LANDTECHNIK 74(6), 2019, 145–154
DOI:10.15150/lt.2019.3216
LANDTECHNIK AGRICULTURAL ENGINEERING

Monitoring of biologically working trickling filters at pig fattening stables

Jochen Hahne

In the present study, 154 test reports of biologically working trickling filters operating at pig fattening stables were evaluated in view of cleaning capacity and functional reliability. Basis of the evaluation were the test protocols which had been compiled with the county of Cloppenburg. Essential test criteria were ammonia reduction efficiency, removal of typical production odor and the usability of electronic logbooks (ELB). By means of these data runs of pH value and electric conductivity in the washing liquid and specific operation data as fresh water and energy consumption and elutriation rate as well were checked in view of plausibility. The results show that all trickling filters secure an ammonia separation efficiency of at least 70%. The mean separation efficiency was 93%. Raw gas typical smells in the outlet air were determined at four facilities only. 87% of the ELB was full usuable. The pH value was kept in the required range at 79% of the facilities. The electric conductivity was kept below 25 mS/cm at 90% of the facilities. Specific operation data, however, showed a wide range. The fresh water consumption varied between 0.12 and 10.41 m^3 per animal place and year (m^3/(AP a) and was 1.5 m^3/(AP a) in mean; median = 1.1 m^3/(AP a). The elutriation rate ranged between 0.07 and 2.19 m^3/(AP a) and was 0.45 m^3/(AP a) on average; median = 0.39 m^3/(AP a). The single power consumption of the exhaust treatment system fluctuated between 1 and 51 kWh/(AP a) and was 17.6 kWh/(AP a) in mean; median = 15.4 kWh/(AP a). Compared with former investigations the cleaning capacity and the functional reliability of trickling filters have been further improved. For some facilities, there is a need for optimization in view of keeping the pH value in the required range and the general system operation as well. For example, this becomes apparent by too high fresh water and power consumptions and elutriation rates as well. A surplus fresh water consumption may be caused by an inadequate droplet catcher function, for example. High energy consumptions is often due to inefficient circulation pumps or incorrectly dimensioned nozzles in the water distribution system. Surplus elutriation rates may result from a wrong working pH control, where the dosage of acid and base are working against each other.

Keywords
Trickling filter, ammonia, odor, separation, functional reliability, monitoring, characteristics, consumption data

Approved exhaust air treatment systems supply an effective and checkable emission reduction at forced ventilated pig stables if they are properly dimensioned and operated. The appropriate dimensioning and the proper system operation of different exhaust air treatment systems are specified in the DLG tests (DLG-Prüfberichte n.d.). But it is a controversial matter, whether exhaust air treatment systems are operated under practical conditions in that way as documented in the DLG tests and is required for keeping the separation efficiency demands in the frame of permission. For evaluating the proper system operation, suitable test protocols were developed in cooperation with the county of

received 18 June 2019 | accepted 4 November 2019 | published 21 November 2019

Cloppenburg (Hahne and Günster 2015) which are available on the Cloppenburg homepage (Landkreis Cloppenburg n. d.). Because of their high market share single-stage biologically working trickling filters were chosen for this survey (Umweltbundesamt 2016). This work aims to assess the actual operation of single-stage trickling filters in practice by means of evaluating test reports on the basis of Cloppenburg county demands and to show options for improvement.

State of knowledge

Maurer et al. (2016) provide a comprehensive overview of the actual state of emission reduction techniques in livestock by an evaluation of 265 references. The evaluation showed for bio filters separation efficiencies of more than 66% for particulate matter and volatile organic compounds and for scrubbers an ammonia removal of more than 66%. In this reference it is relegated to a database (IOWA State University n.d.) which shows good suitability of bio filters to reduce hydrogen sulphide, odor, particulate matter and volatile organic carbon compounds. The potential for ammonia reduction is indicated as moderate. Scrubbers, however, are well suited for ammonia removal, odor, particulate matter and volatile organic carbon compounds. The literature compilation proves the effective emission reduction of scrubbers in livestock. But it is an open question whether these systems do work in practice in a way that an emission removal is secured permanently.

