Chapter 2
Theoretical Considerations

Emission can be defined as the release of pollutants from the source to the environment. Transmission can be defined as the distribution and conversion of pollutants during the atmospheric transport. Immission can be defined as the concentration and deposition of pollutants with impact on the places and creatures exposed (Fig. 2.1).

Livestock housing is a major source of harmful gases, e.g., CH_4, NH_3, CO_2, and N_2O (Zhang et al. 2011). Gaseous emissions measurements in livestock buildings are important as these pollutants may affect the health of farmers and the surrounding environment. Emission monitoring enables judgments on the effectiveness of mitigation strategies and controls on emission targets (Ngwabie et al. 2009), as well as the health and well-being of the animals. Table 2.1 shows the characteristics, global warming potentials, maximum indoor gas concentrations, and physiological effects of CO_2, NH_3, CO, H_2S, CH_4, and N_2O.

Manure management, inside and outside of livestock buildings, is responsible of emitting several gases. Manure is a mixture of solid and liquid animal excreta (feces and urine) collected from animal buildings, whereas dung is solid animal excreta, i.e., feces. Slurry is a mixture of scraped manure and flushing water and is collected from animal buildings. Hence, slurry is a mixture of manure and water. On the other hand, litter is animal excreta and bedding material collected from animal buildings (Samer 2011a). Livestock excreta stored in manure stores, in housing, in beef feedlots, or cattle hardstandings are the most important sources of GHGs and NH_3 in the atmosphere. The storage of dry manure produces large emissions of N_2O, while storage of liquid manure produces large emissions of CH_4 (Janzen et al. 2008). Inventories have shown that stored animal manure, animal housing, and exercise areas account for about 69–80 % of the total emission of NH_3 in Europe (ECETOC 1994; Hutchings et al. 2001). Most of CO_2 is formed by the animals and exhaled by respiration. It can also be part of exhaust gases of heating systems being

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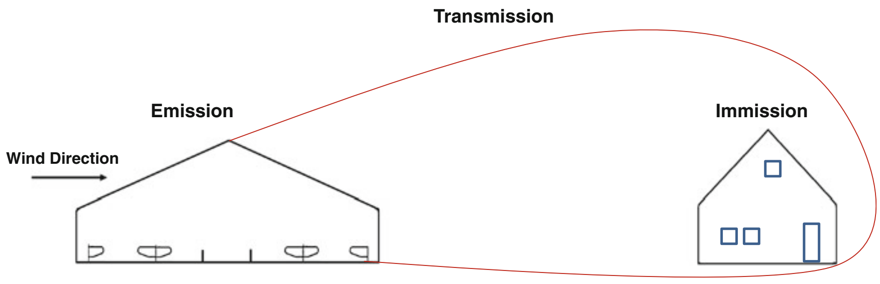

Fig. 2.1 Emission of pollutants from livestock buildings, transmission, and immission into neighborhood (*Amended, redrawn and adopted from* KTBL 2006)

released in the barns. Additionally, a certain portion of CO_2 is released by the manure. The released CO_2 from urine and dung in stored manure is less than 5 % of the amount produced by respiration (Schneider 1988; Aarnink et al. 1992). Low concentrations of N_2O can be measured in dairy barns with liquid manure systems, where daily or frequent manure removal into external storage tanks is applied and this does not constitute a major source of N_2O (Ngwabie et al. 2009).

Several algorithms for calculating methane and nitrous oxide emissions from manure management were developed. The biogenic emissions of CH_4 and N_2O from animal manure are stimulated by the degradation of volatile solids (VS) which serve as energy source and a sink for atmospheric oxygen. Algorithms which link carbon and nitrogen turnover in a dynamic prediction of CH_4 and N_2O emissions during handling and use of liquid manure were developed and include a sub-model for CH_4 emissions during storage relates CH_4 emissions to VS, temperature, and storage time, and estimates the reduction in VS; and a second sub-model estimates N_2O emissions from field-applied slurry as a function of VS, slurry N, and soil water potential, but emissions are estimated using default emission factors. Anaerobic digestion of slurry and organic waste produces CH_4 at the expense of VS. Accordingly, these models predicted a 90 % reduction of CH_4 emissions from outside stores with digested slurry, and a >50 % reduction of N_2O emissions after spring application of digested as opposed to untreated slurry. Additionally, simple algorithms to account for ambient climatic conditions may significantly improve the prediction of CH_4 and N_2O emissions from animal manure. Besides, several algorithms were developed for determining ammonia emission from buildings housing cattle and pigs and from manure stores (Sommer et al. 2004, 2006).

The factors-of-influence (FOI) that strongly influence the dispersion of NH_3 are NH_3 mass flow, internal and external temperatures, mean and turbulent wind components in horizontal and vertical directions, atmospheric stability, and exhaust air height where the continuous measurement of NH_3 remains a challenging and costly enterprise, in terms of capital investment, running costs or both (Von Bobrutzki et al. 2010; Von Bobrutzki et al. 2011). The determination of

Table 2.1 Properties, GWP, maximum gas concentrations, and physiological effects of some noxious gases (CIGR 1984, 1994, 1999; FAO 2006; IPCC 2007a; UNFCCC 2014)

Gas	**Chemical formula**	**Lighter than air**	**Odor**	**GWP (100 years)**	**Class**	**Maximal indoor concentration**	**Comments**
Methane	CH_4	Yes	Odorless	21	Asphyxiant flammable	–	Concentrations between 5000 and 15,000 ppm are explosive, several explosions have occurred due to ignition of methane-rich air in poorly ventilated livestock buildings
Nitrous oxide	N_2O	No	Slightly sweet odor	310	Anesthetic	3 ppm	Colorless and nonflammable gas, with a slightly sweet odor. Known as "laughing gas" due to the euphoric effects of inhaling it
Ammonia	NH_3	Yes	Sharp and pungent	Contributes to global warming only when converted to N_2O	Irritant	20 ppm	Irritation of eyes and throat at low concentrations; asphyxiating, could be fatal at high concentrations with 30–40 min exposure
Hydrogen sulfide	H_2S	No	Rotten eggs	NA	Poison	0.5 ppm (shortly 5 ppm during manure removal)	Headaches, dizziness at 200 mg/L for 60 min; nausea, excitement, insomnia at 500 mg/L for 30 min; unconsciousness, death at 1000 mg/L
Hydrogen cyanide	HCN	Yes	Bitter almond	NA	Poison flammable	10 ppm	A very toxic and explosive gas; released together with H_2S during mixing of manure
Carbon dioxide	CO_2	No	Odorless	1	Asphyxiant	3000 ppm	<20,000 mg/L is in the safe level; increased breathing, drowsiness, and headaches as concentration increases; could be fatal at 300,000 mg/L for 30 min
Carbon monoxide	CO	Yes	Odorless	3	Poison	10 ppm	Colorless, odorless and tasteless gas

emission mass flow is necessary not only to compute dispersion but also to develop mitigation strategies. While husbandry, dunging, and feeding influence the ammonia emission, likewise for both forced ventilation and natural ventilation, the building envelope including ventilation openings (design and control) and the outside climatic conditions are the dominant influencing factors (Samer and Abuarab 2014; Samer 2012b; Samer et al. 2011c).

