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Exhaust air treatment systems for the mitigation of dust, ammonia and odour from poultry housing

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Johanna Carolina Luise Strohmaier

aus

Herrenberg

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Referent:	Prof. Dr. Wolfgang Büscher
Korreferent:	PD Dr. Bernd Diekmann
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Kurzfassung

Abluftreinigung gewinnt in der Geflügelhaltung mit steigender Anzahl gehaltener Tiere pro Betrieb zunehmend an Bedeutung. Eine Adaption der in der Schweinehaltung bereits erfolgreich eingesetzten Systeme funktioniert aufgrund anderer Ausgangsparameter in der Geflügelhaltung nur bedingt, weshalb gezielte Anpassungen vorgenommen werden müssen. In der vorliegenden Dissertation wurden verschiedene Filtertechnologien in unterschiedlichen Haltungssystemen hinsichtlich ihrer Eignung untersucht.

In der ersten Studie wurde ein Trockenabscheider zur Staubminderung untersucht. Vergleichende Untersuchungen unter Laborbedingungen wurden im Windkanal sowie in einem Legehennenstall durchgeführt. Im Windkanal wurden je nach Partikelgrößenfraktion Abscheidegrade zwischen 60 und 79 % gemessen. Im Stall war die Minderungsleistung niedriger, was sich unter anderem dadurch erklären lässt, dass die Abluft dort erhebliche Turbulenzen aufweist.

Die zweite Studie befasst sich mit einer zweistufigen Abluftreinigungsanlage an einem Hähnchenmaststall. Die erste Stufe bestand aus einem Chemo-Wäscher, die zweite aus einem Biofilter. Der Biofilter war in zwei Hälften unterteilt, wovon eine mit einer Wurzelholzschüttung und die zweite mit wabenförmigen Papierpads bestückt war. Neben der Minderungsleistung von Ammoniak aus der Abluft lag der Fokus insbesondere auf der Geruchsminderungswirkung des Biofilters und der Eignung der beiden eingesetzten Filtermaterialien. Bei beiden Filterhälften konnte die Geruchsbelastung deutlich gemindert werden, die Papierpads waren jedoch mit 51 % Minderung effektiver als die Wurzelholzschüttung mit 38 %. Letztere zeigte sich auch als anfällig für Pilzwachstum, was sich auf die Langzeitstabilität und Sekundäremissionen negativ auswirken könnte.

Die dritte Studie in Form eines Tagungsbeitrages veranschaulicht eine Untersuchung einer dreistufigen Abluftreinigungsreinigungsanlage an einem Legehennenstall. Der Trockenabscheider aus Studie 1 bildete die erste Stufe, gefolgt von einem Chemo-Wäscher und einem Biofilter. Die in Studie 2 eingesetzten Papierpads wurden auch hier als Füllmaterial im Biofilter verwendet. Hier konnte eine Geruchsminderung von 68,4 % erreicht werden. Auch die Staubabscheidung konnte im mehrstufigen System gegenüber dem einstufigen deutlich gesteigert werden.

Abstract

Exhaust air treatment is becoming increasingly important in poultry husbandry with a rising number of animals kept per barn. An adaptation of the systems that already have been successfully used in pig husbandry only works out to a limited extent due to other initial parameters in poultry husbandry, which is why specific adjustments need to be carried out. In the present dissertation, different filter components in different housing systems were examined regarding their suitability.

In the first study a dry filter for dust reduction is tested. Comparative investigations under laboratory conditions in a wind tunnel and in a laying hen barn are carried out. Depending on the particle size fraction, separation efficiencies between 60 and 79% are measured in the wind tunnel. In the barn, the reduction efficiency is lower, which can, inter alia, be explained by the fact that the exhaust air is exposed to considerable turbulences there.

The second study deals with a two-stage exhaust air treatment system at a broiler fattening facility. The first stage consists of a chemo-scrubber, the second stage of a biofilter. The biofilter is divided into two halves: one is equipped with root wood, the other one with honeycombed paper pads. Besides the reduction of ammonia from the exhaust air, the focus is especially on the odour reduction efficiency of the biofilter and the suitability of the two filter materials used. Both filter halves are able to reduce the odour load, but the honeycombed paper pads with a reduction of 51% are more effective than the root wood with 38%. The latter also proves to be susceptible to fungal growth, which could have a negative effect on long-term stability and secondary emissions.

The third study in the form of a conference paper illustrates an investigation of a three-stage exhaust air treatment system for cleaning the exhaust air of a laying hen house. The dry filter already used in study 1 forms the first stage, followed by a chemo-scrubber and a biofilter. The honeycombed paper pads used in study 2 are also used as filling material for this biofilter. An odour reduction of 68.4 % is achieved here. The dust reduction performance in the multi-stage system is also significantly higher compared to the single-stage system.

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PM	particulate matter
ppm	parts per million
TSP	total suspended particulate matter
Gg	Gigagram
µm	micrometer (one thousandth of one millimeter)
NH_3	ammonia
N_2O	nitrous oxide
OU_E	European odour units

1 General introduction

1.1 Main emission categories in poultry housing

Poultry production in Europe is steadily increasing with forecasts predicting a further growth for the future due to the attractive pricing of poultry meat for consumers (European Commission 2019). The rising numbers of animals housed lead to a subsequent increase in emissions affecting both the direct environment (for example local residents or fragile natural biotopes) as well as the global environment.

In this thesis emissions are defined as the air pollutants released at the barn. These air pollutants differ in their composition and quantity depending on multiple factors including number and kind of animals kept as well as constructional and ventilation particularities (Arends 2006). Heederik et al. (2007) point out the importance of emission reduction caused by the livestock industry for the sake of the environment as well as improved working conditions for the staff. As a consequence, many countries are continuously strengthening their regulations on both emission limits and the requirements to operate a livestock facility.

In an investigation conducted by Tymczyna et al. (2014) several inorganic compounds were determined in the exhaust air of a layer house, such as sulphates, nitrites, nitrates, chlorides and ammonia. Furthermore, poultry housing exhaust air contains additional pollutants, including bioaerosols and dust (Landesamt für Umwelt, Landwirtschaft und Geologie Freistaat Sachsen 2017). In poultry husbandry the current focus is on three main emission categories: dust, ammonia and odour.

1.1.1 Dust

One of the main emission components from poultry housing, especially for laying hens, is dust. Dust may also be called particulate matter (PM) and includes liquid and solid particles dispersed in the air, for example due to turbulences (GefStoffV 2017; The International VERA Secretariat 2018). PM can be subdivided in different sub-fractions, for example in inhalable PM (the total of inhalable airborne particles), PM_{10}, which passes a 10µm filter with a 50% efficiency cut-off or $PM_{2.5}$, which passes a 2.5µm filter with a 50% efficiency cut-off (The International VERA Secretariat 2018).

15% of the European PM_{10} emissions originate from agriculture (Tista et al. 2019). Public scepticism is growing, as several health issues are linked to fine PM in particular: dust originating from animal housing is a carrier for lots of different types of bacteria and fungi (Martin et al. 1996), which makes it a potential disease vector. Especially these organic parts of the particulate matter are identified as problematic, as they seem to have an impact on respiratory health of residents living close to livestock facilities (Rooij et al. 2019).

Compared to pigs, broiler cause more PM emissions per kg body weight, mainly due to the use of litter (Cambra-López et al. 2010). However, differences in dust emissions can also be observed across varying poultry housing systems: a comparison of aviary housing and a cage system by Mostafa (2008) showed that aviary systems cause more total suspended PM (TSP) emission than cage systems, which was confirmed by Shepherd et al. (2015). Aviary housing systems cause 0.065 kg TSP per year and animal place (Verein Deutscher Ingenieure 2012). This adds up to 1.3 t of TSP per year for an average barn with 20,000 laying hens. Hence, environmental protection and animal welfare are often negatively correlated, as the findings of Mostafa (2008) and Sheperd et al. (2015) illustrate. Moreover, dust emissions can have an impact on other emissions: there is a crosslink between PM_{10} and ammonia emissions, especially during spring (Tista et al. 2019).

PM can be measured using a variety of methods. One commonly used method is the gravimetric measurement. The VDI-Guideline 2463 (Verein Deutscher Ingenieure 1999) specifies the correct excecution of measurements with such systems. In addition, optical systems, such as light-scattering devices, are used in measuring PM. A disadvantage of gravimetric measuring methods is that there is no continuous recording of measured values, but only a total value to be determined for the whole test period. On the other hand, these systems are generally comparatively simple in their construction and thus less susceptible to failure. Light-scattering devices should not be used in environments with high relative humidity, as fine water drops could be counted as PM (The International VERA Secretariat 2018). Suitability of different devices and methods may differ from each other a lot depending on the circumstances (Winkel et al. 2015).

Most of the available PM sampling devices, especially optical systems, are originally designed for measuring PM in environments with significantly lower PM concentrations than those common in livestock housing, for example for measuring PM caused by traffic in city areas. Their special device design can lead to problems with correct detection of the amount of PM originating from poultry houses, which is discussed in more detail in chapter 2.1.

1.1.2 Ammonia

Ammonia (NH_3) is subject of the Gothenburg Protocol (UNECE 1999). Germany is one of Europe's main contributors to NH_3 emissions (Tista et al. 2019). 95% of Germany's NH_3 emissions can be traced back to agriculture (Umweltbundesamt 2019). In 2016, NH_3 from German agriculture summed up to a total of 629.2 Gg (Haenel et al. 2018) with poultry causing 30.3 Gg or 4.8% of it: 30.7% of these NH_3 emissions originated from housing, 45.8% from application and 23.5% from storage (Haenel et al. 2018). In comparison, the authors state that pigs caused 93.4 Gg and cattle (dairy and others) caused 133.1 Gg of the total, which illustrates the proportions of the different species contributing to the total NH_3 emissions originating from German agriculture.