Monitoring results of exhaust air treatment systems can only be found rarely in literature. In the years 2008, 2009 and 2010 20% of the existing exhaust air treatment systems (240 installations at that time, 75% scrubbers and 25% bio filters) were checked, respectively (Lamping 2011). The inspections were announced one week before realisation. 35%of the inspected systems showed not any deficits, while 45% showed considerable faults and 20%of the inspected systems offered serious lacks or were even inoperable. Lacking maintenance by operators, lacking manufacturer instructions, lacking maintainability and lacking material durability as well were conveyed as chief causes. The essential operation faults of scrubbers were wrong pH values, non-calibrated pH sensors, missing acid supply, dirty and clogged pipes and nozzles as well.

Checks of 44 single-stage trickling filters in Cloppenburg county during the years 2009–2013 showed that the mean ammonia reduction was 75% but the odor reduction was only sufficient at 37 installations (Hahne and Günster 2015). An electronic logbook was available at 39 installations but full usable only in 13 cases. Deficits of data logging were observed regarding the fresh water consumption and the elutriation rate as well. The non-compliance of the demanded pH range and the exceeding of the tolerated electric conductivity of 20 mS/cm as well were the main system operation deficits.

In 2015 the LUFA Nord-West monitored 61 exhaust air treatment systems whereat test protocols of the Cloppenburg county in the actual version at that time were used (Broer 2015). During these unheralded inspections, 10 checkups and 51 function control measurements were evaluated. Checkup measurements have to be made during high volume load of the exhaust air treatment system, while function control measurements can be done at lower volume loads. Only 21% of the installations passed the test while 79% failed. Essential sources of errors were:

- raw gas smell in the outlet
- electric conductivity not in the required range
- ammonia removal not sufficient
- missing or incomplete electronic log books
- pH values not in the rated range

The deficient ammonia removal and the formation of secondary trace gases (NO_x) as well were predominantly observed in trickling filters. A missing pH control and an intermittent operation of the circulation pump were indicated as reasons for these results.

All since 2009 DLG-approved trickling filters, however, have to be operated with pH control and continuous irrigation of the packing (DLG-Prüfberichte 5879, 6178 and 6284). In this respect, the detected deficits can be attributed to improper system operation.

Material, methods and assessment criteria

The present evaluation is based on 154 test reports on the reliability of single-stage trickling filters used for exhaust air cleaning in pig fattening units. The test reports were generated by three different and approved test bodies on the basis of the Cloppenburg county demands and correspond to three manufacturers of DLG-approved techniques. The test reports include concrete measurements from the day of inspection, the control of local measurement devices and the evaluation of electronic log books which should confirm the proper system operation between the annual inspection intervals. In this context it has to be differentiated between a function control and a checkup measurement. Function control measurements can be made at less than 60% volume load, while every 24 month a full load measurement with more than 60% volume load has to be conducted. For the evaluation 77 function control and 77 checkup measurements as well were evaluated. The announced inspections took place in the period between March 2017 and December 2018. Ammonia and NO_x measurements were made with detector tubes to limit the costs of control measurements. The odor assessment, whether a raw gas smell can be perceived in the outlet gas, was decided by the test bodies with a qualitative odor reception test.

Due to partly negative results in former inspections besides general parameters mainly following criteria were checked:

- Compliance with the required ammonia and qualitative raw gas odor removal
- Completeness and plausibility of electronic log books
- Compliance with the acceptable ranges for pH and electric conductivity
- Animal-related data of fresh water and power consumption and elutriation rate as well

The evaluation of the electronic log books is the essential basis to assess the long-term and proper system operation. In this connection, it has to be considered that the requirements on data logging have been raised considerably in recent years and older properly constructed installations do not record all today demanded data in the normal case. For example, this applies to data as the cumulative power consumption, the air flow rate and the elutriation rate as well which were not or only partially recorded in older installations. The compliance with demanded pH and electric conductivity values, animal-related data concerning fresh water and power consumption and elutriation rate as well are decisive for a proper system operation of trickling filters.

