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Mitigation of Odor, NH3, H2S, GHG, and VOC Emissions With Current Products for Use in Deep-Pit Swine Manure Storage Structures

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Abstract

Odorous gas emissions from swine production have been a concern for neighbors and communities near livestock farms. Manure storage is one of the main sources of gaseous emissions. Manure additive products are marketed as a simple solution to this environmental challenge. Manure additives are user-friendly for producers and can be applied (e.g., periodically poured into manure) without changing the current manure storage structure. Little scientific data exist on how these products perform in mitigating gaseous emissions from swine manure. The research objective was to evaluate the effectiveness of 12 marketed manure additives on mitigating odor, ammonia (NH3), hydrogen sulfide (H2S), greenhouse gases (GHG), and odorous volatile organic compounds (VOCs) from stored swine manure. A controlled pilot-scale setup was used to conduct 8-week long trials using manufacturer-prescribed dosages of additives into swine manures. Manure was outsourced from three swine farms to represent a variety of manure storage types and other factors affecting the properties. Measured gaseous emissions were compared between the treated and untreated manure. None of the tested products showed a significant reduction in gaseous emissions when all (n = 3) manures were treated as replicates. Selected products showed a wide range of statistically-significant reduction and generation of gaseous emissions when emissions were compared in pairs of manure types from one farm. The latter observation highlighted the lack of consistent mitigation of gaseous emissions by manure additives. The results of this study do not warrant full-scale trials with the tested products.

Keywords

odor mitigation, sustainable agriculture, air quality, gaseous emissions, environmental technologies, animal production systems, swine manure, waste management

Disciplines

Agriculture | Bioresource and Agricultural Engineering | Environmental Health

Comments

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Mitigation of Odor, NH_3, H_2S, GHG, and VOC Emissions With Current Products for Use in Deep-Pit Swine Manure Storage Structures

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Odorous gas emissions from swine production have been a concern for neighbors and communities near livestock farms. Manure storage is one of the main sources of gaseous emissions. Manure additive products are marketed as a simple solution to this environmental challenge. Manure additives are user-friendly for producers and can be applied (e.g., periodically poured into manure) without changing the current manure storage structure. Little scientific data exist on how these products perform in mitigating gaseous emissions from swine manure. The research objective was to evaluate the effectiveness of 12 marketed manure additives on mitigating odor, ammonia (NH_3), hydrogen sulfide (H_2S), greenhouse gases (GHG), and odorous volatile organic compounds (VOCs) from stored swine manure. A controlled pilot-scale setup was used to conduct 8-week long trials using manufacturer-prescribed dosages of additives into swine manures. Manure was outsourced from three swine farms to represent a variety of manure storage types and other factors affecting the properties. Measured gaseous emissions were compared between the treated and untreated manure. None of the tested products showed a significant reduction in gaseous emissions when all ($n = 3$) manures were treated as replicates. Selected products showed a wide range of statistically-significant reduction and generation of gaseous emissions when emissions were compared in pairs of manure types from one farm. The latter observation highlighted the lack of consistent mitigation of gaseous emissions by manure additives. The results of this study do not warrant full-scale trials with the tested products.

Keywords: odor mitigation, sustainable agriculture, air quality, gaseous emissions, environmental technologies, animal production systems, swine manure, waste management

INTRODUCTION

The swine industry has a significant environmental and socio-economic challenge with the gaseous emissions that originate from the storage, handling, and land-application of swine manure. Emissions of ammonia (NH_3), hydrogen sulfide (H_2S), volatile organic compounds (VOCs) contribute to odor nuisance. A relatively small subset of VOCs (e.g., phenolics, fatty acids, sulfur-containing VOCs) has been consistently ranked and prioritized as significant contributors to the characteristic smell of swine odor downwind from farms (Koziel et al., 2006). Researchers have measured gaseous and odor emissions from animal buildings (Akdeniz et al., 2012a; Bereznicki et al., 2012; Cai et al., 2015). Efforts linking concentrations of gases and measured odor are challenging (Akdeniz et al., 2012b; Parker et al., 2012). Concerns about climate change are also relevant to greenhouse gas (carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) emissions from stored manure and land-applied manure (Maurer et al., 2017a). Airborne particulate matter can also sorb VOCs and be a carrier of odor (Cai et al., 2006).

Progress is being made on developing and testing technologies for the mitigation of odor and gaseous emissions from swine farms (Maurer et al., 2016; Iowa State University Extension Outreach, 2020). However, the farm-scale adoption of a particular technology depends on a number of site-specific regulatory and socio-economic factors. The Air Management Practices Assessment Tool (Iowa State University Extension Outreach, 2020) listing 12 approaches to mitigate odor and gaseous emissions. These include manure additives, i.e., products for surficial application to stored manure. Researchers have reported developing and testing manure additives such as various types of biochars (Maurer et al., 2017b; Chen et al., 2020a; Meiirkhanuly et al., 2020a,b), zeolites (Cai et al., 2007), and peroxidase (Maurer et al., 2017c,d). The swine industry has access to a relatively wide range of commercial products marketed as manure additives.

Manure additives are user-friendly for farmers because they can be applied (e.g., periodically poured into manure) without changing the current manure storage structure. The active ingredients are often proprietary, but the majority of products claim to contain microbial flora aiming to minimize odor-causing populations. Unfortunately, little scientific data exist on how these marketed products perform in mitigating gaseous emissions from swine manure, and the impact on odor mitigation is relatively low (Iowa State University Extension Outreach, 2020).

The objective of this study was to test the effectiveness of 12 marketed manure additives on their mitigation of gaseous emissions of odor, ammonia (NH_3), hydrogen sulfide (H_2S), greenhouse gases (GHG), and odorous volatile organic compounds (VOCs) from stored swine manure. The products were selected based on their usage in commercial swine production in the U.S. The 12 products were Triune, Confine, Manure Master Plus (MMP), Sulfi-Doxx dry (Sulfi-Dox), Waste Away, Oxydol, Enviro Lagoon, Penergetic G, Manure Magic (MM), Sludge Away; LLMO-SST (LLMO), and More Than Manure (MTM).

Our working hypothesis was that the tested manure additives will effectively reduce gaseous emissions from different types of swine manure when tested on a pilot-scale using the manufacturer-prescribed dose. This research shows the side-by-side comparisons of commercial additives to help the pork industry understand their performance and potential impact on mitigating odor and gaseous emissions from manure. Additionally, A similar study on the evaluation of manure additives was carried out 20 years ago; however, many new products have been introduced since then (Heber et al., 2001). Farmers and the regulatory community need reliable scientific data on the performance of marketed manure additives that are popular with the U.S. Midwest pork industry.

EXPERIMENTS

The "Experiments" section is largely reduced to the essentials to avoid redundant information that was described in detail in the "Methods" section of the recently published paper (Chen et al., 2020b). The Chen et al. (2020b) paper is focused on methods and raw data presentation in an organized fashion for transparency and reuse. This paper focuses on data analysis, results, discussion, and conclusions.

Experimental Design

Table 1 summarizes the additive products tested in the four, 8-week long Trials of the effectiveness for mitigation of gas emissions from stored swine manure.

A detailed description of the experimental design, key components of manure storage simulators, properties of manure, airflow control, gas (NH_3, H_2S, CO_2, CH_4, N_2O), 11 odorous VOCs and odor concentration measurements are presented elsewhere (Chen et al., 2020b).

The experimental set up of this research was pilot-scale and aimed to simulate the deep pit swine manure storage structure. A total of 15 manure storage simulators are available, and each has a height of 1.22 meters (4 ft) and a diameter of 0.38 m (15 inches), as shown in **Figure 1**. Fresh manure was collected from three farms at different locations in Iowa. The detailed manure properties and manure collection are presented elsewhere (Chen et al., 2020b).

The manure storage simulators were initially filled with 74.6 L of swine manure. Every 2 weeks, 9.5 L of the manure from the same farm was added directly from the top of the simulators to simulate the manure addition in the real swine barn. The airflow rate was kept at 7.5 air exchange per hour (ACH) by FL-3839ST rotameters (Omega Engineering Inc, USA). Each Trial of the experiment lasted for 8 weeks. The baseline gas emissions from each simulator were measured for ∼2 weeks before applying any treatment. The dosage of each product was followed by the recommended dosages on their product labels or websites. The gas concentration measurements for NH_3 and H_2S were done twice a week; GHG, odor concentrations, and VOCs were done weekly.

TABLE 1 | Summary of four, 8-week long Trials to test the effectiveness of additive products for mitigation of gas emissions from stored swine manure.

	Manure additive products tested*	Manure source/storage type	Time of the year for manure collection**
Trial 1	Triune; Confine N; Manure Master plus; Sulfi-Doxx dry;	Deep pit 1; Deep pit 2; Outdoor	December 2018
Trial 2	Waste Away; Enviro Lagoon; More Than Manure; Oxydol	Deep pit 1; Deep pit 2; Outdoor	March 2019
Trial 3	Sludge Away; Penergetic G; Manure Magic	Deep pit 1; Deep pit 2; Deep pit 3	July 2019
Trial 4	LLMO-SST	Deep pit 1; Deep pit 2; Deep pit 3	October 2019

**Detailed description of each product including the mode of operation, the recommended dosage that was followed and used in each Trial, manufacturer name is described in Chen et al. (2020b).*

***Manure was collected at the same farms, but at different times of the year [i.e., manure properties varied significantly for untreated manure (Control), (Chen et al., 2020b)].*

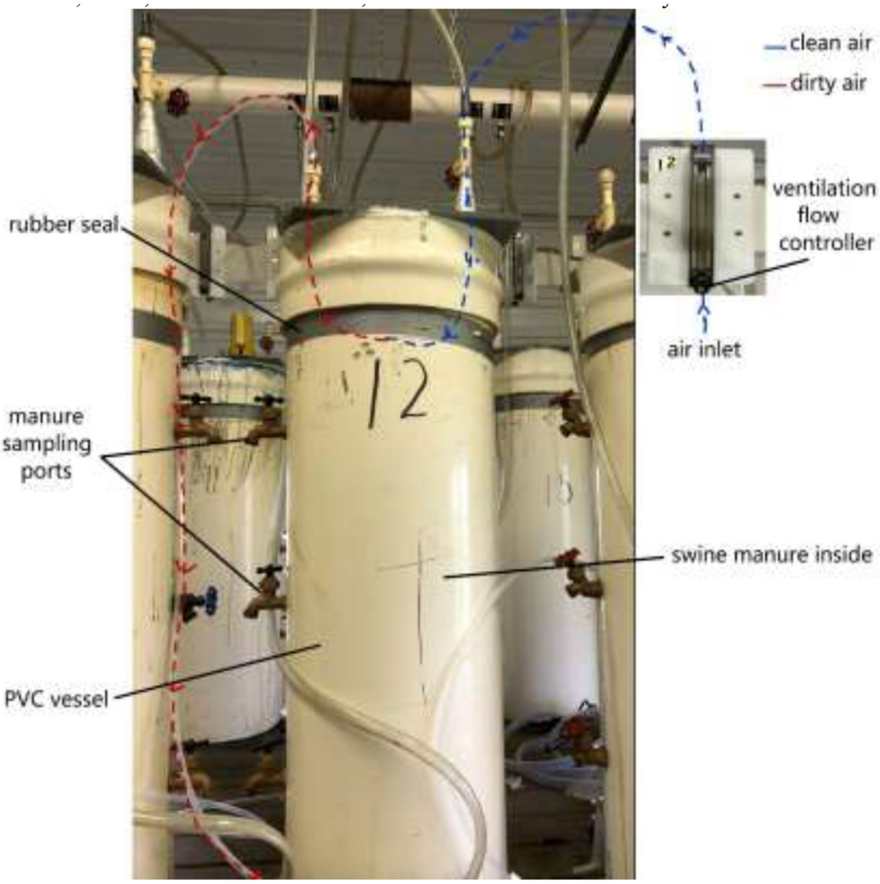

FIGURE 1 | Pilot-scale setup of manure storage simulator to test the effectiveness of manure additives for mitigation of gas emissions. Airflow in the headspace is measured and controlled by a rotameter with a needle valve for each simulator. Gas samples are collected from the "dirty air" outlet. The mitigation effect was estimated by comparing the gaseous emissions between treated and untreated manure.