The highest average ammonia emission coincides with higher environmental temperature. The gaseous emissions from naturally ventilated cattle buildings significantly increase with air temperature (Morsing et al. 2008; Adviento-Borbe et al. 2010; Pereira et al. 2011). Low emission values can only be achieved by reducing the emission source surfaces, decreasing temperature and air velocity near the source, and minimizing volumetric airflow rates throughout the livestock buildings (Adviento-Borbe et al. 2010; Bjorneberg et al. 2009; Blanes-Vidal et al. 2007; Gay et al. 2003). The drawing-off emission flux of harmful gases from a naturally ventilated building is dependent on wind velocity (speed and direction) and turbulence fields inside and over the building envelope; therewith the emission mass flow is highly variable and difficult to estimate (Ngwabie et al. 2009; Van Buggenhout et al. 2009; Hellickson and Walker 1983). The effects on gas emissions are as a consequence of changing airflow patterns and different types of flow in the boundary layer between the slurry and ventilation air.

In order to quantify the gaseous emissions, the tracer gas technique was developed (Samer et al. 2014a). The tracer gas technique is one of the approaches used for quantifying gaseous emissions and estimating ventilation rates in naturally ventilated buildings which including the measurement of infiltration, air exchange, and the dispersion of pollutants (Samer et al. 2011d). This technique implements tracer gases such as CO_2, SF_6, and Krypton 85 for measuring the ventilation rates and to calculate the emission streams. The emission mass flow from the livestock building is then the product of both the concentration difference between emitted and fresh air and the ventilation rate. The gaseous concentrations varied in time and place inside the investigated barn (Samer et al. 2012d; Samer et al. 2011e).

The ventilation rate and the gaseous emissions from a naturally ventilated livestock building are dependent on wind velocity. In order to investigate the distribution of air temperature and gaseous concentrations throughout the different zones of the building and to achieve an efficient control of the bio-responses, continuous monitoring and controlling of the micro-environment to variations of air velocity (direction and speed) inside the building is required. Therefore, the air profiles should be investigated and airflows should be analyzed through the zones of the building (Samer et al. 2011a; Berckmans and Vranken 2006). Large fluctuations occur in ventilation rates estimated using the combined effects of wind pressure and temperature difference forces, owing to large fluctuations in the wind velocity. The fluctuations of wind velocity (direction and speed) negatively affect the estimation of ventilation rates and then the gaseous emissions (Samer et al. 2014a; Samer et al. 2011d, e). Therefore, the airflow profiles should be investigated and airflows should be analyzed in livestock barns.

Investigating the airflow profiles inside a livestock building is important to determine the air and pollutants' distribution (Samer 2012a). The air movement can be characterized by velocity measurements and observation by visualization of the air flow pattern by smoke, where these images can be recorded by video camera and analyzed by computer image analysis. Via laser-light-sheet technique the air flow is made visible by smoke particles. The snapshot is digitally recorded and average images are calculated afterward. Airflow patterns in animal buildings influence the distribution of air temperature, gas concentrations, and the release of gases from manure. Air velocity measurements have been used for airflow pattern measurements.

Odors and gases emitted from animal houses are strongly related to airflows (Morsing et al. 2008). Sun et al. (2002) developed computational fluid dynamics (CFD) models to simulate air velocity and ammonia distribution within a hog building. Snell et al. (2003) stated that ventilation rate could be explained by the climatic values (wind velocity, wind direction, temperature, and relative air humidity), where the wind velocity is of central importance for the ventilation. Bartzanas et al. (2007) stated that air velocity measurements incarnate the corner stone for airflow analysis in rural buildings. Bjerg and Sørensen (2008) carried out numerical analysis and mentioned that to fulfill modern demands of airflow in livestock buildings, several procedures—which requires air velocity measurements—should be implemented, and they are determining air velocity at animal level, limiting air velocity in the animal occupied zone, homogenizing air velocity distribution in the entire barn, determining whether air velocity distribution inside and close to the inlet is similar, investigating air velocity profiles and turbulences, homogenizing air velocity direction throughout the entire barn, and reducing air velocity at floor level at high ventilation rate without increasing the pressure drop over the inlet.

2.1 Nitrogen Cycle

A summary of the major remodeling processes in the terrestrial nitrogen cycle is shown in Fig. 2.2. The individual conversion processes are marked with numbers. The main processes (Fig. 2.2) in the nitrogen cycle are nitrogen assimilation (no. 1 and 2); synthesis of endogenous proteins (no. 3); ammonification (no. 4, 5, and 6); direct deposit into soil (no. 7); emission (no. 8 and 9); transmission, deposition, and immission (no. 10 and 24); immobilization (no. 11); ammonium fixation and release (no. 12 and 13); nitrification (no. 14 and 15); leaching and capillary rise (no. 16 and 17); assimilatory nitrate reduction (no. 18 and 19); denitrification (no. 18, 20, 21 and 22); photochemical oxidation and chemical fixation (no. 23); and biological nitrogen fixation (no. 25).

