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Results from monitoring of single-stage biofilters in pig fattening and options for possible process engineering adjustments for reduction of ammonia emissions

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In the present work results from monitoring of 81 single-stage and quality assured biofilters for cleaning exhaust gas from fattening pig keepings are shown for the period from October 2019 to March 2022. Typical raw gas odours were not perceived in the biofilter outlet at filter loading rates from 42–486 $m^3\ m^{-2}\ h^{-1}$, raw gas temperatures ranged from 13.9–28.4 °C and raw gas moistures from 57.0–80.0 %. The service life of the wood chips was 5.4 ± 3.6 months at the on-site inspections. A transgression of the maximum wood chips service life was ascertained in no case. The homogenity of the filter material was given throughout and also the humidification systems were largely free of defects. At a mean filter material thickness of 0.24 m (wood chips, grading 30–60 mm) the pressure drops were comparatively low with 25.6 ± 20.3 Pascal (Pa). The fresh water consumption per animal place (AP) at 24 biofilters with coherent recordings of more than 365 days was between 0.24 and 2.11 $m^3\ TP^{-1}\ a^{-1}$. On average the fresh water consumption was 1,02 ± 0,53 $m^3\ TP^{-1}\ a^{-1}$. The nitrogen separation of the investigated biofilters over a 12 months service life was at around 13 %. Calculations show that a nitrogen separation of around 40 % is possible at a nutrient reduced feeding by doubling the filter thickness combined with a reduction of the filter loading rate from 440 to 330 $m^3\ m^{-2}\ h^{-1}$ and an annual change of the biofilter material.

Keywords
Biofilter, pig keeping, reliability, ammonia, mitigation

Problem and objectives

Quality assured biofilters for exhaust air cleaning from fattening pig stables without bedding are availabe and used in large numbers at livestock facilities. These biofilters ensure a far-reaching odor reduction and a high separation efficiency for particulate matter if they are dimensioned and operated properly. However, results and key figures for biofilter operation, reliability and fresh water consumption in practice are lacking.

One of the aims of this article is the documentation of the current stand of the single-stage biofilter use and operation in practice and the presentation of results from biofilter monitoring. Another goal is the estimation of the nitrogen reduction which can be achieved with these biofilters in case of regular filter material change and further procedural adjustments. The answer to this question is important because many livestock keepers have to ensure a higher ammonia reduction with the implementation of new technical instructions on air pollution control (TA Luft 2021).

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State of knowledge

Single-stage biofilters are used for exhaust air cleaning from pig stables without bedding for many years (Fachberichte LUA 2003, Hartung et al. 1997, Schirz 2003, VDI 3477 1991, Hahne et al. 2002, Umweltbundesamt 2016). On basis of the DLG test framework a suitability test was completed for a biofilter to be used for exhaust air cleaning from fattening pig stables without bedding (DLG 2006). The results of altogether 16 odor measurements under winter and summer conditions show a high cleaning performance at filter loading rates from 115–371 m^3 m^{-2} h^{-1} and odor concentrations between 1,025 bis 9,413 OU m^{-3}. In the biofilter outlet no process typical odors were perceptible. As a rule, the odor concentrations in the outlet were below 300 OU m^{-3}. At total dust concentrations of 0.5–1.4 mg/m^3 in the raw gas the separation efficiency was between 80 and 100 % with 12 measurements carried out. A fresh water consumption of 5.5 liters per 1,000 m^3 raw gas was measured in the investigations. The fresh water consumption was von 2.25 m^3 AP^{-1} a^{-1} related to animal population of 250 fattening pigs which were kept during the test period. For the suitability test wood chips with a water content of 60–70 % were used. Comparable consumption rates with 5–7 liters per 1,000 m^3 raw air were recommended in the KTBL publication 464 „Exhaust Air Treatment Systems for Animal Housing Facilities“ (KTBL 2008).

According to manufacturer’s specifications a total of 266 quality assured biofilters have been installed in Germany (Hagola Biofilter Gmbh, personal communication, 9 Aug 2022) which underlines the importance of this filter technique for animal husbandry. 82 installations thereof alone were installed in the county of Cloppenburg (Cloppenburg 2022). Different than recommended in the VDI guideline 3477 (VDI 2016) a pre-humidification of the raw gas is usually not performed in animal husbandry. A pre-humidification via a pre-humdifier or an upstream scrubber should secure a moisture saturation of at least 95 % in the raw gas. The raw gas from pig stables shows temperatures between 14 and 28 °C and moisture saturations of 57–80 %. Therefore and especially during summer months a dehydration of the raw gas side filter layer can happen. In addition to a very low cleaning performance too low moisture contents may result in a release of bioaerosols (Mäule and Fischer 2004). Therefore, the authors recommend a continuous monitoring of the biofilter moisture content.

Very different findings are available on water consumptions of biofilters. Hartung et al. (1997) came to consumption rates of 0.8 liters per 1,000 m^3 raw gas at investigations on two biofilters equipped with a coir-fibre peat mix of 0.5 m and operated without pre-humidification. The moisture content of the biofilter material was 20 %. Water consumption rates of 1.1–1.9 liters per 1,000 m^3 raw gas were found at biofilter water contents of 50 %.

In another suitability test for the recognition of a nitrogen removal performance of a biofilter at pig stables a fresh water consumption of 1.5 m^3 AP^{-1} a^{-1} was determined (DLG 2016). Wood chips with a water content of 60–70 % were used in this test and the filter thickness was 0.25 m. At an average load factor of 50 % based on the maximum air load this would correspond to a water consumption of 3.9 liters per 1,000 m^3 raw gas.