Ammonia and Hydrogen Sulfide

NH_3 and H_2S concentrations were measured with both Drager X-am 5600 portable gas analyzer and OMS-300, which can be used to measure real-time gas concentrations. OMS-300 is equipped with NH_3/CR-1000 and H_2S/C-50 electrochemical gas sensors (Wallisellen, Switzerland), and Drager X-am 5600 equipped with NH_3 and H_2S XS sensors (Luebeck, Germany) (Maurer et al., 2017b; Wi et al., 2019; Chen et al., 2020b).

Greenhouse Gases

Greenhouse gases were measured for CO_2, N_2O, and CH_4. First GHG samples were collected with a syringe from the headspace of the manure simulators in 5.9 mL Extainer vials (Labco Limited, U.K.). All Extainer vials have been pre-cleaned with Helium gas (UHP 300) and vacuumed for over 7 cycles. Then the samples were analyzed with GHG-GC (SRI Instruments, Torrance, CA, USA) equipped with flame ionization detector (FID) and electron capture detector (ECD) (Maurer et al., 2017b; Chen et al., 2020b).

Volatile Organic Compounds

For VOC emissions, the manure storage air samples were collected in 1 L gas sampling glass bulbs (Supelco) by using portable sampling pumps. After bringing back to the lab, VOCs were absorbed with a 2 cm divinylbenzene/Carboxen/polydimethylsiloxane (DVB/Carboxen/PDMS) solid-phase microextraction (SPME) fiber (57384-U, Supelco, Bellefonte, PA, USA) for 50 min at lab temperature (23–24°C), then analyzed with a multidimensional GC-MS within 12 h of sample collection.

The SPME fiber loaded with VOCs was inserted into a 260°C G.C. (Microanalytics, Round Rock, TX, USA) inlet; VOCs were thermally desorbed for 2 min and analyzed by a mass spectrometer (Agilent, model 5973N, Santa Clara, CA, USA) (Chen et al., 2020b).

Odor

The odor samples were collected weekly by using Vac-U-Chamber (SKC Inc., Eighty-Four, PA, USA) and transfer back to the lab in 10 L Tedlar sample bags. Tedlar sample bags were flushed and vacuumed with air multiple times before using them. Within 12 h, all the odor samples were analyzed with AC'SCENT International Olfactometer (St. Croix Sensory Inc., Stillwater, MN, USA) using dynamic triangular forced-choice methods. There were four panelists, and each sample was evaluated twice by each panelist (Akdeniz et al., 2012a; Chen et al., 2020b).

Mitigation and Statistical Analyses

The experimental design was a completely randomized design. Gases such as NH_3, H_2S, CO_2, N_2O, and CH_4 initially were all measured or analyzed in units of parts per million. Gas concentrations were first converted from the field condition to standard condition (1 atm, 25°C, and dry air). For odor, the unit was used Odor Units. For VOC, the peak area count was used.

The overall mean percent reduction to emissions was calculated with Equation 1:

$$\%\mathbf{R} = \frac{\mathbf{E_{Control}} - \mathbf{E_{Treatment}}}{\mathbf{E_{Control}}} * \mathbf{100}\% \quad (1)$$

Whereas, %R is the overall mean percent reduction, $E_{control}$ is the average emission of the control, $E_{treatment}$ is the average emission of the treatment.

The two-way ANOVA and Tukey-Kramer Method were used to determine the p-values of the reduction. All statistical analysis was done in JMP software (version Pro 15, SAS Institute, Inc., Cary, NC, USA). When a p-value is less than or equal to 0.05, the reduction is statistically significant.

All data were analyzed in two ways:

(a) Averaging results for treating all types of manure analyzed as replications ($n = 3$ replications, assuming manures from different farms are replicates).
(b) Treating all types of manure as being distinct (no replications, assuming manures from different farms are not replicates; comparing ($n = 1$) control vs. ($n = 1$) treatment using the same manure).

RESULTS

In this research, a total of 12 manure additive products was evaluated (**Table 1**). Four products were evaluated in Trial 1, and another four products were evaluated in Trial 2; 3 products were evaluated in Trial 3; 1 product was evaluated in the last Trial (Trial 4). The percent reduction in gaseous emissions (%R) were all calculated by comparing emissions from the treated manure with the Control in the same Trial. The results are organized by Trials and presented in two types of tables for each Trial. The first table type summarizes results by (a) averaging results for treating all types of manure as replications ($n = 3$ replications, assuming manures from different sources are replicates). The second table type summarizes results by (b) treating all types of manure as being distinct (no replications, assuming manures from different sources are not replicates, comparing ($n = 1$) control vs. ($n = 1$) treatment using the same manure). Rows in each table are organized by targeted gases, starting with NH_3 and followed by H_2S, GHGs, odor, and odorous VOCs.

In addition, the **Supplementary Material** contains detailed comparisons of emissions for each targeted gas over 8 weeks of each Trial, illustrated with 130 figures (**Supplementary Figures 1–130**). **Supplementary Tables 1–3** serve as a guide for finding results on a particular manure additive and targeted gas.

Trial 1 (Confine N, Triune, MMP, and Sulfi-Doxx$_{dry}$)

The four products that were evaluated during Trial 1 of the experiment were Confine N, Triune, MMP, and Sulfi-doxx$_{dry}$. The results of considering the three types of manure sources as triplicate were summarized in **Table 2**. The measurements over the 8-week of the experiment for all four productions are listed in **Supplementary Material** (Triune: **Supplementary Figures 1–9**; MMP: **Supplementary Figures 10–18**; Confine N: **Supplementary Figures 19–27**; Sulfi-dox: **Supplementary Figures 28–36**). For all targeted gases, there was not any statistically significant reduction found.

For NH_3 emission, Sulfi-dox showed the highest percent reduction of 8% with a p-value of 0.5359. Confine N and MMP increased NH_3 emissions. MMP and Sulfi-dox reduced the average H_2S emissions by 34% with a p-value of 0.3525 and 10% with a p-value of 0.9834, respectively. Triune increased the H_2S emissions by 13% with a p-value of 0.9555.

For GHG emissions, all four products did not have a significant impact on CO_2 emissions. But all four products had increased the CH_4 emissions production by 9∼30%. MMP and Sulfi-dox reduced N_2O emissions by 8%; Confine N and Triune reduced N_2O emissions by 5 and 4%, respectively.

MMP had the highest percent reduction in Trial 1, 20%, and followed by Triune with a reduction of 13%. For VOC emissions, There were always mitigations in some targeted gases, and at the same time, generations in others. For example, MMP had mitigations in DEDS and DMTS by 15% and 32% but generated DMDS by 77%. Triune increased the p-cresol emission significantly by 310% with a p-value of 0.0016, and Confine N increased the p-cresol emission by 240% with a p-value of 0.0593.

TABLE 2 | Trial 1-comparison of averaged gaseous emissions (flux or arbitrary units for VOCs) and percent reductions (*%R*) from three types of manure sources (farms) with their standard deviations.

Trial 1	Control	Confine N	MMP	Sulfi-dox	Triune
NH_3 (mg/h/m^2)	88.8 ± 55.0	92.6 ± 54.1	90.6 ± 48.1	81.8 ± 50.4	87.9 ± 41.3
%R		−4 (0.7403)	−2 (0.8761)	8 (0.5359)	1 (0.9361)
H_2S (mg/h/m^2)	0.99 ± 0.62	0.96 ± 0.91	0.65 ± 0.46	0.89 ± 0.58	1.11 ± 1.15
%R		2 (0.9999)	34(0.3525)	10 (0.9834)	−13 (0.9555)
CO_2 (mg/h/m^2)	2,631 ± 778	2,536 ± 566	2,685 ± 865	2,732 ± 1050	2,679 ± 678
%R		4 (0.9849)	−2 (0.9984)	−4 (0.9805)	−2 (0.9988)
CH_4 (mg/h/m^2)	66.4 ± 36.6	77.0 ± 46.5	74.5 ± 47.2	87.7 ± 55.2	72.1 ± 44.6
%R		−16 (0.8721)	−12 (0.9496)	−32 (0.2971)	−9 (0.9852)
N_2O (mg/h/m^2)	1.30 ± 0.43	1.24 ± 0.44	1.20 ± 0.45	1.20 ± 0.45	1.26 ± 0.44
%R		5 (0.9623)	8 (0.8356)	8 (0.8356)	4 (0.9906)
Odor (OU/m^3)	2,835 ± 2,067	2,639 ± 2,286	2,271 ± 2,174	2,706 ± 1,747	2,474 ± 2,164
%R		7 (0.9955)	20 (0.8101)	5 (0.9991)	13 (0.9561)
4EP* (PAC)	1,489,367 ± 995,237	1,464,857 ± 944,412	1,350,266 ± 1,194,695	1,236,546 ± 981,292	1,329,705 ± 1,009,783
%R		2 (1.000)	9 (0.9906)	17 (0.9183)	11 (0.9842)
Acetic acid (PAC)	15,356 ± 33,903	22,834 ± 60,019	33,034 ± 65,464	41,325 ± 108,664	11,428 ± 28,230
%R		−49 (0.9951)	−115 (0.8895)	−169 (0.6617)	25.6 (0.9996)
DEDS* (PAC)	6,855 ± 4,263	7,282 ± 5,513	5,848 ± 5,019	6,352 ± 4,312	5,778 ± 5,017
%R		−6 (0.9949)	15 (0.8855)	7 (0.9904)	16 (0.8583)
DMDS* (PAC)	16,128 ± 13,371	13,545 ± 8,034	28,537 ± 34,989	19,841 ± 19,366	16,568 ± 29,883
%R		16 (0.9954)	−77 (0.3580)	−23 (0.9818)	−3 (1.00)
DMTS* (PAC)	5,234 ± 4,787	3,519 ± 3,358	3,601 ± 3,902	5,506 ± 8,153	5,507 ± 4,651
%R		33 (0.7474)	31 (0.7799)	3 (0.9999)	−5 (0.9997)
Indole (PAC)	19,555 ± 19,289	17,011 ± 13,476	18,558 ± 25,027	18,641 ± 19,961	17,911 ± 17,112
%R		13 (0.9904)	5 (0.9998)	5 (0.9998)	8 (0.9982)
IsB (PAC)	36,091 ± 104,805	31,558 ± 121,494	4,340 ± 157,403	45,488 ± 137,253	15,001 ± 36,108
%R		13 (0.9999)	−20 (0.9996)	−26 (0.9988)	58 (0.9741)
p-Cresol (PAC)	629,279 ± 627,787	2,136,907 ± 2,402,924	671,264 ± 728,725	418,377 ± 433,800	2,581,168 ± 3,429,324
%R		−240 (0.0593)	−7 (1.00)	34 (0.9956)	**−310 (0.0016)**
Phenol (PAC)	1,861,252 ± 1,529,281	1,781,037 ± 1,508,159	1,400,407 ± 1,203,608	1,373,320 ± 1,587,260	1,673,158 ± 1,341,959
%R		4 (0.9997)	25 (0.7863)	26 (0.7488)	10 (0.9903)
PA (PAC)	12,010 ± 34,618	12,815 ± 45,534	22,017 ± 57,369	32,851 ± 109,235	7,833 ± 20,682
%R		−7 (1.00)	−83 (0.9810)	−174 (0.7752)	35 (0.9993)
Skatole (PAC)	1,263,970 ± 747,462	1,223,405 ± 749,454	1,288,386 ± 749,454	1,058,927 ± 736,251	1,494,055 ± 1,114,703
%R		3 (0.9998)	−2 (1.00)	16 (0.9255)	−18 (0.8908)

%R is statistically significant when the p-value < 0.05 (signified by bold font). Negative (-)%R signifies generation.