The noticeable effects of NH_3 emissions are not mainly seen in the direct surroundings of its source due to chemical reactions with other reactants: the substances built in these processes are then carried far by wind (BayStMLF and BayStMLU 2003). 50% of N-oversupply of semi-natural soils is caused by NH_3 deposition (BayStMLF and BayStMLU 2003).

In addition, NH_3 is indirectly contributing to climate change, as about 2% of NH_3 emissions are converted to nitrous oxide (N_2O) (BayStMLF and BayStMLU 2003).

There are regulations not only for emissions, but also for indoor concentrations of ammonia. In Germany, these are regulated in the so-called TierSchNutztV regulation (TierSchNutztV 2017), where a maximum of 20 cm^3 1 m^{-3} ambient air is set in §18 III 1. for broilers. §13 IV TierSchNutztV stipulates that for laying hens the concentration of ammonia in the animal area should not exceed 10 cm^3 1 m^{-3} ambient air and must not exceed 20 cm^3 1 m^{-3} ambient air permanently.

Ammonia emissions originating from livestock systems are commonly measured using photoacoustic spectroscopy because it allows for continuous long-term measurements, as for example used in studies by Alberdi et al. (2016) and Schmithausen et al. (2018).

1.1.3 Odour

Odour is a combination of many different individual components, which makes it difficult to mitigate, as their biological, chemical and physical properties differ from each other (The International VERA Secretariat 2018). Removing individual odorous components often only changes the odour quality, but not the odour quantity. Odorous emissions can have a negative impact on the quality of life of local residents, which in turn might lower acceptance of nearby agricultural facilities (Radon et al. 2004).

In Germany, the assessment of acceptable odour nuisance depends on the place of immission. Immissions are defined as the air pollutants at the place where they finally take effect: air pollutants are emitted at the stable, spread by transmission processes and finally recognised as immissions at another location, for example in a residential area (Arends 2006). In the directive on determination and assessment of odour immissions, the so-called "GIRL-directive" (Landesamt für Natur, Umwelt und Verbraucherschutz NRW 2008), an exceedance frequency of 6.7% per 1 European odour unit (OU_E) m^{-3} is set as permissible for residential areas. Other limits apply in areas where odours originating from animal husbandry are more likely to occur: the limit for village areas is set at 10% and for outdoor areas at 16.7% per 1 OU_E m^{-3}, respectively.

Precise odour emission measurement is complicated compared to measurement of other emissions, as it usually cannot take place onsite, but has to be done under laboratory conditions. Gas samples are taken at the source in accordance with a strict measurement protocol and sent straight to a test laboratory for evaluation, which is also subject to strict criteria. Gas sampling bags should consist of polyethylene terephthalate, polyvinyl fluoride or polytetrafluoroethylene bags to avoid falsifications (The International VERA Secretariat 2018). In the laboratory, a set of trained test personnel is needed for the examination of the samples. Standard method for the determination of odorous emissions is DIN EN 13725:2003-07.

1.2 Mitigation strategies

Two strategies for mitigating emissions exist: the prevention of emission formation and the treatment of exhaust air. Both can be combined for achieving better overall results.

1.2.1 Emission prevention

The prevention of emissions should always be a preferred strategy in livestock production. Useful strategies include, inter alia, feeding, housing and manure handling (Ubeda et al. 2013).

Manure handling can help to prevent emissions of both ammonia and odour (Hayes et al. 2006). Possible adaptions at poultry housing facilities can be the shortening of manure removal intervals or manure belt ventilation (BayStMLF and BayStMLU 2003).

An investigation undertaken by (Bobrutzki et al. 2012) showed a decrease of NH_3-N of 38% from broilers that have been provided with additive-enriched water. Yet, water and feed intake decreased about 4.7%, and 4.0%, respectively. This example shows how important it is to focus on the whole process, as each measure usually influences several factors positively or negatively. Aside from the use of additives in the water, the drinking system also has an impact on ammonia emissions: by the use of nipple drinkers instead of round drinkers, ammonia development can be reduced (BayStMLF and BayStMLU 2003).

To further prevent ammonia emissions, the nitrogen intake via feed should be adjusted to the actual need as far as possible. Crude protein content may be reduced in poultry feed, when it is concurrently being enriched with amino acids (BayStMLF and BayStMLU 2003).

Systems for manure drying may also be used for the mitigation of dust emissions in layer houses, as Winkel et al. (2012) showed in an investigation, where inhalable dust, PM_{10} and $PM_{2.5}$ were significantly lowered.

1.2.2 Exhaust air treatment

Lower air quality caused even by well-managed broiler facilities is a frequently documented problem (Ullman et al. 2004). When the full potential of all prevention strategies is exploited, exhaust air treatment systems can be used in addition to comply with emission limitations. Different systems are available, each with a different focus. Finding the most suitable exhaust air treatment system therefore depends on the facility's size, its surroundings and the type of emissions to be reduced (Ullman et al. 2004; Strogies and Gniffke 2019).

Biofilters, scrubbers and multi-stage systems (which combine different types of exhaust air treatment systems) are most commonly used at livestock facilities (Association for Technology and Structures in Agriculture 2008):

Chemo scrubbers work with acid-enriched washing water (diluted acid on a pH level between 3 and 5). This scrubber type is mainly used for the mitigation of ammonia (Arends et al. 2018). Due to the very low pH of the washing water caused by the acid, microbial metabolism (as found for example in biofilters) is inhibited (Association for Technology and Structures in Agriculture 2008).

Biofilters are mainly used for odour abatement. They can be filled with different materials, such as compost or root wood. The use of wood chips as filling material for biofilters offers several advantages: they are low-cost, while pressure drop is low and airflow is quite even (Phillips et al. 1995). Keeping the filling at an appropriate humidity is mandatory for proper function, as well as sufficient residence time of the exhaust air inside the biofilter and a temperature optimum (about 10 to 35 °C) for the microbiology (Association for Technology and Structures in Agriculture 2008).

Ideal conditions for microbes inside the biofilter are essential for proper results. Not only temperatures must be kept at an optimum level (Association for Technology and Structures in Agriculture 2008), but also moisture, pH and the availability of nutrients in the exhaust air streaming into the filter are of high importance (Feddes and Clark 2004).

In some countries guidelines on the function of exhaust air purification systems have been developed, such as the so-called "Cloppenburg guidelines" (Hahne et al. 2002) in Germany. Based on these guidelines, a test frame was developed by the German Agricultural Society (DLG) (Deutsche Landwirtschafts-Gesellschaft 2009). The DLG-test frame defines threshold values for the mitigation efficiency of exhaust air treatment systems. Mitigation efficiency for each ammonia, TSP, PM_{10} and $PM_{2.5}$ must not fall below 70%. A maximum of 300 OU_E m^{-3} is allowed and no specific odour of the raw gas is allowed in clean gas samples. These and some other additional parameters need to be met in order to get a certification for the specific exhaust air treatment system. A well-functioning system is key to achieve the criteria. For better international comparability, the multilateral cooperation Verification of Environmental Technologies for Agricultural Production (VERA) was created in 2008, which created the VERA test protocol that can be used for investigating performance and stability of exhaust air treatment systems across different countries (The International VERA Secretariat 2018).

Proper exhaust air treatment requires a multifactorial approach. The systems mentioned above are not always sufficiently efficient in regards to reducing dust, ammonia and odour (van der Heyden et al. 2015). In this context, especially dust may be challenging for efficient and stable operation of an exhaust air treatment system. Higher dust loads, which are common for poultry compared to other productive livestock (cf. chapter 1.1.1), have an influence on pressure drop due to dust accumulation inside filters (Melse and Hol 2017). Overcoming higher pressure differences leads to increased energy consumption and consequently to increased operating costs. Therefore, the aim of the present dissertation is to improve existing systems and adapt them for poultry housing.

1.3 Study design

Three main research questions are defined for the present dissertation in the light of the issues mentioned above:

Evaluation of

1. the efficiency of a dry filter for the mitigation of a layer houses' exhaust air dust load;
2. a multi-stage system for exhaust air treatment at a layer house;
3. suitability of different filter systems and materials for different housing systems.

A brief overview of the studies carried out in the context of the present dissertation is described below:

Study 1 – *Evaluation of a dry filter for dust removal under laboratory conditions in comparison to practical use at a laying hen barn* – published

Study 1 was published in *Environmental Science and Pollution Research* (Springer-Verlag GmbH Germany).

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DOI: 10.1007/s11356-018-2981-3

Main topic of study 1 is the evaluation of a dry filter for the mitigation of dust. Research was conducted under laboratory conditions as well as on farm level.

Study 2 – *Suitability of different filling materials for a biofilter at a broiler fattening facility in terms of ammonia and odour reduction* – published

Study 2 was published in the Special Issue *Livestock Odor and Air Quality* of *Atmosphere* (MDPI, Basel, Switzerland).

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In study 2 a two-stage exhaust air treatment system is tested. Stage 1 is a chemo-scrubber and stage 2 a biofilter equipped with root wood and honeycombed paper pad layers (half/half). The study is designed for a direct comparison of two filter materials at once.

