Minnesota Pork Board Research Grant Final Report

I. Project title: Energy Efficient Biofilter Media

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Principal Investigator: Kevin A. Janni
Institution: University of Minnesota
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II. Abstract

Wood chips and bark mulch are commonly used biofilter media. These organic materials degrade quickly and replacement of the media is required every 2 to 5 years. In this study, airflow characteristics and gas reduction efficiencies of two alternative biofilter media (pine nuggets and lava rock) with high porosity and potentially longer service lives were evaluated at three empty bed contact times (1, 3, and 5 s) and two moisture levels (82 and 90% relative humidity). Lava rock had a lower pressure drop across the media and maintained higher media depth during the study. Higher gas reduction efficiencies were measured for the lava rock. Percent gas reduction efficiencies were highest for lava rock at 5 s empty bed contact time and 90% relative humidity. The reduction efficiencies at these conditions were 56, 88, 87, 25, and 0.7% for ammonia (NH_3), hydrogen sulfide (H_2S), total reduced sulfur (TRS), methane (CH_4) and nitrous oxide (N_2O), respectively. In some cases, biofilters generate N_2O rather than reducing N_2O emissions. No N_2O generation was measured from the lava rock and pine nuggets. Odor reduction up to 48% was observed but was not consistent.

III. Introduction

Gas phase biofilters have been used to reduce odor and gas emissions from swine facilities (Nicolai and Janni, 2001a; Janni et al., 2009; Deng et al., 2009). Desirable biofilter media properties include suitable environment for microorganisms (nutrients, moisture, pH, temperature), large surface area to maximize sorption capacity, high pore space to maximize empty bed contact time (EBCT), minimal pressure drops to reduce operating energy requirements, and low bulk density to decrease media compaction. The pressure drop versus airflow rate relation is an important media characteristic. Low pressure drop is preferred to minimize energy requirement for passing target air through the media. Low cost, local availability and sufficiently long lifespan are additional desirable properties (Williams and Miller, 1992; Swanson and Loehr, 1997; Nicolai and Janni, 2001a; Chen and Hoff, 2009). Wood chips, bark mulch, compost and the mixtures of these are commonly used media. They are generally locally available and inexpensive (Nicolai and Janni, 2001a; Morgan-Sagastume and Noyola, 2006; Chen and Hoff, 2009). Wood chips and bark mulch increase surface area and porosity while compost provides microorganisms and micronutrients. One problem with these common organic materials is that they degrade easily which decreases porosity and increases compaction over time (Nicolai and Janni, 2001a; Chen and Hoff, 2009; Janni et al., 2009). Media replacement every 2 to 5 years is a significant investment in materials, time and labor. Also there is an operational downtime as the media is replaced and a lag time until the new media acclimates and removal efficiencies reach previous levels (Langolf and Kleinheinz, 2006). An alternative biofilter media that will address concerns about the media compaction over time and large footprint required by flat-bed biofilters is needed. With proper moisture content and empty bed contact time, a new media would help swine producers to lower their electrical fan operating costs and save energy and time.

The new media could have lower odor reduction efficiencies than those of commonly used media. Early studies of acclimated biofilters achieved 90 to 95% odor removal treating pit fan exhaust air (Nicolai and Janni, 1997; Nicolai and Janni, 1999). Experience using Odor from Feedlot Setback Estimation Tool (OFFSET) (Jacobson et al., 2005; Guo et al., 2005) showed that 90 to 95% odor removal was not always needed. In many cases, partial odor removal combined with dispersion was sufficient to reduce odor levels below detection levels before reaching receptors.

Pine nuggets and lava rock are two alternative biofilter media. They have large porosity and potentially long service lives. Pine bark was used to treat odors and gases from animal rendering process (Luo and Lindsey, 2006) and lava rock was used to treat gases from press wood production (Langolf and Kleinheinz, 2006). Janni et al. (2009) tested cedar chips, wood mulch, pine nuggets, lava rock, western pine bark, and wood shreds and reported that among these six media pine nuggets and lava rock had the lowest pressure drops.

IV. Objectives

In this study, two biofilter media (pine nuggets and lava rock) with large porosity and potentially long service lives were used to treat air from a swine manure and wastewater storage pit. The objective of the study was (i) to evaluate media characteristics and (ii) to evaluate gas phase reduction efficiencies of pine nuggets and lava rock at different operating conditions to find an alternative to commonly used biofilter media. The two media were evaluated based on their airflow characteristics and ability to reduce hydrogen sulfide (H_2S), total reduced sulfur (TRS), ammonia (NH_3), methane (CH_4), nitrous oxide (N_2O) and odor emissions at two moisture levels (low and high) and three empty bed contact times (1, 3, 5 s).