**%R = percent reduction with respect to Control (untreated); PAC = peak area count (arbitrary unit); N/A = Below the detection limit; 4EP = 4-ethyl phenol; DEDS = Diethyl disulfide; DMDS = Dimethyl disulfide; DMTS = Dimethyl trisulfide; IsB = Isobutyric acid; PA = propanoic acid.*

The user's instructions for the manure additive products tested in this research did not specify "*what kind of manure*" they target to treat. These products are marketed for generic use in stored swine manure regardless of environmental conditions. Thus, we also analyzed the data by considering that the manure sources are "different" (no replication), which is summarized in **Table 3** for Trial 1. Similar tables are also provided for Trials 2, 3, and 4.

In general, the second approach to data analysis did not yield consistent results. For example, Triune showed generations of NH_3 emission for outdoor storage manure by 93% with a *p*-value of 0.0014, but a 24% reduction on manure from deep pit 1 and no impact on NH_3 emission from deep pit 2 manure. Triune also generated 937% more p-cresol with a *p*-value of 0.0001 in outdoor manure. A similar lack of trend also occurred for other products. Confine N showed a reduction of 58% with a *p*-value of 0.0211 for outdoor manure but generated 42% more H_2S in manure from pit 2. Sulfi-dox generated 55% more on CH_4 emission in deep pit 1 manure with a *p*-value of 0.0105. Confine N mitigated the odor concentration by 48% with a *p*-value of 0.0129 in manure from pit 2 and generated 604% more of p-cresol in outdoor manure with a *p*-value of 0.0064.

Trial 2 (WA, MTM, Enviro Lagoon, and Oxydol)

The four products tested in the second Trial were WA, MTM, Enviro Lagoon, and Oxydol. The analyzed results, which

TABLE 3 | Trial 1-comparison of averaged gaseous emissions (flux or arbitrary units for VOCs) and percent reductions (*%R*) analyzed separately for each type of manure sources (farms) with their standard deviations.

Trial 1	Manure Source	Control	Confine N	MMP	Sulfi-dox	Triune
NH_3 flux (mg/h/m^2) ± st. dev.	Pit 1	121 ± 25.0	126 ± 40.4	129 ± 39.7	128 ± 36.9	92.6 ± 32.8
			−4 (0.7403)	−6 (0.8761)	−6 (0.5359)	24 (0.9361)
	Pit 2	117 ± 53.5	112 ± 51.2	101 ± 36.0	91.9 ± 24.7	117 ± 40.8
%R (*p*-value)			5 (0.9933)	14 (0.7072)	21 (0.2989)	0 (1.00)
	Outdoor	28.3 ± 11.7	40.3 ± 21.1	42.4 ± 16.1	25.2 ± 11.5	54.6 ± 23.3
			−43 (0.3620)	−50 (0.2074)	11 (0.9901)	**−93 (0.0014)**
H_2S flux (mg/h/m^2) ± st. dev.	Pit 1	0.80 ± 0.33	0.79 ± 0.36	0.77 ± 0.34	0.96 ± 0.45	0.38 ± 0.44
			0 (1.00)	3 (0.9999)	−21 (0.7398)	**52 (0.0291)**
	Pit 2	1.19 ± 0.67	1.69 ± 1.20	0.37 ± 0.37	0.47 ± 0.39	2.36 ± 1.13
%R (*p*-value)			−42 (0.5105)	69 (0.0809)	60 (0.1606)	**−99 (0.0035)**
	Outdoor	0.97 ± 0.74	0.40 ± 0.37	0.81 ± 0.53	1.23 ± 0.61	0.59 ± 0.42
			58 (0.0211)	17 (0.9016)	−27 (0.6013)	39 (0.2309)
CO_2 flux (mg/h/m^2) ± st. dev.	Pit 1	3,380 ± 661	2,938 ± 415	3,485 ± 835	3,769 ± 1,071	2,967 ± 687
			13 (0.4166)	−3 (0.9937)	−11 (0.5475)	12 (0.4852)
	Pit 2	2,410 ± 568	2,453 ± 518	2,293 ± 573	2,400 ± 508	2,364 ± 488
%R (*p*-value)			−2 (0.9992)	5 (0.9611)	0 (1.00)	2 (0.9989)
	Outdoor	2,102 ± 448	2,218 ± 536	2,278 ± 565	2,028 ± 524	2,707 ± 749
			−6 (0.9856)	−8 (0.9344)	4 (0.9974)	−29 (0.0708)
CH_4 flux (mg/h/m^2) ± st. dev.	Pit 1	91.4 ± 22.9	103 ± 38.1	108 ± 33.0	142 ± 40.9	82.8 ± 38.1
			−13 (0.9375)	−18 (0.8174)	**−55 (0.0105)**	9 (0.9738)
	Pit 2	42.12 ± 28.3	42.0 ± 33.3	33.6 ± 13.5	32.5 ± 19.6	40.7 ± 22.9
%R (*p*-value)			0 (1.00)	20 (0.9009)	23 (0.8547)	3 (0.9999)
	Outdoor	65.5 ± 40.4	86.0 ± 46.8	82.3 ± 82.6	89.0 ± 33.7	92.9 ± 52.1
			−31 (0.6802)	−26 (0.8137)	−36 (0.5508)	−42 (0.4001)
N_2O flux (mg/h/m^2) ± st. dev.	Pit 1	1.33 ± 0.45	1.21 ± 0.46	1.23 ± 0.47	1.22 ± 0.48	1.28 ± 0.44
			9 (0.9695)	7 (0.9846)	8 (0.9722)	3 (0.9992)
	Pit 2	1.31 ± 0.44	1.24 ± 0.43	1.16 ± 0.44	1.18 ± 0.46	1.26 ± 0.48
%R (*p*-value)			5 (0.9943)	12 (0.9119)	10 (0.9452)	4 (0.9983)
	Outdoor	1.27 ± 0.45	1.25 ± 0.47	1.20 ± 0.47	1.20 ± 0.47	1.23 ± 0.43
			1 (1.00)	5 (0.9953)	6 (0.9943)	3 (0.9992)
Odor concentration (OU/m^3) ± st. dev.	Pit 1	2,288 ± 1,820	2,652 ± 2,699	2,206 ± 1,550	2,442 ± 2,141	2,054 ± 1,404
			−16 (0.9832)	4 (1.00)	−7 (0.9994)	10 (0.9968)
	Pit 2	4,303 ± 2,477	4,095 ± 2,069	2,237 ± 2208	2,757 ± 1791	4,684 ± 1,965
%R (*p*-value)			5 (0.9968)	**48 (0.0129**)	36 (0.0995)	−9 (0.9687)
	Outdoor	1,914 ± 901	1,169 ± 845	2,370 ± 2,870	2,919 ± 1,452	684 ± 321
			39 (0.8615)	−24 (0.9740)	−52 (0.6788)	64 (0.4946)
4EP* (PAC) ± st. dev.	Pit 1	2,428,215 ± 895,705	2,184,407 ± 718,889	2,126,714 ± 1,402,887	2,231,119 ± 864,003	1,739,410 ± 493,606
			10 (0.9829)	12 (0.9630)	8 (0.9923)	28 (0.5607)
	Pit 2	612,650 ± 558,574	531,698 ± 241,714	217,772 ± 141,488	273,271 ± 178,466	338,353 ± 184,038
%R (*p*-value)			13 (0.9592)	64 (0.0724)	55 (0.1591)	45 (0.3438)
	Outdoor	1,427,236 ± 499,994	1,678,465 ± 846,344	1,706,313 ± 633,990	1,205,248 ± 439,900	1,911,353 ± 1,170,956
			−18 (0.9592)	−20 (0.9412)	16 (0.9739)	−34 (0.6856)
Acetic acid (PAC) ± st. dev.	Pit 1	9,567 ± 23,397	48,594 ± 89,414	58,847 ± 98,219	56,974 ± 138,341	17,997 ± 41,989
			−408 (0.8976)	−515 (0.7911)	−496 (0.8132)	−88 (0.9997)
	Pit 2	24,104 ± 47,880	18,980 ± 50,142	28,026 ± 45,885	62,284 ± 131,575	11,915 ± 26,770
%R (*p*-value)			21 (0.9999)	−16 (1.00)	−158 (0.8188)	51 (0.9969)
	Outdoor	12,395 ± 28,303	929 ± 1,852	12,229 ± 32,306	4,715 ± 5,788	4,373 ± 5,679
			93 (0.7648)	1 (1.00)	62 (0.9325)	65 (0.9218)
DEDS* (PAC) ± st. dev.	Pit 1	6,654 ± 5,876	9,442 ± 7,858	8,087 ± 7,288	6,355 ± 4,950	6,773 ± 4,949
			−42 (0.7347)	−22 (0.9688)	4 (0.9999)	−2 (1.00)
	Pit 2	7,470 ± 3,875	5,819 ± 3,939	5,332 ± 3,439	6,346 ± 4,238	5,170 ± 4,030

(Continued)