Study 3 – *Combined exhaust air treatment at a laying hen facility for mitigation of dust, ammonia and odour* – published

Study 3 was published as a conference paper in the conference proceedings of the 3rd International Symposium on Emission of Gas and Dust from Livestock (EmiLi, May 21-24, 2017; Saint-Malo, France).

Study 3 shows the results of an investigation carried out at a laying hen barn, where a three-stage exhaust air treatment system is installed. Mitigation efficiency is measured for dust, ammonia and odour.

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2 Main research

2.1 Evaluation of a dry filter for dust removal under laboratory conditions in comparison to practical use at a laying hen barn

Carolina Strohmaier[a*], Alexander J. Schmithausen[a], Manuel S. Krommweh[a], Bernd Diekmann[b], Wolfgang Büscher[a]

[a]Institute of Agricultural Engineering, University of Bonn, Nußallee 5, 53115 Bonn, Germany

[b]Institute of Physics, University of Bonn, Nußallee 12, 53115 Bonn, Germany

*corresponding author. Email: strohmaier@uni-bonn.de

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Abstract

The high amount of particulate matter from poultry houses in the exhaust air, especially at different types of laying hen barns, are the main challenge farmers are faced with concerning emissions. As a possibility for the mitigation of particulate matter in the outgoing air, a dry filter based on the principle of centrifugal force was investigated under laboratory and field conditions. Aerosol spectrometers were used for continuous measurements in raw and clean gas. Field experiments took place under summer and winter conditions, so that filter efficiency under different climate conditions could be compared and measurement values at the barn were continuously collected over 24 h periods. Data collected under laboratory conditions showed a high efficiency of the dry filter, whereas results of the field experiments differed in each size fraction of the particulate matter. These differences may be explained by the fact that under laboratory conditions better circumstances for correct measuring were created, e.g. laminar flow of the air.

Keywords: particulate matter; poultry housing; mitigation strategies; dust

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Introduction

As shown in earlier studies, aviary housing systems cause more dust emissions than cage or battery systems (Costa et al. 2012; Nimmermark et al. 2009; Le Bouquin et al., 2013; Sheperd et al., 2015). In many countries, as for example all EU member states, the housing of laying hens in battery cage systems is prohibited (European Commission 1999). Therefore many farmers have to deal with increasing emissions, especially after changing from cage to aviary housing, which had to be done by the year 2010.

The amount of dust in different farming types in Europe was investigated by Radon et al. (2002). Their results showed highest concentrations of particulate matter (PM) in poultry housing. They also showed that the highest concentration of endotoxins in the particulate matter was found at poultry barns. Being exposed to high concentrations of PM in the ambient air may lead to several pulmonary diseases, as for example asthma or bronchitis (Rylander 1986). Indeed respiratory diseases are common amongst farm workers (Schenker 2002). Takai et al. (1998) discovered that the average concentration of dust in laying hen barns is much higher during daytime in comparison to the night. This observation was confirmed by Mostafa (2008) and Zheng et al. (2012), showing that increasing dust concentrations followed rising animal activity and *vice versa*. Particle sizes in the exhaust air of laying hen barns differ in dependency of their origin, as Cambra-López et al. (2011) showed: particles from mineral sources, as for example feed components, are mostly smaller than those coming from organic sources such as feathers. Mostafa (2008) brought out the correlation of dust concentration with temperature and relative humidity (RH) of the ambient air. Huneau-Salaün et al. (2011) underline the negative correlation of dust concentration and relative humidity, while indoor air temperature is positively correlated with dust concentration at poultry buildings. The results of Mostafa (2008) for emission rates also differ significantly between summer and winter measurements, however, the winter emission rates (734 µg h^{-1} $animal^{-1}$) were clearly lower than the summer rates (2,917 and 2,682 µg $animal^{-1}$ h^{-1} in June and August) due to climate conditions.

The impact of different housing types, variations in ventilation, amongst several others, on the range of dust concentrations measured at poultry barns was underlined by Demmers et al. (2010). The singularity of each animal housing facility, which may influence the amount of PM measured at a specific housing type, was also pointed out by Yang (2010). The fact that the farm management strongly affects PM concentrations was also proved by Ni et al. (2017b) and Costa et al. (2012).

A dust filter for field application in laying hen barns needs to cover all of the above-mentioned special requirements that occur in poultry housing facilities in order to properly reduce dust emissions. Studies, such as Winkel et al. (2015), have been carried out concerning *StuffNix*, a dry filter for dust removal. The results of these studies occasionally differed, as Winkel et al. (2015) summed up: PM_{10} removal efficiency range lay between 19.9% (field experiment at an aviary housing system) and about 82% (laboratory investigation inside a wind tunnel) in dependence of measuring method and conditions.

The overall objective of this research was

(1) to determine the optimal assembly of the dry filter under different experimental conditions in laboratory (in a wind tunnel), and

(2) to test the optimal assembly (based on results of objective 1) of the dry filter in a trial under field conditions.

Animals, materials and methods

Experimental setup

Laboratory conditions (wind tunnel)

The experiments under laboratory conditions were conducted in a wind tunnel. Figure 1 shows a technical drawing of the dimensions. The wind tunnel had dimensions of a quadratic square with 0.9 m length of the edge, a total length of 9.8 m. The total volume of the wind tunnel was 7.97 m^3. Four axial fans (Ø 300 mm) manufactured by Ziehl Abegg (Künzelsau, Germany) were used to adjust different flow rates during the measurement. A flow straightener was used for a consistent dispersion of air velocity and to avoid incoming air turbulences. Data were collected in five different fan modes: at 25%, 30%, 35%, 40% and 45% of the possible fan performance. Since the wind tunnel measurements were conducted inside a machine laboratory, temperature and RH could be kept on a constant level. Dust used at the laboratory was collected at the barn where the field experiments took place. The dust was injected via a vibratory releasing unit.

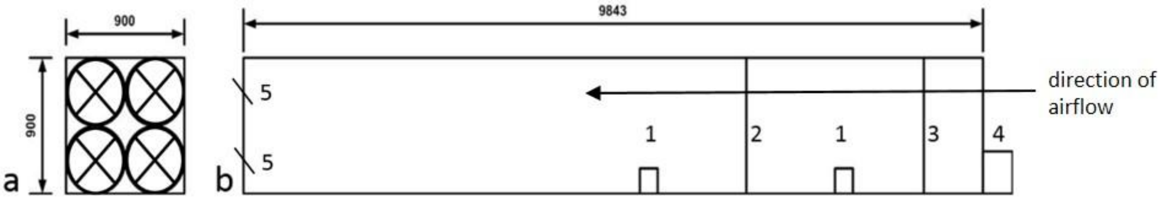

Figure 1:schematic draft of the wind tunnel. a: front view onto the four axial fans (Ø 300 mm each); b: side view onto the wind tunnel, 1: position of the aerosol spectrometers, 2: filter wall, 3: flow straightener, 4: position of the dust inlet, 5: position of the fans. Dimensions in mm

The same dust filter type was used both for laboratory and field experiments. As shown in Figure 2, the dust filter was investigated in three different variations (described as following: trial 1, 2 and 3). In trial 1 the filter was installed as a vertical filter wall as recommended for use in practice by the manufacturer. The size of the filter wall inside the wind tunnel was 0.81 m^2. For trial 2, the installation angle was changed from 90° (trial 1) to 60°. Trial 3 consisted of a double-wall filter with a distance of 0.3 m between both filter elements.

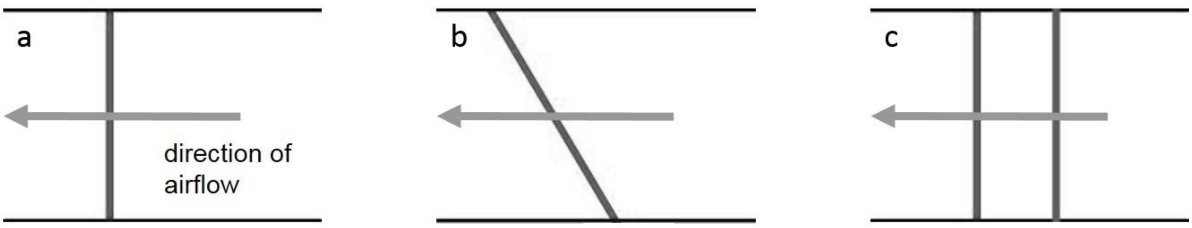

Figure 2: filter variations in the wind tunnel (side view): a) trial 1: single vertical installed filter wall, b) trial 2: single filter wall with an angle of 60°, c) trial 3: double filter wall with a distance of 300 mm in between filter walls

Field conditions

The field experiments were conducted at an aviary laying hen barn in North Rhine-Westphalia, Germany. The barn housed 39,782 laying hens (barn egg production) on two floors (19,891 animals at each floor). It had a length of 67.6 m and a width of 18.7 m. For ventilation the barn was equipped with 16 frequency-controlled ventilation fans (Ø 920 mm) installed in an exhaust air tower at the gable end of the building. Supply air inlets were located on the eaves sides of the barn. For summer ventilation, additional supply air fans at the roof ridge could be switched on to complement the air exchange rate during extreme weather conditions. Measurements took place only on the ground floor. The filter wall had a size of 47.9 m^2 and was placed right in front of the air-inlet of the exhaust air tower. Installation of the filter wall was similar to trial 1 of the laboratory experiment, as shown in Figure 2a. The first field experiment (FE_1) was conducted under summer conditions (mean outside air temperature 16.4 °C), the second (FE_2) under winter conditions (mean outside air temperature 3.6 °C).