V. Procedures

Experimental set-up

Six biofilter columns (140 cm tall and 46 cm inside diameter) built from PVC (polyvinyl chloride) were used to treat air from a swine manure and wastewater storage pit between January and June, 2010 (Fig. 1). The media height was 71 cm and a stainless steel screen was placed 30 cm from the column base to support the media. Each column had an independent watering system and axial centrifugal fan (Continental Fan Manufacturing Inc., AXC150A, Buffalo, NY) so moisture content and EBCT of the columns could be controlled separately.

The watering system consisted of three Tygon tubing (0.63 cm O.D. and 0.158 cm wall thickness, US Plastic Corp., Lima, OH) loops. Small holes were made on the loops with a needle every 2.5 cm to spray water on the media. The biggest loop (40.6 cm diameter) was sitting on the top of the media. The medium (30.5 cm diameter) and small (15.2 cm diameter) loops were placed 30.5 cm below the top of the media. The small loop was placed inside the medium loop.

The three loops were used to reduce uneven moisture distribution (e.g., dry media across the column wall or dry media at the top and wet media at the bottom) with minimal airflow obstruction. The water flow rate supplying each column was 2 L/min and adjusted using separate flow meters (FL 818, Omega Engineering, Stamford, CT). The watering system for each column was controlled using an on-off timer (H3CR-F, Omron Electronics, Canada). The timers were set to provide water to the columns for 5 to 40 s every 2 h depending on EBCT and moisture content treatment.

The columns pulled air from a common plenum which was fed by the air from the surface of a swine manure and wastewater storage pit (Fig. 1). The pit was located in the Waste Treatment Building at the University of Minnesota, St. Paul Campus. It received flushed swine manure and wastewater every day.

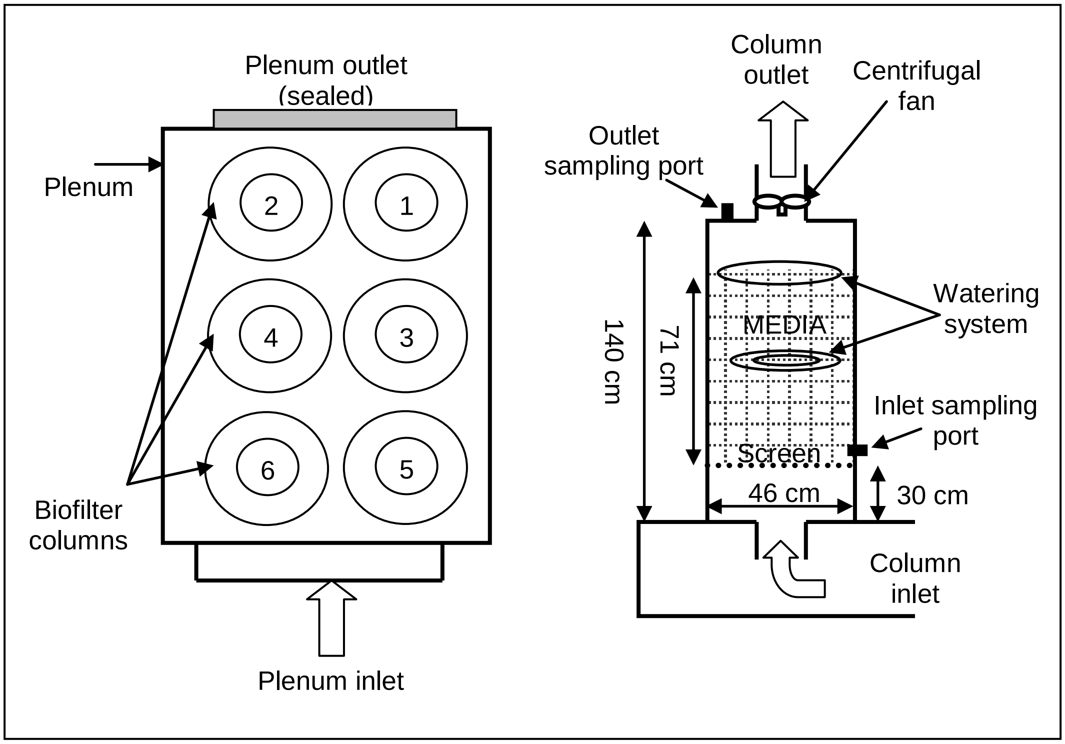

Fig 1. Top view of the plenum (left) and cross-sectional view of the biofilter columns (right)

Two biofilter media (pine nuggets and lava rock), three EBCT (1, 3, 5 s) and two moisture contents (low and high) were tested. Pine nuggets and lava rock were purchased from a local market. The media was acclimated for 4 months at high moisture content and 5 s EBCT before starting the experiments.