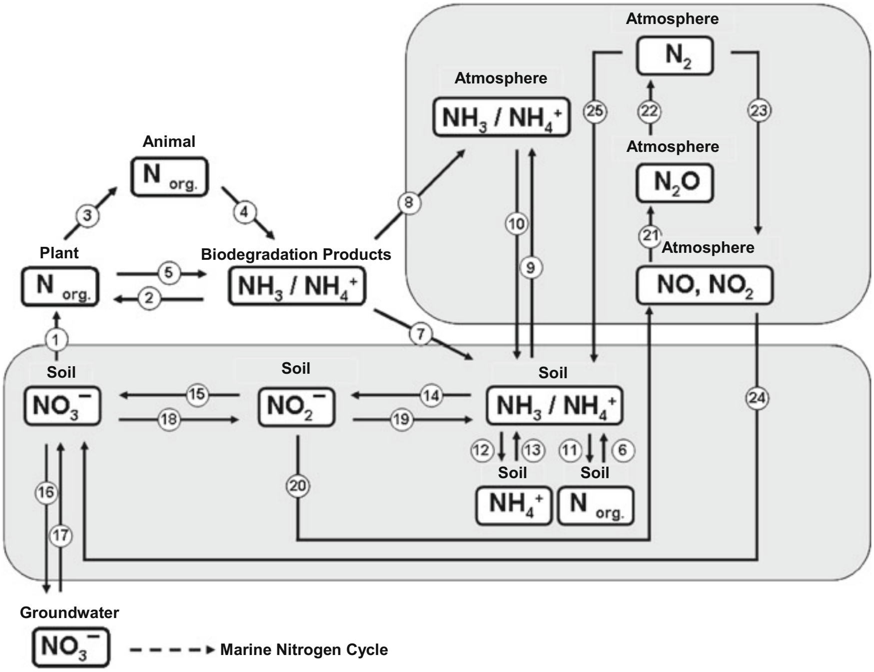

Fig. 2.2 Nitrogen cycle in the environment (*Amended, translated and adopted from* Jensen 1974; Lehninger 1977; Schilling et al. 1989; Reinhardt-Hanisch 2008)

2.2 Nitrogen Oxides

Nitrogen oxides (NO_x) consist of nitric oxide (NO), nitrogen dioxide (NO_2), and nitrous oxide (N_2O) and are formed when nitrogen (N_2) combines with oxygen (O_2). Nitrous oxide and nitric oxide can be released through nitrification and denitrification processes. Nitrification is the bacterial oxidation from nitrite to nitrate under aerobic conditions, as follows:

$$NH_4{}^+ \rightarrow NH_2OH \rightarrow N_2O(\uparrow) \rightarrow NO_2^- \rightarrow NO_3{}^-$$

Denitrification is the reduction of nitrite/nitrate to N_2 under anaerobic conditions, as follows:

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O\,(\uparrow) \rightarrow N_2$$

If the above-mentioned processes do not result in a fully conversion of the N-bonds because of suboptimal conditions, N_2O can be released.

Both nitrite and nitrate bacteria are carbon-autotrophic bacteria. Under strictly aerobic conditions, the bacteria use the released energy during nitrification for

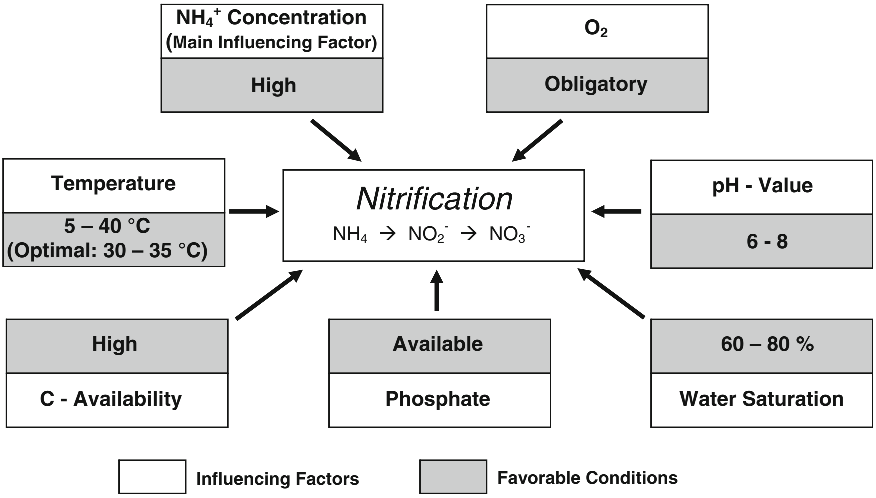

Fig. 2.3 Influencing factors of autotrophic nitrification (*Amended, translated and adopted from* Amon 1998; Reinhardt-Hanisch 2008)

assimilation of carbon dioxide (chemosynthesis) and therefore do not require organic carbon. The optimum pH is between pH 6 and 8. The influencing factors of nitrification and denitrification (Figs. 2.3 and 2.4) were illustrated by Amon (1998) and further amended by Reinhardt-Hanisch (2008). Under adverse conditions N_2O and NO can be released during nitrification (Fig. 2.5).

Under adverse conditions, such as increasing nitrate or nitrite concentrations (electron acceptors), increasing oxygen concentration, decreasing concentration of carbon, decreasing pH, decreasing temperature, and decreasing N_2O reductase activity, incomplete denitrification occurs and N_2O and NO are released (Fig. 2.5).

Nitrogen has enormous environmental effects, where humans have radically changed natural supplies of nitrates and nitrites. The main cause of the addition of nitrates and nitrites is the extensive use of fertilizers. Combustion processes can also increase the nitrate and nitrite supplies, due to the emission of nitrogen oxides that can be converted into nitrates and nitrites in the environment. Nitrates and nitrites also form during chemical production and they are used as food conservers. This causes groundwater and surface water nitrogen concentration, and nitrogen in food to increase greatly. The addition of nitrogen bonds in the environment has various effects. First, it can change the composition of species due to susceptibility of certain organisms to the consequences of nitrogen compounds. Second, mainly nitrite may cause various health effects in humans and animals. Food that is rich in nitrogen compounds can cause the oxygen transport of the blood to decrease, which can have serious consequences for cattle. High nitrogen uptake can cause problems in the thyroid gland and it can lead to vitamin A shortages. In the animal stomach and intestines, nitrates can form nitroamines, dangerously carcinogenic compounds.

