Final Report

The effect of vermifiltration on gaseous emissions from dairy wastewater

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Abbreviations: BOT, bottom of vermifilter; EFF, effluent; GHG, greenhouse gas; INF, influent; LAG, lagoon water; N, nitrogen; TOP, top of vermifilter; VOC, volatile organic compound

Core ideas

1. Vermifiltration decreases emission of ammonia from dairy wastewater by 90.2%.
2. Vermifiltration slightly increased N_2O, CO_2, CH_4, and EtOH emission from wastewater.
3. The vermifilter is not a significant source of GHG or noxious emissions.

1 ABSTRACT

Dairy lagoon water contains high concentrations of nitrogen (N), giving it the potential to pollute groundwater and the atmosphere. To reduce N loading of an anaerobic lagoon at a commercial dairy, a pilot project vermifilter was installed, which used earthworms embedded in woodchips to enhance removal of solids and contaminants. However, it was unclear whether the removal of N occurred at the expense of increasing nitrogenous gases, greenhouse gases (GHGs), volatile organic compounds (VOCs), and criteria pollutants from lagoon water treated with this new technology. Thus, emissions were measured from untreated dairy lagoon water (LAG), as well as from the vermifilter's influent (INF), effluent (EFF), the top (TOP), and bottom (BOT) of the filter to assess filter performance. Ammonia (NH_3) and ethanol (EtOH) were measured using an Innova 1412 analyzer, while nitrous oxide (N_2O), carbon dioxide (CO_2), methane (CH_4), and hydrogen sulfide (H_2S) were measured using Thermo analyzers. Gases were measured using flux chambers for LAG, INF, and EFF, a triangular shaped wind tunnel for TOP, and from an exhaust pipe for BOT. Results suggested the vermifilter versus the untreated lagoon water reduced NH_3 emission by 90.2% without substantially increasing emission of N_2O, CO_2, CH_4, and EtOH from other sampling locations of the vermifilter system. Although this study must be replicated across other dairy operations to verify these results, these preliminary findings suggest vermifiltration technology is a potential solution for N removal particularly in regions like the San Joaquin Valley of California, where dairy air- and water quality issues are most sensitive.

2 INTRODUCTION

In Central California, increasingly intensive dairy production produces more waste than dairy farmers can apply to cropland at agronomical rates. Combined with the shallow water basin, the large amount of waste produced threatens ground water - and air quality, soil quality, and downstream ecosystems. To mitigate nutrient loading in dairy wastewater, a vermifilter was built at a commercial dairy in Central California to treat lagoon water before it was applied to cropland or recycled as flush water to the freestall barns. Vermifiltration is a wastewater treatment system composed of a bed of organic media, such as woodchips or sawdust, seeded with earthworms that bio-oxidizes applied waste, outputting effluent that is lower in nutrients and vermicompost and earthworms that can be sold for profit. Previous studies have reported high nutrient removal under optimal wet:dry ratios and earthworm loading rates, reaching removal efficiencies up to 77.9% for NH_3-N, and 66.6% for total N (TN) (Wang et al., 2014b, Wang et al., 2013). Because this technology is a relatively low-cost, low-maintenance wastewater system, vermifiltration has been adopted recently to treat domestic wastewater in developing countries (Xing et al., 2015, Xing et al., 2016), industrial waste (Lin et al., 2013), and livestock waste (Li et al., 2008, Luth et al., 2011, Wang et al., 2014a). Similar to these studies, preliminary chemical analysis of the influent and effluent by the manufacturer (BioFiltro) reported high nitrogen (N) removal efficiency (>90%) from the wastewater.

Although these results were promising, it was unclear how the vermifilter affected gaseous emissions, namely ammonia (NH_3), nitrous oxide (N_2O), carbon dioxide (CO_2), methane (CH_4), ethanol (EtOH), and hydrogen sulfide (H_2S). NH_3 and H_2S are nuisance gases and respiratory irritants, whereas CO_2, CH_4, and N_2O are greenhouse gases (GHGs) with global warming potentials (GWPs) of 1, 28, and 298, respectively (IPCC, 2013). Specifically, the removal of N from wastewater via enhanced N-cycling in the vermifilter had the potential to increase production of N_2O, a byproduct of incomplete denitrification (Figure 3). Similarly, it was imperative that nutrients removed from the wastewater were not converted into EtOH or other volatile organic compounds (VOCs), a group of smog precursors regulated in the present air shed.

