Removal efficiencies in full-scale biotrickling filters used to clean pig house exhaust air

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Abstract: In this study, we tested the performance and perspectives of four full-scale biotrickling filters based on Leca® (Light Expanded Clay Aggregates), a mechanically stable, non-degradable filter media, known to absorb odorous compounds such as H2S and methanethiol. The four filters varied in: filter thickness, carrying media, and the presence of dust filters. Biological Leca® filters, operated with EBRT between 1.7-8.9 s, were found to be capable of reducing NH3, H2S and odour, from a pig house, by up to 96%, 81% and 80%, respectively. Clogging was observed to occur after approximately 100 days, however the installation of a dust filter was observed to minimize this problem.

Keywords: Biotrickling filters, odour, ammonia, full-scale, pig house exhaust air, Denmark

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1 Introduction

In recent decades, global pork production has been increasing rapidly, resulting in an increased emission of odorous compounds and nutrients. Emissions of odour and ammonia are a known nuisance/pollutant to those living in the vicinity of pig farms (Schiffman et al., 1995), leading to increased pressure to find technical solutions. Biological filtration (bio/biotrickling filters) currently seems to be the most cost-effective technology for removing odorous compounds from the exhaust air (Chen and Hoff, 2009; O'Neill et al., 1992). The basic principle of biological air filtration is to lead the air through a carrying media on which a living biomass degrades the air content of various compounds and particles. The cost-effectiveness of biological filters (bio/biotrickling filters) is closely related to the filter carrying media which preferable satisfy several characteristics including (Andreasen and Poulsen, 2013; Chen and Hoff, 2009; Delhomenie and Heitz, 2005; Swanson and Loehr, 1997):

1) a high specific surface area - promotes good gas/biofilm exchange

2) the presence of available intrinsic nutrients - promotes biological growth

3) high moisture holding capacity - promotes media absorption capacity and active microorganisms

4) a high porosity/large pore size - promotes low pressure drop and homogeneous gas distribution

5) structural integrity - promotes resistance to media compaction

Organic carrying media such as compost, peat, woodchips, bark mulch and mixtures of these are often applied as carrying media in biological filters as they satisfy of the described characteristics, but with the main drawback being degradation of the organics comprising the bed (Chen and Hoff, 2009; Delhomenie and Heitz, 2005; Phillips et al., 1995; Scotford et al.,1996; Swanson and Loehr, 1997). An exception for this is woodchips which seems mechanically stable and therefore relatively robust when it comes to compaction and the associated

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pressure drop (Phillips et al., 1995), at least until the media becomes degraded.

In contrast to organic media, inorganic media are not a subject to degradation and the associated compaction, on the downside this kind of carrying media may lack proper nutrient supply for the microbes, why inorganic media need an external nutrient supply to function properly (Swanson and Loehr, 1997). For pig house exhaust air such nutrient supply could most likely be the exhaust air itself as this is known to contain high ammonia levels.

Though inorganic media are generally not affected by degradation, it is still highly affected by pore clogging caused by dust and biomass accumulation (Andreasen et al., 2011; Morgan-Sagastume et al.,, 2001; Ryu et al., 2010). An inorganic, mechanically stable media may therefore easily reach the limits for its operational pressure drop unless its accumulation of dust and biomass are addressed properly. Though many studies considered the clogging of biofilters (Andreasen et al., 2011; Delhomenie et al., 2003; Morgan-Sagastume et al., 2001; Ryu et al., 2010) full scale clogging studies seems quite scarce. Laboratory studies have shown clogging to be easily reversed by simply stirring the media (Delhomenie et al., 2003; Morgan-Sagastume et al., 2001; Ryu et al., 2010) unfortunately such mechanical treatment likely complicates in larger scales. In addition backwashing the media or limiting/controlling the supply of nutrients, in the form of nitrogen, have been shown to reduce backpressure created by biomass accumulation (Delhomenie et al., 2003). Again this seems problematic for full scale biological filters cleaning pig house exhaust air as: 1) backwashing 20-40 cm filters may simply just move the accumulated mass from the front and into the middle of the filter, 2) the nutrient supply cannot really be controlled as the main source of nitrogen most likely are the pig house exhaust air itself.