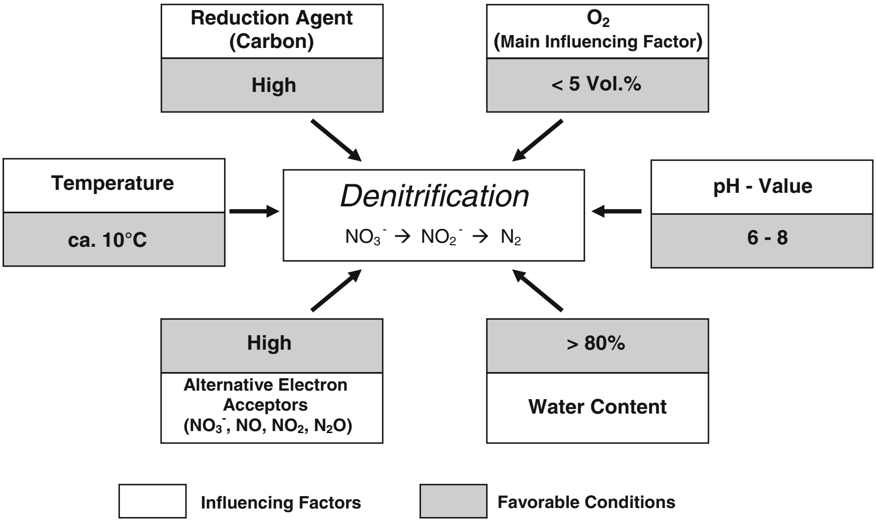

Fig. 2.4 Influencing factors of denitrification (*Amended, translated and adopted from* Amon 1998; Reinhardt-Hanisch 2008)

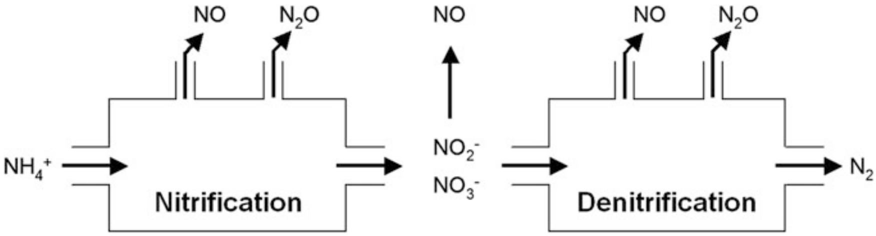

Fig. 2.5 Formation and release of N_2O and NO by nitrification and denitrification (*Amended by* Reinhardt-Hanisch 2008 *adopted from* Colbeck and Mackenzie 1994)

2.3 Ammonia

Ammonia, a colorless and highly water-soluble gas, is primarily an irritant and has been known to create health problems for animals in confinement building. Irritations of the eyes and respiratory tract are common problems from prolonged exposure to this gas. Ammonia can be detected by humans at levels as low as 5 mg/L and can reach levels of 200 mg/L in poorly ventilated buildings. Recently, the most common complaints against animal producers involve odor, and the primary component of odor is ammonia. Furthermore, very high levels of ammonia concentrations, such as 2500 ppm, may even be (rapidly) fatal. In several countries the labor inspectorate has established standards for ammonia concentrations, the so-called threshold values that should not be exceeded. In many countries, the threshold limit is 25 ppm (time weighted) for an 8 h working day for staff and for the living environment for livestock, while a higher limit is often applied for short-term exposures, e.g., 35 ppm over 15 min in England. However, sometimes the limit is stricter, e.g., 10 ppm for stockmen in Sweden. Shorter working days may allow higher threshold values, but little is known about the long-term effects of gaseous ammonia in the working environment. However, lower concentrations are always preferable to higher concentrations, both for workers and livestock. Ammonia emissions are expressed in mg NH_3 m^{-2} h^{-1}; however, ammonia emission factor is expressed in kg NH_3 per place and year where this value is 4.86 for tie-stalls and 14.57 for freestalls.

The effect of ammonia on the environment due to acidification and eutrophication can be severe. It is associated with soil acidification processes and eutrophication. Ammonia and its chemical combinations (NH_x) are important components of acidification in addition to sulfur compounds (SO_x), nitrogen oxides (NO_y), and volatile organic compounds (VOC). Ammonia is released from manure and urine, and is most noticeable during storage and decomposition. Formation of ammonia is induced by catalytic breakdown of urea as follows (Reinhardt-Hanisch 2008):

$$CO\,(NH_2)_2 + H_2\,O \xrightarrow{\text{urease}} 2NH_3 + CO_2$$

Regarding the $NH_3 \leftrightarrow NH_4^+$ equilibrium in liquid, the higher the temperature and the higher the pH value of manure, the more the NH_3 production, i.e., the higher the emission potential. Furthermore, NH_3 release is based on mass transfer from NH_3 solved in the liquid to NH_3 in the air (Fig. 2.6). The main accelerating factors are high temperature, high air velocity, high turbulence of the air stream, and large size of the emitting surface. Seethapathy et al. (2008) stated that in winter lower atmospheric NH_3 concentrations occur due to the reduced volatility, lower temperatures, and the generally higher relative humidity.

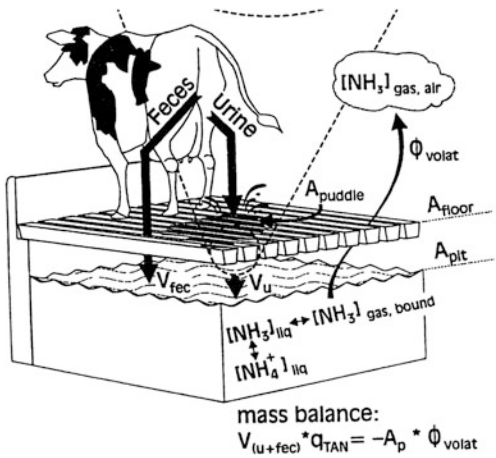

Fig. 2.6 Ammonia formation and release (Monteny 2000)

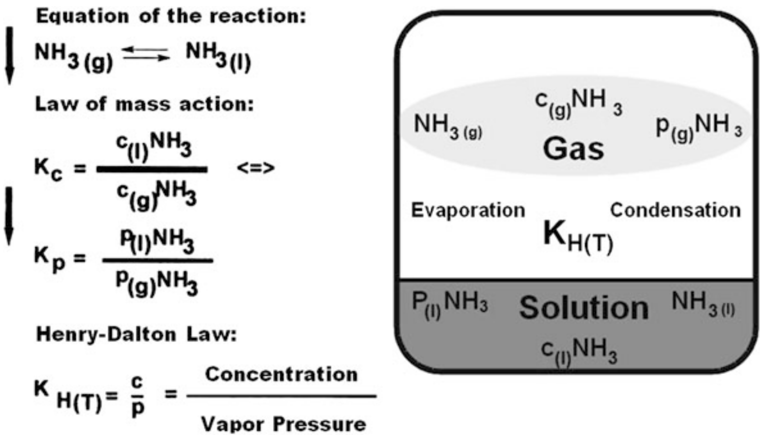

Fig. 2.7 Ammonia mass transfer from liquid to gas (*Amended, translated and adopted from* Hartung 1995)

The difference between the partial pressure of ammonia in the liquid and the partial pressure of the gaseous ammonia in the air of the boundary layer above the contact surface is the partial pressure difference. In a closed system (Fig. 2.7), a dynamic balance occurs between the amount of dissolved ammonia ($NH_{3(l)}$) and the amount of gaseous ammonia ($NH_{3(g)}$) is established. Figure 2.7 shows the ammonia mass transfer from liquid to gas, where in practice, the liquid is the manure and/or the contaminated surfaces inside the livestock building and the gas is the indoor air of the building.