Dry filter

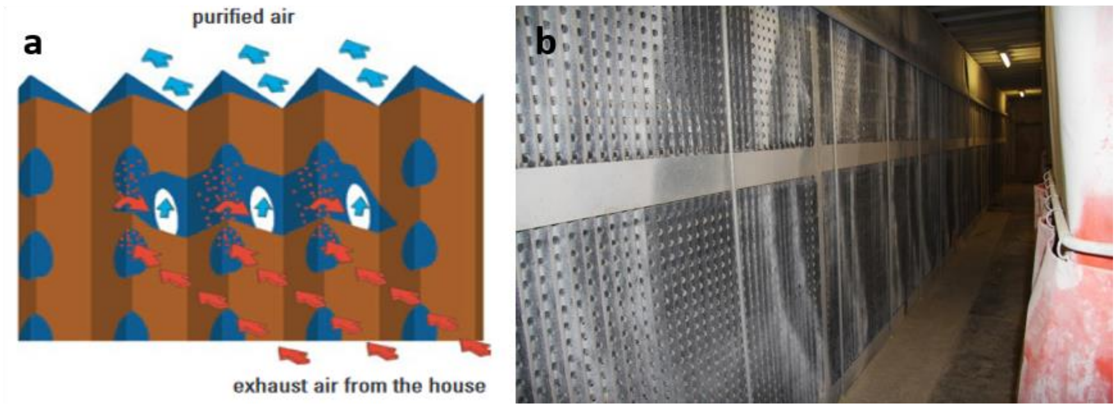

Figure 3: a) schematic view of StuffNix (Big Dutchman AG, 2017); b) filter wall installed in the barn of the field experiments

The dry filter used for this research was produced by Big Dutchman AG (Vechta, Germany), designed for barns with high dust loads and named StuffNix (Figure 3). The filter material consists of polyethylene. Indoor air passes the holes of the filter, which is built as a two-layered wall. Thereby the air is getting cleaned from dust before it leaves the barn. While passing the filter, incoming air is exposed to fast changes in direction. Due to the principle of centrifugal force PM is separated from the air and accumulates inside the V-shaped compartments of the filter (Figure 3). PM collected in the filter chambers needs to be removed frequently, which can be conducted with an industrial vacuum cleaner. At this particular barn, cleaning was done manually in periodic intervals. Workers were protected by wearing specific respiratory protection. The filter holes have a diameter of 25 mm each and there are 2184 holes per filter element of 4 m^2 distributed offset over the two layers of the filter (around 547 holes m^{-2}). The filter is also precisely described by Winkel et al. (2015), although they used an older version of StuffNix. The new StuffNix model was used for the present study, where slight modifications in material compounds have been conducted for higher form stability in comparison to the older model.

Measurement equipment and data collection

Particulate matter was measured continuously by using aerosol spectrometers (model 1.109A, Grimm Aerosol Technik GmbH & Co. KG, Ainring, Germany). These devices use light scattering technology for the measurement of particle size distribution and mass concentration in the ambient air and work with a reproducibility of 5% for whole range (manufacturer information). Additional information was collected by Peters et al. (2006) and Burkart et al. (2010). Two spectrometers were used simultaneously, in raw and clean gas respectively, and recorded data for PM_{10}, $PM_{2.5}$ and PM_1. Experimental setup of the aerosol spectrometers was the same for laboratory as well as for field experiments: One device was positioned in front of the filter wall and one behind it, each at a distance of 1 m. Both devices were calibrated by the manufacturer and then validated again in the laboratory of the Institute of Agricultural Engineering (University of Bonn) before their use in the experiments.

In the wind tunnel data was recorded for ten minutes (n = 100 single values) for each of the three trials. Due to the longer continuous measurement (24 h) in the barn, the data recording interval there was one sample per minute, which sums up to a total of n = 1,440 values. For measurement of the total suspended particulate matter (TSP) in the field experiments, gravimetric dust samplers built according to VDI-Guideline 2463-Part 1 (1999) were used. They were set up right next to the aerosol spectrometers. Air velocity in front of the dry filter was measured by using a vane anemometer in combination with a data logger (model ALMEMO® 2590A, Ahlborn Mess- und Regelungstechnik GmbH, Holzkirchen, Germany). The same data logger model was used for the recording of differences in pressure in front of and behind the filter wall.

One sample per minute was taken both for air velocity and pressure during the laboratory investigation with a measuring accuracy of ±0.5% for each indicator (manufacturer information). During the field experiments, air velocity and decrease in pressure were measured corresponding to the laboratory conditions. Ambient temperature and RH were captured continuously (data logger model testo 174h, measurement accuracy ±0.5 °C according to the manufacturer, Testo SE & Co. KGaA, Lenzkirch, Germany) in front of and behind the filter wall, also with a distance of 1 m to the dry filter.

Data analysis

Results were presented as arithmetic means. For statistical analysis IBM SPSS statistics version 24 (IBM Corporation, USA, 2016) was used. Outliers were identified, but were not significant. Normal distribution was tested by using the Kolmogorov-Smirnov-test, which showed that the data was not normally distributed. Afterwards, the non-parametric Kruskal-Wallis-test (laboratory data) and the non-parametric Mann-Whitney-U-test (field experiment data) were used for the determination of statistically significant differences between the areas investigated. Statistical significance was reached when associated probability values were less than 0.05 ($p < 0.05$). Humidity and temperature data were also presented as arithmetic means and summarized for each trial in laboratory and for each day at the barn, respectively.

Results and discussion

Laboratory conditions (wind tunnel)

Mean temperature during the laboratory investigation was 21.3 °C (±0.3) and mean RH lay at 55.5% (±1.7).

Trial 1 showed the highest efficiency for removal of PM_{10} with a total of 60% (Table 1). Low total filtration efficiency in trial 3 originates in the results at low fan performance. For PM 2.5 trial 3 showed the best results with 93% mean filtration efficiency (Table 1). Mean air velocity was also the highest in trial 1 with 0.68 m s^{-1}, while mean decrease of pressure was the highest in trial 3 with 14.30 Pa. While in trial 1 air velocity of 0.4 m s^{-1} was reached with the lowest fan performance tested (25%) and the decrease of pressure at the filter was only 4.3 Pa, in trial 3 a related air velocity of 0.43 m s^{-1} and 0.44 m s^{-1} was reached only with higher fan performances (40% and 45%). These velocities were linked to comparatively high pressure differences in front of and behind the filter wall (21.92 Pa and 21.96 Pa for 40% and 45%, respectively). A similar wind tunnel investigation Mostafa (2008) conducted showed likewise results for $PM_{2.5}$ (about 76%) as measured in the present laboratory investigation (79%).

Trial 2 showed improved results for $PM_{2.5}$ and PM_1 (83% and 88%, respectively) compared to trial 1 (79% for both), but distinctly lower efficiency for PM_{10} (32% compared to 60%). At 45% fan performance more PM_{10} was measured in clean gas than in raw gas.

Table 1: Mean filtration efficiency, air velocity and decrease in pressure at the filter wall during trial 1, 2 and 3 in the wind tunnel at the different ventilation steps and in total for each whole trial

	25%	30%	35%	40%	45%	Total
Trial 1						
PM_{10} (%)	71	62	75	51	41	60
$PM_{2.5}$ (%)	82	84	84	73	72	79
PM_1 (%)	82	84	84	74	70	79
Air velocity (m s^{-1})	0.40	0.57	0.69	0.80	0.93	0.68
Decrease in pressure (Pa)	4.3	8.1	11.3	14.3	20.6	11.7
Trial 2						
PM_{10} (%)	57	54	27	27	-6	32
$PM_{2.5}$ (%)	90	86	82	78	77	83
PM_1 (%)	91	89	89	85	86	88
Air velocity (m s^{-1})	0.22	0.28	0.49	0.60	0.82	0.48
Decrease in pressure (Pa)	6.5	9.8	13.4	15.6	22.1	13.5
Trial 3						
PM_{10} (%)	4	8	53	64	58	37
$PM_{2.5}$ (%)	94	90	92	94	94	93
PM_1 (%)	96	90	88	91	90	91
Air velocity (m s^{-1})	0.00	0.20	0.19	0.43	0.44	0.25
Decrease in pressure (Pa)	5.4	9.6	12.5	21.9	21.9	14.3

In trial 2, as shown in Figure 4, the amount of PM_{10} is distributed identically ($p>0.05$) over the different fan performance steps in raw gas. In clean gas, however, the distribution differs between the fan performance steps ($p<0.05$). With higher air velocities inside the wind tunnel the amount of PM_{10} also increased (Figure 4).