In addition to the fundamental proof of the biofilter suitability for the cleaning of exhaust air from pig stables a proof of permanent function has to be provided in future, especially for facilities which are subject to approval. According to the technical instructions on air pollution control (TA Luft) exhaust air treatment systems as biofilters must be equipped with an electronic operating logbook. With regard to the facility function the installations must be checked once a year by a recognized testing laboratory (TA Luft 2021).

Only a few representative experiences about the functionality of biofilters in pig keepings are available from practice. Each 20 % of the existing exhaust air treatment systems (at that time 240 facilities, 75 % scrubbers, 25 % biofilters) were checked in the county of Vechta in 2008, 2009 and 2010 (Lamping 2011). The reviews were previously registered one week before. Little or no defects were found at 35 % of the reviewed facilities, while 45 % of the facilities showed considerable shortcomings and 20 % had serious defects or were even functionless. Lack of maintenance, lack of instruction by manufacturer, lack of maintainability and a too low service life of materials used were cited as main causes. Collapsed filter material layers, insufficient humidification and exceeding the useful life of the filter material were the major deficiencies in biofilters.

A high odor reduction of 91 % at a mean odor concentration of 1,360 OU m^{-3} in the raw gas is reported from 7 facilities operating at fattening and piglet stables (Schilling 2022).

In the order of the county of Cloppenburg test protocols were developed for monitoring exhaust air treatment systems by means of which the system function is checked annually. The test protocols for biofilters without nitrogen separation are available on the homepage of Cloppenburg county (Landkreis Cloppenburg 2023). The test protocols allow an evaluation comparable across facilities even if the on-site inspections were carried out by different testing bodies.

Material and methods

In the period from October 2019 to March 2022 a total of 81 test reports of single-stage biofilters were evaluated for monitoring the functionality. The review included results of on-site measurements carried out by recognized testing laboraties as well as an in-depth evaluation of the electronic operating logbooks.

Description of studied biofilters

In the DLG-approved biofilter (DLG 2006) the raw gas is pressed uniformly over sufficiently stable fans (1) in the pressure chamber (2) and a perforated support base (3) through the filter layers (4–6) (Figure 1). The filter layers consist of wodden slats laid crosswise (4), a recyclate layer made from shredded plastic (5) and a layer of wood chips (6) with a thickness of 0.25 m and a grain size of 35–65 mm. For mechanical change the wood chips layer can be equipped with a nylon net. The regular intermittend humidification is made with fresh water via a water distribution system (7). A freeboard (8) should reduce the aerosol drift during irrigation. The maximum loading rate is limited to 440 m^3 m^{-2} h^{-1}. In-depth information with regard to biofilter design is available in the DLG test report (DLG 2006). The biofilter is recognized for particulate matter separation and removal of process-typical odors but not for ammonia reduction.

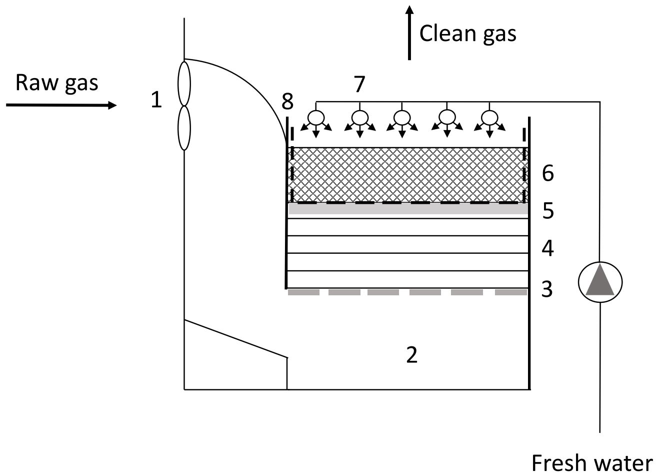

Figure 1: Schematic illustration of a single-stage biofilter for cleaning of exhaust air from pig stables without bedding with essential functional elements (fan (1); pressure chamber (2); supporting floor (3); wooden slats (4); recyclate layer (5); biofilter material (6): humidification system (7) and freeboard (8))

Within the framework of the investigations biofilters were checked for 132–1,344 fattening pig places with air flow rates from 13,358–118,272 m^3 h^{-1} (Table 1). The mean design air flow rate per animal was 86.0 m^3 h^{-1} and the mean biofilter material thickness was 0.24 m.

Table 1: Essential characteristics of the investigated biofilters in pig fattening facilities (n = 81)

Parameter	Unit	Minimum	Maximum	Mean	Standard deviation	Median
Approved fattening pig places	n	132	1,344	544	276.6	560
Maximum air flow rate[1)]	m^3 h^{-1}	13,358	118,272	46,505	23,507.8	44,000
Filter area	m^2	30.4	273.2	109.3	54.3	101.2
Design air flow rate / animal place (AP)	m^3 h^{-1} AP^{-1}	68.5	101.2	86.0	7.6	88.0
Thickness of biofilter material	m	0.20	0.30	0.24	0.016	0.24

[1)] According to manufacturer's specification.

Evaluation of the test reports

The Institute of Agricultural Technology has developed test protocols for monitoring the functionality of biofilters which are used by the county of Cloppenburg among others. The total inspection scope can be taken from the protocols (Landkreis Cloppenburg 2023). Test reports prepared by different testing laboraties were merged in a database and evaluated for 81 biofilters. The data each represent single measurement results from the on-site inspection day. For the parameters air flow rate, filter loading rate, temperature, relative humidity, raw gas ammonia concentration and pressure drop mean value, standard deviation, minimum, maximum and median were calculated in each case. Deviations of the on-site measuring devices compared to the results of the testing laboratory were checked and evaluated.