Ammonia is released by excrements under special biochemical (pH value, temperature, and microorganisms) and physiological (species, age, feeding, and animal activity) conditions. NH_3 is released from different places, e.g., contaminated laying and walking areas, dirty animals, and manure stored inside the barn. NH_3 is released into indoor air in a certain concentration (g m^{-3}) which depends on the airflow, partial pressure, surface areas, manure handling system and housing system, and design (Fig. 2.8). Depending on the volumetric airflow rate, i.e., ventilation rate (m^3 h^{-1}), NH_3 is emitted in the exhaust air to outside of the barn in a certain mass flow emission rate (g h^{-1}).

Ammonia is only transported over short distances (transmission) in the atmosphere, and is deposited close to the emission source as dry deposition and is then entered into the soil. In the form of ammonium and various intermediates (Fig. 2.9), the nitrogen can be transported over long distances before it is usually deposited as wet deposition and entered into the soil (Dämmgen and Erisman 2006). An overview of the emission, dispersion, vertical and horizontal transport, and chemical reactions and deposition of ammonia and ammonium is shown in Fig. 2.9.

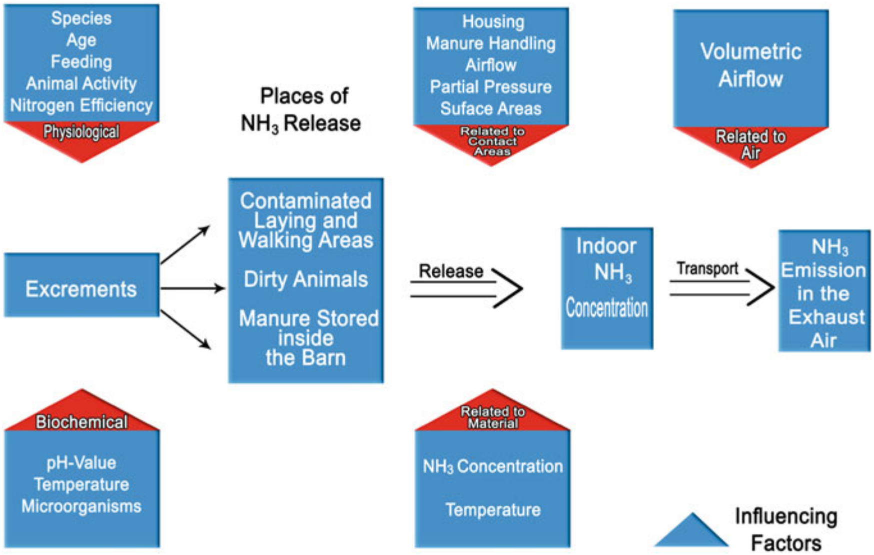

Fig. 2.8 Development, release, and spreading of ammonia inside the barn (*Amended, translated, redrawn and adopted from* Keck 1997)

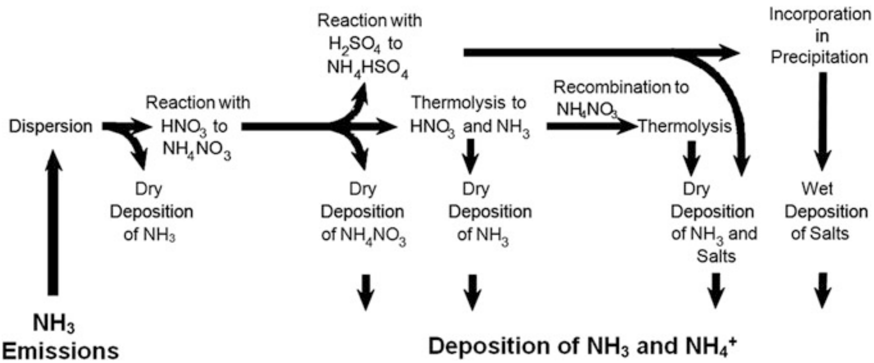

Fig. 2.9 Emission, dispersion, vertical and horizontal transport, chemical reactions, and deposition of ammonia and ammonium (*Amended, translated and adopted from* Dämmgen and Erisman 2002), where NH_3 is ammonia; HNO_3 is nitric acid; NH_4NO_3 is ammonium nitrate; NH_4HSO_4 is ammonium hydrogen sulfate; and H_2SO_4 is sulfuric acid

2.4 Hydrogen Sulfide

Hydrogen sulfide (H_2S), an aggressive trace gas, is generated from anaerobic breakdown of manure after some time in storage, where it is stored in the manure as gas bubbles (CIGR 1994). H_2S is highly toxic, poisonous, deadly, odorous (odor of rotten eggs/low concentrations contributed significantly to odor), colorless, and heavier than air, at low concentrations (<10 ppm). H_2S could cause dizziness, headaches, and irritation to the eyes and the respiratory tract. In addition to causing adverse effects to human and animal health, H_2S might be oxidized in the air forming sulfuric acid (H_2SO_4) resulting in acid rain that could cause ecological damage. H_2S concentration of 0.1 % can cause unconsciousness and death through respiratory paralysis unless artificial respiration is applied immediately. H_2S deadens the olfactory nerves (the sense of smell); therefore, if the smell of rotten eggs appeared to have disappeared, this did not indicate that the area was not still contaminated with this highly poisonous gas (CIGR 1984, 1994, 1999). Manure tank agitation is then followed by H_2S emission, and consequently, possible death occurs. Therefore, after manure tank agitation the area must be evacuated and the team members must leave the area.