TABLE 3 | Continued

Trial 1	Manure Source	Control	Confine N	MMP	Sulfi-dox	Triune
%R (*p*-value)			22 (0.6938)	29 (0.4586)	15 (0.9008)	31 (0.3853)
	Outdoor	6,440 ± 3,081	6,585 ± 3,778	4,123 ± 2,895	6,356 ± 4,315	5,391 ± 6,343
			−2 (1.00)	36 (0.7143)	1 (1.00)	16 (0.9782)
DMDS* (PAC) ± st. dev.	Pit 1	7,503 ± 5,763	9,415 ± 6,342	11,870 ± 7,507	8,128 ± 5,976	10,636 ± 5,255
			−25 (0.9236)	−58 (0.3544)	−8 (0.9988)	−42 (0.6695)
	Pit 2	28,603 ± 14,346	21,663 ± 6,102	64,675 ± 41,032	429,00 ± 16,157	31,250 ± 50,042
%R (*p*-value)			24 (0.9904)	−126 (0.1438)	−50 (0.8769)	−9 (0.9998)
	Outdoor	12,279 ± 8,281	9,557 ± 4,653	9,065 ± 6,254	8,495 ± 4,892	7,817 ± 5,307
			22 (0.7991)	26 (0.6853)	31 (0.5410)	36 (0.3779)
DMTS* (PAC) ± st. dev.	Pit 1	4,217 ± 3,727	3,914 ± 4,399	4,143 ± 3,179	3,253 ± 3,445	6,111 ± 5,888
			7 (0.9999)	2 (1.00)	23 (0.9864)	−45 (0.8573)
	Pit 2	8,198 ± 5,971	4,724 ± 2,983	4,833 ± 5,694	10,442 ± 12,319	6,133 ± 3,213
%R (*p*–value)			42 (0.8317)	41 (0.8472)	−27 (0.9602)	25 (0.9705)
	Outdoor	3,286 ± 3,193	1,920 ± 2,010	1,827 ± 1,351	1,472 ± 1,797	4,278± 4,848
			42 (0.7994)	44 (0.7589)	55 (0.5847)	−30 (0.9267)
Indole (PAC) ± st. dev.	Pit 1	6,881 ± 4,843	7,739 ± 4,782	9,790 ± 4,100	9,475 ± 9,798	11,655 ± 13,940
			12 (0.9991)	−42 (0.9120)	−38 (0.9402)	−69 (0.6327)
	Pit 2	16,221 ± 15,966	12,519 ± 8,698	5,518 ± 5,136	5,346 ± 3,408	18,826 ± 23,479
%R (*p*-value)			23 (0.9824)	66 (0.5302)	67 (0.5147)	−16 (0.9953)
	Outdoor	35,563 ± 21,331	30,776 ± 12,663	40,365 ± 12,663	41,101 ± 18,083	23,251 ± 11,758
			13 (0.9895)	−14 (0.9893)	−16 (0.9818)	35 (0.7450)
Isobutyric acid (PAC) ± st. dev.	Pit 1	66,525 ± 175,417	84,118 ± 208,548	102,748 ± 270,721	85,894 ± 225,713	28,127 ± 60,609
			−26 (0.9998)	−54 (0.9960)	−29 (0.9997)	58 (0.9950)
	Pit 2	30,527 ± 58,673	9,518 ± 15,098	22,832 ± 42,026	41,693 ± 85,661	9,684 ± 16,488
%R (*p*-value)			69 (0.9193)	25 (0.9980)	−37 (0.9918)	68 (0.9214)
	Outdoor	11,221 ± 8,719	1,038 ± 1,606	4,622 ± 11,043	8,878 ± 14,128	7,194 ± 6,291
			91 (0.2260)	59 (0.6388)	21 (0.9875)	36 (0.9137)
P-cresol (PAC) ± st. dev.	Pit 1	534,234 ± 315,599	742,864 ± 510,016	1,037,243 ± 967,635	617,710 ± 667,664	435,788 ± 237,403
			−39 (0.9361)	−94 (0.3532)	−16 (0.9900)	18 (0.9960)
	Pit 2	734,609 ± 1,037,615	1,308,301 ± 923,136	164,226 ± 191,558	171,126 ± 142,810	891,792 ± 643,553
%R (*p*-value)			−78 (0.4780)	78 (0.4838)	77 (0.4958)	−21 (0.9910)
	Outdoor	618,994 ± 309,165	4,359,556 ± 3,034,468	812,322 ± 549,734	466,295 ± 185,044	6,415,923 ± 3,583,622
			−604 (0.0064)	−31 (0.9997)	25 (0.9999)	**−937 (0.0001)**
Phenol (PAC) ± st. dev.	Pit 1	2,641,727 ± 1,749,816	3,266,446 ± 1,517,507	1,559,044 ± 819,677	2,356,688 ± 2,161,493	2,411,186 ± 1,359,152
			−24 (0.5960)	41 (0.1084)	11 (0.9625)	9 (0.9827)
	Pit 2	394,924 ± 337,458	468,653 ± 533,751	135,796 ± 134,117	129,380 ± 180,173	265,798 ± 64,068
%R (*p*-value)			−19 (0.9795)	66 (0.2978)	67 (0.2750)	33 (0.8597)
	Outdoor	2,547,105 ± 904,176	1,608,011 ± 601,267	2,506,382 ± 903,151	1,633,891 ± 788,861	2,342,490 ± 817,053
			37 (0.1692)	2 (1.00)	36 (0.194)	8 (0.3901)
Propionic acid (PAC) ± st. dev.	Pit 1	14,718 ± 38,284	30,721 ± 78,455	29,291 ± 77,680	37,777 ± 105,427	10,273 ± 27,753
			−109 (0.9909)	−99 (0.9936)	−157 (0.9650)	30 (0.9999)
	Pit 2	19,259 ± 47,616	7,322 ± 8,889	27,749 ± 63,422	60,776 ± 161,056	12,643 ± 23,222
%R (*p*-value)			62 (0.9982)	−44 (0.9995)	−216 (0.8368)	34 (0.9998)
	Outdoor	2,053 ± 4,785	401 ± 1,135	9,010 ± 21,588	N/A*	583 ± 1,649
			80 (0.9972)	−339 (0.6303)	100	72 (0.9982)
Skatole (PAC) ± st. dev.	Pit 1	1,603,388 ± 601,593	1,385,116 ± 598,248	1,686,521 ± 648,027	1,510,296 ± 782,516	1,619,319 ± 521,900
			14 (0.9557)	−5 (0.9988)	6 (0.9982)	−1 (1.00)
	Pit 2	496,532 ± 489,222	573,741 ± 285,065	1,686,521 ± 648,027	208,085 ± 192,715	451,585 ± 237,533
%R (*p*-value)			−16 (0.9869)	47 (0.5654)	38 (0.7415)	9 (0.9984)
	Outdoor	1,691,991 ± 469,405	1,711,358 ± 788,673	1,915,340 ± 661,213	1,358,401 ± 389,827	2,411,262 ± 1,237,952
			−1 (1.00)	−13 (0.9736)	20 (0.8943)	−43 (0.3146)

%R is statistically significant when the p-value < 0.05 (signified by bold font). Negative (-)%R signifies generation.

**%R = percent reduction with respect to Control (untreated); PAC = peak area count (arbitrary unit); N/A = Below the detection limit; 4EP = 4-ethyl phenol; DEDS = Diethyl disulfide; DMDS = Dimethyl disulfide; DMTS = Dimethyl trisulfide.*

TABLE 4 | Trial 2-comparison of averaged gaseous emissions from three manure sources (farms) with their standard deviations.

Trial 2	Control	Enviro Lagoon	MTM	Oxydol	WA
NH_3 (mg/h/m^2)	218 ± 71.1	232 ± 110	220.88 ± 95.14	249 ± 187	243 ± 171
%R		−6 (0.9801)	−1 (1.00)	−14 (0.7321)	−11 (0.8603)
H_2S (mg/h/m^2)	11.4 ± 18.3	11.2 ± 17.4	11.1 ± 17.0	12.8 ± 18.3	12.4 ± 18.8
%R		1 (1.00)	2 (1.00)	−13 (0.9926)	−9 (0.9981)
CO_2 (mg/h/m^2)	2,568 ± 432	2,587 ± 494	2,548 ± 419	2,577 ± 461	2,443 ± 441
%R		−1 (0.9979)	1 (0.9984)	0 (0.9999)	5 (0.3821)
CH_4 (mg/h/m^2)	296 ± 232	352 ± 279	308± 238	346 ± 300	335 ± 274
%R		−19 (0.9530)	−4 (0.9999)	−17 (0.9685)	−13 (0.9868)
N_2O (mg/h/m^2)	0.83 ± 0.27	0.89 ± 0.33	0.84 ± 0.28	0.84 ± 0.28	0.86 ± 0.30
%R		−7 (0.8063)	−1 (1.00)	−1 (0.999)	−3 (0.9854)
Odor (OU/m^3)	3,100 ± 1,872	2,996 ± 1,930	2,937 ± 1,899	3,350 ± 1,927	3,135 ± 1,647
%R		3 (0.9986)	5 (0.9919)	−8 (0.960)	−1 (1.00)
4EP* (PAC)	315,524 ± 312,464	400,297 ± 291,552	360,170 ± 341,195	408,875 ± 416,706	333,335 ± 344,618
%R		−27 (0.8115)	−14 (0.9786)	−30 (0.7514)	−6 (0.9994)
Acetic acid (PAC)	22,745 ± 55,311	25,071 ± 59,554	43,197 ± 111,130	41,778 ± 83,311	24,909 ± 43,100
%R		−10 (1.00)	−90 (0.8803)	−84 (0.9053)	−10 (1.00)
DEDS* (PAC)	6,616 ± 5,805	8,026 ± 6,348	5,416 ± 4,817	6,733 ± 5,712	5,931 ± 6,462
%R		−21 (0.8608)	18 (0.9177)	−2 (1.00)	10 (0.9891)
DMDS* (PAC)	16,186 ± 7,326	18,471 ± 9,665	14,811 ± 7,382	14,355 ± 8,652	24,097 ± 21,404
%R		−14 (0.9657)	9 (0.9949)	11 (0.9848)	−49 (0.1657)
DMTS* (PAC)	5,156 ± 5,205	7,302 ± 8,675	6,581 ± 7,398	3,644 ± 3,377	4,136 ± 5,366
%R		−42(0.7509)	−28 (0.9309)	29 (0.9154)	20 (0.9790)
Indole (PAC)	15,747 ± 15,056	16,486 ± 15,677	19,915 ± 21,246	17,636 ± 19,196	13,311 ± 17,403
%R		−5 (0.9999)	−26 (0.9196)	−12 (0.9956)	16 (0.9884)
IsB (PAC)	362,361 ± 849,333	366,919 ± 887,485	361,165 ± 803,300	371,755 ± 845,689	375,740 ± 865,046
%R		−1 (1.00)	0 (1.00)	−5 (1.00)	−4 (1.00)
p–Cresol (PAC)	1,529,173 ± 1,415,358	1,266,610 ± 1,144,601	1,648,778 ± 1,890,610	2,198,355 ± 1,816,109	1,333,436 ± 1,457,440
%R		17 (0.9578)	−8 (0.9978)	−44 (0.4001)	13 (0.9856)
Phenol (PAC)	2,054,211 ± 2,436,085	2,766,911 ± 3,266,006	2,404,184 ± 2,778,151	2,446,857 ± 3,470,660	2,366,274 ± 3,308,158
%R		−35 (0.9290)	−17 (0.9940)	−19 (0.9919)	−15 (0.9967)
PA (PAC)	30,393 ± 34,409	34,575 ± 57,908	43,120 ± 59,699	56,522 ± 104,674	25,664 ± 36,334
%R		−14 (0.9993)	−42 (0.9503)	−86 (0.5721)	16 (0.9988)
Skatole (PAC)	351,819 ± 336,608	446,898 ± 394,217	367,570 ± 343,087	512,562 ± 447,024	477,183 ± 533,742
%R		−27 (0.8885)	−5 (0.9999)	−46 (0.5287)	−36 (0.7435)

%R is statistically significant when the p-value < 0.05 (signified by bold font if present). Negative (-) %R signifies generation.

**%R = percent reduction with respect to Control (untreated); PAC = peak area count (arbitrary unit); N/A = Below the detection limit; 4EP = 4-ethyl phenol; DEDS = Diethyl disulfide; DMDS = Dimethyl disulfide; DMTS = Dimethyl trisulfide; IsB = isobutyric acid; PA = propanoic acid.*

considering three types of manure sources were triplication, are summarized in **Table 4**. The measurements over the 8-week of the experiment for all four productions are listed in **Supplementary Material** (WA: **Supplementary Figures 37–71**; MTM: **Supplementary Figures 72–80**; Enviro Lagoon: **Supplementary Figures 81–89**; Oxydol: **Supplementary Figures 90–98**).