The thickness of the biofilter material (wood chips) and the layer homogenity are checked during the on-site inspection of the testing laboratory based on a predefined evaluation system. The biofilter material thickness which must be at least 0.2 m is measured at different biofilter points and the homogenity is evaluated qualitatively. For the assessment of an uniform flow-through a use of thermal imaging cameras might be useful in future.

The wood chips must be replaced regularly every 12 months but after 15 months at the latest. The service life is checked by the testing laboratories.

Of considerable importance for the biofilter functionality is the uniform humidification of the total biofilter surface. The efficiency (Eff) of the biofilter irrigation system (bis) is calculated as a percentage value at the on-site inspection with the following equation:

$$EFF_{bis} = ((\text{all nozzles} - \text{defect nozzles}) / \text{all nozzles}) \cdot 100 \quad \text{(Eq. 1)}$$

with:
efficiency of the biofilter irrigation system (Eff) in %

A predefined rating system is used for evaluation whereby at least 90% of the nozzles must function properly. The evaluation of the odor reduction is carried out only qualitatively by the testing laboraties that takes odor samples and evalutate in neutral ambient air, whether process-typical smell is perceptible in the outlet air. For routine monitoring of exhaust air treatment systems this approach was chosen because the olfactometry is expensive and time-consuming.

Evaluation of electronic logbooks

For the assessment of a permanent system function on-site inspections are not sufficient on their own. Therefore, all DLG-approved exhaust air treatment systems must be equipped with an electronic logbook which contains a gapless data recording. In case of biofilters, ambient air and raw gas temperature, air flow rate, pressure drop and the fresh water consumption must be recorded in 30-minute intervals.

Due to the lack of representative sampling points in the biofilter outlet (large filter surfaces, non-uniform flow rate, wind influences) the outlet air temperature and humidity are neither measured nor stored in the electronic logbook.

The stored data must cover the time period since the last on-site inspection. For the extraction of representative data, the evaluation of complete annual cycles are required because air flow rates, temperatures and fresh water consumptions in particular may change over the year.

For further evaluation 24 electronic logbooks of the total of 81 logbooks with coherent data of at least 365 days were used. From these electronic logbooks minimum, maximum and mean value were calculated for the parameters raw gas temperature, pressure drop and air flowe rate. The mean biofilter capacity (mbc) was calculated from the mean volume air flows with the following equation:

$$mbc = (\text{mean volume air flow} / \text{maximum volume air flow}) \cdot 100 \quad \text{(Eq. 2)}$$

with:
mean biofilter capacity (mbc) in %
mean volume air flow in $m^3\ h^{-1}$
maximum volume air flow in $m^3\ h^{-1}$

The maximum volume flow was taken from the manufacturer's specification in each case. For 13 of 24 biofilters, the fresh water consumption in relation to the volume air flow per calendar day was calculated from the 30-minute intervals data as an example because a sufficient humidification is of decisive importance for the biofilter function. From the quantity of fresh water dosed on the respective calendar day and the associated air volume flow the mean water consumption per m^3 air could be calculated for each calendar day. The available data per calendar day of the different biofilters were then combined to daily and monthly mean values.

After allocation to the calendar days the ambient air and raw gas temperatures recorded in 30-minute intervals were also combined to daily and monthly means.

For the imputed calculations of the required fresh water consumption for a proper biofilter function an online calculator was used to determine the water vapour content (Bauratgeber 2022). The clean gas temperature and relative humidity in the biofilter outlet were taken from datasets which were collected during another DLG test (DLG 2016). This approach was chosen because the corresponding values were collected throughout over the whole testing period under representative and proper conditions.

Results

The on-site inspections by the testing laboratories were carried out distributed over the year, resulting in different filter loading rates at the inspection days (Table 2). The filter loading rate was 242 $m^3\ m^{-2}\ h^{-1}$ in mean which correponds to a mean load factor of 55 % related to the maximum load of 440 $m^3\ m^{-2}\ h^{-1}$. The raw gas temperatures showed a relevant fluctuation range with 13.9–28.4 °C and was 22.5 °C in mean. Raw gas temperatures of maximum 18 °C, 18.1–20 °C, 20.1–25 °C and more than 25.0 °C were measured at 6, 11, 44 and 20 biofilters. The on-site temperature measuring devices showed with 0.9 °C in mean only a low deviation from the data measured by the testing laboratories. Only in individual cases a significant deviation was measured with 6.2 °C in maximum. In raw gas the range of relative humidity values was 57–80 % and 70.6 % in mean. The limit value of 20 ppm ammonia was never achieved or exceeded. In mean the ammonia concentration in the raw gas was 11.9 ppm measured with test tubes. The mean pressure drop across the filter layer was comparably low with 25.6 Pa and thus at the same level of the winter measurements during the DLG test. Only at two biofilters pressure drops of more than 80 Pa were measured. In mean the on-site measuring devices showed an acceptable deviation of 4.7 Pa in relation to the measurements of the testing laboratories. The maximum deviation was 15 Pa. The qualitative odor assessment by the testing laboratories showed for all 81 biofilters that no raw gas-typical smell was perceptible in the biofilter outlet.