Treatment conditions were assigned to the six biofilter columns randomly. At the beginning of each round, the media inoculated with swine manure and compost was placed in the columns. The media was given one week to acclimate before gas and odor sampling was started. Gas sampling started in the second week of each round. Gas samples were collected from the column inlets and outlets (12 samples) twice a week for three weeks. Odor samples were collected in the third and fourth weeks of the round. A total of 12 odor samples were collected during each round. In the third week, six odor samples were collected from the inlets and outlets of three randomly selected columns. In the fourth week, six more odor samples were collected from the remaining three columns. After each round, the columns were emptied and small amounts of new inoculated media were mixed before the assigned columns were filled again for the next round. Small amounts of new media were added at the beginning of each round to replace media lost during mixing and handling and due to degradation.

Objective i: Measurement of media characteristics

Five media characteristics including pressure drop, porosity, particle size, density, and water absorption were measured. Media pressure drop versus the unit airflow rate was measured as described in Nicolai and Janni (2001b) and Janni et al. (2009). The media column was filled with media at the depths of 10, 20, 30, 40, and 50 cm and dropped 10 times from a height of 15 cm to settle the media. After filling the column and settling the media, the inlet air flow rate was measured with a vane anemometer (RVA801, Alnor, Shoreview, MN) and static pressure was measured with a pressure sensor (Setra, 267, Boxborough, MA) at six fan (Continental Fan, AXC150A, Buffalo, NY) settings (20, 30, 40, 60, 80, and 100% power).

Media porosity was measured using a bucket procedure described by Nicolai and Janni (2001b). The bucket was filled approximately one third of its volume and the media was settled by dropping ten times from a 15 cm height. The media level was marked and water was added to fill the voids up to the marked level. The media volume in the bucket was known and the water volume added to fill the voids was measured. Porosity (%) was found by multiplying the ratio of the water volume to media volume by 100.

Media particle size distributions were measured by using seven sieves with 38.1, 25.4, 19.05, 15.87, 12.7, 9.42 and 4.75 mm mesh sizes and a solid tray at the bottom. Samples weighing between 100 to 200 g were placed on the top sieve (the one with the largest mesh size) and shaken for five minutes with a sieve shaker (W.S. Tyler, Co., #13237, Mentor, OH). Media particle size distribution (%) was calculated by multiplying the ratio of the weight of the media on each sieve to total media weight by 100.

Media density was measured by filling 1 L glass container with media and weighing it. Density (kg/m^3) was calculated as the ratio of the weight of the media to 1 L.

Media water absorption capacity was measured by soaking media into water. The media weight was recorded and then water was added until the media was completely covered with water. The excess water was drained off and the weight of the absorbed water was measured. Water absorption capacity (%) was calculated by multiplying the ratio of the weight of the absorbed water to the weight of the initial media by 100.

In addition to these five media characteristics, biofilter column pressures were measured weekly with a pressure sensor (Setra, 267, Boxborough, MA) and final media depths of the columns were measured within ± 3 cm using a tape measure at the end of each round after opening the columns.

Objective ii: Measurement of gas phase reduction efficiencies

Fifty liter FlexFoil® bags (0.58 m × 0.9 m) equipped with single polypropylene fittings (SKC Inc., Eight Four, PA) were used to collect gas samples for analysis. A dual vacuum pump (model 2107CA18, Thomas, Sheboygan, WI) was used to pull air from the inlet and outlet of the columns simultaneously. The pump airflow rate was 5 L/min and the bags were filled 80% (40 L) in 8 min. The 40 L of sample air was necessary to measure five gases (H_2S, TRS, NH_3, CH_4, and N_2O) using different instruments. H_2S was measured with a pulsed fluorescence analyzer (450i, Thermo Electron Corporation, Franklin, MA), TRS was measured with a Jerome meter (631-X, Arizona Instruments, AZ), NH_3 was measured with a chemiluminescence analyzer (TEC 17C, Thermo Electron Corporation, Franklin, MA), CH_4 was measured with a back-flushed gas chromatography analyzer (TEC 55C, Thermo Electron Corporation, Franklin, MA), and N_2O was measured with an infrared analyzer (Teledyne API 320EU, San Diego, CA). The gas sampling procedure with FlexFoil® bags were reported in Akdeniz et al. (2010a).