There was no significant reduction found for all of those four products. All four manure additives treatments increased NH_3 emissions ($p > 0.05$). Oxydol and WA increased the H_2S emissions by 9∼13% ($p > 0.05$). There was no significant impact on CO_2 and N_2O emissions, and more CH_4 emissions were generated for all four products. For odor concentrations, Enviro Lagoon and MTM treatments decreased by 3% with a p-value of 0.9986 and 5% with a p-value of 0.9919, whereas Oxydol and WA treatments increased by 8% with a p-value of 0.9600 and 1% with a p-value of 1.00, respectively.

A similar lack of trend was observed for VOCs as in Trial 1. There are random effects ($p > 0.05$) of mitigation and generations among the fatty acid, sulfide groups, and phenolic groups. But overall, no statistical significance was found in Trial 2 as we considering three manure sources as triplications.

In general, when we considered the manure sources are not replications, the second approach of data analysis did not yield consistent results to the %*R* in Trial 2 as shown in **Table 5**. One similar trend observed is that manure additives often have some degree of mitigation on one type of manure, but also generation in emissions in another manure source. Different

TABLE 5 | Trial 2-comparison of gaseous emissions from each of the three manure sources (farms) with their standard deviations.

Trial 2	Manure source	Control	Enviro Lagoon	MTM	Oxydol	WA
NH_3 flux (mg/h/m^2) ± st. dev.	Pit 1	257 ± 95.0	289 ± 162	272 ± 141	351 ± 300	337 ± 272
			−12 (0.9801)	−6 (0.9987)	−37 (0.4651)	−31 (0.6174)
	Pit 2	210 ± 14	211 ± 31	210 ± 207	207 ± 15	228 ± 27
%R (*p*–value)			0 (1.00)	0 (1.00)	1 (0.9966)	−9 (0.2423)
	Outdoor	188 ± 63	197 ± 75	181 ± 53	189 ± 48	163 ± 23
			−5 (0.9730)	4 (0.9919)	−1 (1.00)	13 (0.5204)
H_2S flux (mg/h/m^2) ± st. dev.	Pit 1	25.5 ± 25.0	25.5 ± 22.9	24.4 ± 22.3	28.8 ± 22.4	28.7 ± 24.8
			0 (1.00)	4 (0.9996)	−13 (0.9675)	−13 (0.9735)
	Pit 2	1.94 ± 2.34	1.53 ± 2.28	1.18 ± 0.91	1.68 ± 1.67	1.99 ± 1.24
%R (*p*-value)			21 (0.9619)	39 (0.7253)	13 (0.9934)	−2 (1.00)
	Outdoor	6.66 ± 9.08	6.71 ± 9.06	7.72 ± 9.06	7.72 ± 10.3	6.40 ± 7.56
			−1 (1.00)	−16 (0.9894)	−17 (0.9860)	4 (1.00)
CO_2 flux (mg/h/m^2) ± st. dev.	Pit 1	2,636 ± 485	2,663 ± 507	2,555 ± 479	2,630 ± 507	2,480 ± 424
			−1 (0.9996)	3 (0.9741)	0 (1.00)	6 (0.7813)
	Pit 2	2,586 ± 458	2,530 ± 569	2,607 ± 468	2,512 ± 477	2,511 ± 419
%R (*p*-value)			2 (0.9925)	−1 (0.9999)	3 (0.9780)	3 (0.9769)
	Outdoor	2,482 ± 392	2,575 ± 457	2,482 ± 346	2,590 ± 453	2,338 ± 514
			−4 (0.8720)	0 (1.00)	−4 (0.8030)	6 (0.5858)
CH_4 flux (mg/h/m^2) ± st. dev.	Pit 1	529 ± 172	647 ± 186	547 ± 170	637 ± 295	625 ± 207
			−22 (0.7535)	−3 (0.9998)	−20 (0.8111)	−18 (0.8679)
	Pit 2	33.5 ± 9.49	34.3 ± 9.49	32.5 ± 9.55	38.3 ± 9.11	34.3 ± 7.86
%R (*p*-value)			−3 (0.9992)	3 (0.9998)	−14 (0.8100)	−3 (0.9995)
	Outdoor	325 ± 74.2	373 ± 73.0	345 ± 61.4	362 ± 55.4	347 ± 61.4
			−15 (0.6109)	−6 (0.9126)	−11 (0.8020)	−3 (0.9660)
N_2O flux (mg/h/m^2) ± st. dev.	Pit 1	0.85 ± 0.27	0.88 ± 0.32	0.79 ± 0.27	0.80 ± 0.30	0.84 ± 0.31
			−3 (0.9971)	7 (0.9552)	5 (0.9865)	1 (1.00)
	Pit 2	0.86 ± 0.27	0.93 ± 0.34	0.91 ± 0.28	0.89 ± 0.29	0.91 ± 0.33
%R (*p*-value)			−8 (0.9398)	−6 (0.9830)	−3 (0.9918)	−5 (0.9843)
	Outdoor	0.78 ± 0.30	0.85 ± 0.38	0.81 ± 0.30	0.82 ± 0.29	0.82 ± 0.30
			−9 (0.9404)	−4 (0.9973)	5 (0.9931)	−5 (0.9942)
Odor concentration (OU/m^3) ± st. dev.	Pit 1	3,898 ± 2,061	3,747 ± 2,388	3,546 ± 1,820	4,073 ± 1,345	3,614 ± 2,056
			4 (0.9994)	9 (0.9835)	−5 (0.9989)	7 (0.9927)
	Pit 2	2,487 ± 1,494	2,204 ± 1,343	2,088 ± 1,621	2,233 ± 1,496	2,556 ± 1,014
%R (*p*–value)			11 (0.9750)	16 (0.9162)	10 (0.9833)	−3 (0.9999)
	Outdoor	2,915 ± 1,960	3,035 ± 1,836	3,179 ± 2,144	3,742 ± 2,440	3,236 ± 1,733
			−4 (0.9990)	−9 (0.9801)	−28 (0.4156)	−11 (0.9594)
4EP* (PAC) ± st. dev.	Pit 1	264,499 ± 262,741	275,364 ± 308,681	229,382 ± 245,650	418,202 ± 478,103	301,198 ± 471,300
			−4 (1.00)	13 (0.9990)	−58 (0.7919)	−14 (0.9988)
	Pit 2	173,737 ± 58,676	466,087 ± 246,690	383,589 ± 209,298	252,275 ± 255,243	307,733 ± 298,910
%R (*p*-value)			−168 (0.0685)	−121 (0.3033)	−45 (0.9464)	−77 (0.7190)
	Outdoor	508,336 ± 424,126	459,440 ± 310,439	467,540 ± 494,977	556,149 ± 473,179	391,073 ± 270,197
			10 (0.9912)	8 (0.9956)	−9 (0.9919)	23 (0.9160)
Acetic acid (PAC) ± st. dev.	Pit 1	18,290 ± 34,022	11,448 ± 21,551	22,167 ± 33,256	32,119 ± 56,196	19,696 ± 26,224
			37 (0.9945)	−21 (0.9994)	−76 (0.9284)	−8 (1.00)
	Pit 2	44,893 ± 89,002	50,967 ± 99,429	82,861 ± 184,242	92,648 ± 121,001	53,577 ± 61,757
%R (*p*-value)			−14 (1.00)	−85 (0.9688)	−106 (0.9304)	−19 (0.9999)
	Outdoor	5,051 ± 5,661	24,561 ± 53,167	24,561 ± 53,167	566 ± 698	1,453 ± 1,693
			−153 (0.9643)	−386 (0.4762)	89 (0.9954)	71 (0.9980)
DEDS* (PAC) ± st. dev.	Pit 1	7,983 ± 6,082	8,614 ± 5,013	6,473 ± 5,013	8,143 ± 6,611	7,495 ± 7,945
			−8 (0.9990)	19 (0.9714)	−2 (1.00)	6 (0.9996)

(Continued)

TABLE 5 | Continued

Trial 2	Manure source	Control	Enviro Lagoon	MTM	Oxydol	WA
	Pit 2	4,791 ± 5,559	6,902 ± 6,602	5,003 ± 4,802	4,426 ± 5,363	2,815 ± 6,014
%R (p-value)			−44 (0.9272)	−4 (1.00)	8 (0.9999)	41 (0.9418)
	Outdoor	7,073 ± 6,056	8,561 ± 6,189	4,772 ± 5,108	7,630 ± 5,046	7,484 ± 4,610
			−21 (0.9574)	33 (0.8223)	−8 (0.9990)	−6 (0.9997)
DMDS* (PAC) ± st. dev.	Pit 1	17,464 ± 7,628	26,013 ± 10,680	19,790 ± 6,951	11,572 ± 7,009	28,888 ± 22,763
			−49 (0.6226)	−13 (0.9951)	34 (0.8645)	−65 (0.3414)
	Pit 2	18,606 ± 7,081	18,134 ± 6,864	14,393 ± 4,084	19,103 ± 11,924	30,706 ± 27,236
%R (p-value)			3 (1.00)	23 (0.9740)	−3 (1.00)	−65 (0.4326)
	Outdoor	12,490 ± 6,622	11,267 ± 4,617	10,249 ± 7,859	12,390 ± 3,952	12,695 ± 4,539
			10 (0.9910)	18 (0.9197)	1 (1.00)	−2 (1.00)
DMTS* (PAC) ± st. dev.	Pit 1	6,449 ± 4,563	6,425 ± 4,517	8,172 ± 8,532	2,834 ± 1,966	7,617 ± 6,919
			0 (1.00)	−27 (0.9730)	56 (0.7088)	−18 (0.9937)
	Pit 2	3,751 ± 4,520	1,0436 ± 13,954	6,320 ±6,172	4,341 ± 5,068	2,063 ± 4,580
%R (p-value)			−178 (0.3288)	−68 (0.9464)	−16 (0.9998)	45 (0.9884)
	Outdoor	5,270 ± 6,603	5,045 ± 3,773	5,251 ± 7,995	3,759 ± 2,571	2,721± 2,181
			4 (1.00)	0 (1.00)	29 (0.9775)	48 (0.8660)
Indole (PAC) ± st. dev.	Pit 1	20,021 ± 20,685	13,717 ± 12,859	18,705 ± 18,372	16,895 ± 26,463	21,329 ± 27,056
			31 (0.9601)	7 (0.9999)	16 (0.9971)	−7 (0.9999)
	Pit 2	16,900 ± 12,592	26,016 ± 19,743	30,937 ± 28,231	28,242 ± 15,101	11,942 ± 10,116
%R (p-value)			31 (0.9601)	7 (0.9999)	16 (0.9971)	−7 (0.9999)
	Outdoor	10,321 ± 10,118	9,724 ± 9,360	10,104 ± 9,905	7,772 ± 6,484	6,662 ± 5,886
			6 (0.8511)	2 (0.5482)	25 (0.7286)	35 (0.9822)
Isobutyric acid (PAC) ± st. dev.	Pit 1	217,723 ± 582,682	238,743 ± 531,079	247,671 ± 562,042	295,883 ± 627,015	310,527 ± 797,894
			−10 (1.00)	−14 (0.9999)	−36 (0.9977)	−43 (0.9955)
	Pit 2	348,985 ± 892,041	326,888 ± 840,012	315,408 ± 804,025	335,036 ± 864,325	389,754 ± 1,018,264
%R (p-value)			6 (1.00)	10 (1.00)	4 (1.00)	−12 (1.00)
	Outdoor	520,376 ± 1,087,338	535,126 ± 1,243,912	520,417 ± 1,054,417	514,345 ± 1,085,674	426,939 ± 881,554
			−3 (1.00)	0 (1.00)	1 (1.00)	18 (0.9995)
P-cresol (PAC) ± st. dev.	Pit 1	1,157,879 ± 1,251,761	990,549 ± 1,182,166	1,195,216 ± 1,425,154	1,054,019 ± 1,109,347	1,272,492 ± 2,032,069
			14 (0.9985)	−3 (1.00)	9 (0.9998)	−10 (0.9997)
	Pit 2	1,939,021 ± 948,842	1,533,312 ± 1,216,556	1,421,606 ± 1,178,315	3,323,033 ± 1,414,225	1,264,592 ± 1,063,902
%R (p-value)			21 (0.9466)	27 (0.8801)	−71 (0.1124)	35 (0.7386)
	Outdoor	1,490,619 ± 1,940,009	1,275,968 ± 1,121,891	2,329,513 ± 2,738,851	2,218,014 ± 2,159,586	1,463,223 ± 1,299,686
			14 (0.9972)	−56 (0.6912)	−49 (0.7897)	2 (1.00)
Phenol (PAC) ± st. dev.	Pit 1	1,103,816 ± 835,232	1,164,209 ± 960,538	650,525 ± 811,873	479,278 ± 510,677	1,161,132 ± 1,375,503
			−5(0.9999)	41 (0.8039)	57 (0.5575)	−5 (0.9999)
	Pit 2	4,412,143 ± 2,910,423	6,525,652 ± 3,054,830	5,432,687 ± 2,403,042	6,504,135 ± 3,304,190	5,722,162 ± 3,771,118
%R (p-value)			−48 (0.5660)	−23 (0.9487)	−47 (0.5756)	−30 (0.8819)
	Outdoor	646,675 ± 824,836	610,871 ± 631,507	1,129,340 ± 1,752,613	357,157 ± 413,890	215,529 ± 167,396
			6 (1.00)	−75 (0.8420)	45 (0.9717)	67 (0.8889)
Propionic acid (PAC) ± st. dev.	Pit 1	23,044 ± 28,932	43,620 ± 84,769	51,543 ± 83,396	83,344 ± 166,798	33,937 ± 57,145
			−89 (0.9905)	−124 (0.9682)	−262 (0.6664)	−47 (0.9992)
	Pit 2	33,177 ± 39,307	30,769 ± 45,513	36,745 ± 56,745	60,093 ± 69,224	20,217 ± 19,327
%R (p-value)			7 (1.00)	−11 (0.9999)	−81 (0.8019)	−47 (0.9992)
	Outdoor	34,958 ± 37,600	29,336 ± 40,240	41,071 ± 37,402	26,130 ± 38,658	22,838 ± 24,028
			16 (0.9960)	−17 (0.9945)	25 (0.9779)	35 (0.9321)
Skatole (PAC) ± st. dev.	pit 1	285,740 ± 221,045	370,655 ± 323,806	190,971 ± 182,813	483,969 ± 386,006	446,497 ± 521,668
			−30 (0.9500)	33 (0.9271)	−69 (0.4562)	−56 (0.6525)
	Pit 2	597,053 ± 445,997	784,215 ± 420,112	675,648 ± 364,606	873,957 ± 461,121	779,632 ± 644,116
%R (p-value)			−31 (0.8640)	−13 (0.9938)	−46 (0.6043)	−31 (0.8741)
	Outdoor	172,663 ± 118,789	185,825 ± 121,252	236,092 ± 237,760	179,762 ± 134,813	205,420 ± 242,875
			−8 (0.9992)	−37 (0.7729)	−4 (0.9999)	−19 (0.9797)