The pH value in the washing liquid should be kept between pH 6.5 and 7.0 by adequate pH control and sufficient water circulation (Figure 1, green). Amongst 6.0–6.5 and 7.0–7.5 there are two tolerance ranges (yellow), where a certain ammonia removal is still possible but combined with a rising risk of insufficient separation efficiency. Above a pH value of 7.5, a stable ammonia removal with an ammonia separation efficiency of 70% at least can not be secured in any circumstance (red). Beneath a pH value of 6.0 it has to be calculated with increasing and unwanted NO_X emissions resulting from decomposition of nitrites in the washing liquid (red marked range). The pH value should be measured in the return from the packing.

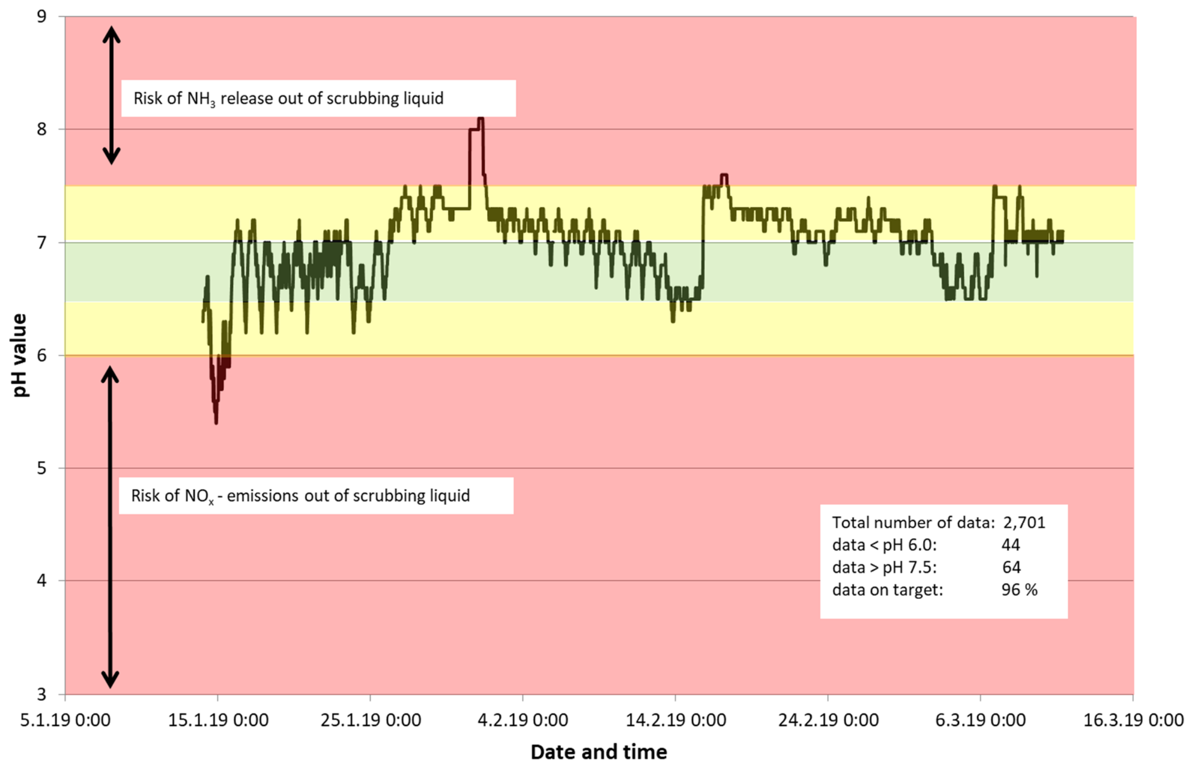

Figure 1: Tolerance ranges for the pH value in the washing liquid of biologically working trickling filters

The electric conductivity in the washing liquid of the DLG-approved trickling filters to date is limited to 20 mS/cm and must not exceed 25 mS/cm at maximum. By an exceeding of this value, a sufficient nitrogen removal can not be secured in all circumstance. Ongoing values of more than 25 mS/cm illustrate a serious fault.

