (except for turkeys) | 2.1 |
| Piglets | 1.6 |
| Growing-finishing pigs - traditional | 1.4 |
| Growing-finishing pigs - low emission, dry feed | 1.6 |
| Growing-finishing pigs - low emission, liquid feed | 1.6 |
| Dry and pregnant sows - individual housing | 1.3 |
| Dry and pregnant sows - group housing | 1.3 |
| Average pigs | 1.5 |

Figure 6 presents corrected real-time PM10 mass concentration using linear regression equations and custom calibration factors for our data set (excluding turkeys) (Figure 6). This figure shows that above 1 mg $m^{-3}$, corrected PM10 concentration using custom calibration factors was higher than using linear regression equation. This difference is attributable to the intercept (systematic bias) in regression equations, which pulled down the corrected values. Therefore, for correcting PM data form poultry and pig houses, we recommend linear regression equations as animal-specific calibration factors for DustTraks instead of manufacturer calibration factors, especially in heavily dusty environments such as animal houses where PM10 concentrations above 1 mg $m^{-3}$ are common.

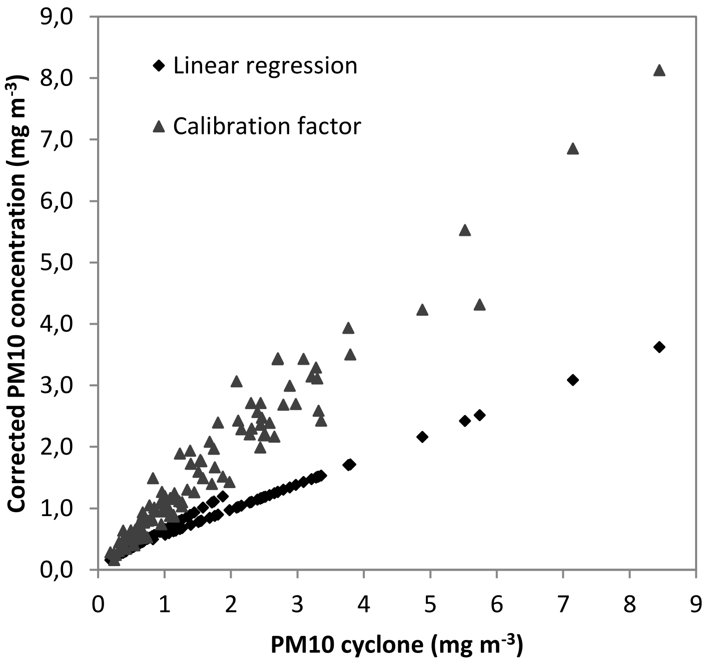


Figure 6. Comparison between corrected DustTrak PM10 concentration using linear regression modeling and custom calibration factors for poultry and pig dataset (n= 112, excluding turkeys).

Standardized measuring protocols to measure PM levels in different size fractions need to be developed and harmonization is needed. DustTraks are useful to measure relative PM, but not absolute values (Park *et al.*, 2009). These instruments are suitable where only relative values are required (Kuusisto, 1983). Direct-reading instruments are better adapted to time and space monitoring than for exposure assessment. Therefore, they complement traditional gravimetric techniques rather than replace. Nevertheless, they are very suitable to evaluate PM control measures (Görner *et al.*, 1995).

Moreover, they are easy to operate, portable, and provide a continuous output of instant time-resolved data at a relatively low cost. Consequently, the characteristics of real-time samplers result in advantages compared with gravimetric samplers; and although gravimetric samplers are recognized as the standard method and provide accurate time-averaged measurements independent from particle characteristics, they have some disadvantages compared to light scattering photometers, they require weighing filters on an analytical balance, and can only provide cumulative mass concentration results 24-48 h after conducting measurements on-field. These facets, in combination with reliable correction factors, could allow the DustTrak to be used in cost effective and low maintenance monitoring networks (Kingham *et al.*, 2006).

The regression equations obtained per animal category can be used in the future to correct real-time PM10 mass concentrations measured using DustTraks. (to improve precision compared with gravimetric data). If DustTraks are to be used to verify exceedance of certain thresholds or in exposure assessment studies, especial care should be taken in interpreting results (Liu *et al*., 2002).

## Conclusions

Paired DustTrak light scattering device (DustTrak aerosol monitor, TSI, U.S.) and PM10 gravimetric cyclone sampler were used for measuring PM10 mass concentrations during 24 h periods (from noon to noon) inside animal houses. Sampling was conducted in 32 animal houses in the Netherlands, including broilers, broiler breeders, layers in floor and in aviary system, turkeys, piglets, growing-finishing pigs in traditional and low emission housing with dry and liquid feed, and sows in individual and group housing. A total of 119 pairs of 24 h measurements (55 for poultry and 64 for pigs) were recorded and analyzed using linear regression analysis. The following conclusions can be drawn:

- Measured PM10 concentrations using DustTraks were clearly underestimated (approx. by a factor 2) in both poultry and pig housing systems compared with cyclone pre-separators. Absolute, relative, and random deviations increased with concentration.
- In poultry, cyclone and DustTrak data fitted well to a linear regression line ($P<0.0001$), with a regression coefficient equal to 0.41 ($P=0.008$; test for difference from 1), an intercept of 0.16 mg m$^{-3}$ ($P<0.0001$; test for difference from 0) and a correlation coefficient of 0.91 (excluding turkeys).
- In pigs, cyclone and DustTrak data also fitted well to a linear regression line ($P<0.0001$), with a regression coefficient equal to 0.61 ($p=0.07$), an intercept of 0.05 mg m$^{-3}$ ($P<0.0001$) and a correlation coefficient of 0.84.
- DustTraks results should be interpreted carefully to quantify PM10 in animal houses, when appropriate calibration factors are not used. The regression equations obtained per animal category can be used in the future to correct real-time PM10 mass concentrations measured using DustTraks. We recommend linear regression equations as animal-specific calibration factors for DustTraks instead of manufacturer calibration factors, especially in heavily dusty environments such as animal houses with PM10 concentrations exceeding 1 mg m$^{-3}$.

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