%R is statistically significant when the p-value < 0.05 (signified by bold font if present). Negative (-) %R signifies generation.

**%R = percent reduction with respect to Control (untreated); PAC = peak area count (arbitrary unit); N/A = Below the detection limit; 4EP = 4-ethyl phenol; DEDS = Diethyl disulfide; DMDS = Dimethyl disulfide; DMTS = Dimethyl trisulfide.*

TABLE 6 | Trial 3-Comparison of averaged gaseous emissions from three manure sources (farms) with their standard deviations.

Trial 3	Control	MM	Penergetic G	Sludge Away
NH_3 (mg/h/m^2)	499 ± 328	472 ± 324	521 ± 346	524 ± 309
%R		5 (0.9760)	−4 (0.9861)	−5 (0.9781)
H_2S (mg/h/m^2)	42.6 ± 44.3	35.0 ± 41.4	32.1 ± 43.8	45.0 ± 54.4
%R		18 (0.8519)	25 (0.6747)	−6 (0.9936)
CO_2 (mg/h/m^2)	3,719 ± 2,095	3,865 ± 2,140	3,874 ± 2,183	3,662 ± 1,799
%R		−4 (0.9890)	−4 (0.9868)	2 (0.9993)
CH_4 (mg/h/m^2)	1,431 ± 1,139	1,877 ± 1,656	1,967± 1414	1,545 ± 908
%R		−31 (0.5091)	−37 (0.3452)	−8 (0.9848)
N_2O (mg/h/m^2)	1.24 ± 0.95	1.20 ± 0.97	1.13 ± 0.93	1.12 ± 0.91
%R		3 (0.9989)	9 (0.9765)	10 (0.9697)
Odor (OU/m^3)	5,327 ± 1,960	5,274 ± 1,546	5,178 ± 1,546	5,166 ± 1,425
%R		1 (0.9950)	3 (0.9885)	3 (0.9856)
4EP* (PAC)	535,075 ± 472,795	535,756 ± 583,474	571,498 ± 646,729	585,506 ± 537,207
%R		0 (1.00)	−7 (0.9953)	−9 (0.9877)
Acetic acid (PAC)	23,342 ± 28,898	20,914 ± 20,322	16,683 ± 37,832	19,641 ± 22,376
%R		10 (0.9898)	29 (0.8336)	16 (0.9657)
DEDS* (PAC)	16,055 ± 7,681	20,318 ± 12,152	19,059 ± 7,697	19,045 ± 5,464
%R		−27 (0.3362)	−19 (0.6351)	−19 (0.6387)
DMDS* (PAC)	9,683 ± 5,222	12,145 ± 9,519	11,740 ± 6,630	15,336 ± 19,405
%R		−25 (0.8800)	−21 (0.9255)	−58 (0.3284)
DMTS* (PAC)	6,410 ± 3,962	6,652 ± 4,259	7,374 ± 4,233	6,667 ± 3,892
%R		−4 (0.9971)	−15 (0.9971)	−4 (0.9965)
Indole (PAC)	22,622 ± 28,450	28,133 ± 53,123	35,317 ± 67,489	19,938 ± 23,026
%R		−24 (0.9708)	−56 (0.7381)	12 (0.9964)
IsB (PAC)	30,041 ± 37,914	28,461 ± 37,042	26,025 ± 50,780	38,675 ± 54,742
%R		5 (0.9992)	13 (0.9880)	−29 (0.8964)
IsV (PAC)	44,428 ± 41,204	51,481 ± 57,988	43,732 ± 65,978	108,720 ± 169,837
%R		−16 (0.9945)	2 (1.00)	−145 (0.1132)
p-Cresol (PAC)	3,258,433 ± 4,389,300	1,885,515 ± 2,221,119	3,147,694 ± 5,532,756	3,312,823 ± 4,372,801
%R		42 (0.6819)	3 (0.9997)	−2 (1.00)
Phenol (PAC)	799,378 ± 836,566	2,814,616 ± 7,842,467	983,504 ± 1,416,374	1,546,183 ± 2,421,635
%R		−252 (0.3338)	−23.0 (0.9987)	−93.4 (0.9231)
PA (PAC)	37,670 ± 51,824	37,897 ± 58,272	41,567 ± 107,198	53,339 ± 70,261
%R		−1 (1.00)	−10 (0.9979)	−42 (0.8880)
Skatole (PAC)	745,597 ± 550,321	930,146 ± 860,934	845,938 ± 872,312	820,813 ± 672,384
%R		−25 (0.7951)	−14 (0.959)	−10 (0.9820)

%R is statistically significant when the p-value < 0.05 (signified by bold font if present). Negative (-)%R signifies generation.

**%R = percent reduction with respect to Control (untreated); PAC = peak area count (arbitrary unit); N/A = Below the detection limit; 4EP = 4-ethyl phenol; DEDS = Diethyl disulfide; DMDS = Dimethyl disulfide; DMTS = Dimethyl trisulfide; IsB = isobutyric acid, PA = propanoic acid; IsV = isovaleric acid.*

targeted gases also might be the opposite results for the same kind of manure. Nevertheless, no matter which data analysis approach was used, the results were not statistically significant and lacked clear trends.

Trial 3 (MM, Penergetic G, Sludge Away)

The three products included in the third Trial were MM, Penergetic G, and Sludge Away. The measurements over the 8-week of the experiment for the three productions are listed in **Supplementary Material** (Sludge Away: **Supplementary Figures 99–107**; Penergetic G: **Supplementary Figures 108–116**; MM: **Supplementary Figures 117–125**). When we consider the manure to be replicated, there was no overall statistical significance to %*R* in any of the products tested in Trial 3, as shown in **Table 6**. For NH_3 emissions, MM showed a 5% reduction, whereas Penergetic G and Sludge Away showed 4 and 5% generations, respectively. For H_2S emission, MM and Penergetic G showed 18 and 25% reductions, Sludge Away still had 6% generation. For GHG emissions, MM showed a 4% generation in CO_2 emission, a 31% generation in CH_4 emission, and a 3% reduction in N_2O; Penergetic G had a 4% generation in CO_2 emission, a 37% generation in CH_4 emission, and a 9% reduction in N_2O emission. For odor, there was no statistical effect associated with all three products ($\leq$3%*R*). For VOC

TABLE 7 | Trial 3-comparison of gaseous emissions from each of the 3 manure sources (farms) with their standard deviations.