Although earthworms in vermifilters do not directly emit significant amounts of NH_3, CO_2, CH_4, and H_2S, the physical and chemical modifications they impose upon the media impact the emission of these gases. As for N_2O, current literature debates whether earthworms increase or decrease emissions of this GHG. Drake et al. (2007) hypothesized that the earthworm gut favored incomplete denitrification to N_2O production over complete denitrification to dinitrogen gas (N_2) due to restriction in moisture and nutrient availability at the posterior of the gut. Experimentally, Lubbers et al. (2013) found that earthworms increased emission of N_2O and CO_2 from soil by 42% and 33%, respectively. Contrarily, in a pilot study examining the effects of vermifiltration on pig slurry, Li et al. (2008) observed minor increases in N_2O emissions and a 50% reduction in NH_3 emission on a whole wastewater system basis. Furthermore, Li et al. (2008) attributed these observations to increased rates of nitrification and complete denitrification to N_2 in the vermifilter. Similarly, Luth et al. (2011) examined the effect of application rate of pig slurry on NH_3 and GHG emissions and found that under the optimal application rate, vermifiltration reduced NH_3, N_2O, and CO_2 emissions, and acted as a CH_4 sink compared with equivalent filters without earthworms. To explain these conflicting results for N_2O emission, Luth et al. (2011) proposed that there was a threshold of N input above which the presence of earthworms would decrease N_2O emission; however, the dosage dependence of N_2O emission on N input has yet to be explicitly tested.

Little research has examined VOC emissions from dairy production and waste management (Shaw et al., 2007), let alone the specific effect of vermifiltration on VOC emission from dairy wastewater. Although Bhattacharya et al. (2016) showed that the presence of earthworms in composting cattle manure decreased VOC emission, they did not measure EtOH emission. To our knowledge, no literature has directly assessed the effect of vermifiltration on H_2S, although Sinha et al. (2008) alluded to the potential of vermifiltration to reduce H_2S emissions.

The majority of previous research in vermifiltration focused on optimizing vermifilter performance as measured through nutrient removal efficiency (Liu et al., 2012, Wang et al., 2014b, Wang et al., 2011, Wang et al., 2013) and elucidating the microbial communities responsible for these effects (Li et al., 2013, Liu et al., 2012, Wang et al., 2014b, Wang et al., 2016, Wang et al., 2011); however, very little is known about the effect of vermifiltration on emissions. Additionally, the bulk of these studies involved domestic wastewater; few studies examined vermifiltration of livestock wastewater. To date, the only study using cattle manure as substrate focused on vermicomposting, which involved actively mixing and turning over the media (Bhattacharya et al., 2016), as opposed to vermifiltration, in which the media is undisturbed during operation. Thus, because the present study concerns the only vermifilter built at a commercial dairy in Central California, it is descriptive by nature. The objective of this study was to assess the effectiveness of the vermifilter on the reduction of GHGs, VOCs, and criteria pollutants from treated lagoon water. Based on past findings (Li et al., 2008, Luth et al., 2011), we hypothesized that the vermifilter enhanced nitrification and complete denitrification to reduce NH_3 emission without significantly increasing N_2O emission.

3 MATERIALS AND METHODS

3.1 Experimental site

The present study was conducted at a commercial dairy with approximately 760 milking cows and 1,300 head total in the California San Joaquin Valley, CA. The first sampling period occurred during the summer in July 2015, while the second sampling period occurred during the winter in December 2016. The dairy that hosted the vermifilter, used a conventional wastewater management system, in which the manure in the freestall barns was flushed daily 3 times for 6 min to remove manure from the barn floor. Flushwater was stored in an uncovered anaerobic lagoon with a ~5.7 million L holding capacity. A portion of this water was recycled through the freestall barns during the next flushing period but eventually, all water was applied to surrounding cropland as fertilizer (FIG. 1**Error! Reference source not found.**). In contrast, the vermifilter wastewater management system treated the lagoon water before it was recycled back to the freestall barns as flushwater (Fig. 1**Error! Reference source not found.**). During the July 2015 sampling, the vermifilter system was composed of a solids separator followed by application to the vermifilter. However, during the December 2016 sampling, the vermifilter system had been modified to include pre-filters between the solids separator and the vermifilter for improved solids removal.