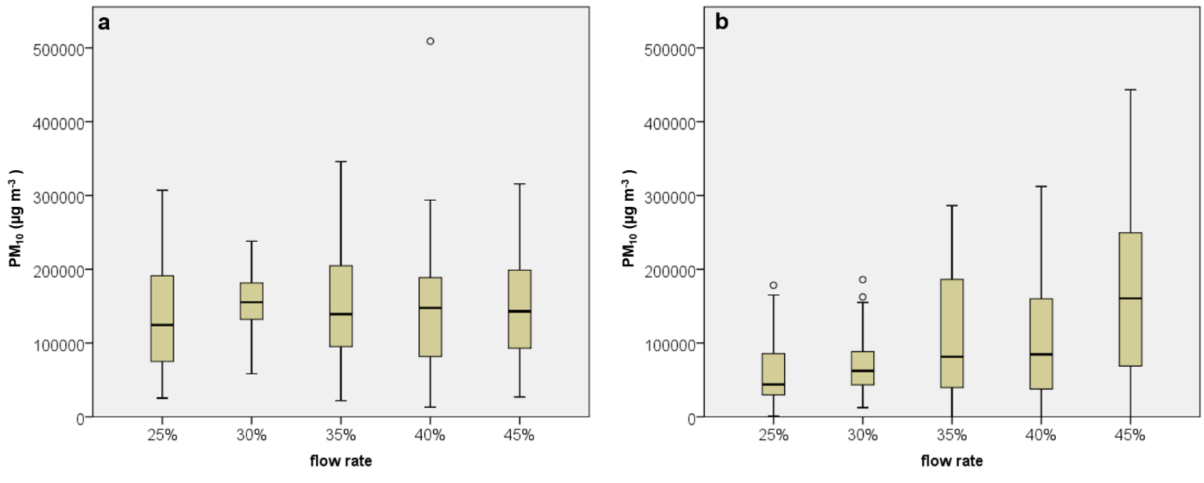

Figure 4: Amount of PM_{10} (µg m^{-3}) (a) in raw gas ($p<0.05$) and (b) in clean gas ($p<0.05$) of trial 2 at the different fan performance steps (25% up to 45%) inside the wind tunnel

Mostafa and Buescher (2011) conducted a comparable investigation to the present study with a dry filter in a wind tunnel, also using laying hen dust. Their results showed a higher efficiency of the dry filter at an air velocity of 1.0 m s^{-1} than at 0.75 m s^{-1}. In the present research the best results were obtained at an air velocity of 0.69 m s^{-1}, as shown in Table 1. A further increase of the air velocity was associated with a decrease in filtration efficiency, which may be lead back to resuspension due to higher turbulences caused by higher air velocities. The results of filter efficiency, however, differ in each of the PM categories (Table 1).

After investigating the three different trials, it turned out that it was not possible to improve the original assembly by changing the angle or the number of filter walls. Trial 2 and 3 showed remarkably lower efficiency concerning higher particle size fractions. Comparable results in trial 3 were only reached at high fan performance levels. Due to higher decreases in pressure induced by the use of two filter walls more electric energy was needed to ensure steady performance. This led to higher electric energy use and, in consequence, to more CO_2 emissions. Eckel et al. (2014) estimated that the yearly electric energy consumption of the ventilation at a laying hen barn amounts to 1.11 kWh per year and animal place. Electricity consumption of the ventilation fans captured over a two-year period in the barn where the current field measurements took place was 1.3 kWh per year and animal. These numbers show an increase of operating costs due to the use of a single filter wall. Establishing another wall to the system would further increase electricity use and subsequently energy costs as well as CO_2 emissions.

The experimental setup of trial 3 is also less economic due to higher material costs compared to a single filter wall (as in trial 1) and may not be suitable for each barn due to lack of space, especially in case of modifications at established buildings. Trial 3 was conducted due to special interest of the owner of the barn, where the field experiments took place. Economic aspects of exhaust air treatment systems are of high relevance to farmers, as they do not generate revenues.

In consequence of these experiments it was decided to use the filter wall assembly of trial 1 for the field experiments, also to investigate whether it is possible to gain likewise results as in the laboratory. Earlier studies showed a distinct gap between laboratory and on farm tests (e. g. Mostafa and Buescher 2011, Lim et al. 2003 2003, Winkel et al. 2015).

Field experiments

Mean temperature and RH in raw gas during FE_1 were 23.8°C ±1.4 and 55.6% ±5.1, respectively. Both values did not change significantly from raw to clean gas. During FE_2, mean temperature in raw gas was 14.4°C ±1.5. Clean gas temperature did not differ significantly, while relative humidity was 64.9% ±10.5 in raw and 70.2 ±2.9 in clean gas. Mean dust concentrations in raw gas of FE_1 (summer) were 15,040 µg m^{-3}, 2,389 µg m^{-3}, 712 µg m^{-3} and 51 µg m^{-3} for TSP, PM_{10}, $PM_{2.5}$ and PM_1, respectively. FE_2 (winter) raw gas concentrations were lower for TSP, PM_{10} and $PM_{2.5}$ with 12,530 µg m^{-3}, 450 µg m^{-3} and 664 µg m^{-3}, whereas concentration of PM_1 increased to a mean of 209 µg m^{-3}. Data of FE_1 was not distributed identically over the two categories raw and clean gas for TSP, PM_{10} and PM_1 ($p<0.05$). Only the distribution of data for $PM_{2.5}$ was identically in raw and clean gas ($p>0.05$). Data of FE_2 was not distributed identically over all determined categories ($p<0.05$). In comparison, the amount of PM in the winter situation was significantly lower ($p>0.05$) than in summer. Also, air velocity was lower in winter than in summer. Mostafa (2008) measured an air volume flow of 27.472 m^3 h^{-1} during winter and 67.448 m^3 h^{-1} and 64.719 m^3 h^{-1} in June and August, respectively, at an aviary system. In this study of Mostafa (2008), the higher air volume flow was explained by the higher temperatures inside the barn, which were 27°C in June and 23°C in August. Temperature captured during the winter measurement was only 20°C. According to the DIN 18910 (2017), the optimum of ambient temperature for laying hens (with a liveweight of more than 1.25 kg per animal) ranges between 15°C and 22°C. An increased airflow helps keeping climate conditions inside the recommended figures while outside temperatures are higher. For laying hens with a liveweight of 2 kg the DIN 18910 (2017) recommends an airflow per animal of 1.4 m^3 h^{-1} during winter and an airflow of 5.2 m^3 h^{-1} during summer. The data captured in the present study matches these suggestions for successful heat dissipation.

While the amount of removed TSP was higher during FE_1 (67%) than during FE_2 (50%), fine particles were not removed as efficient as in FE_2 (Table 2). According to Guarino et al. (1999) the higher airflow rates during summer (FE_1) may have led to increased resuspension of dust particles.

Table 2: Mean filtration efficiency and air velocity at field experiment 1 and 2 (FE1 and FE2); PM10: particulate matter ≤10 µm, PM2.5: particulate matter ≤2.5 µm, PM1: particulate matter ≤1 µm, TSP: total suspended particulate matter

	FE_1	FE_2
TSP (%)	67	50
PM_{10} (%)	24	63
$PM_{2.5}$ (%)	42	74
PM_1 (%)	31	37
Air velocity (m s^{-1})	0.78	0.27
Decrease in pressure (Pa)	38.6	31.6

When comparing wind tunnel data to that measured in the field experiments, the result was that concerning air velocity, performance step “40%” of trial 1 (0.80 m s^{-1}) matches best with FE_1 (0.78 m s^{-1}). Nevertheless, decrease of pressure at the filter wall was higher with a mean of 38.6 Pa compared to 14.3 at the laboratory investigation. This can be explained by the fact that the extent of pressure is positively correlated with the surface it is effecting: $p = \frac{F}{A}$

Winkel et al. (2015) measured a removal efficiency of 39.4% (PM_{10}) and 0.1% ($PM_{2.5}$) at an aviary housing system. In particular for $PM_{2.5}$, these results show a strong deviation to the data of the present study. This low value may also be lead back to the challenges the present study was faced with. An explanation for these differences may be turbulent airflow at and resuspension of PM behind the dry filter wall as well as measurement technique problems caused by the comparatively high PM concentration. Further investigations with different measurement equipment need to be carried out to determine the influence of measurement devices. At the investigation Ni et al. (2017a) conducted, results for PM_{10} of two laying hen houses had the greatest variation of all determined emissions. Another PM sampling method as in the present study, Tapered Element Oscillating Microbalances (TEOM), was used, yet, they also faced inconsistency in data recorded (Ni et al. 2017a).

Concerning PM concentration, various data are available from rather high to very low results: Winkel et al. (2015) measured 2,915 µg m^{-3} for PM_{10} in raw gas, which matches the FE_1 data of the present study (2,389.2 µg m^{-3}) better than the indoor PM results of Costa et al. (2012), which sum up to a mean of 215 µg m^{-3} (PM_{10}), 32 µg m^{-3} ($PM_{2.5}$) and 7 µg m^{-3} (PM_1). Those values are more comparable to FE_2, although they are lower than FE_2 data. The wide distribution of measurement data once more shows the impact of, amongst others, management and season on PM concentration and approves this common theory (cf. (Ni et al. 2017b; Demmers et al. 2010; Yang 2010).

The mean air velocity in FE_1 was much higher due to a higher ventilation rate in summer. In consequence, the relative humidity was lower in both raw and clean gas than in FE_2. These results correspond with those made by Huneau-Salaün et al. (2011). The dust concentration of FE_1 and FE_2 are positively correlated with the indoor temperature, which followed outside temperatures. A negative correlation between the dust concentrations and humidity was also confirmed during the field experiments. The difference between RH in raw and clean gas in FE_2 may be explained by the fact that the weather was rainy on that day. Raindrops falling through the ventilation fans into the exhaust air tower may have caused a 5.3% higher RH in clean gas compared to raw gas.