Table 2: Essential results of the on-site inspections by the testing laboraties (n = 81)

Parameter	Unit	Minimum	Maximum	Mean	Standard deviation	Median
Volume air flow	$m^3\ h^{-1}$	3,802	82,426	26,463	18,089	22,939
Filter loading rate	$m^3\ m^{-2}\ h^{-1}$	42	486	242	95.2	259
Temperature, raw gas	°C	13.9	28.4	22.5	3.1	22.3
Relative humidity, raw gas	%	57.0	80.0	70.6	3.8	71.0
Ammonia, raw gas	ppm	5.0	19.0	11.9	3.9	12.0
Pressure drop	Pa	2.0	112.0	25.6	20.3	19.0
		Assessment by testing laboratories				
Raw gas smell in biofilter outlet	-	No raw gas smell in the biofilter outlet in 81 tests				

The testing for homogenity of the biofilter material showed no complaints in 81 test reports. All biofilter fillings were assessed to be homogeneous. The result for the nozzle function of the irrigation system was slightly worse. The values varied between 85 and 100%. But in mean the proper nozzle function was on a good level with 98.4%. Only in two cases the values were deficient with 85%. The sevice life of the wood chips in the examined biofilters varied between 0.5 and 15 months. In mean of available data (n = 78) the service life was 5.4 ± 3.6 months.

In order to determine representative annual data 24 electronic logbooks were evaluated with a complete dataset of at least 365 days due to seasonal fluctuations of the operating condtions. Since fresh water consumption in particular is subject to seasonal fluctuations electronic logbooks with shorter datasets were not longer taken into account. Reasons for shorter recordings may be caused by the timing of on-site inspections with the testing laboratories, in hardware and software adaptions and interim vacancy periods as well.

The evaluation of the electronic logbooks showed that they were complete throughout and that the recording of the required parameters was gapless. The mean load of the 24 biofilters varied between 28.7 and 80.7% related to the maximum load given by the manufacturer's specification. In mean the biofilter load was 51.1% (Table 3). The mean raw gas temperatures of the 24 biofilters varied between 16.7 and 24.9 °C and the mean pressure drops were between 5.3 and 61.4 Pa. In mean of the 24 biofilters the pressure drop was 23.2 Pa. A comparable variation showed the fresh water consumption with data between 0.24 and 2.11 $m^3\ AP^{-1}\ a^{-1}$. On average of all 24 biofilters, it was 1.02 $m^3\ AP^{-1}\ a^{-1}$ with a standard deviation of 0.53 $m^3\ AP^{-1}\ a^{-1}$. The fresh water consumption was calculated on the basis of the mean livestock numbers in the evaluation period. The mean livestock numbers were determined based on manual operating books.

Table 3: Essential results from the electronic logbook evaluations of biofilters with coherent data of at least 365 days (n = 24)

Parameter	Unit	Minimum	Maximum	Mean	SD	Median
Mean biofilter load	%	28.7	80.8	51.1	13.4	47.3
Mean raw gas temperature	°C	16.7	24.9	21.5	1.9	21.8
Mean pressure drop	Pa	5.3	61.4	23.2	13.9	18.3
Fresh water consumption	$m^3\ AP^{-1}\ a^{-1}$	0.24	2.11	1.02	0.53	0.99

SD: Standard deviation

For 13 biofilters, as an example, the fresh water consumption was calculated from the recordings in the electronic logbooks for complete calendar months. Using the volume flow data conveyed per month, the specific water consumption per m^3 could be calcuated for every single month. The fresh water consumption showed a pronounced annual cycle (Figure 2). While the fresh water consumption was between 0.9 and 1.6 g m^{-3} raw gas in the months November to February and between 2.1 and 2.9 g m^{-3} in the transition months (March, April, September and October), it was 2.8–3.2 g m^{-3} in the months from May to August. On an annual average, the fresh water consumption was 2.39 g m^{-3} raw gas (2020) and 2.24 g m^{-3} (2021). The overall mean was 2.3 g m^{-3}.

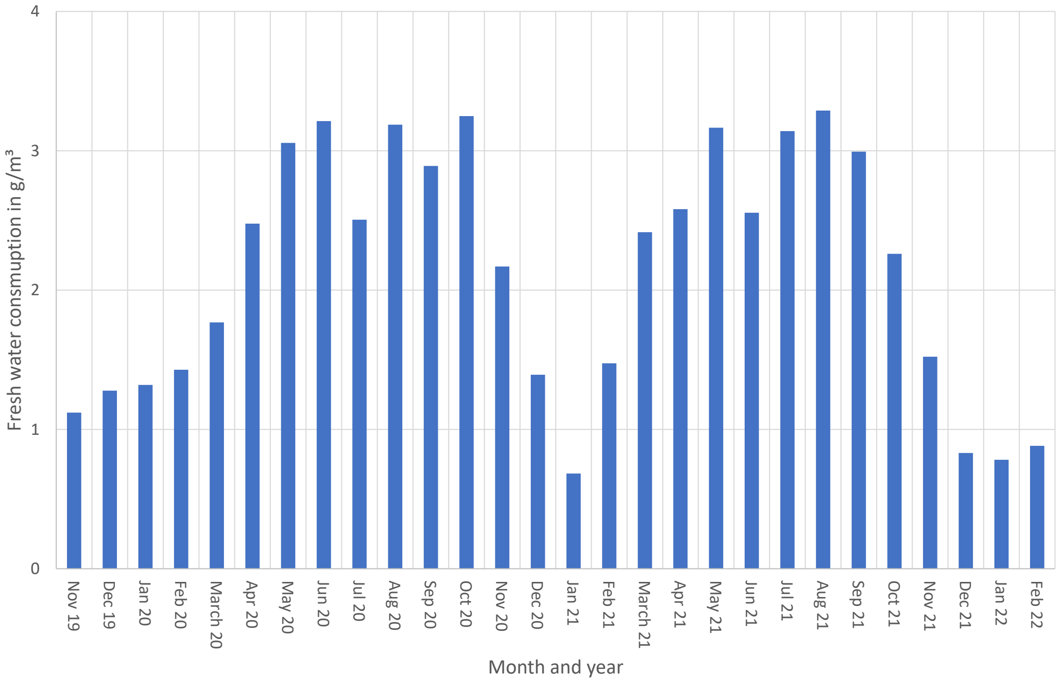

Figure 2: Mean fresh water consumption of biofilters per m^3 raw gas during the year (n = 13)