2.5 Methane

There are two sources of methane production: (1) anaerobic decomposition of manure, and (2) enteric fermentation of fodder by anaerobic bacteria in of rumen where CH_4 is released by eructation. A cow's rumen produces 37 L of CH_4 per kg dry matter of feed intake. A cow digests 17 kg dry matter per day which release 0.5 m^3 CH_4 day^{-1} (CIGR 1994). Concentrations between 5000 to 15,000 ppm are explosive; several explosions have occurred due to ignition of methane-rich air in poorly ventilated livestock buildings. Figure 2.10 shows the anaerobic decomposition of organic matter (e.g., manure).

2.6 Carbon Dioxide

The CIGR report (1994) stated that the total CO_2 production is a sum of the following three components: animal respiration, rapid breakdown of urea in urine, and anaerobic decomposition of dry matter in the slurry. Over 96 % of the total CO_2

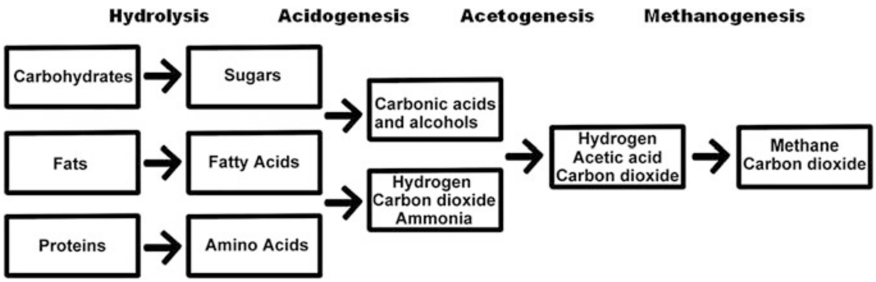

Fig. 2.10 Anaerobic decomposition of organic matter

production is from animals' respiration. Under normal conditions in livestock buildings CO_2 concentration is between 500 and 3000 ppm. There is no health risk for animals and humans at this level. The threshold limit is set to 3000 ppm.

2.7 Carbon Monoxide

Carbon monoxide is produced by incomplete combustion of fuels inside livestock buildings. For instance, when tractors operate some machines to accomplish an operation-like feed distribution and manure management. The threshold limit for CO is 10 ppm. Carbon monoxide can cause death in adult pigs at concentrations around 4000 ppm and in broilers at 2000 ppm (CIGR 1994).

2.8 Odors

The aerobic and anaerobic breakdown of organic substances (manure, feed left-overs) results in over 300 odorous components, whose mixture gives the smell impression in addition to the smells of animals and feed. The compounds of odors are produced from manure inside livestock buildings. Different gases are produced as livestock manure is degraded by microorganisms as previously maintained. Under aerobic conditions, CO_2 is the principal gas produced. Under anaerobic conditions, the primary gases are CH_4 and CO_2. About 60–70 % of the gas generated in an anaerobic lagoon is methane, and about 30 % is carbon dioxide. However, trace amounts of more than 40 other compounds had been identified in the air exposed to degrading animal manure. Some of these included mercaptans (this family of compounds included the odor generated by skunks), aromatics, sulfides, and various esters, carbonyls, and amines (CIGR 1999). Furthermore, odorous compounds in swine manure were ranged between 30 compounds that were the likely contributors of the odor nuisance and 168 compounds which had been identified by previous researches. The gases of most interest and concern in manure management are CH_4, CO_2, NH_3, and H_2S.

Manure handling and storage facilities can be a source of malodors in dairy operations. Offensive odor is partly the result of incomplete anaerobic decomposition of stored manure. Zhu and Jacobson (1999) found that the most important genera for odor production were *Eubacterium* and *Clostridium*. Studies have identified 35–73 volatile compounds in dairy manure (Filipy et al. 2006; Rabaud et al. 2003; Sunesson et al. 2001) with the most important odorous manure components found to be the volatile fatty acids (VFA), *p*-cresol, indole, skatole, along with hydrogen sulfide (H_2S) and ammonia (NH_3) by virtue of either their high concentrations or low odor thresholds (O'Neil and Phillips 1992). Wright et al. (2004) identified *p*-cresol, *p*-ethyl phenol, and isovaleric acid as the most persistent and biggest contributors to odor downwind of the source. Miller and Varel (2001) noted that ethanol, acetate, propionate, butyrate, lactate, and hydrogen were the major fermentation products of stored cattle manure. Due to far-reaching environmental and socioeconomic concerns, efforts to reduce odor, NH_3, H_2S, and greenhouse gas emissions from animal agriculture are essential (Wheeler et al. 2011b, c).

2.9 Dust and Aerosols

Aerosols can be defined as solid or liquid particles which remain suspended in the air for longer periods because of their minute dimensions of between 10^{-4} and 10^2 μm. The aerosols can combine chemically with gases emitted into the air and these new compounds are inhaled by living organisms. Airborne particulates can include both solid and liquid particles. Viable particles are living microorganisms or any solid or liquid particles which have living microorganisms associated with them. Dusts can be defined as dispersed particles of solid matter in gases which arise during mechanical processes or have been stirred up. Dust may cover a wide range of sizes and shapes, and can be airborne or settled (Hartung and Saleh 2007).

Generally, dust can be considered as one of the most important sources for air contamination in livestock buildings, where it may be generated from forages (ingredients, form, water, and fat contents), fur of animals (species, genotype, age, and number), bedding materials as litter (type, amount, and water content), dried manure, feathers/fur, dander (hair and skin cells), molds, pollen, grains, grain mites, insect parts, mineral ash, gram-negative bacteria, endotoxin, microbial proteases, ammonia adsorbed particles, infectious agents, and building materials (Robert 2001).

Dust formation on surfaces occurs by the effect of several forces, e.g., drying, chewing crushing cleaning, management (bedding, feeding, manure handling, etc.), and sedimentation. Further forces as animal activity, human activity, and airflow rates generate airborne dust in livestock building. The influencing factors are animal weight, animal density, housing system, ventilation system, daytime, and season (Aarnink and Ellen 2007). Affected by the ventilation, dust is emitted outside of the livestock building and this forms the dust emissions. Dust carries some pathogens, bacteria, and microbes. Additionally, some gases as NH_3 are adsorbed on the surface of the particulate matter (PM) of the dust. Figure 2.11 shows dust sources with attributes, processes, and forces that influence dust formation and dust emission from animal houses.