Odor samples were collected inside 10-L Tedlar® bags (SKC Inc., Eight Four, PA). Two vacuum pumps (224-PCXR3, SKC Inc., Eight Four, PA) and vacuum boxes (Vac-U-Chamber, SKC Inc., Eight Four, PA) were used to simultaneously fill the bags from the inlets and outlets of the columns. Dynamic triangular forced choice olfactometer (AC'SCENT International Olfactometer, St Croix Sensory, Inc.) was used to analyze odor samples at the University of Minnesota Olfactometry Laboratory. All the samples were analyzed within 24 hours of collection to determine detection threshold (DT) following international olfactometry standards (ASTM, 2001; CEN, 2001). Odor DT was reported as odor units per cubic meter (OU/m^3). European odor concentrations (OU_E/m^3) were also calculated using 40 ppb n-butanol standard. The odor analysis procedures were reported in Jacobson et al. (2008) and Akdeniz et al. (2010b).

Percent reduction in gas and odor concentrations was calculated by dividing the difference between inlet and outlet concentrations by inlet concentration and multiplying this value by 100.

Quality control

Control EBCTs of the columns: Airflow rates through the columns were measured weekly using a vane anemometer (RVA801, Alnor, Shoreview, MN) and adjusted if the flow rates were off more than 5% from the rate needed to maintain the assigned EBCT.

Control moisture contents of the columns: Relative humidity of the columns was calculated by using dry and wet bulb temperatures in the inlet of the plenum and outlets of the columns. Dry and wet bulb temperatures were measured with a digital thermometer (HH12, Omega Engineering, Stamford, CT) weekly. Wet bulb temperatures were measured by wrapping a piece of wet gauze around the thermocouple and placing it in the airstream.

Statistical analysis

Experiments were run in triplicate and experimental conditions were assigned to six columns randomly during each round (Table 1). Statistical analyses were conducted using JPM software version 8.0.1 from SAS (SAS Institute Inc, Cary, NC). The data was log transformed and log transformed data had a normal distribution.

Media characteristics (porosity, density, and water absorption capacity) were compared using one-way analysis of variance (ANOVA) with the main effect of media type ($P<0.05$).

Percent gas reductions were measured six times for each replicate. Averages of the six measurements were calculated and percent gas reductions were compared using three-way ANOVA. The data was compared with the main effects of media type, EBCT, and moisture level. The interactions between the main effects (media type × EBCT, media type × moisture level, EBCT × moisture level, and media type × EBCT × moisture level) were also investigated ($P<0.05$).

Odor reduction efficiencies, final media depth and pressure drop values were compared considering the same main effects and interactions with the gas reduction efficiencies ($P<0.05$).

High and low moisture levels of the columns were compared using one-way ANOVA for both of the media at each EBCT ($P<0.05$). This test was done to check the success of moisture management. It was expected to find a significant difference between low and high moisture levels.

Table 1. Randomization table of the biofilter conditions (12 conditions × 3 replicates=36 runs were randomly assigned to six biofilter columns during each round)

Rounds → Columns ↓	1	2	3	4	5	6
1	PN, 5 s, low[1]	PN, 1 s, low	PN, 3 s, high	LR, 1 s, low	LR, 5 s, low	LR, 3 s, low
2	PN, 1 s, high	LR, 3 s, low	LR, 5 s, high	PN, 3 s, low	LR, 1 s, high	PN, 5 s, low
3	LR, 1 s, low	PN, 3 s, high	PN, 5 s, low	LR, 3 s, high	PN, 1 s, low	LR, 5 s, high
4	PN, 3 s, low	LR, 5 s, low	PN, 1 s, low	PN, 5 s, high	LR, 3 s, high	LR, 1 s, low
5	LR, 5 s, high	LR, 1 s, high	LR, 3 s, low	PN, 1 s, high	PN, 5 s, high	PN, 3 s, high
6	LR, 3 s, high	PN, 5 s, high	LR, 1 s, high	LR, 5 s, low	PN, 3 s, low	PN, 1 s, high

[1] PN and LR stands for pine nuggets and lava rock, respectively. 1, 3, and 5 s are the target empty bed contact times (EBCTs). Low and high are the moisture levels tested.

VI. Results

Objective i: Evaluate media characteristics

The average porosity, density and water absorption capacity of the media are listed in Table 2. No significant difference was found between porosities and water absorption capacities of the pine nuggets and lava rock. Porosities of both media were similar to the porosity of the wood chips (around 65%). The pine nuggets were found to be significantly less dense (around 250 kg/m^3) than the lava rock.

Unit static pressure drop versus airflow rate and particle size distribution of the media were shown in Fig. 2a and b. Lines that fit the data were plotted to show the trend for each media. Both media showed increasing pressure drop as the airflow rate increased but the pine nuggets demonstrated a greater pressure drop than lava rock (Fig. 2a). The wood chips usually had larger pressure drop values (up to 1,800 Pa/m).