The specific data as fresh water and power consumption and the elutriation rate as well will be calculated using the recordings of the electronic log books. For this purpose, the data from the test period will be normalized to an one year period and subsequently converted to animal-related data using the number of approved animal heads. If, for example, the cumulative fresh water consumption for 1,000 heads was 1,586.7 m^3 in 387 days, this result is converted to an annual consumption (1,586.7 $m^3 \cdot 365$ d/(a · 387 d)). The annual fresh water consumption of 1,496.5 m^3 is then divided by the number of approved animal places (1,496.5 $m^3\ a^{-1}$/1,000 heads). This procedure results in fresh water consumption of rounded 1.5 m^3/(AP a).

The secure nitrogen removal of biologically working trickling filters requires sufficent elutriation rate which results from the following equation 1:

$$ER = \frac{APN \cdot spec.E\text{-}factor \cdot F \cdot calc.SE}{N\ conc.WL} \quad \text{(Eq. 1)}$$

with

ER: Elutriation rate in m^3/a
APN: Animal place number
spec. E-factor: Specific ammonia emission factor of the pig keeping in kg/(AP · a), for liquid manure pig fattening systems with overflow ventilation = 3.64 kg/(AP · a)
F: Factor conversion NH_3-N/NH_3 = 14/17 = 0.824
calc. SE: Calculated separation efficiency (70/100, for instance)
N conc. WL: N concentration in the washing liquid (3.34 kg/m^3 at 20 mS/cm)

For a livestock of 1,000 fattening pigs the required elutriation rate is 628.1 m^3/a, for example (Figure 2). Since the emission factor for pig fattening of 3.64 kg/(TP a) is already documented in 2002 and a significant improvement in nutrient adopted pig feeding can be expected in the meantime, a tolerance of 30% was used as a basis for the minimum elutriation rate. In the example, the minimum elutriation rate would be 440 m^3/(AP a) in this example (rounded).