An inorganic, relatively cheap, mechanically stable and non-degradable filter media, Leca® (Light Expanded Clay Aggregates), has recently been found to remove H_2S and methanethiol by chemisorption (Tabase et al., 2013). This media therefore expels several highly valued carrying media properties of an odour/ammonia removing filter.

The objective of this study was to clarify if biological trickling filters based on Leca® could provide acceptable: operation time/ stable pressure drop, ammonia removal and odour removal, when applied for cleaning of pig house exhaust air.

In addition to this performance test a practical solution to filter clogging in the form of a dust filter were also be tested.

2 Materials and methods

2.1 Set-up

2.1.1 Media

The filters used in this study are all based on 10-20 mm Leca® (Light Expanded Clay Aggregates) with an estimated external specific surface area of 270 m^2/m^3 (assuming an ellipsoid shape and a smooth surface). This media was either applied directly or after mechanical treatment (to increase surface roughness). These will be denoted as NT (Non-Treated) and MT (Mechanically-Treated).

2.1.2 Filters 1 and 2

Two filters, constructed by Saint-Gobain Weber A/S, were installed vertically outside a pig production facility and operated by the Danish Food and Agricultural Council, Pig Research Centre. The filters were hollow with an inner diameter of 1.45 m, a height of 2.45 m and a wall thickness of either 0.2 m (Filter 1) or 0.4 m (Filter 2). The filter walls were supported by an inner and outer grid (Figure 1).