Pine nuggets had more large particles; 40.8% (by weight) of the media was retained above the 38.1 mm mesh. The lava rock had smaller particles compared to pine nuggets with only 11.7% of the media retained above 38.1 mm mesh while 30.8% of the media was retained above 25.4 mm mesh (Fig. 2b). The wood chips usually had more small particles than the pine nuggets and lava rock (around 3.5% of the wood chips can retain above 38.1 mm mesh).

Pressure drop across the media ranged from 43.8 to 271 Pa (Table 3). Pine nuggets, shorter EBCT, and low moisture level showed higher pressure drop compared to lava rock, longer EBCT, and high moisture level, respectively. Some of these results were expected because the unit pressure drop versus airflow rate relation for pine nuggets shown in Fig. 2a was higher than for the lava rock. Columns with lower EBCT had higher airflow rates than those columns with higher EBCT since the media volume was initially the same. It was not clear why moisture level affected the pressure drop. The difference in moisture level was not expected to significantly affect pore size and airflow through the pores.

The initial media depth at the beginning of each round was 71 cm. The final media depth ranged from 61 to 71 cm (Table 3). The pine nuggets media depth declined in the columns during each round but the lava rock had little to no decline. The lava rock at the high moisture level had the highest final media depth while the pine nuggets at the low moisture level had the lowest final media depth. The organic media had more compaction. Settling and organic matter breakdown contributed to the lower final media depth of the pine nuggets compared to lava rock.

Table 2. Porosity, density and water absorption capacity (n=3)

Media	Porosity (%)	Density (kg/m^3)	Water absorption capacity (%)
Pine nuggets	68.2±2.6^{A}[1]	189.5±24.9^{B}	31.8±6.6^{A}
Lava rock	65.4±1.4^{A}	591.7±17.0^{A}	28.9±4.3^{A}

[1] Within each column, averages that are not connected with the same letter are significantly different (*P*<0.05).

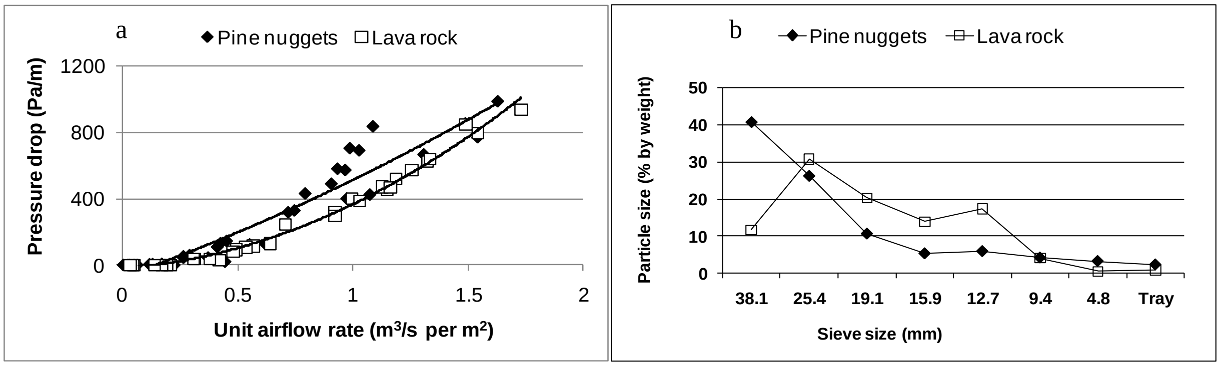

Fig. 2. Unit pressure drop versus airflow rate (a) and particle size (b) for pine nuggets and lava rock.

Table 3. Final media depths, achieved EBCTs, and pressure drops across the media

	Pine nuggets					
	Low moisture level			High moisture level		
Target EBCT (s)	1	3	5	1	3	5
Achieved EBCT (s)[1]	1.2	2.7	4.7	1.2	2.9	4.8
Final media depth (cm)	64.3±1.47	62.6±1.47	61.0±0.0	64.3±1.47	65.2±1.47	65.2±1.47
Pressure drop (Pa)	271±4.37	129±6.68	75.1±3.36	243.0±4.48	95.2±0.69	68.2±3.42
	Lava rock					
	Low moisture level			High moisture level		
Target EBCT (s)	1	3	5	1	3	5
Achieved EBCT (s)	1.2	2.8	4.9	1.3	3.1	5.1
Final media depth (cm)	65.2±1.47	65.2±1.47	65.2±1.47	71.0±0.0	70.3±1.47	70.3±1.47
Pressure drop (Pa)	239±2.91	68.1±3.40	43.8±2.41	196±0.88	61.0±1.20	24.0±1.33

[1] Achieved EBCTs were calculated as the ratio of the average airflow rates to the average media volume.