Trial 3	Manure source	Control	MM	Penergetic G	Sludge away
NH_3 flux (mg/h/m^2) ± st. dev.	Pit 1	270 ± 180	257 ± 154	302 ± 132	344 ± 169
			5 (0.9893)	−12 (0.8624)	−28 (0.2789)
	Pit 2	824 ± 327	784 ± 354	859 ± 393	850 ± 288
%R (*p*-value)			5 (0.9851)	−4 (0.9900)	−3 (0.9960)
	Pit 3	402 ± 133	375 ± 132	401 ± 125	379 ± 128
			7(0.8842)	0 (1.00)	6 (0.9207)
H_2S flux (mg/h/m^2) ± st. dev.	Pit 1	22.3 ± 24.4	21.7 ± 15.6	13.8 ± 15.9	25.6 ± 18.6
			3 (0.9996)	38 (0.5233)	−15 (0.9484)
	Pit 2	88.4 ± 45.2	63.2 ± 60.8	67.9 ± 59.8	93.7 ± 70.7
%R (*p*-value)			29 (0.5991)	23 (0.7416)	−6 (0.9938)
	Pit 3	17.0 ± 12.3	20.3 ± 13.2	14.5 ± 10.7	15.8 ± 9.59
			−19 (0.8532)	15 (0.9249)	7 (0.9904)
CO_2 flux (mg/h/m^2) ± st. dev.	Pit 1	5,048 ± 2,961	4,941 ± 2,762	5,001 ± 3,138	4,632 ± 2,456
			2 (0.9994)	1 (1.00)	8 (0.9701)
	Pit 2	3,390 ± 1,237	3,752 ± 1,934	3,795 ± 1,482	3,372 ± 1,288
%R (*p*-value)			−11 (0.8910)	−12 (0.8547)	1 (1.00)
	Pit 3	2,720 ± 924	2,901 ± 1,132	2,825 ± 948	2,981 ± 1,114
			−7 (0.9339)	−4 (0.9857)	−4 (0.9857)
CH_4 flux (mg/h/m^2) ± st. dev.	Pit 1	1,771 ± 1,743	2,301 ± 2,142	2,386 ± 1,988	1,646 ± 1,143
			−30 (0.8750)	−35 (0.8181)	7 (0.9979)
	Pit 2	1,342 ± 810	2,089 ± 1,828	2,129 ± 1,270	1,507 ± 911
%R (*p*-value)			−56 (0.2598)	−59 (0.3156)	−12 (0.9826)
	Pit 3	1,181 ± 599	1,242 ± 605	1,386 ± 626	1,482 ± 745
			−5 (0.9975)	−17 (0.9906)	−25 (0.7840)
N_2O flux (mg/h/m^2) ± st. dev.	Pit 1	1.31 ± 1.01	1.25 ± 1.04	1.11 ± 0.94	1.12 ± 0.94
			4 (0.9995)	15 (0.9786)	15 (0.9806)
	Pit 2	1.24 ± 0.99	1.15 ± 0.99	1.16 ± 1.02	1.19 ± 1.03
%R (*p*-value)			7 (0.9981)	7 (0.9986)	5 (0.9995)
	Pit 3	1.17 ± 0.99	1.20 ± 1.01	1.11 ± 0.96	1.05 ± 0.85
			−2 (0.9999)	5 (0.9947)	10 (0.9947)
Odor concentration (OU/m^3) ± st. dev.	Pit 1	4,725 ± 981	4,967 ± 972	4,810 ± 1,143	4,655 ± 1,060
			−5 (0.9610)	−2 (0.9981)	1 (0.9990)
	Pit 2	6,457 ± 2,429	5,587 ± 1,915	5,907 ± 2,089	5,474 ± 1,567
%R (*p*-value)			13 (0.8167)	9 (0.9447)	15 (0.7562)
	Pit 3	4,800 ± 1,888	5,270 ± 1,739	4,816 ± 1,276	5,368 ± 1,626
			−10 (0.9381)	0 (1.00)	−12 (0.8970)
4EP* (PAC) ± st. dev.	Pit 1	103,325 ± 30,556	239,533 ± 113,100	153,907 ± 110,400	270,541 ± 162,902
			−132 (0.084)	−49 (0.7916)	−162 (0.0241)
	Pit 2	950,935 ± 464,587	875,791 ± 827,157	978,295 ± 763,987	1,094,951 ± 547,226
%R (*p*-value)			8 (0.9848)	−3 (0.9997)	−15 (0.9600)
	Pit 3	550,966 ± 326,689	491,942 ± 432,430	582,293 ± 624,390	391,026 ± 411,127
			11 (0.9905)	−6 (0.9985)	29 (0.8496)
Acetic acid (PAC) ± st. dev.	Pit 1	14,052 ± 12,374	25,320 ± 17,576	10,099 ± 14,439	11,225 ± 16,849
			−80(0.4756)	28 (0.9556)	20 (0.9829)
	Pit 2	42,720 ± 34,584	7,134 ± 8,061	13,489 ± 11,997	36,287 ± 25,169
%R (*p*-value)			**83 (0.0200)**	68 (0.0703)	15 (0.9409)
	Pit 3	13,253 ± 27,395	30,288 ± 25,365	26,460 ± 64,651	11,410 ± 15,897
			−129 (0.7872)	−100 (0.8867)	14 (0.9996)
DEDS* (PAC) ± st. dev.	Pit 1	18,040 ± 3,544	20,408 ± 10,275	20,147 ± 8,565	19,106 ± 3,647
			−13 (0.8969)	−12 (0.9243)	−6 (0.9890)
	Pit 2	12,364 ± 8,751	15,163 ± 4,437	18,809 ± 9,327	19,251 ± 5,847
%R (*p*-value)			−23 (0.8765)	−52 (0.3317)	−56 (0.2767)
	Pit 3	17,763 ± 9,016	25,383 ± 17,328	18,222 ± 5,663	18,777 ± 7,103
			−43 (0.4944)	−3 (0.9998)	−6 (0.9975)

(Continued)

TABLE 7 | Continued

Trial 3	Manure source	Control	MM	Penergetic G	Sludge away
DMDS* (PAC) ± st. dev.	Pit 1	11,128 ± 6,414	10,972 ± 6,966 1 (1.00)	11,163 ± 7,198 0 (1.00)	11,445 ± 7,162 −3 (0.9997)
%R (*p*-value)	Pit 2	7,740 ± 4,979	7,849 ± 2,565 −1 (1.00)	11,255 ± 8,096 −45 (0.5063)	9,406 ± 3,704 −22 (0.9087)
	Pit 3	10,181 ± 4,083	17,613 ± 13,630 −73 (0.8236)	12,803 ± 5,013 −26 (0.9900)	25,156 ± 31,694 −147 (0.3239)
DMTS (PAC) ± st. dev.	Pit 1	6,982 ± 1,756	6,069 ± 3,577 13 (9322)	7,444 ± 4,170 −7 (0.9902)	6,614 ± 2,870 5 (0.9950)
%R (*p*-value)	Pit 2	5,879 ± 5,069	7,189 ± 4,739 −22 (0.9546)	7,082 ± 5,746 −20 (0.9642)	5,246 ± 4,570 11 (0.9944)
	Pit 3	6,371 ± 4,703	6,698 ± 4,861 −5 (0.9986)	7,597 ± 2,884 −19 (0.9350)	8,142 ± 3,981 −28 (0.8309)
Indole (PAC) ± st. dev.	Pit 1	6,273 ± 1,910	16,661 ± 11,508 −166 (0.0604)	11,469 ± 10,068 −83 (0.5555)	14,841 ± 8,298 −137 (0.153)
%R (*p*-value)	Pit 2	50,397 ± 35,585	55,255 ± 88,181 −10 (0.9968)	46,877 ± 60,303 7 (0.9988)	35,485 ± 34,616 30 (0.9211)
	Pit 3	11,196 ± 7,290	12,484 ± 9,643 −11 (0.9999)	47,607 ± 101,255 −325 (0.4612)	9,489 ± 6,657 15 (0.9999)
Isobutyric acid (PAC) ± st. dev.	Pit 1	42,030 ± 35,130	53,020 ± 35,039 −26 (0.9661)	48,075 ± 82,667 −14 (0.9940)	46,633 ± 54,415 −11 (0.9973)
%R (*p*-value)	Pit 2	46,646 ± 45,478	32,364 ± 40,597 31 (0.9033)	27,825 ± 19,791 40 (0.8060)	67,191 ± 65,983 −44 (0.7618)
	Pit 3	1,446 ± 2,650	N/A 100	2,175 ± 6,152 −50 (0.9768)	2,203 ± 3,082 −52 (0.9741)
Isovaleric acid (PAC) ± st. dev.	Pit 1	62,604 ± 39,504	90,932 ± 49,936 −45 (0.8060)	79,106 ± 102,217 −26 (0.9528)	101,829 ± 98,672 −63 (0.6056)
%R (*p*-value)	Pit 2	61,056 ± 41,550	48,114 ± 65,610 21 (0.9974)	42,409 ± 31,482 31 (0.9924)	207,988 ± 250,536 −241 (0.9924)
	Pit 3	9,624 ± 14,615	15,398 ± 31,156 −60 (0.9682)	9,682 ± 10,317 −1 (1.00)	16,345 ± 34,685 −70 (0.9513)
P-cresol (PAC) ± st. dev.	Pit 1	244,552 ± 200,288	760,927 ± 263,992 −211 (0.0878)	402,709 ± 414,911 −65 (0.873)	995,238 ± 676,960 **−307 (0.0067)**
%R (*p*-value)	Pit 2	8,319,774 ± 4,290,638	3,856,350 ± 2,965,233 54 (0.2928)	7,781,386 ± 7,835,989 6 (0.9963)	8,032,055 ± 4,839,862 3 (0.9994)
	Pit 3	1,210,973 ± 635,523	1,039,267 ± 802,786 14 (0.9773)	1,258,988 ± 1,333,730 −4 (0.9995)	911,175 ± 872,773 25 (0.8944)
Phenol (PAC) ± st. dev.	Pit 1	631,754 ± 284,180	1,241,418 ± 800,840 −97 (0.0933)	961,757 ± 297,353 −52 (0.5582)	1,570,707 ± 567,309 **−149 (0.0044)**
%R (*p*-value)	Pit 2	1,501,318 ± 1,085,634	7,060,285 ± 13,032,311 −370 (0.3151)	1,826,114 ± 2,205,721 −22 (0.9996)	2,828,552 ± 3,876,724 −88 (0.9746)
	Pit 3	265,062 ± 344,421	142,145 ± 106,434 46 (0.7200)	162,641 ± 236,362 39 (0.8162)	239,289 ± 292,553 10 (0.9961)
Propionic acid (PAC) ± st. dev.	Pit 1	51,961 ± 56,942	88,866 ± 77,687 −71 (0.8981)	95,954 ± 179,436 −85 (0.8405)	85,769 ± 96,087 −65 (0.9192)
%R (*p*-value)	Pit 2	52,889 ± 62,535	16,197 ± 19,266 69 (0.3024)	20,213 ± 15,009 62 (0.4013)	54,183 ± 45,336 −2 (0.9999)
	Pit 3	8,160 ± 13,345	8,627 ± 16,254 −6 (1.00)	8,533 ± 13,652 −5 (1.00)	20,065 ± 49,641 −146 (0.8346)
Skatole (PAC) ± st. dev.	Pit 1	350,734 ± 123,349	504,306 ± 330,762 −44 (0.5976)	431,247 ± 285,926 −23 (0.9116)	486,758 ± 189,994 −39 (0.6850)
%R (*p*-value)	Pit 2	1,238,345 ± 548,016	1,585,219 ± 1,150,551 −28 (0.7976)	1,444,474 ± 1,124,639 −17 (0.9476)	1,481,592 ± 754,456 −20 (0.9178)
	Pit 3	647,713 ± 461,439	700,912 ± 494,467 −8 (0.9944)	662,094 ± 713,471 −2 (0.9999)	8,494,090 ± 362,816 24 (0.8880)

%R is statistically significant when the p-value < 0.05 (signified by bold font). Negative (-) %R signifies generation.

**%R = percent reduction with respect to Control (untreated); PAC = peak area count (arbitrary unit); N/A = Below the detection limit; 4EP = 4-ethyl phenol; DEDS = Diethyl disulfide; DMDS = Dimethyl disulfide; DMTS = Dimethyl trisulfide.*

emissions, no statistically significant %R was found, similar to the lack of trends observed in the first two Trials.

In general, when we considered the manure sources are not replications, we found the statistical significance of %R for one product and one manure, and one VOC, as shown in **Table 7**. MM showed an 83% reduction with a p-value of 0.02 in acetic acid emitted from the manure of pit 2. However, a statistically significant generation was also observed. Sludge Away showed 307% generation with a p-value of 0.0067 and 149% generation with a p-value of 0.0044 in p-cresol and phenol, respectively, emitted from the manure of deep pit 1.