The vermifilter was a concrete enclosure (49 m x 11 m x 1.5 m) filled with a 1.2 m layer of woodchips produced from heartwood of Douglas fir, white fir, and ponderosa pine, the top 30 cm of which were seeded with ~300 kg (live weight) of earthworms (*Eisenia fetida*) and a microbial inoculant (Biofiltro) (Fig. 2Figure 2). Below the woodchips was a 30-cm layer of river cobbles (10 cm x 20 cm) to improve drainage. Twenty peripheral PVC pipes (12 cm diameter) extended from the surface of the vermifilter to the bottom layer of river gravel to allow air exchange between the bottom layer and ambient air.

Lagoon water (LAG) was first pumped into the solids separator (i.e. Biofiltro) using a rotary screen (200 µm hole size) to remove sand and solids (Fig. 2Figure 2). The resulting influent (INF) was then stored in a storage tank until it was applied to the surface of the vermifilter (TOP) using rotary head sprinklers. Every hour, a total of 2,100 L of INF was applied over 10 min to the TOP, after which the sprinklers were shut off to prevent pooling on the surface of the vermifilter. The INF percolated to the bottom of the filtration system where the resulting effluent (EFF) exited from the BOT. The EFF was stored until it was recycled as flush water or applied as fertilizer to cropland.

During vermifilter operation in December 2016, LAG was processed through the solids separator and stored. Prior to sprinkling, this stored wastewater was then applied to 8 wood shavings filters in parallel to improve solids removal and prevent congestion of sprinkler heads downstream. The wood shavings filters were 3,937 L (1,040 gallon) intermediate bulk containers (IBCs) filled with pine shavings. To apply wastewater to the wood shavings filters, wastewater was channeled through PVC pipe into a dual-layer mesh box filter (inner shell: 80% sunshade mesh, outer shell: wood block fabric) inset in the IBC level with the surface of the shavings. After treatment with the wood shavings filters, 2,100 L of the resulting INF was applied to half of the vermifilter using one of the two lines of sprinklers over 10 minutes. (INSERT NEW SPRINKLER HEADS SPECIFICATIONS) The sprinkler line used to apply the INF to its respective half of the vermifilter alternated with each hour to permit the INF more time to percolate through the vermifilter between sprinkling periods.

3.2 Summer gas sampling

To estimate the gaseous emissions from the vermifilter system, gas concentrations were measured from subsamples of the system, emission rates were calculated for each subsample, and finally subsample emission rates were scaled up to the entire system.

The University of California, Davis, Mobile Agricultural Air Quality (MAAQ) Lab containing the necessary gas analyzers was transported to the study site and used for the air monitoring. After three days of stabilization, gas analyzers were calibrated and used to measure gas concentrations first from the wastewater samples (LAG, INF, and EFF), and then from TOP and BOT. Ammonia and ethanol concentrations were measured using an Innova 1412 photoacoustic multi-gas analyzer (AirTech Instruments, Ballerup, Denmark), which had detection limits of 0.2 μg L^{-1} for NH_3 and 0.08 μg L^{-1} for EtOH. Nitrous oxide was measured using a 46i N_2O analyzer (Thermo Environmental Instruments, Waltham, MA), which had a detection limit of 0.02 μg L^{-1}. Carbon dioxide was measured using a LI-6252 CO_2 analyzer (LI-COR Biosciences, Lincoln, NE), which had a detection limit of 1 ppm. Methane was measured using a 55C Direct CH_4 and NMHC analyzer (Thermo Environmental Instruments, Waltham, MA), which had a limit of detection of 20 ng L^{-1} for CH_4. All gas analyzers measured gas concentrations every minute during the sampling period.