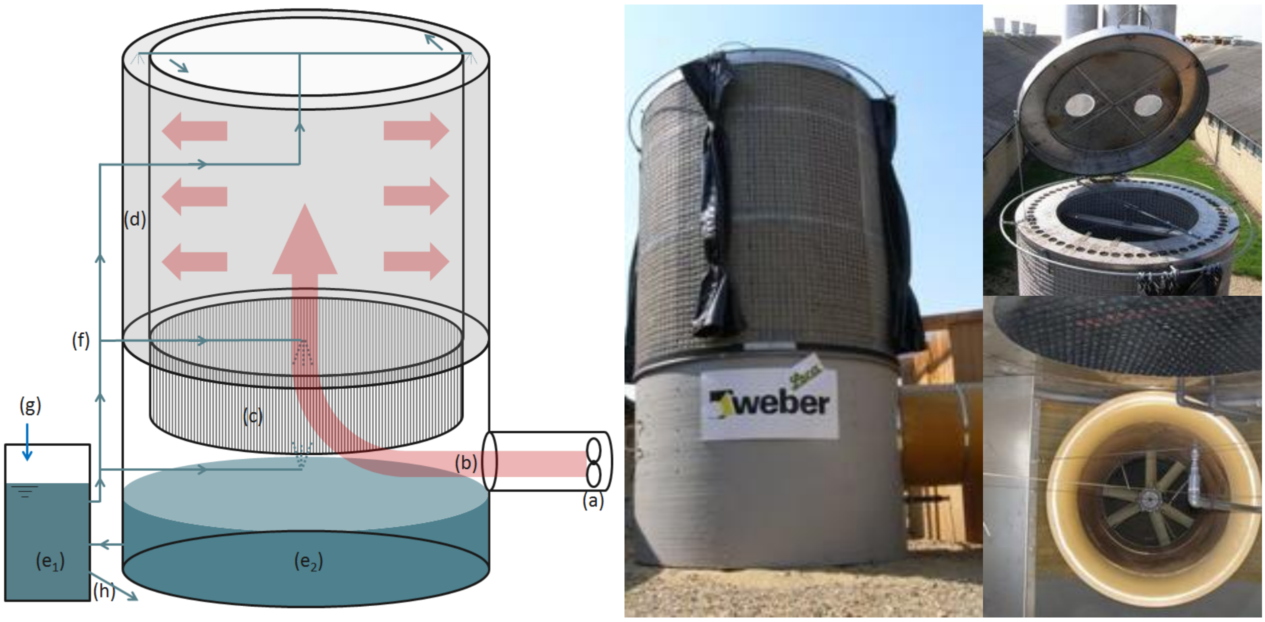

Figure 1 Diagram and pictures of the Leca®-based biofilter

(a) ventilation fan, (b) contaminant airflow, (c) dust filter (Filters 3 and 4), (d) Leca® filter media, (e1) recirculating pond receiving overflow from (e2) water catchment and sedimentation area (only Filters 3 and 4), (f) recirculating water irrigation system, (g) freshwater supply and (h) water drainage

The grids consisted of an outer 5 x 50 x 50 mm stainless steel grid and an inner 8 mm plastic grid. The empty grid walls were filled with 10-20 mm MT Leca® pellets.

Filters 1 and 2 were initiated in the beginning of July 2010 (without inoculation), and their performance was tested based on exhaust air from two batches of finishers in the period 1 August - 15 December 2010. The performance tests during batches 1 and 2 will be referred to in this text as period 1 and period 2, respectively.

Each filter wall was continuously irrigated by a rotating bar at the top of the filters. Settlements in the flow-controlling valves complicated a steady irrigation flow. Therefore, the valves were continuously adjusted manually to stabilise the flow to approximately 800 L/h in performance period 1 and 400 L/h in performance period 2.

Irrigation water was taken from the recirculating pond (600 L) of each filter. Fresh water was automatically added to the recirculating ponds at a low water level, while drainage was performed manually at conductivities of 10-15 mS/cm. During the tests, the filters treated an identical airflow of 1500-6000 m^3/h.

2.1.3 Filters 3 and 4

Filters 3 and 4 were identical to Filter 2 except for a few dissimilarities. Both bio trickling filters had a horizontal FKP319 filter (Gea 2H Water Technologies, Northampton, UK) installed as a dust filter at the air inlet at the bottom of the filters. The installed dust filters were 30 cm thick and had a diameter of 1.2 m, void ratio >97% and a specific surface area of 150 m^2/m. Each dust filter was constantly irrigated with a flow of approximately 1500 L/h by two nozzles (TF14, 120°, BTE, USA), one installed at the top and one at the bottom of the filters. Water was supplied from the recirculation pond. Both filters had a wall thickness of 40 cm, but, whereas Filter 3 was filled with MT Leca® (similar to Filter 2), Filter 4 used NT Leca® as filter material. Drainage was controlled automatically based on conductivity.

Filters 3 and 4 were initiated on 1 May 2011 (without inoculation), and their power and water consumption were monitored until February 2012. Filter performance tests were conducted during August - October 2011.

An overview of the filter set-ups used in this study, including choice of material, wall thickness, operation period, performance test period and presence of dust filter, is given in Table 1.

Table 1 Characteristics and operation/performance periods of the four filters. "-" indicate time frames while"," indicates individual dates

Filter	Leca® type	Filter wall	Dust filter	Operation period		Performance test period	
1	MT	20 cm	-	P1	12^{th} July-2010 – 8^{th} November-2010	P1	NH_3+H_2S : 7/9-2010,15/9-2010 Odour : 7/9-2010, 15/9-2010
2	MT	40 cm	-				
1	MT	20 cm	-	P2	16^{th} November-2010 – 15^{th} December-2010	P2	NH_3+H_2S : 16/11- 2010- 6/12-2010
2	MT	40 cm	-				
3	MT	40 cm	+	P3	1^{st} May5 2011- 1^{st} February2 2012	P3	NH_3+H_2S : 31/8-2011 – 10/10-2011 Odour: 8/9-2010, 12/9-2010, 19/9-2010, 26/9-2010, 3/10-2010, 10/10-2010
4	NT	40 cm	+				

2.2 Measurements

2.2.1 Physical measurements

Biotrickling filter performance parameters were monitored throughout the performance test. Airflow was continuously monitored using a Fancom fan wheel anemometer (Fancom, Panningen, Netherlands) while the pressure drop across the filters was measured manually using a TSI VelociCalc 8386 (TSI, Minneapolis, USA). Water and power consumption were monitored by a water meter and a watt-hour meter, respectively.