In general, the lack of statistical significance and trends was observed for the remainder of targeted gases. For NH_3 emissions, MM showed 5% reductions for manure from pit 1 and 2, a 7% reduction for manure in pit 3; Penergetic G showed 12% and 4% generations in manure from pit 1 and 2, respectively, and no impact on emission for pit 3; Sludge Away showed 28 and 3% generations in manure from pit 1 and 2, a 6% reduction for manure from pit 3. For H_2S emissions, MM showed 3% and 29% reductions in manure from pit 1 and 2, a 19% generation in manure from pit 3; Penergetic G showed 38, 23, and 15% reductions in manure from pit 1, 2, and 3, respectively; Sludge Away showed 15 and 6% generations in manure from pit 1 and 2, a 7% reduction in manure from pit 3. For GHG emissions, MM, Penergetic G, and Sludge Away showed 2, 1, and 8% reduction in CO_2 emissions, respectively, in manure from pit 1; MM and Penergetic had 11 and 12% generations in CO_2 emissions emitted from pit 2, and Sludge Away showed 1% reduction; MM, Penergetic G, and Sludge Away showed 7, 4, and 4% generations in CO_2 emissions from pit 3. All three products showed generations in CH_4 emissions, except manure from pit 1 treated with Sludge Away with a 7% reduction. All three products showed reductions in all manure sources, excepted a 2% generation in manure from pit 3 treated with MM. Odor and VOCs shared a similar lack of trends like the first two Trials in which emissions were reduced in one or two types of manure but also generated in other types of manure sources.

Trial 4 (LLMO-SST)

One product, LLMO-SST, was tested in the last Trial. H_2S emissions and selected VOCs were not detected in this Trial (**Supplementary Figures 126–130**). When we consider the manure to be replicated, there was no statistically significant *%R* found, as shown in **Table 8**. LLMO showed a 5% reduction in NH_3 emission, a 3% reduction in CO_2 emission, a 13% generation in CH_4 emission, no impact on N_2O emission, and a 1% reduction in odor concentration. For VOCs, we still observed the random pattern in which some gases were reduced, and other gases were generated.

Table 9 below summarized the results analyzed by each manure source for Trial 4. For NH_3 emissions, LLMO showed a 24% generation with a p-value of 0.0272 in manure from pit 1, but a 20% reduction with a p-value of 0.0101 in manure from pit 2. The rest of the detected gases still did not show any statistical significance, except for a 57% reduction with a p-value of 0.0381 for skatole emission from pit 3.

TABLE 8 | Trial 4-comparison of averaged gaseous emissions from three manure sources (farms) with their standard deviations.

Trial 4	Control	LLMO
NH_3 (mg/h/m^2)	128 ± 50.5	122 ± 37.1
%R		5 (0.5143)
CO_2 (mg/h/m^2)	2,084 ± 585	2,029 ± 421
%R		3 (0.6008)
CH_4 (mg/h/m^2)	347 ± 311	390 ± 374
%R		−13 (0.6591)
N_2O (mg/h/m^2)	0.87 ± 0.28	0.87 ± 0.29
%R		0 (0.9532)
Odor (OU/m^3)	3,102 ± 1,447	3,066 ± 1,491
%R		1 (0.9291)
4EP* (PAC)	160,294 ± 120,122	132,522 ± 146,228
%R		17 (0.4349)
Indole (PAC)	27,332 ± 111,018	5,349 ±8,017
%R		80 (0.3357)
p-Cresol (PAC)	761,873 ± 737,937	570,982 ± 683,040
%R		25 (0.3448)
Phenol (PAC)	302,851 ± 371,239	420,707 ± 768,945
%R		−39 (0.4880)
Skatole (PAC)	227,858 ± 153,010	175,769 ± 199,646
%R		23 (0.2946)

%R is statistically significant when the p-value < 0.05 (signified by bold font if present). Negative (-) %R signifies generation.

**%R = percent reduction with respect to Control (untreated); PAC = peak area count (arbitrary unit); N/A = Below the detection limit; 4EP = 4-ethyl phenol.*

DISCUSSION

The results of this pilot-scale study aimed to be fair in the presentation of results pertaining to each of the commercial products that were tested in a particular set of conditions. The presented results could help the farmers and the swine industry to find the detailed performance data of all the targeted gases for the particular tested product. The results also provided the important metric of the popular technology used by some U.S. farmers to mitigate gaseous emission for the environmental regulatory agencies and researchers.

The side-by-side comparison of the 12 manure additives tested in this study did not show that treatment with any product resulted in statistically significant and comprehensive reductions to emissions of targeted gases such as NH_3, H_2S, GHGs, VOCs, and odor. Very similar findings were reported on the pilot-scale study of manure additives conducted almost 20 years ago (Heber et al., 2001). Maurer et al. (2016) summarized the performance data for technologies to control gaseous emissions in which manure additives have shown inconsistent performance, and little or no data was available for testing on farm/field scales. The lack of consistent, significant, and comprehensive performance in mitigating gaseous emissions at lab-scale is often precluding the continuation of testing and scaling to the pilot- and farm-trials. This is also the major

TABLE 9 | Trial 4-comparison of gaseous emissions from each of the three manure sources (farms) with their standard deviations.

Trial 4	Manure source	Control	LLMO
NH_3 flux (mg/h/m^2) ± st. dev.	Pit 1	86.2 ± 22.0	107 ± 27.5
			−24 (0.0272)
	Pit 2	182 ± 42.6	146 ± 38.7
%R (*p*-value)			**20 (0.0101)**
	Pit 3	117 ± 25.5	114 ± 33.6
			2(0.7894)
CO_2 flux (mg/h/m^2) ± st. dev.	Pit 1	2,256 ± 720	2,142 ± 524
			5 (0.5263)
	Pit 2	2,060 ± 637	1,932 ± 382
%R (*p*-value)			6 (0.5099)
	Pit 3	1,936 ± 375	2,014 ± 371
			−4 (0.6119)
CH_4 flux (mg/h/m^2) ± st. dev.	Pit 1	644 ± 397	772 ± 447
			−20 (0.4562)
	Pit 2	168 ± 51	160 ± 61
%R (*p*-value)			5 (0.7773)
	Pit 3	229 ± 63	238 ± 64
			−4 (0.7787)
N_2O flux (mg/h/m^2) ± st. dev.	Pit 1	0.85 ± 0.29	0.94 ± 0.32
			−11 (0.1403)
	Pit 2	0.83 ± 0.26	0.83 ± 0.26
%R (*p*-value)			0 (0.9982)
	Pit 3	0.93 ± 0.31	0.83 ± 0.30
			11 (0.1334)
Odor concentration (OU/m^3) ± st. dev.	Pit 1	2,864 ± 1,832	3,494 ± 1,272
			−22 (0.2201)
	Pit 2	3,313 ± 1,429	2,985 ± 1,581
%R (*p*-value)			10 (0.6784)
	Pit 3	3,129 ± 1,168	2,719 ± 1,682
			13 (0.5895)
4EP* (PAC) ± st. dev.	Pit 1	114,423 ± 106,615	104,903 ± 99,961
			8 (0.7671)
	Pit 2	202,510 ± 152,615	200,741 ± 208,891
%R (*p*-value)			1 (0.9833)
	Pit 3	163,949 ± 91,080	91,922 ± 92,496
			44 (0.1485)
Indole (PAC) ± st. dev.	Pit 1	3,848 ± 3,823	6,227 ± 6,257
			−62 (0.3790)
	Pit 2	76,381 ± 190,653	8,971 ± 11,371
%R (*p*-value)			88 (0.3317)
	Pit 3	1,768 ± 2,542	849 ± 1,923
			52 (0.4428)
p-Cresol (PAC) ± st. dev.	Pit 1	439,151 ± 509,045	701,402 ± 817,918
			−60 (0.3837)
	Pit 2	664,168 ± 606,317	599,360 ± 724,727
%R (*p*-value)			10 (0.8439)
	Pit 3	1,182,300 ± 911,344	412,185 ± 538,082
			65 (0.0688)
Phenol (PAC) ± st. dev.	Pit 1	227,636 ± 172,740	284,373 ± 206,643
			−25 (0.4656)
	Pit 2	648,720 ± 442,547	960,668 ± 1,165,643
%R (*p*-value)			−48 (0.4394)
	Pit 3	32,196 ± 15,704	17,081 ± 26,464
			47 (0.1832)
Skatole (PAC) ± st. dev.	Pit 1	225,228 ± 150,751	222,264 ± 138,227
			1 (0.9404)
	Pit 2	289,066 ± 191,910	231,892 ± 297,051
%R (*p*-value)			20 (0.6651)
	Pit 3	169,282 ± 95,702	73,152 ± 74,249
			57 (0.0381)

*%R is statistically significant when the p-value < 0.05 (signified by **bold** font). Negative (-) %R signifies generation.*

**%R, percent reduction with respected Control (untreated); PAC, peak area count (arbitrary unit); N/A, Below the detection limit; 4EP, 4-ethyl phenol.*

recommendation from this research, i.e., the results for the 12 manure additives tested in this study do not warrant scaling up tests and studies.

However, the experimental manure additives evaluated in recent years have shown the potential to mitigate the emissions from manure. Maurer et al. (2017b) showed up to 68% reduction of NH_3 and 80–90% reduction on the various types of VOCs by using soybean peroxidase with calcium peroxide in a pilot-scale study. The same additive (soybean peroxidase + calcium peroxide) was found to be effectively mitigating NH_3, H_2S, and some targeted VOCs on the farm-scale study (Maurer et al., 2017d). In recent years of studies of using the various types of biochar as manure additives, there are many significant reductions of targeted gases reported. Biochar made from pine could mitigate NH_3 but the generation of CH_4 (Maurer et al., 2017c). Biochar made from corn stover and red oak could mitigate NH_3 and some targeted VOCs (Meiirkhanuly et al., 2020b). Chen et al. (2020a) showed a significant reduction of H_2S emissions during the manure agitation.

Manure additives, especially the ones with physical and chemical modes of treatment, still have the potential to comprehensively mitigate gaseous emissions from swine manure. However, the impact of these manure additives such as (biochar, soybean peroxide) still needed further research on larger scales and farms with different manure management systems. Most recently, research has shown that biochar-treated manure can have beneficial agronomic effects, as reported by Banik et al. (2020). There is an early indication that biochar-manure mixture has the potential to further improve the nitrogen and carbon cycling and sustainability of animal and crop production.

CONCLUSIONS

The following conclusions can be made based on the results of this research:

1. This pilot-scale study of 12 marketed manure additive products did not show a consistent, comprehensive, and overall statistically significant reduction for mitigation of gaseous emissions from swine manure for targeted gases including NH_3, H_2S, GHGs, VOCs, and odor.
2. The more detailed analysis based on separating each treated manure indicates large variability in performance ranging from mitigation to generation of targeted gaseous emissions.
3. Manure additives tested based on microbial mode action did not show consistent effects in mitigating emissions.
4. The manufacturer-prescribed dosages of products were not effective in pilot-scale testing that used manure from different swine farms and storage systems.
5. Based on the lack of mitigating effect of gaseous emissions in this pilot-scale study, testing of these 12 manure additives products on farms is not recommended.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Materials**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

JK and DA: conceptualization, validation, and resources. BC, JK, and DA: methodology. BC: formal analysis and wrote—original draft preparation. BC, HM, ML, ZM, PL, JW, and CB: investigation. BC and JK: data curation. BC, JK, SO'B, and AB: wrote—review and editing. BC and ML: visualization. JK: supervision. JK, DP, and DA: project administration and funding acquisition. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2020.613646/full#supplementary-material

Detailed graphical comparisons of emissions for each targeted gas over 8 weeks of each Trial, illustrated with 130 figures (**Supplementary Figures 1–130**). **Supplementary Tables 1–3** serve as a guide for finding results on a particular manure additive and targeted gas.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.