Objective ii: Evaluate gas phase reduction efficiencies

Inlet gas concentrations changed significantly during the six month sampling period that the study was conducted. The average, minimum and maximum inlet concentrations were reported in Table 4. The change in gas concentrations was due to the change in the organic content of the storage pit. Most of the time recycled water was used to flush swine barns but occasionally fresh water was used due to the breakdown of the water recycling pump. The pump broke down four or five times during the six month sampling period. When fresh water was used to flush the barns, the organic content of the storage unit was lower, which caused generation of fewer odors and lower gas concentrations.

Table 4. Average, minimum and maximum inlet gas concentrations

	NH_3 (ppm)	H_2S (ppm)	TRS (ppm)	CH_4 (ppm)	N_2O (ppb)
Average ±Stdev	2.6±0.33	108±63.0	111±71.1	31.0±10.7	428±22.2
Min-max	2.19-3.30	11-212	12-213	15.1-46.8	391-465

Percent gas reductions for all five gases at high and low moisture levels and 1, 3, and 5 s EBCTs were given in Fig. 3a-j. Percent gas reduction efficiencies for the high moisture treatment were shown on the left side and reduction efficiencies for the low moisture treatment were shown on the right side of the Fig. 3.

Percent NH_3 removal ranged from 32.7 to 55.6% (Fig. 3a and b). Significant differences were found between media, EBCT, and moisture levels. No significant interactions were found between these factors. Percent NH_3 reduction in columns with lava rock was significantly higher than with pine nuggets. Percent NH_3 reduction at the high moisture level was also significantly higher than at the low moisture level. No significant difference was found between 1 and 3 s EBCTs but percent NH_3 reduction at 5 s was significantly higher (Fig. 3a and b).