2.2.2 Chemical measurements

Hydrogen sulphide was measured manually in triplicate in both the inlet and outlet air using a Jerome 631-XE (Arizona Instrument LLC, Chandler, Arizona). Ammonia was measured by single measurement in both the inlet and outlet air using Kitagawa gas detection tubes (105SD) (Kitagawa, Kanagawa, Japan). pH and conductivity were measured manually for Filters 1 and 2 using an Eutech PCD 650 (Thermo Fisher Scientific Inc., Massachusetts, USA), while in Filters 3 and 4 a JUMO CTI-500 transmitter (JUMO, Fulda, Germany) was used for continuous conductivity measurements.

2.2.3 Odour measurements

Odour was measured by olfactometry according to the "CEN EN 13725:2003" standard, with least four panellists who uses the yes/no method to estimate the odour detection threshold of gaseous samples using Ecoma olfactometers.

For Filters 1 and 2, odour measurements were performed on 7 September 2010 and on 15 September 2010 by taking two inlet and two outlet measurements, sampled in Nalophan bags over a period of 30 minutes and analysed within 24 hours at the Danish Meat Research Institute, Roskilde, Denmark.

For Filters 3 and 4, odour measurements were performed on six measurement days between 8 September 2011 and 10 October 2011 using a similar procedure, although the samples were analysed at LUFA North-West, Germany.

3 Results and discussion

3.1 Pressure drop

Pressure drop was found to increase at increasing flow rates following a second order relationship (Figure 2a) in accordance with previous studies (Andreasen et al., 2012; Andreasen and Poulsen, 2013; Ergun, 1952; Macdonald et al. , 1979; Poulsen, Minelgaite et al., 2013).