Conclusion

The aim of the present study was the evaluation of a dry filter under different conditions concerning the measurement possibilities. It turned out that:

- The dry filter showed high filtration efficiency at the examination inside the wind tunnel particularly for fine PM sizes: 60%, 79% and 79% for PM_{10}, $PM_{2.5}$ and PM_1, respectively.
- Changing the filter assembly did not lead to an overall improvement of the investigated spots. A different assembly is not recommended.
- In the field experiments results for filtration efficiency were lower and differed in between the two trials (summer and winter measurement), yet mitigation of TSP determined by gravimetric samplers added up to 67% (summer) and 50% (winter).
- Only the results for PM_{10} at the winter trial were in accordance with the wind tunnel data, all other size fractions of PM did not reach the results obtained under laboratory conditions.
- Lower filtration performance may be explained by turbulent airflow and resuspension at the dry filter in the barn and also by the applied measurement technique, which encounters its limit at such high concentrations of PM inside an aviary housing system.

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2.2 Suitability of Different Filling Materials for a Biofilter at a Broiler Fattening Facility in Terms of Ammonia and Odour Reduction

Carolina Strohmaier *, Manuel S. Krommweh and Wolfgang Büscher

Institute of Agricultural Engineering, University of Bonn, Nußallee 5, 53115 Bonn, Germany;

krommweh@uni-bonn.de (M.S.K.); buescher@uni-bonn.de (W.B.)

* Correspondence: strohmaier@uni-bonn.de

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Abstract: A two-stage exhaust air treatment system installed at a broiler fattening facility with 40,000 animals was investigated. The facility's exhaust air was treated first by use of a chemo-scrubber (stage 1) and afterwards by a vertical biofilter (stage 2). The biofilter was equipped with root wood and honeycombed paper pad layers (half/half) to enable a direct comparison of both filter materials' suitability. Odour samples were taken on site and afterwards analysed at an olfactometry laboratory. Ammonia concentration values were collected continuously using a photoacoustic multi-gas monitor. High mitigation performance was achieved with both filter materials, with the honeycombed paper pad layer being less susceptible to fungal growth than the root wood filter. Cellulose seems to be a proper alternative for use in biofilters, but further research is needed to estimate the long-term stability of this material.

Keywords: broiler chicken; mitigation strategies; treatment technologies; odour; emission; exhaust air treatment; root wood; chemical scrubber; air quality; paper pads

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1. Introduction

Livestock facilities contribute considerably to anthropogenic ammonia emissions. In addition, odorous emissions affect the surroundings, especially of poultry housing facilities, so that farmers are challenged not only by environmental issues concerning their farms' emissions, but are also faced with negative attitudes of residents towards their farms. Residents often feel bothered by odours which originate from agriculture. According to the European Union emission inventory report 1990–2017 [1], 92% of the EU ammonia emissions in 2017 originated from agriculture. The main contributors were Germany, France and Spain. Besides ammonia, odorous emissions also play a major role, especially those originating from poultry housing: research undertaken by Valli et al. [2] showed that compared to pigs and cattle, laying hens and broilers have the highest odorous emissions per animal live weight unit.

As a consequence, an increasing number of farms need to be equipped with exhaust air treatment systems for environmental or politic reasons. Mitigation techniques are often linked with additional workloads and, most importantly, costs for farmers [3,4]. The exhaust air treatment system to be installed should therefore be able to deliver satisfactory results while being low maintenance. In addition, the efficiency of each system needs to be verified in a comparable way; for this reason, the Verification of Environmental Technologies for Agricultural Production (VERA) test protocol, a multinational collaboration between Denmark, The Netherlands and Germany, was established [5]. For the mitigation of odorous emissions from livestock buildings, biofilter systems have notably proven their worth [4, 6, 7].

Different filter materials are used for stuffing biofilters; the most popular materials are different kinds of wood chips. Chen et al. [8] tested two types of wood-chips as filter materials: western cedar and hardwood. They noted the importance of an appropriate moisture content of 60%, at which both tested chip materials led to odour reduction efficiencies of 48% to 93%. Nicolai and Janni [9] used a mixture of 50% brush wood chips and 50% sandy loam soil at a laying hen facility (caged). High amounts of dust made a correct measurement impossible. The authors recommend against the use biofilters at poultry facilities without upstream dust filters. An upstream treatment of the exhaust air, especially for the removal of dust, is also recommended by Harmon et al. [10] to help prevent the clogging of biofilters. Melse and Hol [7] also observed a high pressure drop in a biofilter downstream from a poultry manure dryer (laying hens) that was caused by dust, among other factors.

Exhaust air treatment systems used at broiler fattening facilities are faced with circumstances that can change quickly. Exhaust air, which feeds microorganisms and maintains the climatic conditions that are appropriate for these microorganisms, is ensured only during fattening periods. These periods often last no longer than about four weeks, followed by the transient vacancy of the facility in combination with intensive hygienic action. Even during a fattening period, conditions keep changing: Ogink et al. [11] noted that increasing ammonia emissions correlated with the increased size of the broilers, while Huang [12] identified the influence of outdoor climate conditions on emissions, such as temperature (outside temperatures as well as exhaust air temperatures, with the latter ranging from ca. 32°C to 20°C, depending on animal age and size). In correlation with outdoor temperatures, air ventilation rates need to be adjusted to keep inside temperatures at an optimum level [13]. Another unstable parameter correlated with temperatures and air ventilation rates is the relative humidity inside the facility (ranging from ca. 55% to 80% [14]).

All the circumstances mentioned above were taken into account in the experimental design to generate a suitable exhaust air treatment system for the mitigation of dust, ammonia and mainly, odour at a broiler fattening facility.

2. Experiments

The field experiments took place at a broiler fattening facility in Lower Saxony, Germany. The facility housed 40,000 broilers. Broilers were kept on the floor, which was covered with saw dust. Manure was not removed during the fattening period. The facility had six frequency-controlled ventilation fans at the gable end. Supply air inlets were located at the eave’s sides. The exhaust air treatment system comprised two stages: first a chemo-scrubber, and then a biofilter downstream. Figure 5 shows a schematic representation of the system. The chemo-scrubber was equipped with sulfuric acid-enriched water. The pH of this cleaning fluid was kept below 2.7. The biofilter was equipped with two different filter materials at the same time: half of the biofilter stage was filled with root wood (variant 1), while the other half was equipped with honeycombed paper pads made of impregnated cellulose (variant 2). Each biofilter layer measured 7.5 m (width) × 0.6 m (length) × 2.5 m (height). The experimental setup enabled a direct comparison of the two filter materials' efficiency under identical conditions. As a consequence, the data for the raw gas of both filter materials tested at the broiler fattening facility is the same.

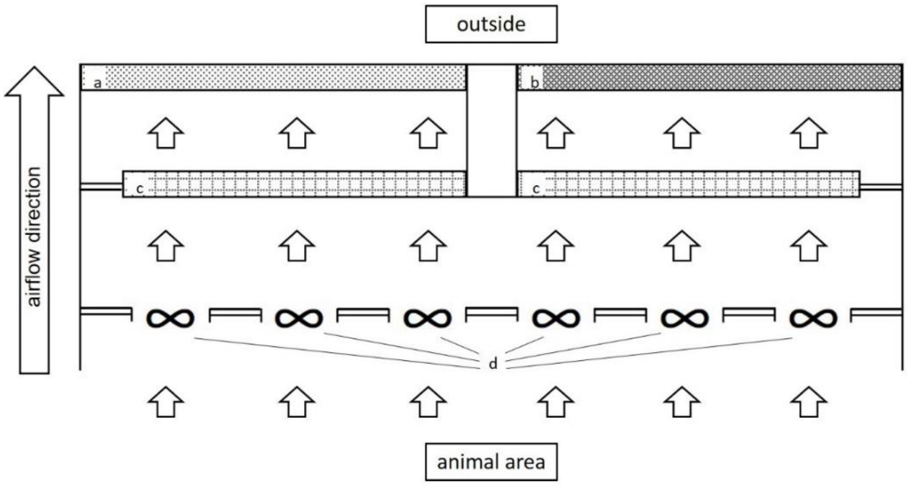

Figure 5: Schematic representation of the examined filter (a: root wood biofilter layer; b: honeycombed paper pads biofilter layer; c: chemo-scrubber; d: fans).

Ammonia concentration values were measured using a photoacoustic multi-gas monitor (INNOVA 1412 in combination with multiplexer 1309, LumaSense Technologies A/S, Ballerup, DK; cf. [15]. Odour samples taken on site were analysed at the olfactometry laboratory (n = 4 samples per day) according to DIN EN 13725:2003–07 [16] test scheme using an olfactometer (TO 8, ECOMA, Weyhe-Dreye, Germany).

Samples were taken on three days during different production cycles throughout the year in 2017, each time during the fourth week of fattening, as emissions rise with the age and size of the animals. Three odour samples were taken at each measuring point in clean gas and one in raw gas at the end of each 24 h interval. Samples were taken with a low-pressure sampling device connected to a hood. A hood was attached to each of the clean gas sampling points on the outside of the biofilter to avoid cross-influences, as for example, from wind. The bags were made of Nalophan™. The material was chosen as it helps to avoid the contamination of the examined air. Additionally, ammonia was measured at an interval of 3 minutes over a period of 24 h. This sums up to 480 measured values for each measured spot (raw gas, honeycomb paper filter and root wood filter) per day, and to a total of 1440 values for the whole trial. The results are presented as arithmetic means. For statistical analyses, IBM SPSS statistics version 24 (IBM Corporation, USA, 2016) was used.