The mean ambient and raw gas temperatures calculated from November 2019 to February 2022 are shown in Figure 3. In the months November to February the monthly mean ambient air temperatures ranged between 1.3 and 5.9 °C. In the months March, April and May the values increased to 5.8–13.5 °C, whereby the values in the different years sometimes differed considerably (April 2020 and April 2022). Monthly mean ambient air temperatures of 16.8–20.7 °C were measured from June to August. The highest monthly mean values for the ambient air temperature were found in August 2020 with 20.7 °C and in June 2021 with 19.9 °C. In the transient months September and October the monthly mean values declined to 10.3–15.4 °C.

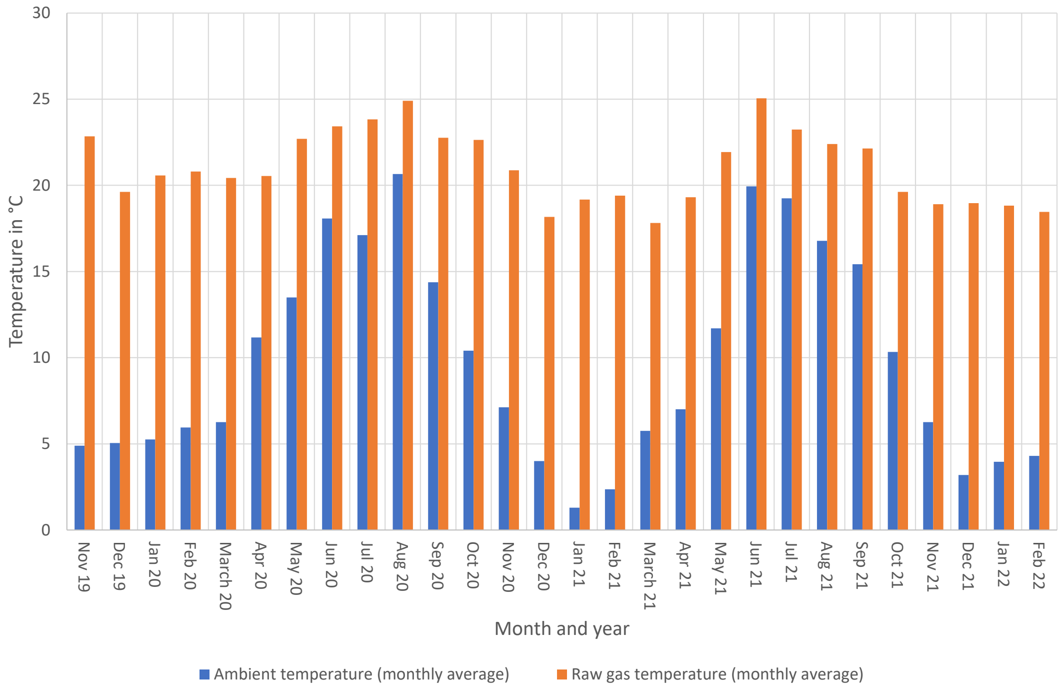

Figure 3: Course of monthly mean temperatures in ambient air and in the biofilter raw gas (n = 13)

While the ambient air temperatures showed a pronounced annual cycle the raw gas temperatures varied less. The lowest monthly mean values were found in March 2021 with 17.8 °C and the highest with 25.4 °C in June 2021. Increased monthly mean raw gas temperatures of more than 22 °C were mainly recorded in the period from May to September, in individual cases also in October and November.

Available data from the period November 2019 – February 2022 were merged to respective monthly means to assess the fresh water consumption. Figure 4 shows the measured mean fresh water consumption of 13 biofilters (black boxes in Figure 4) and the calculatory fresh water requirement for achieving humidity values of 90, 95 and 100 % in the outlet air as well.