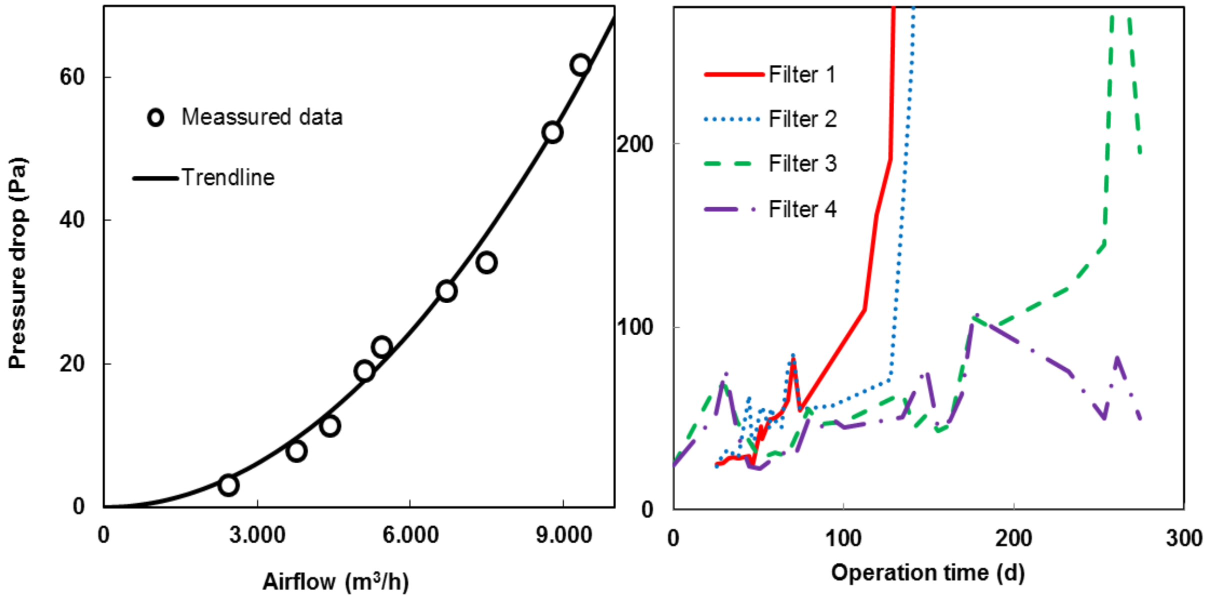

Figure 2(a) Pressure drop as a function of airflow in Filter 2, prior to initiation. The trend line represents Equation 2 with K = 6.797. (b) Pressure drop corresponding to 6000 m^3/h^*. *Pressure drop measurements with flow > 30% of 6000 m^3/h were converted based on, Equation 2, to represent a flow of 6000 m^3/h. Since this procedure assumes viscous forces to be insignificant for the total pressure drop, pressure drop measured at low velocity may lead to overestimated "6000 m^3/h equivalent pressure drops", inducing scatter in the figure.

The relationship between flow and pressure drop in biotrickling filters and other porous media (Q-ΔP relationship) is known to be constituted by viscous and inertial forces (Andreasen et al., 2012; Andreasen and Poulsen, 2013; Ergun, 1952; Macdonald et al., 1979; Poulsen et al., 2013) as described by the Forcheimer equation (Forcheimer, 1901) (Equation 1),

$$\frac{\Delta P}{L} = \frac{\mu}{k_a}\frac{Q}{A_C} + C_f\rho\left(\frac{Q}{A_c}\right)^2 \qquad (1)$$

where ΔP is the pressure drop (Pa) across the media, μ is air viscosity (Pa s), Q is the volumetric air flow (m^3/s), A_c (m^2) is the cross sectional area of the filter perpendicular to the flow direction, ρ is the air density (kg/m^3), and finally k_a and C_f, which are the porous media air permeability (m^2) and form coefficient (L/m), both known to be dependent on the characteristics of the porous media. At higher velocities, the viscous forces become insignificant (compared with the inertial forces), causing the Q-ΔP relationship to be described by Equation 2,

$$\Delta P = Q^2 \cdot K \qquad (2)$$

where K is an aggregated constant, ($C_f \cdot \rho \cdot A_c^{-2}$), unique for a given set of filter characteristics. As Equation 2 fitted the data well, the inertial forces seem to be dominant for the observed pressure drops, as seen in similar studies (Andreasen and Poulsen, 2013; Macdonald et al., 1979).

The filter media pressure drop for Filters 1 and 2 was found to increase non-linearly over time (Figure 2b). Since Leca® is a mechanically stable, non-degradable media, this increase was most likely due to the accumulation of dust and biomass, as observed in previous studies (Andreasen et al., 2012; Morgan-Sagastume et al., 2001). The pressure drop for

Filters 1 and 2 was found to be unacceptably high after approximately 100 days of filtration.

Filters 1 and 2 were found to constitute a similar pressure drop despite having different filter wall thicknesses. This observation indicates that the accumulation of dust and biomass dominates the observed pressure drop, since pressure drops across clean porous media are generally believed to be directly proportional to the media length (Darcy, 1856; Ergun, 1952; Forcheimer, 1901; Macdonald et al., 1979). Recent studies have found minor losses at the entrance of porous flow-conducting media (Poulsen et al., 2013). However, since this minor loss has been found to constitute only up to 10% of the clean media pressure drop (based on similar media), this is not assumed to be a dominant factor in the observed similarities. In contrast, the accumulation of biomass could easily cause such similarities, since biomass is known to mainly affect ΔP in the first part of the filter (Andreasen et al., 2012; Morgan-Sagastume et al., 2001).