3. Results and Discussion

Table 3 shows the mean values of all three days for ammonia and odour in raw and clean gas. Low ammonia concentration values ($\bar{x}$ 3.99 ppm) were measured in raw gas. Despite these already low initial values, a further reduction of 71% (chemo-scrubber combined with root wood filter, variant 1) and 68% (chemo-scrubber combined with honeycombed paper pad filter, variant 2) was achieved through the use of the exhaust air treatment system. The odour concentration measured in raw gas had an average of 256OU$_E$ m^{-3}. This initial value could be reduced in variant 1 by 97OU$_E$ m^{-3} to 159OU$_E$ m^{-3} and in variant 2 by 131 OU$_E$ m^{-3} to 125OU$_E$ m^{-3}. No specific odour of the raw gas was detected in a clean gas sample at any time.

Table 3: Ammonia and Odour concentration in raw gas, clean gas and total difference for different biofilter filling materials (variant 1: root wood; variant 2: honeycombed paper pads); mean values over three days with n=1440 for ammonia and n=3 for raw gas odour

Parameter	Raw gas	root wood	paper pads
Ammonia (ppm)	3.99	1.14 (71%)	1.29 (68%)
Odour (OU$_E$ m^{-3})	256	159[1] (38%)	125[1] (51%)

[1] no specific odour of the raw gas in clean gas detected.

The honeycombed paper pad filter seems to be of higher efficiency than the root wood filter. A possible explanation of the higher clean gas values for variant 1 may be the inherent odour of the root wood material; shortly after the installation of the biofilter, fungal growth was observed in this filter material. Despite these differences in efficiency, both variants were suitable for achieving a substantial reduction of odour concentration. Nevertheless, even after several fattening periods, the fungal growth was considerably lower at the honeycombed paper pad filter than at the root wood filter, which makes it less susceptible to disturbances, and more suitable overall. Fungal growth accelerates the process of material degradation. Degraded material tends to settle, which increases the risk of air leaks, where air can pass the filter untreated [10]. The honeycombed paper pad filter was less susceptible to degradation during the experimental period. Furthermore, another advantage of the honeycombed paper layer compared to root wood is a steadier airflow due to the constant pore size across the whole filter.

The advantages of combining an acid scrubber with a biofilter are, amongst others, the mitigation of ammonia and moisturising of the air before entering the biofilter and thus, better conditions for the microorganisms inside the biofilter. This worked out very well for the honeycombed paper pad filter, while the chemo-scrubber stage could not prevent fungal growth inside the root wood filter. Also, clogging in the biofilter by dust was not observed, which matches the findings of Nicolai and Janni [9] and Harmon et al. [10]. Yet, there is still need for further investigation to increase the odour reduction efficiency and to clarify the impact of the inherent odour development inside biofilters.

4. Conclusions

In this preliminary study, the suitability of impregnated cellulose pads for biofilters was tested on a farm scale and simultaneously compared to root wood as a commonly used biofilter filling material.

The main conclusions of this study are:

- Both the root wood and honeycombed paper pad material helped to mitigate odour concentrations of exhaust air by up to 51%.
- The honeycombed paper pad filter provided better results, presumably due to lower inherent odour and lower fungal growth.
- Further investigation according to the VERA protocol [5] is needed for a long-term stability evaluation of the honeycombed paper pad material, as well as for objective comparability to other systems.

Author Contributions: conceptualization, C.S., M.S.K. and W.B.; methodology, C.S., M.S.K.; software, C.S., M.S.K.; validation, C.S., M.S.K.; formal analysis, C.S.; investigation, C.S.; resources, W.B.; data curation, C.S.; writing—original draft preparation, C.S.; writing—review and editing, C.S.; M.S.K. and W.B.; visualization, C.S.; supervision, M.S.K. and W.B.; project administration, W.B..; funding acquisition, W.B.

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Conflicts of Interest: The authors declare no conflict of interest.

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2.3 Combined exhaust air treatment at a laying hen facility for mitigation of dust, ammonia and odour

Strohmaier, J.C.L.[1], Diekmann, B.[2], Kuennen, S.[3], Büscher, W.[1]

[1]Institute of Agricultural Engineering, University of Bonn, Nußallee 5, 53115 Bonn, Germany;

[2]Institute of Physics, University of Bonn, Nußallee 12, 53115 Bonn, Germany;

[3] Big Dutchman AG, Auf der Lage 2, 49377 Vechta, Germany

Abstract*:* Exhaust air treatment systems for animal husbandry, especially for poultry housing, have become more and more important in the recent past. In some cases they are mandatory in approval procedures for new animal husbandry buildings. Yet farmers as well as engineers are still faced with some difficulties while using available techniques. Particularly efficient odour removal is very challenging especially at poultry housing facilities. Special focus of this research project is on applicability of dry filters for dust removal and the use of additive compounds for possible improvement of the biological filter reducing odour emissions. A special facility for partial treatment of a two-storey barn's (40,500 laying hens, located in North Rhine-Westphalia, Germany) exhaust air was used for this research. The exhaust air treatment system consisted of three different filter stages. Over three 24-hour-periods data were collected. During this measuring periods 93.4% of the total suspended particulate matter and 85.7% of the ammonia were removed out of the exhaust air and odour intensity was lowered by a mean of 80.9 OU m^{-3}. The data collected at this point suggest that this exhaust air treatment system may be appropriate for efficient mitigation of dust, ammonia and odour emitting out of a laying hen barn. Similar data recording procedures are needed for a certification process, which is a prerequisite for practical use on farms.

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Introduction: In Germany, almost 12 billion eggs were produced in barns with a minimum of 3,000 animal places in 2016. That sums up to an increase of 1.5% compared to the previous year (Destatis, 2017). Exhaust air treatment systems for the mitigation of ammonia, dust and odour emissions are increasingly being demanded in poultry farming in Germany for the approvability of the sites. Various factors, as for example ventilation or management, influence the amount of emissions from different husbandry systems, as Demmers et al. (2010) report. Currently there are only few tested systems due to challenges with high dust loads especially at laying hen barns and a high variability of the ventilation rate at broiler fattening facilities. The aim of the current investigation is the development of a suitable system for an efficient exhaust air treatment with a special focus on different filling materials inside the biofilter.

1. Material and Methods: The investigation was conducted at a two-storey aviary laying hen barn with 40,500 animals located in North Rhine-Westphalia, Germany. For ventilation the barn was equipped with 16 ventilators installed inside an exhaust air tower at the gable end of the building. Supply air inlets were located on the eaves sides of the barn. For summer ventilation, additional supply air fans at the roof ridge could be switched on to complement the air exchange rate during extreme weather conditions. A partial flow of the exhaust air was treated by a purification system consisting of three stages:

First stage: physical cleaning using dust filter StuffNix (Big Dutchman AG, Vechta, Germany)

Second stage: chemical cleaning via chemo-scrubber MagixX-B (Big Dutchman AG, Vechta, Germany)

Third stage: biological cleaning via biofilter based on paper pads

Dust, ammonia and odour concentrations were measured both in raw and clean gas. The dust concentrations were recorded using aerosol spectrometers (Model 1109A, Grimm Aerosol Technik GmbH, Ainring, Germany). To measure the concentrations of ammonia, a photoacoustic multi-gas monitor (INNOVA 1412 in combination with multiplexer 1309, LumaSense Technologies A/S, Ballerup, DK) was used (n=144 measurements per day and measuring point). Odour samples were taken on site and analysed at the olfactometry laboratory (n=4 samples per day) using an olfactometer

(TO 8, ECOMA, Weyhe-Dreye, Germany). Furthermore, the air volume flow as well as temperature and humidity were recorded continuously.

The data were collected in three measurement campaigns in August and September 2016 as well as in February 2017, so that both summer and winter situations could be recorded.

2. Results and discussion: The total dust concentration could be reduced by an average of 93.4% (Table 4). The average concentration of ammonia was reduced from 3.24 ppm to 0.46 ppm by the use of the exhaust air treatment system, which sums up to a reduction of 85.7%. The average mitigation of the odour intensity was 80.9 OU m^{-3}. Furthermore, no raw gas odour was detected in a clean gas sample at any of the three measurement campaigns.

Table 4: Mitigation performance of the exhaust air treatment system

	raw gas	clean gas	mitigation
total suspended particulate matter (µg m^{-3})	901.9	58.7	93.4 %
ammonia (ppm)	3.2	0.5	85.7 %
odour (OU m^{-3})	118.3	37.4	80.9 OU

The results obtained in the present study suggest that this system is suitable for efficient mitigation of dust, ammonia and odour at a laying hen facility. Due to the expansion from one to three stages, the dust removal performance was enhanced. In an earlier investigation of the system's first stage, the dry filter "StuffNix", a mitigation of 67% of the total suspended particulate matter was measured (Strohmaier and Büscher, 2016). Another earlier study conducted with this filter showed a retention of 72% of total suspended particulate matter (Mostafa and Büscher, 2011). These mitigation values were outnumbered by the average separation efficiency of 93.4% (Table 1) in the multi-stage exhaust air treatment system.

3. Conclusion: A special focus in the present research project is on the reduction of odour. This goal has been achieved by the use of paper pads inside the biological filter. Both a significant reduction of the odour intensity as well as the absence of raw gas odour in the clean gas were determined. However, it should be noted that the mean odour concentrations in raw gas have already been very low (Table 1). In further investigations of the exhaust air treatment system at a broiler fattening barn, higher odour loads in the raw gas are to be expected (Verein Deutscher Ingenieure, 2011). In further procedures of the research and development project, the investigations are to be continued with particular attention to different filter materials for the biological cleaning stage at the broiler fattening facilities.