Gas concentrations from liquids (LAG, INF, EFF) were measured using flux chambers containing a sample of their respective wastewaters. The LAG sample was collected from an outlet on the solids separator pulling water from the surface of the lagoon. The INF sample was collected from a spigot in the pipe between the first storage tank and the vermifilter. The EFF sample was collected from the outlet pipe channeling the EFF into the second storage tank. Each of the three flux chambers consisted of a 19 L container capped with a lid, equipped with an inlet for emissions sampling, an outlet for equilibration with ambient air, and an opening for air pump tubing. During gas sampling, the flux chambers were filled with 5 L of their respective wastewater and ambient air was bubbled directly into the wastewater at a flow rate of 15 Lpm (liters per minute) to force the gases out of solution at a standardized rate. Ambient air was sampled from an inlet affixed below the MAAQ. Gas concentration measurements and bubbling began simultaneously and continued for 48 h. Gas concentrations were sampled sequentially: each liquid was sampled for 30 min followed by sampling ambient air for 10 min before sampling switched to the next liquid.

To capture gases from TOP, a triangular wind tunnel (equilateral triangle with 1.2 m sides) was constructed using a PVC pipe frame covered with tarp, leaving the bottom open. The wind tunnel was placed on the surface of the filter and spanned the entire internal width of the filter, excluding the exhaust pipes (Fig. 4Figure 4). A fan on the east side of the tunnel pushed air from east to west to reduce background emissions from the lagoon directly south of the filter. An ultrasonic anemometer (Model 81000, R. M. Young Company, Traverse City, Michigan) was installed on the inside of the south side of the triangular sampling tunnel to measure wind speed and wind direction (Fig. 4Figure 4). Ambient air entering the tunnel was sampled from air entering the fan on the north side of the sampling tunnel.

For the BOT, the inlet for emission sampling was secured in the pipe at the top of the elbow joint. To prevent ambient air from flowing into the exhaust pipe, unidirectional airflow out of the pipe was created by pumping pure air through tubing threaded to the bottom of the exhaust pipe at 10 Lpm. Ambient air was sampled directly above the exhaust pipe. Emissions were sampled cyclically as follows: 20 min for TOP, 10 min for ambient air outside the sampling tunnel, 20 min for the BOT, and 10 min for ambient air outside the exhaust pipe.

4.1 Winter gas sampling

For the winter sampling, the same procedure was performed as for the summer sampling with three exceptions: (1) INF was collected from the same INF spigot as in the summer; however, by the winter sampling, pre-filtration steps were added between the LAG and the INF sampling spigot to enhance solids removal in response to clogging sprinkler heads. Specifically, the wood shavings filters, a cone filter in the INF holding tank, a mesh irrigation filter-lined pre-booster pump, three parallel hydro-cyclone sand filters, and three banks of sand media filter (garnet media) were added in that order between the rotary screen and the INF spigot; (2) EtOH was not measured from the TOP and BOT due to negligible emission rates observed during the summer sampling; and (3) gases were sampled for 24 hours at all locations.

3.3 Emission rate calculation

For both sampling periods, gasGas concentrations measured over time were used to calculate emission rates on a bihourly (LAG, INF, and EFF) or hourly (TOP and BOT) basis and scaled up to the daily turnover of wastewater over the entire area of the vermifilter. To account for instrumental error of initial gas concentration measurements, the first 3 h for the liquid samples and the first 4 h for the TOP and BOT samples were removed for the summer sampling only. . To account for residual gas in the sampling system, the first 4 min and the last minute of each sampling period were removed before data analysis. Net gas concentrations were calculated as the difference between the inlet and outlet (i.e. sample site and ambient, respectively), gas concentrations averaged over the 26-min sampling period for the liquids (LAG, INF, and EFF), and the 16-min sampling period for TOP and BOT.

For the summer sampling, theThe averaged net gas concentrations were multiplied by airflow rates respective to each location, adjusted for temperature, molecular weight and volume, and the resulting average net emission rates were then scaled up to the whole system per day for each sampling site. The wastewater emissions (LAG, INF, and EFF) were scaled up to the total volume added to the vermifilter every day (50,000 L d^{-1} during the time of the study). The TOP emissions were scaled up to the total surface area of the vermifilter (520 m^2), and BOT emissions were multiplied by the total number of exhaust pipes around the vermifilter (20 exhaust pipes). Subsequently, the daily gas output for the INF, EFF, TOP, and BOT (Q_{INF}, Q_{EFF}, Q_{TOP}, and Q_{BOT}, respectively) were used in the following equations to calculate the daily net emissions from within the vermifilter ($Q_{Vermifilter}$):

$$Q_{EFF} + Q_{TOP} + Q_{BOT} + Q_{Vermifilter} = Q_{INF} \tag{1}$$

$$Q_{Vermifilter} = Q_{INF} - (Q_{EFF} + Q_{TOP} + Q_{BOT}) \tag{2}$$

Because $Q_{Vermifilter}$ was considered separate from Q_{TOP} and Q_{BOT}, the phrase "emissions from the vermifilter" refers to emissions from *within* the vermifilter and does not include emissions from the surface or the bottom of the vermifilter.