The dust filter installed in Filters 3 and 4 seemed to increase the operation time considerably, as can be seen from the relatively low pressure drop for Filter 3. However, the pressure drop still increased in the later period. For Filter 4, the pressure drop remained acceptable throughout the test period of filter 4 (274 days). The observed differences between Filters 3 and 4 are probably caused by the presence of clay dust as well as a reduced particle size of the mechanically treated Leca®. Dust is known to clog media pores, while reduced particle size facilitates reduced pore size, both phenomena causing an increased airflow resistance of the media (Andreasen et al., 2012; Ergun, 1952; Pugliese et al., 2013). Based on these observations it is expected that installed dust filters in combination with NT-Leca® media can provide biotrickling filters with operation periods > 1 year.

3.2 Filter efficiency

All filters were observed to reduce the emission of NH_3, H_2S and odour (Figure 3).

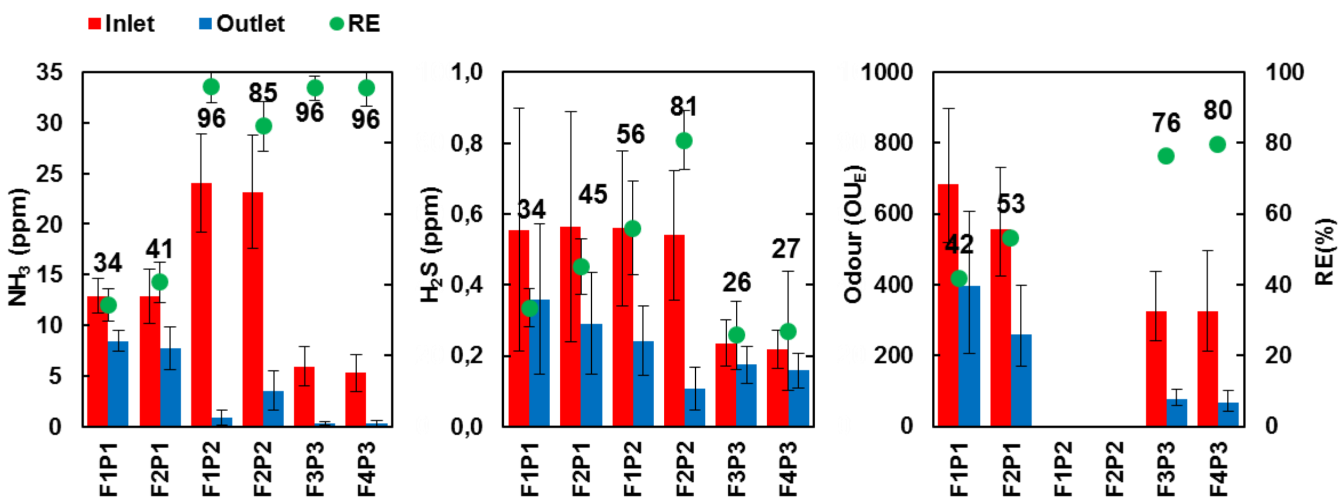

Figure 3 Inlet concentrations, outlet concentrations and removal efficiency (RE, also shown as data labels) for the four filters. F1, F2, F3 and F4 indicate Filters 1, 2, 3 and 4, while P1, P2 and P3 indicate periods 1, 2 and 3, respectively. Three pollutants are shown: (a) NH_3, (b) H_2S, and (c) OU_E. Error bars of NH_3 and H_2S indicate standard deviation. Due to the high variation in odour measurements error bars in this plot are set to represent the 95% confidence interval instead

During the first period, both filter1 and filter 2 had measurable removal efficiency (RE) of ≈ 35-50% for all measured pollutants. The removal efficiency was enhanced during the second period, probably due to an increased biomass accumulation and/or an increased retention time, as P2 measurements were conducted under winter conditions in contrast to P1 (Table 2).