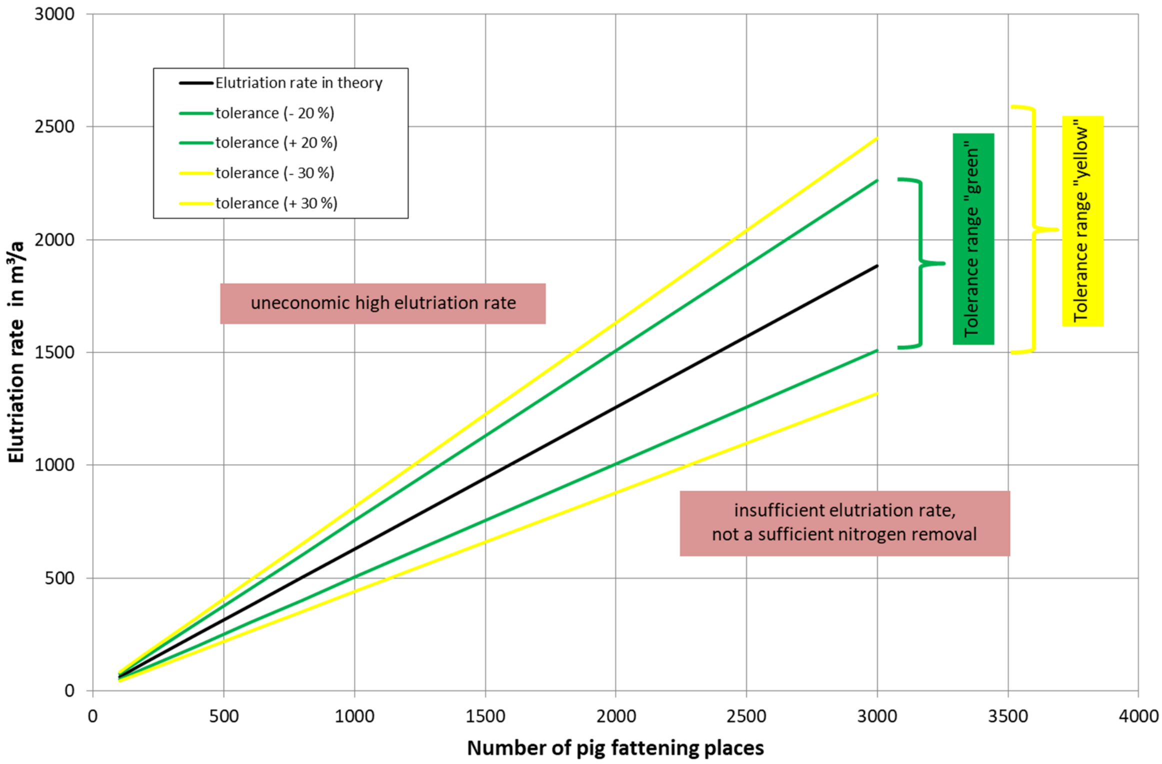

Figure 2: Required elutriation rate in biologically working trickling filters with a maximum tolerated conductivity of 20 mS/cm as a function of animal places

Results

The investigated exhaust air treatment systems were dimensioned for 297–4,800 pig places with air loads between 26,000 and 360,000 m^3/h. Based on 152 farmer specifications the livestock was 89% of the approved number of animal places at the time of inspection. The trickling filter loading rate varied between 424 and 5,500 $m^3/(m^2\ h)$ on the basis of 131 usable data sets and was 2,570 $m^3/(m^2\ h)$ in mean. During the functional tests, the average utilization was 44% and during the check-up measurements 80% of the maximum ventilation rate according to the manufacturer's specifications.
A comparison of selected results of function control and checkup measurements shows only slight differences in spite of different plant utilization (Table 1). Like this the evaluation showed that the mean ammonia removal efficiency was only marginal better with 94% during function control measurements compared to 92% during checkup measurements. The reason for this result may be supposed in a high resiliency of exhaust air treatment systems due to the changing daily and annual fluctuations in the plant utilization. On the basis of these results function control measurements and checkup measurements will not be differentiated anymore in the following information.

Table 1: Selected results of function and checkup control measurements on single stage, biologically working trickling filters at fattening pig keepings (mean values of 77 control measurements each)

Parameter	Function control	Checkup control
Utilization in %	44	80
Temperature (Raw gas/Clean gas) in °C	22/20	24/20
Relative humidity (Raw gas/Clean gas) in %	67/95	66/96
NH_3 concentration (Raw gas/Clean gas) in ppm	15/0.9	13/0.9
NO_x concentration (Clean gas) in ppm	0,5	0,2
Typical raw gas smell in clean gas in number	2	2

Due to comparable requirements in view of system operation and cleaning efficiency, a differentiated presentation and evaluation of the techniques of the different manufacturers is dispensed with. Comparisons of random samples show that performance fluctuations during function and checkup control measurements of one manufacturer may be greater than differences between the manufacturers.

The essential results which have been collected by the inspection authorities on the day of in situ inspection are summarized in Table 2. On average of 154 inspections, the raw gas temperature was reduced about 2.4 °C during exhaust air cleaning in the trickling filter. The relative humidity was increased on average from 66.6% to 95.8%. In view of the pressure drop, there was a wide range between 1 and 191 Pascal (Pa) with an average value of 39.9 Pa (median = 27.5 Pa). The mean pH value in the washing liquid was 6.9 on the day of inspection with a range between 5.8 and 7.6. The mean electric conductivity in the scrubbing liquid was 19.7 mS/cm and varied between 13.2 and 29.0 mS/cm. At ammonia concentrations between 6.0 and 31.0 ppm in raw gas and 0.0 to 5.0 in the clean gas, the minimum separation efficiency was 70.6% and 100% at maximum. On average the ammonia reduction was 93.2%. A certain portion of ammonia which has been separated in the trickling filter may be released as a secondary trace gas. Therefore the NO_x concentration in the clean gas was measured. It was only 0.3 ppm in mean. At 107 of 149 available data, there was not any NO_x in the clean gas. In 28 installations the NO_x concentration in the clean gas was 1 ppm and in 14 installations 4 ppm at maximum. At a concentration of more than 2 ppm, there is a need for action according to the test protocol to mitigate the emission of secondary trace gases by appropriate measures. Suited measures are uprating of the irrigation density and the pH value as well. In some cases, packing cleaning is advisable, especially at increased pressure drops.