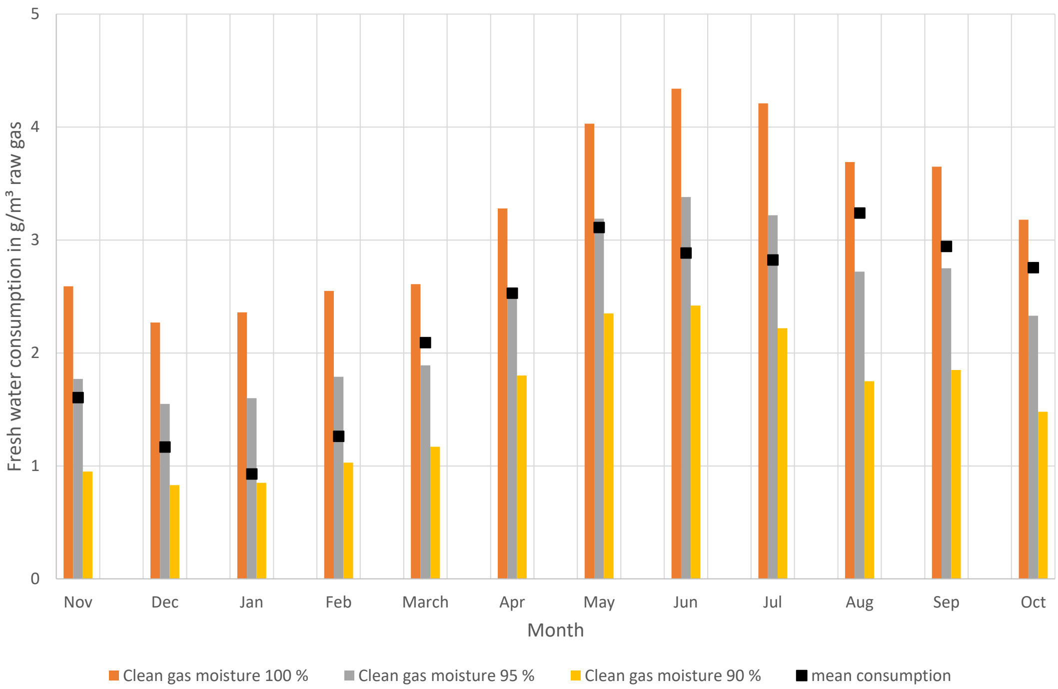

Figure 4: Monthly mean fresh water consumption of biofilters (n = 13) in comparison to calculated consumption rates for achieving humidity values of 90, 95 and 100 % in the outlet

The results show that the measured mean fresh water consumption fits well with the seasonal conditions. In all months a calculatory humidification of at least 90 % in the outlet air was secured with the measured fresh water consumption. For the months March and August–October the calculated humidity in the outlet would even be more than 95 %. A mean humidification of 100 % was never achieved, however. In the 2-year average the fresh water consumption was 2.3 g m^{-3} raw gas.

For operators of biofilters the calculation of the required fresh water consumption in different months and over the year is important (Table 4). The mean monthly fresh water consumption was calculated based on available records concerning raw gas temperature, air volume flow and humidity measurements during the on-site inspections as well.

The results show that the water consumption for fattening pigs per month may fluctuate between 43 and 98 liters at mean air volume flows between 29–41 m^3 h^{-1} AP^{-1}. High consumption rates with 82–98 liters were ascertained in the months from May to July, while low consumption rates with 43–48 liters were found in the period from December to March. On the basis of the calculations the mean fresh water consumption for fattening pigs must be around 0.77 m^3 TP^{-1} a^{-1} to achieve a mean humidity of 95 % in the biofilter outlet.

Table 4: Monthly mean values for raw gas temperature, relative humidity, filter load, air volume flow and calculated fresh water consumption as well to secure a relative humidity of 95 % in the biofilter outlet for biofilters with coherent data of at least 365 days (n = 13)

Month	**Temp. raw gas °C**	**Relative humidity, raw gas %**	**Filter load %**	**Volume air flow $m^3\ h^{-1}\ AP^{-1}$**	**Water consumption, raw gas[1)] $g\ m^{-3}$**	**Water consumption, raw gas[1)] $L\ TP^{-1}\ month^{-1}$**
November	20.9	72.7	45.4	40.0	1.77	51.0
December	18.9	72.6	42.5	37.4	1.55	43.1
January	19.5	72.7	42.4	37.3	1.6	44.5
February	19.6	71.7	44.9	39.5	1.79	47.5
March	18.9	70.6	34.7	30.5	1.89	42.9
April	19.2	67.0	33.4	29.4	2.54	53.8
May	21.3	65.6	39.4	34.7	3.19	82.3
June	23.5	67.0	45.6	40.1	3.38	97.7
July	24.0	68.7	46.3	40.7	3.22	97.5
August	23.5	70.5	41.9	36.8	2.72	74.5
September	22.4	69.4	40.5	35.6	2.75	70.6
October	21.5	70.2	44.5	39.1	2.33	67.8
Mean, year	21.1	69.9	41.8	36.8	2.4	64.4
Sum, year $L\ AP^{-1}\ a^{-1}$						**773.1**

[1)] For a humidity of 95 % in the outlet.

Estimate of a possible ammonia reduction of single-stage biofilters with regular biofilter material change

Biofilter according to the type described in Figure 1 are not recognized for ammonia reduction. Therefor a minimum ammonia and nitrogen reduction of at least 70 % would be required for a recognition (DLG 2022). Such an ammonia cleaning performance is permanently not possible with these filters in view of the high ammonia loads in pig keeping. Nevertheless, these biofilters can reduce ammonia and nitrogen to some extent with sufficient humidification throughout and a regular change of the biofilter material. Without a regular change of the biofilter material, however, there is no ammonia and nitrogen reduction. An earlier publication already referred to nitrogen enrichment in the biofilter material (Hahne and Pfeifer 2017). The figure 5 shows exemplarily the increase of the nitrogen concentration in the wood chips with proper humidification over the service life.