Airborne particulates can include both solid and liquid particles. Viable particles are living microorganisms or any solid or liquid particles which have living microorganisms associated with them. Dusts are dispersed particles of solid matter in gases which arise during mechanical processes or have been stirred up. Dust may cover a wide range of sizes and can be airborne or settled. Chemical properties of dust particles must be analyzed according to their chemical compositions which are divided into inorganic and organic (viable and nonviable) components.

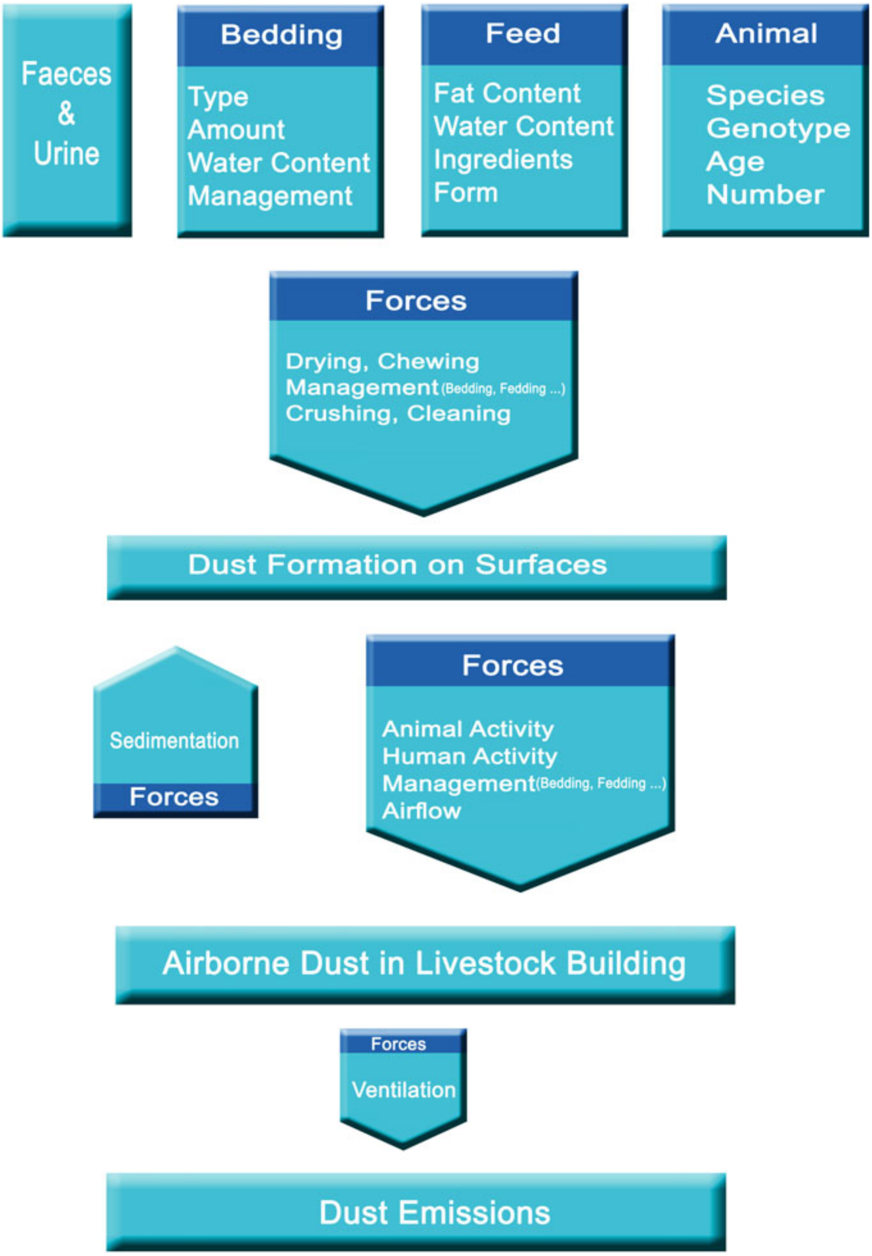

Fig. 2.11 Development, release, and spreading of dust inside the barn (*Amended, translated, redrawn and adopted from* Aarnink and Ellen 2007)

The chemical composition of dust from different sources shows that the airborne and the settled dust have nearly the same concentrations of Dry Matter (DM), ash, N, P, K, Cl, and Na. The dust particles are subjected to a variety of physical processes according to their density, size, and shape (Fig. 2.12). The most important physical effects said are sedimentation, agglomeration (particles collide due to the turbulence and adhere to each other forming agglomerates), aerodynamics, adsorption, and resuspension. The dust is characterized by sedimentation experimentation and microscopic analysis.

The dust contained in the exhaust emissions should not exceed a 20 mg/m^3 mass concentration or 0.20 kg/h of emission mass flow according to the maximum acceptable concentration (MAC) list (DFG 2006). The respirable dust (<5 μm) may