Table 2: Results of local measurements on single stage biologically working trickling filters (n = 154)

Parameter	**Value/specification**		
	Minimum	**Maximum**	**Mean**
Raw gas temperature in °C	12.4	30.0	22.7
Clean gas temperature in °C	12.7	26.0	20.3
Temperature, washing liquid in °C	10.6	25.2	18.6
Relative humidity, raw gas in %	23.5	84.0	66.6
Relative humidity, clean gas in %	85.0	100	95.8
Pressure drop in Pa	1.0	191.0	39.9
pH value	5.8	7.6	6.9
Conductivity in mS/cm	13.2	29.0	19.7
NH_3 concentration, raw gas in ppm	6.0	31.0	14.0
NH_3 concentration, clean gas in ppm	0.0	5.0	0.9
NH_3 separation efficiency in %	70.6	100	93.2
NO_x concentration, clean gas in ppm	0.0	4.0	0.3
Raw gas smell in clean gas	yes		no
with number of trickling filters	4		150

Besides in situ measurements, the evaluation of the electronic log book is part of the plant monitoring. On the basis of 151 log books the results show that in 32 installations less than 90% of the recorded pH values met the required range between 6.0 and 7.5. In only three of it, the required pH range was held in less than 70% of the inspection time. In 32 installations 90–95% of the pH values were within the tolerance range and in 87 other installations, 95–100% of the data met the requirements.

A maximum electric conductivity of 20 mS/cm was permanently met in 81 installations of 147 available data sets. In 51 installations the maximum conductivity ranged between 20 and 25 mS/cm and only at three installations values of more than 25 mS/cm were recorded.

The fresh water consumption of a properly operated trickling filter results from the sum of water evaporation and elutriation rate. In pig fattening installations it was 1.4 m^3/(AP a) in the annual mean at DLG approved trickling filters with pH control and an elutriation rate controlled by conductivity. The evaluation of 147 data sets showed a fresh water consumption of less than 1 m^3/(AP a) in 58 installations, 1.0 and 1.5 m^3/(AP a) at other 53 and more than 1.5 m^3/(AP a) in 36 installations. The mean fresh water consumption was 1.5 m^3/(AP a) in the present study; median = 1.1 m^3/(AP a).

At DLG approved trickling filters with a permanent washing water circulation the mean annual power consumption was 24.8 kWh/(AP a) in fattening pig installations. On basis of 86 available data sets the power consumption of installations working under practical conditions was less than 10 kWh/(AP a) in 12 installations, 10–15 kWh/(AP a) in 30 installations, 15–20 kWh/(AP a) in 17 installations and more than 20 kWh/(AP a) in 27 installations. At the time of inspection in 68 installations no logging of power consumption was installed or the data were not feasible.

The mean elutriation rate was 0.74 m^3/(AP a) at DLG approved trickling filters. As described in the method chapter and in consideration of a 30% tolerance related to the theoretical elutriation rate a minimum elutriation rate of 0.44 m^3/(AP a) is demanded in the frame of inspection. Results of 149 electronic log books show that the elutriation rate was less than 0.44 m^3/(AP a) in 89 installations and higher in 60 installations. These data were calculated on the basis of the approved livestock, because these data could not be controlled in the frame of inspection. Taking the data of operators into account (mean livestock capacity = 89%) the elutriation rate was less than 0.44 m^3/(AP a) in 74 and higher in 75 installations.

Discussion

The current investigation of single-stage biologically working trickling filters shows the improvement of the cleaning capacity of these systems in recent years. In situ measurements result in a mean ammonia reduction of 93% and in clearance of production-typical odors in 150 of 154 cases. The quality of data in the electronic logbooks has also been improved. Serious faults stated in former investigations were significantly reduced by a consequent monitoring and a thereby associated improvement of facility management. While 37% of 61 checked installations showed faults in keeping the pH value in the required range in 2015 (Broer 2015), these faults occurred only in 21% of the installations (32 of 151 installations) in the time period from 2017 to 2018. According to this, the proven ammonia reduction came along very well. While the ammonia reduction was insufficient at 14% of the installations in 2015 (Broer 2015), the ammonia reduction efficiency of at least 70% was kept without any exception in the actual investigation. Furthermore less than 3% of the installations (4 of 154) showed a raw gas smell in the clean gas, compared to 10% in former investigations.