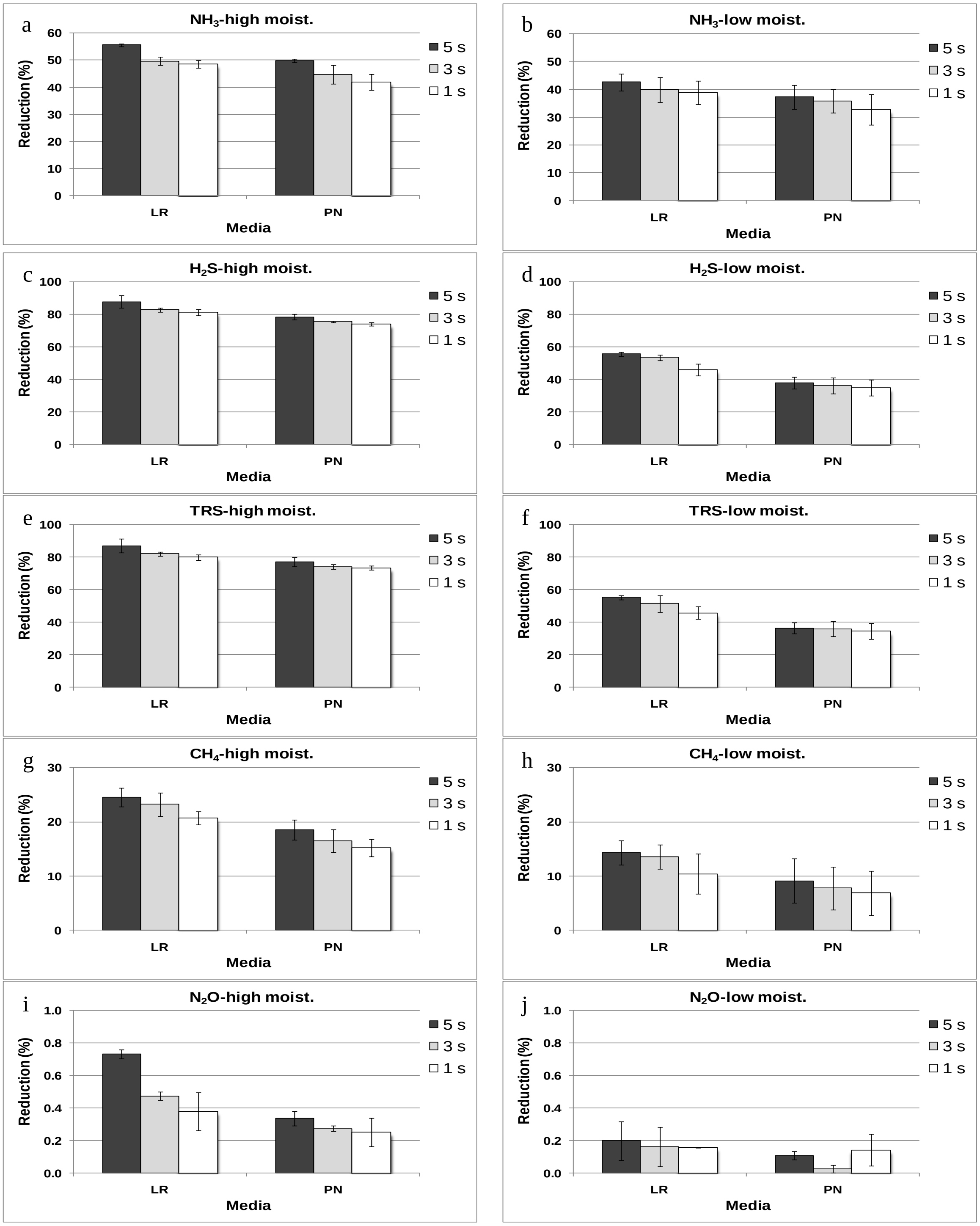

Fig. 3. Average percent reduction of the gases at low and high moisture levels and 1, 3, and 5 s empty bed contact times (3 replicates × 3 weeks each replicate× 2 measurements per week=18 measurements)

Percent H_2S and TRS removal ranged from 35.0 to 87.9% and from 34.4 to 87.0%, respectively (Fig. 3c, d, e, and f). Significant differences were found between media, EBCT, and moisture levels. Also, a significant interaction was found between media and moisture level. The H_2S and TRS removal efficiency at 5 s EBCT was significantly higher than at 1 s EBCT. There was no significant difference between 5 s and 3 s or 3 s and 1 s. The highest H_2S and TRS reduction was observed for the lava rock at the high moisture level which was followed by pine nuggets at the high moisture level, lava rock at the low moisture level and pine nuggets at the low moisture level.

Percent CH_4 and N_2O reduction efficiencies ranged from 6.9 to 24.5% and 0.13 to 0.73%, respectively (Fig. 3g, h, i, and j). No interaction was found between the main effects. Also no significant difference was found among three EBCTs. Percent CH_4 and N_2O reduction efficiency with the lava rock was found to be significantly higher than the pine nuggets. The high moisture level had higher CH_4 and N_2O percent reduction efficiencies compared to the low moisture level. Neither media showed any indication of N_2O generation in the columns.

Similar to inlet gas concentrations, inlet odor concentrations also varied during the six month sampling period. The average inlet odor concentrations and European odor concentrations (odor concentrations corrected using n-butanol detection threshold of the panel) are shown in Table 5.

Odor reduction efficiencies were highly variable. The standard deviation of the odor reduction data ranged from 14.9 to 69.6%. Sometimes negative odor reduction efficiencies were calculated (Fig. 4). No significant difference was found between the two media, three EBCTs, and two moisture levels. It can be concluded that although some odor reduction (up to 48 %) was observed especially at the high moisture level, consistent odor reduction was not achieved during the study. The low inlet odor concentrations of the biofilter columns might have caused odor detection problem. For instance, the minimum inlet odor concentration measured during the study was 142 OU/m^3 (Table 5). Akdeniz et al. (2010b) reported that the average odor concentrations measured from swine barns with deep pits ranged from 795 to 4,556 OU/m^3.

Table 5. Average, minimum, and maximum inlet odor concentrations

	Odor conc. (OU/m^3)[1]	European odor conc. (OU_E/m^3)
Average ±Stdev	1,459±1,297	2,685±2,145
Min-max	142-5,294	430-7,965

[1] OU: Odor unit, OU_E: European odor unit

Percent odor reduction efficiencies of the biofilter columns were different than their gas reduction efficiencies. In fact, similar results were expected for NH_3 and H_2S gases and odor since NH_3 and H_2S are odorous gases and they are found in the headspace of the manure and wastewater storage pits at relatively high concentrations. But there are over 300 compounds that can be found in the headspace of swine manure. Some compounds such as 4-methyl phenol (p-cresol), indole, and 3-methyl-1H-indole (scatole) might be found at low concentrations but still cause the dominant odor of the air sample (Jacobson et al., 2010). This study was focused on treating hydrophilic odorous gases (H_2S, TRS and NH_3) and greenhouse gases (CH_4 and N_2O). In the future studies, it is recommended to design biofilters that can reduce hydrophobic odorous gases (e.g., 4-methyl phenol, indole, 3-methyl-1H-indole) that are usually found at low concentrations but have very dominant odors.