Table 2 Ventilation rate and corresponding Empty Bed Retention Time (EBRT), based on the volume of the Leca® filter, during performance measurements (concentrations of NH_3, H_2S and odour)

Filter	Performance period	Ventilation rate, m^3/h		EBRT(s)	
		NH_3/H_2S	Odour	NH_3/H_2S	Odour
1	P1	4784	5235	1.9	1.7
2		4593	5175	4.5	4.0
1	P2	1884		4.9	
2		2300		8.9	
3	P3	4795	5213	4.3	3.9
4		4853	5663	4.2	3.6

The prolonged filter length of Filter 2 (compared with Filter 1) was not found to significantly increase the removal of NH_3 during the first two periods. In contrast, H_2S seemed to be greatly affected by the filter length in both periods. The fact that different mechanisms affect NH_3 and H_2S removal could be the cause of this discrepancy. In a biotrickling filter, NH_3 is metabolized by the present biomass. Since the first part of a biological filter typically has a stronger density of biomass (Andreasen et al., 2012; Morgan-Sagastume et al., 2001), this part has a higher potential for NH_3 degradation. After proper filter initiation time, the first part is likely to dominate the NH_3 degradation, making the later part insignificant for the NH_3 removal. This also applies to H_2S, although H_2S most likely also are a subject to chemisorption to the Leca® media, as the Leca's® content of iron and other oxidized metals constitutes an oxidation potential (Tabase et al., 2013). Oxidation products of e.g. H_2S, Methane thiol and other gaseous compounds will likely in time occupy the active sorption sites of Leca® and prevent further chemisorption (Tabase et al., 2013). However, when applied in a biological filter, microorganisms may constitute a continuous drain for of soluble reaction products as well as a re-generation of the media(Tabase et al., 2013). In this case the non-biological (but biological regenerated) potential for H_2S would increase with increasing filter length, which could explain why the prolonged filter length of Filter 2 increases H_2S RE but not NH_3 RE.

For the construction of Filters 3 and 4, a wall thickness of 40 cm was chosen, since this resulted in the best performance and an acceptable pressure drop.

Both Filters 3 and 4 showed NH_3 RE >95%, approximately 20% of which was removed by the dust filter (data not shown). The fact that NH_3 is highly water soluble is probably the main reason for the dust filter to acts as an air scrubber for this pollutant.

Despite this increased removal of NH_3, only a limited removal of H_2S was observed for Filters 3 and 4, and this was lower (not significantly) than the observed H_2S removal of Filters 1 and 2 in P1. For these filters, the observed H_2S concentration between the dust filter and the Leca® filter was only eight percent lower than the observed inlet concentration (data not shown), indicating that the "scrubber effect" was less pronounced for H_2S than that observed for NH_3, most likely due to the low water solubility of H_2S.

The low H_2S RE of Filters 3 and 4, compared with the short (20 cm) Filter 1, indicates that the previously identified parameters "Chemisorption" and "EBRT" are insufficient to describe the complete H_2S RE. The presence of biomass in the first part of the filters therefore seems to be a crucial parameter for the removal of both H_2S and NH_3.

Despite the reduced H_2S removal, Filters 3 and 4 demonstrated the best odour RE of the four filters tested in this study. However, since odour samples during Period 3 were analysed at a different laboratory (LUFA) than the samples from the first period (DMRI), the odour removal performance cannot be compared across periods, since quantitative olfactometry measurements are known to have a high variation when comparing different laboratories (Jonassen et al., 2014; Jonassen et al., 2012).

The observed RE of up to 96%, 81% and 80%, for NH_3, H_2S and odour respectively, indicated the external supply of nutrients from the exhaust air itself to be sufficient to support appropriate microbiological activity on the non-organic Leca® media in the bio trickling filters.