The operating costs for exhaust air treatment were caused by power consumption to an extent of 40–45% (KTBL 2006). With consumptions of 1–51 kWh/(AP a) for fattening pig keepings, the current investigation shows a considerable range. The mean consumption was 17.6 kWh/(AP a). Values of less than 10 kWh/(AP a) under conventional conditions may be attributed to a deficient data recording or improper system operation. At values of more than 30 kWh/(AP a) the link-up of other power consumers has to be assumed which are not part of the exhaust air treatment. Power consumptions of merely 5.7 kWh/(AP a) were recorded at novel trickling filters with improved circulation pump quality and sinusoidal irrigation intensity (Oldenburg 2018). These results show insofar a considerable potential for cost reduction in practice.

Fresh water consumptions and elutriation rates as well showed also considerable ranges. The mean fresh water consumption (n = 147) amounted to 1.5 m^3/(AP a) and was hence only slightly higher than the mean consumption in various DLG tests. Very high fresh water consumption is not only uneconomical but may also be a sign of faulty plant operation. As possible reasons besides a correct data recording an increased aerosol release caused by a partial blockage of the packing should be taken into consideration. The elutriation rate was 0.45 m^3/(AP a) on average of 149 available data sets and corresponded insofar with the minimum requirements. Inadequate elutriation rates despite keeping the demands for pH value and electric conductivity may be caused by lower livestock during the test period. The approved livestock is the basis to determine the elutriation rate. However, if the livestock in the test period was below the approved number the total elutriation rate would decrease and scaling to the approved livestock would result in insufficient specific elutriation rates. Another reason for too low elutriation rates may be supposed in a surplus aerosol release, especially if no or incorrectly dimensioned droplet catchers are used or if the packing is partially blocked. NO_x emissions which predominantly occur in some installations with pH values below 6 may be another reason for the decrease of the elutriation rate. Because the ammonia load is the decisive factor for the resulting elutriation rate, all measures within the stable which reduce the ammonia release lead also to a reduction of elutriation from trickling filters.

Several factors may be causative for increased elutriation rates despite the keeping of required operating conditions. The livestock in the stable may be higher than approved. Of prime importance, however, may be an inadequate air flow within the stable, which creates higher emissions, especially in cases of increased underfloor extraction. The stable management is very important in this respect. A surplus nitrogen feeding, increased feed loss or strong pollutions may increase the ammonia loads from the stable and consequently the elutriation rates of the trickling filter.

Conclusions

The evaluation of 154 test reports from biologically working trickling filters in pig fattening has shown for the years 2017 and 2018 that an improved facilities management and increased monitoring lead to constant and high cleaning efficiencies on average of all installations. The monitoring by means of the test protocols has proved its worth and should be maintained. Especially the determination of animal place related values as power and fresh water consumption and elutriation rate as well secures in connection with pH and conductivity courses a safe assessment of the operating reliability.

But the results show still a need for improvements in single installations. Among other things, this pertains to a further improvement of pH control and a reduction of running costs as well. This becomes apparent considering the very different animal-related power consumption data. The use of energy-efficient circulation pumps and the improvement of water irrigation systems as well will contribute to a significant reduction of running costs.

References

Broer, L. (2015): Erfahrungen bei Bau und Überwachung von Abluftreinigungsanlagen in Niedersachsen. Vortrag auf der 12. KTBL-Veranstaltung „Aktuelle rechtliche Rahmenbedingungen für die Tierhaltung“ am 02.06.2015 in Ulm und am 17.06.2015 in Hannover, https://www.ktbl.de/fileadmin/user_upload/Allgemeines/Download/Tagungen-2015/Rechtliche_Rahmenbedingungen_Tierhaltung/Broer_Erfahrungen_von_Abluftreinigungsanlagen.pdf, accessed on 09 Apr 2019