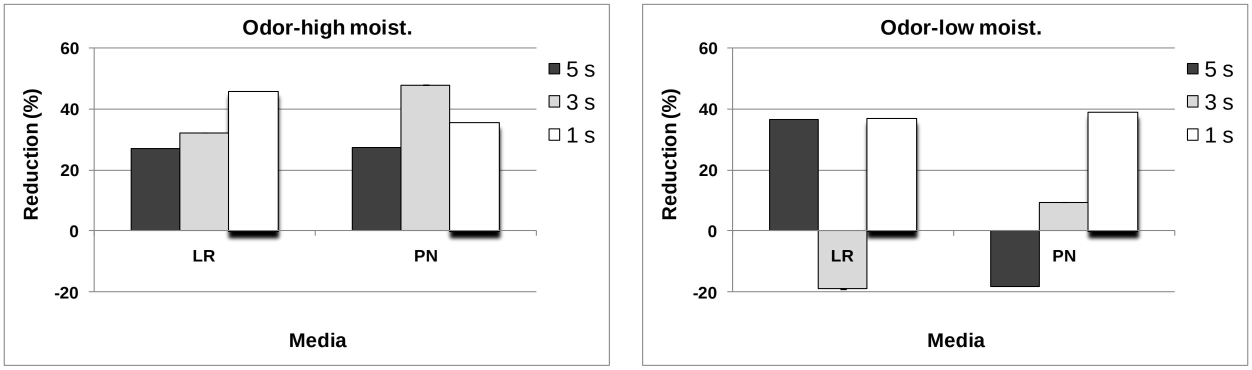

Fig. 4. Average percent reduction of the odor at low and high moisture levels and 1, 3, and 5 s empty bed contact times

Quality control

Control EBCTs of the columns: Achieved EBCTs based on average media depth (average of initial and final depths) ranged from 1.2 to 1.3 s for 1 s, 2.7 to 3.1 s for 3 s, and 4.7 to 5.1 for 5 s target EBCTs. The achieved EBCTs were slightly different than the target EBCTs but were considered to be within acceptable ranges.

Control moisture contents of the columns: Average column exhaust relative humidity values are shown in Fig. 5a and b. A significant difference between high and low moisture levels of the media was observed. The high moisture levels ranged from 81.5 to 89.5%, while the low moisture levels ranged from 72.9 to 78.0%. It was concluded that water management of the columns was done successfully and the experiments were conducted with two different water levels.

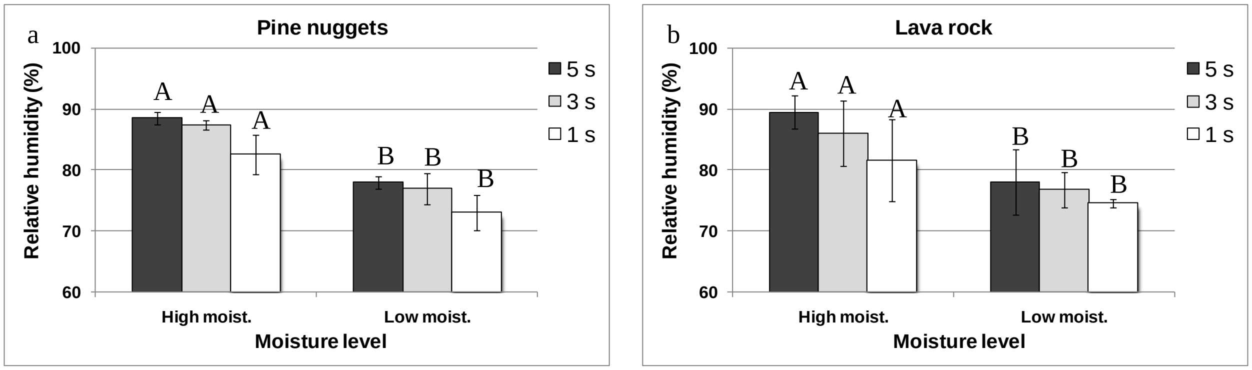

Fig. 5. Measured relative humidity values of pine nuggets and lava rock columns (3 replicates × 3 weeks each replicate × 1 measurement per week = 9 measurements). Within each EBCT, averages that are not connected with the same letter are significantly different ($p<0.05$).

Summary

This study will immediately benefit to pork producers. Both of the media tested in this study had more big particles and lower pressure drops compared to commonly used biofilter media (wood chips). Lava rock had little to no compaction during the study. Pine nuggets had lower final media depths than lava rock due to settling and organic matter breakdown. Percent gas reduction efficiencies were the highest for the lava rock at 5 s EBCT and high moisture level (56% NH_3, 88% H_2S, 87%TRS, 25% CH_4, and 0.7% N_2O). No N_2O production was measured during the study. Odor reduction using pine nuggets and lava rock was variable and needs further study. In conclusion, lava rock at 5 s EBCT and 90% relative humidity is recommended as an energy efficient flat-bed biofilter media.

Acknowledgements

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