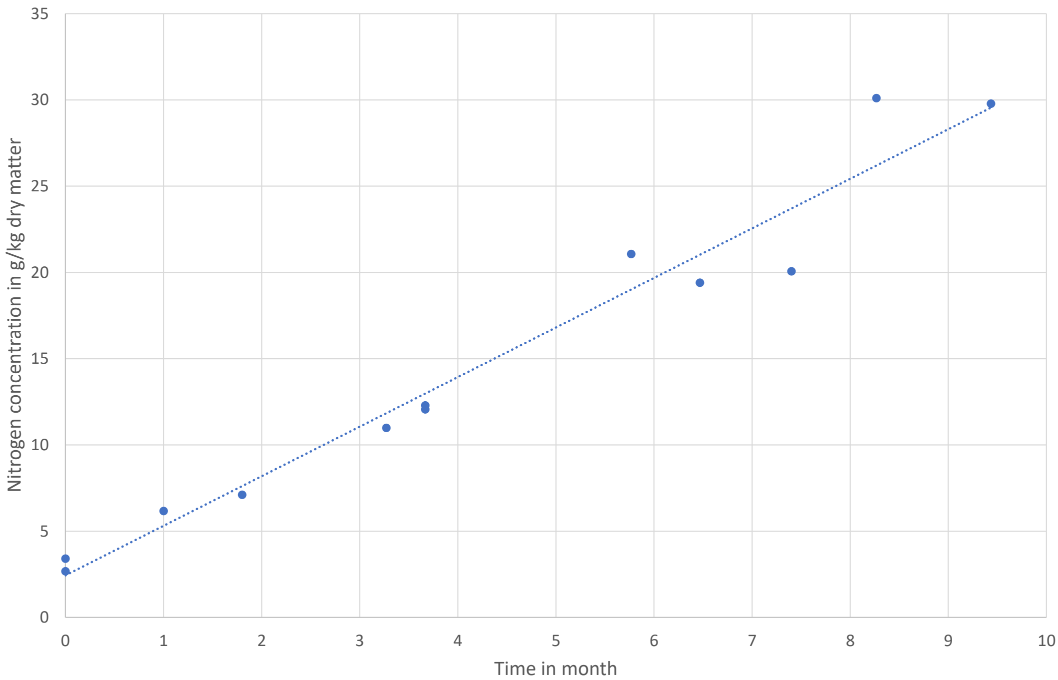

Figure 5: Example for temporal increase of the nitrogen content in the wood chip layer of single-stage biofilters in pig farming during proper operation

With the new version of the TA Luft, pig farms subject to approval must reduce a further 40 % of their ammonia emissions by 2029 at the latest in addition to a nitrogen reduction of 20 % via more efficient feeding (TA Luft 2021). This means that the previous ammonia emission factor of 3.64 kg NH_3 AP^{-1} a^{-1} must be reduced to 2.91 kg NH_3 AP^{-1} a^{-1} via feeding and then on to 1.74 kg NH_3 AP^{-1} a^{-1}via appropiate measures. The question now arises if and how single-stage biofilters can achieve these reduction targets with correspondingly more efficient feeding.

Multiple scenarios were calculated based on own measurements to answer that question under following assumptions:

- The nitrogen concentration in fresh wood chips is 3.21 g kg^{-1} dry matter
- The mass of wood chips is 250 kg per bulk cubic meter
- The filter module has a filter area of 5.06 m^2 and a biofilter material thickness of 0.25 m at a maximum filter load of 440 m^3 m^{-2} h^{-1} (starting situation)
- The filter module is designed for 25.3 fattening pigs with a design air rate of 88 m^3 h^{-1} AP^{-1} (starting situation)
- The dry matter content of the wood chip layer per module is 284.6 kg and remains unchanged during operation
- The nitrogen increase in the biofilter material is 0.096 g kg^{-1} d^{-1} with proper humidification

The results of the calculations are presented in Table 5. The current situation corresponds to an emission factor of 3.64 kg NH_3 AP^{-1} a^{-1} and 3.0 kg N AP^{-1} a^{-1}, respectively, and a maximum filter load of 440 m^3 m^{-2} h^{-1}. In scenario 1 a nitrogen reduction of 20 % via feeding is calculated. In scenario 2 the thickness of the biofilter layer has also been increased in addition from 0.25 to 0.50 meters. In scenario 3 the nitrogen reduced feeding, a filter layer thickness of 0.5 m and a reduction of the filter load from 440 to 330 m^3 m^{-2} h^{-1} is calculated.

Table 5: Achievable nitrogen reduction with suitability-tested single-stage biofilters with nitrogen reduced feeding, various process engineering adaptions and an annual change of the biofilter material

Parameter	Current situation	Scenario 1	Scenario 2	Scenario 3
N emission kg AP^{-1} a^{-1}	3.0	2.4	2.4	2.4
N input kg N $modul^{-1}$ a^{-1}	75.84	60.72	60.72	45.60
N accumulation kg N $module^{-1}$ a^{-1}	9.80	9.80	19.60	19.60
N separation in % with annual change of the biofilter material	12.9	16.1	32.3	43.0

Szenario 1: 20% N reduction via feeding
Szenario 2: N reduction via feeding and doubling the thickness of the biofilter layer to 0.5 m
Scenario 3: N reduction via feeding, doubling the thickness of the biofilter layer to 0.5 m and reduction of the filter load from 440 to 330 m^3 m^{-2} h^{-1}

The scenarios show that the reduction of the nitrogen input via feeding with constant N accumulation in the biofilter would cause a slight improvement in the separation efficiency from 12.9 to 16.1%. A doubling of the biofilter layer thickness would enable a nitrogen reduction efficiency of 32.3% via doubling the nitrogen mass in the filter layer but this would still not be quite sufficient overall. Only the combination of the measures reduction of the N input via feeding, doubling of the filter layer height and reduction of the maximum filter load from 440 to 330 m^3 m^{-2} h^{-1} would ensure a sufficient N reduction with 43%.

Discussion

Single-stage biofilters are predominantly built for small and medium size pig farms. One of the reasons for this can be seen in the large space requirement for biofilters. For installations with 1,500 fattening pigs a filter area of 300 m^2 would be necessary. Other aspects are likely to be, in particular, the lower investment and operating costs for smaller installations compared with exhaust air scrubbers or multistage processes (DLG 2018).