In comparison has RE's of NH_3 in bio trickling filters been found to be in the range of 35-90% while odour typically are removed by an efficiency of 37%-49% (Melse and Ogink, 2005). The lower ends of these ranges are further believed to be represented by filters with NH_3 or NO_2^- inhibition. Though the main observation in this study seems within these ranges the odour removal of filter 3 and 4 seems to stand out. One possible explanation for this could be the chemical properties of Leca® as it has been found to convert methanethiol into less odourous compounds such as dimethyl disulphide and dimethyl trisulphide (Tabase et al., 2013).

Another possible reason could be the relatively high EBRT during odour measurements in this test, as the minimum EBRT (based on a maximum flow of 6000 m^3/h) of filter 3 and 4 were relatively high (3.4 s) compared to the minimum EBRT of the filters referred to by Melse and Ogink (2005) (0,5-2,3). Studies of organically based (compost and woodchips) biofilters (non-moving water phase) with EBRT of roughly 5s has been estimated able to achieve an average RE of 81%, 78% and 78% for NH_3, H_2S and odour, respectively (Chen and Hoff, 2009). This EBRT are closer to the ones in this study and the RE levels of NH_3 and odour are also quite similar to the observed RE of filter 3 and 4. In contrast could neither filter 3 nor 4 could achieve a H_2S removal in this area, which could be due to a relatively high irrigation rate in these filters as a thick water film may prevail the low soluble H_2S to reach the active sites of the Leca® media(Tabase et al., 2013).

3.3 Secondary parameters

During the test periods, the fan power consumption, ranging between 15.5 and 25.2 kWh/d, was observed (Table 3).

Table 3 Operation parameters for the four tested biofilters

Filter	Operation Period	Power consumption		Water		Water flow		Conduc-tivity	pH
		Fan	Pump	Consumption	Drainage	Leca® filter	Dust filter		
		kWh/d	kWh/d	m^3/d	m^3/d	L/d	L/d	ms/cm	pH
1	P1	25.2	16.1	0.114	0.007	800	-	10.2*	7.2*
2		25.2	15.8	0.225	0.017	800	-	14.7*	7.1*
1	P2	16.6	16.9	0.199	0.003	400	-	8.1	7.1
2		16.5	16.7	n.a.	n.a.	400	-	24.2	7.4
3	P3	15.5	16.1	0.378	0.167	900	1500	9.5*	7.2*
4		17.7	14.7	0.183	0.032	900	1500	10.3*	7.2*

Note: * In Periods 1 and 3, conductivity and pH were averaged after the filter start-up phase defined as 1/9-2010 and 31/8-2011, respectively.

This high power consumption was mainly caused by the use of an oversized fan. Simulations using the ventilation simulating program "StaldVent 5.0" (DXT, 2014) found that the power consumption for ventilating air through the filters was capable of being reduced to 6.4 kWh/d/filter, if connected to 10% partial air cleaning (assuming a pressure drop of 60 Pa across the filters). Only filters with a dust filter (Filters 3 and 4) had a stable pressure drop. These filters had average power consumption for water circulation of 15.4 kWh/d/filter. Due to leakages and overflow, Filter 3 had a higher water consumption/drainage than Filter 4. The levels observed in Filter 4 are therefore assumed to be the most representative of the perspectives of the Leca® filter.

4 Conclusion

In this study, we tested the performance and perspectives of four full-scale biotrickling filters based on Leca® (Light Expanded Clay Aggregates), a mechanically stable, non-degradable filter media. Biological Leca® filters, operated with EBRT between 1.7-8.9 s, were found to be capable of reducing NH_3, H_2S and odour, from a pig house, by up to 96%, 81% and 80%, respectively. The supply of nutrients, including nitrogen, from the exhaust air therefore seems capable of supporting microbial activity.

Clogging was observed to occur after approximately 100 days, but the installation of a dust filter was found to minimize this problem and to keep the pressure drop acceptable throughout the test period (274 days).

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