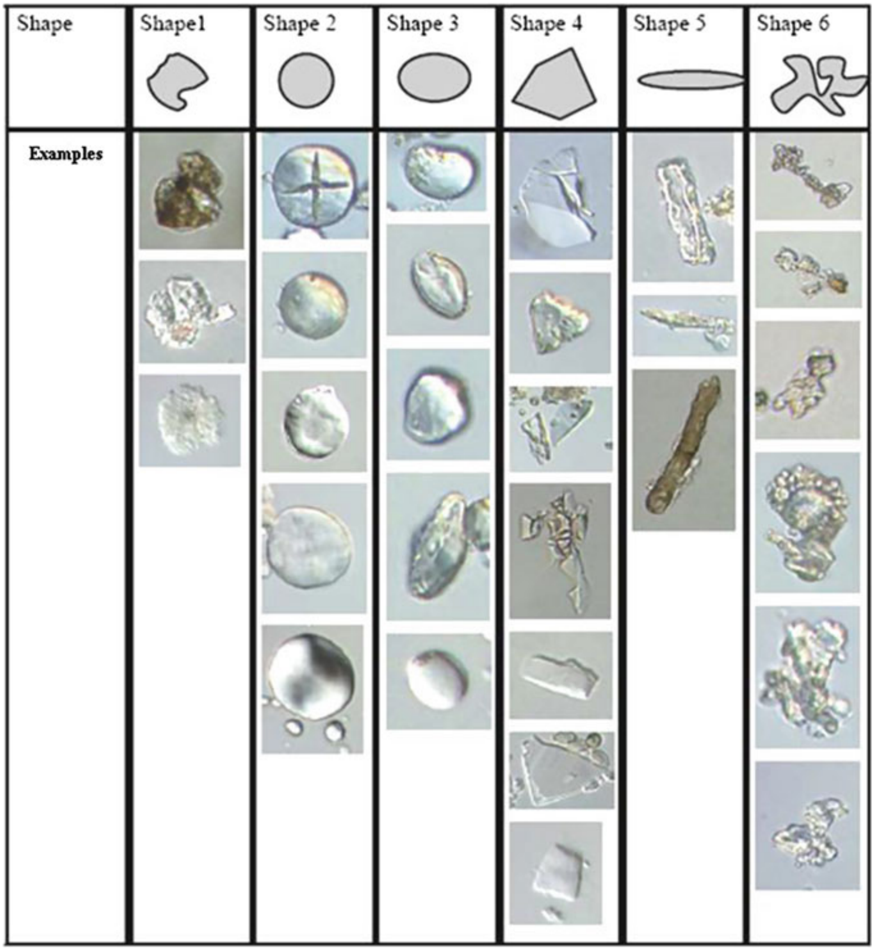

Fig. 2.12 Classification of particle structure after shapes (*adopted from* Mostafa 2008 *after* Nannen 2005)

not exceed a concentration of 4 mg/m^3 and for the alveolar dust (<1.1 μm) the limit value is 1.5 mg/m^3 (DFG 2006). Pedersen et al. (2000) showed that the limit recommendations for humans under Danish conditions are 2.4 mg/m^3 of total dust, 0.23 mg/m^3 of respirable dust with a total of 800 EU/m^3 (EU: Endotoxin Unit), and 7 ppm of ammonia. Endotoxins are toxins, poisonous substances produced by living cells or organisms, associated with certain bacteria.

An "endotoxin" is a toxin that, unlike an "exotoxin," is not secreted in soluble form by live bacteria, but is a structural component in the bacteria which is released mainly when bacteria are lysed. Lysis refers to the breaking down of a cell, often by viral, enzymatic, or osmotic mechanisms that compromise its integrity. Together with the dust particles microorganisms can be transported into the respiratory system causing infections. Endotoxins can trigger allergic reactions in the airways of susceptible humans even in low concentrations. PM carries odor, NH_3, endotoxin, bacteria, and fungi.

The hazard caused by aerosols, suspension of fine solid particles, or liquid droplets in a gas depends on their chemical composition as well as where they deposit within human respiratory system. Aerosols are solid or liquid particles which remain suspended in the air for longer periods because of their minute dimensions of between 10^{-4} and approximately 10^2 μm. The aerosols can combine chemically with gases emitted into the air and these new compounds are inhaled by living organisms or can settle on them. The mixture "air with dust particles" is considered as Newtonian fluid, where the flow of this mixture is treated as "single phase flow" in fluid mechanics. The Brownian motion rules the suspended aerosol particles in air, where the aerosols undergo irregular random motion due to bombardment by surrounding fluid molecules.

Pedersen et al. (2000) classified the dust into the following:

1. Total dust: the fraction containing particles below 20 μm in aerodynamic diameter collected by the use of 38 mm filter cassettes with 5 mm downward inlets.
2. Respirable dust: the fraction collected using a cyclone pre-separator (50 % cut-off effectiveness value of 5 μm).
3. Inhalable dust: the diameter of these dust particles is slightly larger than 20 μm. The inhalable concentration will be about 25 % higher than the "total dust" concentration, but it depends on the particle size distribution.

The airborne inhalable and respirable fractions are overall higher in pig and poultry buildings than in cattle houses. Dust concentrations and emissions are affected significantly by several things such as housing type, the season of year, and day/night time. The inhalable and respirable dust concentrations in the poultry buildings are 3.60 and 0.45 mg/m^3, respectively. The dust emission rates on a 500 kg AU are between 2118 and 248 mg/h for inhalable and respirable, respectively (Takai et al. 1998).

The particulate matters (PM) are categorized as PM_{10}, PM_5, $PM_{2.5,}$ and PM_1. PM_{10} is particulate matter smaller than 10 μm aerodynamic equivalent diameter. Similarly, PM_5, $PM_{2.5}$, and PM_1 are particulate matters smaller than 5, 2.5, and

1 μm aerodynamic equivalent diameter, respectively. On the other hand, the total suspended particles (TSP) are tiny particles of aerosols or particulates at high concentrations in the air and could raise air pollution concerns. TSPs range in size from 0.001 to 500 μm.

There are several parameters that affect the dust formation and emission. The housing system and design affects indoor dust concentration and emission rate. For instance, the air in floor housing systems for laying hens may be more polluted than in traditional cage systems. The year seasons have significant effect on dust concentrations and emission rates where several studies showed that the dust concentrations are the highest in summer compared to the other seasons. On the other hand, the mean inhalable dust emission rates in winter and summer were estimated to be 1590 and 2388 mg/h for 500 kg live weight basis, respectively (Takai et al. 1998). The diurnal change and animal activity have significant effect on indoor dust concentration and emission rate, where Hessel and Van den Weghe (2007) found that the dust concentrations are twice as high during the light period (5542 $\mu g/m^3$) compared to the dark period (2598 $\mu g/m^3$). Indoor dust concentration is directly proportional to animal activity which is higher during lights-on. The ventilation rate greatly affects the indoor dust concentration and emission rate, where there is a high variation in the pattern of spatial dust distribution in mechanically ventilated pig buildings. Thus, the ventilation systems have direct effects on the spatial dust concentration, whereas the increase of the ventilation rate will not necessarily reduce the overall dust level effectively because the dust production rate will increase with increasing ventilation. The dust concentration can be measured using the following methods (Gustafsson 1997; Lim et al. 2003; Mölter and Schmidt 2007):

1. Gravimetric measurements of the amount of total dust (mg/m^3) with 37 mm diameter millipore filters at a flow rate of 1.9 L/min.
2. Counting the number of different sized particles with a Rion optical particle counter.
3. Weighing the settled dust on 0.230 m^2 settling plates.
4. Tapered element oscillating microbalance (TEOM).
5. Optical aerosol spectrometers (OAS).

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