The on-site inspections confirm at filter loads between 42 and 486 m^3 m^{-2} h^{-1} a secure elimination of process-typical raw gas smells. With this result evaluations of the DLG test report are also confirmed (DLG 2006). The relative humidity in the raw gas varied between 57 and 80% and the raw gas temperature values were between 14 and 28 °C. These results fit well with former investigations (VDI 2016).

Based on electronic logbook evaluations with coherent data of at least 365 days a mean capacity utilisation of 41.8% across the year was calculated related to the maximum load according to the manufacturer's specification. This value is lower than common characteristics which are given with about 50%. With regard to improved marketing opportunities, the reason for this might be probably the somewhat reduced number of animals in the stables (Haltungsform 2 – Stallhaltungplus 2022). Accordingly, the mean pressure drops were comparatively low with around 26 Pa.

An in-depth evaluation of the fresh water consumption of this biofilter type showed depending on calendar month values between 0.9 and 3.2 g m^{-3} raw gas whereby the 2-year average was 2.3 g m^{-3}. This value is significantly below previous recommendations (KTBL 2006), the consumption rates of the first DLG test (2006) and also below the findings of the second DLG test with 3.9 g m^{-3} raw gas. The mean value of 2.3 g m^{-3} results to a not inconsiderable extent from the comparatively low consumption rates of less than 1.5 g m^{-3} in the months December – February (Figure 4). It can be assumed that the earlier consumption determinations referred to shorter assessment periods and that the best possible humidification of the biofilters was ensured during the DLG tests.

The water consumption rates determined are mathematically sufficient to ensure an outlet air humidity of 90 %, in many cases even 95 %. However, a complete saturation with 100 % humidity was never achieved. The recommended relative humidity of 95 % (VDI 2016) was therefore not permanently secured in either the raw gas or in the outlet gas. This result is also understandable because these biofilters do not have a sump to collect and recycle excess water. An oversaturation of the biofilter material may also lead to a compaction of the filter material, an increase of the pressure drop (VDI 2016) and should therefore be avoided. Furthermore, the cleaning-active surface of the biofilter material can decrease if it is oversaturated with water and thus adversely affect the cleaning performance (VDI 2016).

The fresh water consumption of 13 in-depth evaluated biofilters showed a mean annual consumption of around 0.77 m^3 AP^{-1} a^{-1}. This value is quite realistic if one compares the water consumption of single-stage biotrickling filters (Hahne 2022). The fresh water consumption of this system was between 1.2 and 1.5 m^3 AP^{-1} a^{-1}. In view of the required and proven discharge of washing water in the amount of 0.45 to 0.57 m^3 AP^{-1} a^{-1} the fresh water requirement of biotrickling filters for evaporation would be 0.63–0.95 m^3 AP^{-1} a^{-1}.

Biofilter of the type described are not approved for ammonia reduction. The reasons for this are, in addition to strongly fluctuating separation efficiencies for ammonia, above all, the relevant formation of secondary trace gases during operation (Hahne and Pfeifer 2017). However, due to the annual change of the biofilter material, a certain N reduction is given. According to own calculations based on measured nitrogen enrichment in the biofilter material, N removal should be around 13 % if the biofilter material is continuously and sufficiently humidified and changed annually.

For livestock facilities within the scope of the new TA Luft (2021), in addition to the reduction of N emissions though optimized feeding (reduction of 20 %), a further NH3 reduction of at least 40 % must be achieved. The previous calculated N reduction of 13 % in proper operating biofilters is therefore far from sufficient.

Against this background effects of doupling the filter height in combination with a reduced filter load and a nitrogen reduced feeding were calculated. According to this, an N reduction of 43 % would be given when doubling the filter height in combination with a reduction of the filter load to 330 m^3 m^{-2} h^{-1}, if the filter material is properly moistened and changed annually. The pressure drop will increase by doupling the filter height and only partially compensated by the reduction of the filter load. The implementation of these measures would therefore require sufficiently pressure-stable and powerful fans.

The doupling of the filter layer height, however, should be possible because the pressure drops measured during the tests were in the range of 25.6 ± 20.3 Pa (Table 2). Furthermore, ist may be necessary to increase the freeboard somewhat to be able to accomodate double the layer thickness.

Conclusions

The investigations have shown that single-stage biofilters secure a very good odor reduction and work predominantly good in agricultural practice. However, the humidification was not sufficient for some biofilters and must therefore be increased. The fresh water consumption should secure a outlet humidity of 95 %. With this specification calculations showed that the water consumption in pig fattening should be at least 0.77 m^3 AP^{-1} a^{-1} in the annual mean. During the summer months the mean fresh water consumption is higher by a factor of 2.3. Furthermore, the monthly average air rate is 38 % higher than in winter so that the additional consumption of water in summer can be higher than in winter by a factor of 3.2. The humidification control of biofilters should be checked accordingly and adapted if necessary. As own calculations show, the nitrogen separation of single-stage biofilters is insufficient at around 13 % with standard feeding, proper operation and annual change of the biofilter material with regard to the implementation of the new TA Luft. This is based on the fact, in addition to a nitrogen reduction of 20 % via feeding, a further reduction of 40 % in ammonia emissions (corresponds to an N-reduction of 33 %) must be ensured.

In order to be able to reliably achieve this reduction, doubling the filter layer thickness, reducing the filter load to 330 $m^3 m^{-2} h^{-1}$and an annual change of the filter material would be necessary in addition to the reduction via feeding.

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