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit BMU (2002) : Erste allgemeine Verwaltungsvorschrift zum Bundes-Immissionsschutzgesetz (Technische Anleitung zur Reinhaltung der Luft – TA Luft) vom 24. Juli 2002. https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Luft/taluft.pdf, accessed on 16 Apr 2019

DLG-Prüfberichte (n.d.): https://www.dlg.org/de/landwirtschaft/tests/suche-nach-pruefberichten/#!/p/3/u/95/1?locale=de, accessed on 11 Apr 2019

DLG-Prüfbericht 5879 (2009): Abluftreinigungsanlage „Biologic Clean Air Kombiwäscher BCA 70/90“. https://pruefberichte.dlg.org/filestorage/5879.pdf, accessed on 11 Apr 2019

DLG-Prüfbericht 6178 (2018): Biologischer Rieselbettreaktor BioCombie. https://pruefberichte.dlg.org/filestorage/6178.pdf, accessed on 11 Apr 2019

DLG-Prüfbericht 6284 (2015): 1-stufiger biologischer Abluftwäscher, System RIMU für die Schweinehaltung. https://pruefberichte.dlg.org/filestorage/6284.pdf, accessed on 11 Apr 2019

Hahne, J.; Günster, H. (2015): Überwachung von Abluftreinigungsanlagen in der Tierhaltung. In: KTBL (Hrsg.): 12. Tagung: Bau, Technik und Umwelt 2015 in der landwirtschaftlichen Nutztierhaltung, Darmstadt, S. 438–443

Iowa State University (n.d.): Air Management Practices Assessment Tool. https://www.extension.iastate.edu/ampat/literature-database, accessed on 7 Nov 2019

KTBL (Hrsg.) (2006): Abluftreinigung für Tierhaltungsanlagen. KTBL-Schrift 451, Darmstadt

Lamping, H. (2011): Problematik der behördlichen Überwachung von Abluftreinigungsanlagen in der Tierhaltung. Vortrag auf dem Workshop „Emissionsminderung Tierhaltung – Abluftreinigung, 20. und 21. Juli 2011, http://www.buendnis-mut.de/mediapool/109/1096844/data/140222-Genehmigungsvoraussetzungen/110620-LK_Vechta-Behoerdliche_Ueberwachung_von_Abluftreinigungsanlagen_in_der_Tierh.pdf, accessed on 9 Apr 2019

Landkreis Cloppenburg (n.d.): Abluftreinigungsanlagen (z.B. Biofilter und Abluftwäscher) in der Tierhaltung. https://www.lkclp.de/bauen-umwelt/bauen-planen/abluftreinigungsanlagen-z.-b.-biofilter-und-abluftwaescher-in-der-tierhaltung.php, accessed on 11 Apr 2019

Maurer, D. L.; Koziel, J. A.; Harmon, J. D.; Hoff, S. J.; Rieck-Hinz, A. M., Anderson, D. S. (2016): Summary of performance data for technologies to control gaseous, odor, and particulate emissions from livestock operations: Air management practices assessment tool (AMPAT). Data in Brief 7, https://doi.org/10.1016/j.dib.2016.03.070

Oldenburg, J. (2018): Prüfbericht 17.181 Rev. 1: 1-stufiger biologischer Abluftwäscher System RIMU für die Schweinehaltung. Ingenieurbüro Prof. Dr. Oldenburg, https://www.ing-oldenburg.de/images/files/2018-10-26-Anerkennung-ARA-RIMU-Rev-1.pdf, accessed on 18 Apr 2019

Umweltbundesamt (Hrsg.) (2016): Aktuelle Entwicklung Kostennutzenanalyse und Vollzugsempfehlungen für den Einsatz von Abluftreinigungsanlagen in der Tierhaltung. https://www.umweltbundesamt.de/publikationen/aktuelle-entwicklung-kosten-nutzenanalyse, accessed on 11 Apr 2019

Author

Dr. Jochen Hahne is research assistant at Johann Heinrich von Thünen Institute, Federal Research Institute for Rural Areas, Bundesallee 47, 38116 Braunschweig. E-mail: jochen.hahne@thuenen.de