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3 General conclusions

In the light of the study results this thesis answers the central research questions as follows:

3.1 Evaluation of the efficiency of a dry filter for the mitigation of a layer houses' exhaust air dust load

The dry filter worked very well under laboratory conditions. Yet, efficiency on farm level still needs to be improved, as other factors may affect the function, which cannot be controlled as under laboratory conditions. Dust is mainly problematic at laying hen housing and less at broiler fattening, which makes this filter type reasonable mostly for laying hen housing or as a preliminary stage in a multi-stage exhaust air treatment system for keeping subsequent stages dust-free in order to prevent them from clogging.

Nevertheless, in order to achieve dust reduction the dry filter is a favourable measure, which is easy to handle. Yet, it is only applicable at strictly forced-ventilated barns. Exhaust air of free-range barns with their multiple outlets for the hens cannot be properly cleaned as it is the case with aviary housing. This is yet another example that environmental issues and animal welfare are often incompatible.

Exhaust air treatment systems also impose an additional financial burden, especially for smaller agricultural businesses: the average number of laying hens housed per farm in Germany was 23,000 in 2018, while only 5% housed more than 100,000 hens (Johann Heinrich von Thünen-Institut 2019). Smaller farms can currently simply not afford exhaust air treatment. Any official requirement for mandatory use might even endanger the existences of these smaller farms.

Another question that arises with the use of filters for the mitigation of PM is the proper waste material disposal. Depending on the size of the barn, several hundred kilograms up to tons of contaminated waste mass accumulate per year (c.f. chapter 1.1.1), which might have to be disposed of in accordance with legal requirements for the disposal of hazardous waste. The authors of a similar investigation, Winkel et al. (2015), who compared the dry filter used in study 1 to an electrostatic precipitator, also point out that this is a problem still requiring a satisfactory answer. The safe disposal could then represent an additional cost factor, which one must consider when determining costs for operating a livestock facility with a dry filter attached.

In addition, it is crucial to take occupational health and safety measures into account during waste disposal. Although filter manufacturers offer solutions such as explosion-proof industrial vacuum cleaners, they often come along with additional cost and require professional use. During disposal, as little dust as possible should be whirled up and thus released back into the cleaned air in order not to impair the separation efficiency of the system. In order to perform stable operation, it is important to clean the filters regularly and to remove the separated dust. Clogged filters impair the separation efficiency and increase energy consumption of the exhaust air ventilators due to higher flow resistance.

Moreover, it is pivotal to protect the responsible staff against the inhalation of dust. As pointed out by the World Health Organization (2013), morbidity as well as mortality are linked with a long-term exposure to the size fraction $PM_{2.5}$. In this context long-term exposure means for years, which is, nevertheless, common practice not only for operators and employees of livestock buildings, but also for local residents of livestock facilities. The consequence of the exposure to $PM_{2.5}$ are chronic cardiovascular diseases, which are more prevalent in these groups of individuals and in addition, the influence on the promotion of other diseases, such as diabetes, is discussed (World Health Organization 2013).

In this context, the design of test protocols used for the investigation of exhaust air treatment system efficiencies such as the VERA protocol should also be subject to regular critical review: for measurements according to the VERA protocol, the recording of PM_{10} and a larger fraction is mandatory, whereas $PM_{2.5}$ is optional (The International VERA Secretariat 2018). A specific statement concerning the particularly harmful size fractions cannot be made this way.

The results of study 1 also underline that, due to a filter's removal efficiency for one size fraction, no direct conclusions can be drawn about its efficiency regarding other size fractions. In order to obtain reliable figures on certain size fractions, inclusion of these in the measurements is mandatory.

Without reliable data, especially on the small size fractions, it is impossible to make resilient statements about the extent to which an exhaust air treatment system may help to minimise health risks.

In summary, regular maintenance carried out by qualified staff in compliance with occupational health and safety measures is essential for the proper functioning even of a comparatively simple exhaust air treatment system.

3.2 Evaluation of a multi-stage system for exhaust air treatment at a layer house

Dust removal efficiency increased considerably after adding two further stages to the dry filter compared to the single use of a dry filter. Nevertheless, it is important to take into consideration when using a chemo-srubber that the use of an acid leads to an increased safety risk.

Handling acids not only involves a high health risk for the person working with them, but also for the environment if the substances are not handled properly. In order to maintain stable removal efficiencies, it is important to replace and dispose the scrubbing liquids regularly.

Compared to a simple dry filter, a multi-stage system requires more effort, higher costs (in acquisition as well as in operation) and the functional reliability is lower which each stage added, which makes such a system high maintenance. Areas of the exhaust air treatment system that could possibly come into contact with acid must be designed corrosion-resistant and legal requirements regarding substances hazardous to water must be observed during handling and storage (Arends et al. 2018). Sulphuric acid, which was used for the chemo-scrubbers during both studies 2 and 3, is also a substance potentially hazardous to health: it has an irritant and corrosive effect on mucous membranes and skin and can cause severe damage to affected body parts (Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung 2020). Due to the hazardous nature of the substance, training of the persons working at the livestock facility equipped with an exhaust air treatment system using acid is essential to keep both the health and environmental risk as low as possible.

In the present case, the single use of the first stage (dry filter wall) already led to higher electricity consumption and in consequence to higher costs (compare study 1, which was carried out at the same barn). Electricity consumption could not be measured during study 2, but the flow resistance was even higher in study 2 with its three-stage system compared to study 1 with only one stage. Higher flow resistances lead to a higher load on the ventilation fans and thus to increased energy consumption. Other authors support this thesis: exhaust air treatment systems at a barn with central forced ventilation lead to significantly increased electricity costs (Association for Technology and Structures in Agriculture 2008), (Landesamt für Umwelt, Landwirtschaft und Geologie Freistaat Sachsen 2014).

The thesis cannot provide precise statements concerning the costs of exhaust air treatment systems in general, as one must consider costs of multifactorial origin, such as animal and housing type, barn construction, pressure loss to overcome, exhaust air treatment system used, type and load of pulltant(s), climate conditions and operating costs (Association for Technology and Structures in Agriculture 2008), (Landesamt für Umwelt, Landwirtschaft und Geologie Freistaat Sachsen 2017). This applies to pig farming as well, although the data situation is slightly better because the exhaust air treatment is more widespread there. According to the Association for Technology and Structures in Agriculture (2008), exemplary annual total costs for the operation of a 3-stage exhaust air treatment system with a chemical stage at a pig housing facility with a plant capacity of 150,000-157,000 $m^3 h^{-1}$ may range between 153 and 171 € per 1000 $m^3 h^{-1}$ exhaust air.

3.3 Suitability of different filter systems and materials

Study 2 and study 3 used honeycombed paper pads as a filling material for a biofilter. For both housing types, aviary layer housing and broiler fattening, the filter efficiencies were satisfactory. In contrast to root wood, which was also tested in study 2, the honeycombed paper pads showed no fungal growth. This filter material seems promising, although long-term investigations are still pending for both housing systems. The chemo-scrubber stage worked properly for both laying hen housing and broiler fattening but carries several environmental and health risks (cf. chapter 3.2).

As already mentioned above, the use of an exhaust air treatment system on a forced-ventilated barn means that higher flow resistance must be overcome by the ventilation fans. Particularly in summer, when the pressure-sensitive ventilation fans need to be used at maximum output to maintain a comfortable climate for the animals inside the barn, an exhaust air treatment system may increase the risk of ventilation failure and thus create a considerable animal welfare risk, which is also correlated to economic effects: in an investigation undertaken by Geraert et al. (1996) showed a significant decrease of feed-intake for broilers kept at 32°C compared to a group of broilers kept at 22°C. Lower feed-intake leads to lower body weights of the broilers. For laying hens, heat has a significant negative effect on feed-intake as well as on egg-weight, as shown by Mashaly et al. (2004). The authors also found out that constant heat stress lowers the daily egg production and increases mortality amongst the hens.

Flow resistance is a measure to supervise the exhaust air treatment system: an increase in pressure allows conclusions to be drawn about the contamination of the system: as contamination increases, for example due to dust deposits, flow resistance and in order to keep up ventilation rates, energy consumption increases (Arends et al. 2018). Excessively overloaded ventilation fans are less long-term stable and have a shortened service life. Therefore, regular maintenance and supervision are mandatory.

Overall, a reduction of dust, ammonia and odour was achieved with all filters tested. Though, one should not neglect the costs incurred by the filters and the increased working hours. There is no such thing as a gold standard exhaust air treatment system suitable for every poultry housing facility. A well-functioning system requires careful planning and steady maintenance to keep mitigation efficiencies at a satisfying level.

Nevertheless, electricity consumption due to the mitigation of NH_3 carried out by exhaust air treatment systems leads to a higher carbon footprint of the livestock products. While the impact of these systems on the local environment might be a positive one, the global impact must be assessed negatively, when NH_3 is expressed in CO_2-equivalents and balanced with formation of CO_2 during power generation (Pommer 2015).

In conclusion, the question arises if emission reduction is a reasonable long-term measure to combat the effects of intensive livestock farming or if farmers, scientists and economists must reconsider the forms of modern livestock farming for the sake of animal welfare as well as local and global environment. The future challenge will be to overcome the negative correlation between the two, which can be seen for most measures undertaken. One approach could be to raise animal welfare standards while reducing the consumption of animal products (for poultry housing: meat as well as eggs). In this way, animal welfare could be improved without causing increased negative effects on the environment. However, one must implement this approach from a social and global perspective. In the light of a slowly but steadily increasing awareness of the consequences of anthropogenic climate change, society must hope that changes will also be accepted and implemented in the animal husbandry sector in the future.

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