The gas removal efficiency was then calculated as follows:

$$\text{Gas removal efficiency [\%]} = Q_{Vermifilter}/Q_{INF} \tag{3}$$

3.4 Wastewater chemistry analysis

For INF and EFF, ~500 mL wastewater samples were collected and sent to Denele Analytical, Inc. (Turlock, CA), for water chemistry analysis to measure the concentration of NH_3, nitrate-nitrogen (NO_3^--N), nitrite (NO_2^-) and total Kjeldahl N. Samples were processed within 48 hours of collection. Nitrite nitrogen (NO_2^--N) concentration was empirically calculated from the concentration of NO_2^-.

4 RESULTS AND DISCUSSION

Emissions from wastewater before and after treatment (i.e. LAG, INF, and EFF) were measured to elucidate the effect of vermifiltration on wastewater emissions, whereas emissions from the TOP and BOT of the vermifilter were measured to discern whether the TOP, BOT, and the middle of the vermifilter itself was a significant source of emissions. Collectively, the INF, EFF, TOP and BOT emissions encompass emissions from the entire wastewater treatment system after solids separation, allowing us to calculate by difference the gas removal efficiency of the vermifilter.

Among the liquids, LAG and INF exhibited similar emission profiles for all measured gases, implying that the solids separator and subsequent storage in the INF storage tank did not drastically affect emissions. However, the emission profiles of LAG and INF differed from that of EFF, indicating that the vermifilter altered emissions. Even when scaled to the entire system, the BOT consistently emitted less gas than the TOP for all measured gases, likely due to nutrient adsorption and conversion, which reduced emissions as the wastewater percolated through the vermifilter.

4.1 Summer sampling

4.1.1 Ammonia

After accounting for losses from TOP and BOT emissions, the vermifilter reduced NH_3 emissions from the INF by 90.24% (Table 1) and soluble NH_3 from 361 mg/L in the INF to 56 mg/L in the EFF (Table 1). Among the liquids, NH_3 emissions from LAG and INF were nearly identical, with an estimated emission of 17.57 and 17.21 kg d^{-1}, respectively (Table 1). The loss of 0.36 kg d^{-1} from LAG to INF was likely volatilized during solids separation: the rotary screen agitated the wastewater and exposed the wastewater to air, increasing the surface area exposed to volatilization. Contrarily, NH_3 emission from EFF was 1.54 kg d^{-1}, considerably lower than that of LAG and INF (Table 1). Ammonia emission from the TOP of the vermifilter was 0.14 kg d^{-1} and negligible (<0.001 kg) from the BOT. The emissions from the surface of the vermifilter were likely due to increased volatilization when the INF was sprinkled over the filter. Similar to the action of the solids separator, as wastewater was forced through the sprinklers into smaller droplets, the increased surface area of the wastewater exposed to air increased NH_3 volatilization. The BOT of the vermifilter lacked NH_3 emission because the wastewater was not agitated as it passed through the BOT. Li et al. (2008) also observed a large reduction in NH_3 emissions after vermifiltration of swine slurry, reporting a 50% reduction in NH_3 emission from the whole swine facility. Unlike the present study, Li et al. (2008) did not discern the effects of the vermifilter from the rest of the system, so the effects of the vermifilter may have been masked by the continued emission of NH_3 from the barn floor. Nonetheless, Li et al. (2008) hypothesized the reduction in NH_3 emission was due to the efficient adsorption of NH_3 by the vermifilter and subsequent microbial transformation of NH_3 through nitrification, though they did not assay for an increase in products of nitrification (NO_3^- and NO_2^-). The findings of the present study supported this hypothesis. The reduction in volatile and soluble NH_3 was coupled with an increase in NO_3^--N and NO_2^--N (Table 2), indicating that the NH_3 was undergoing nitrification.

Regardless of treatment or sampling site, temperature and wind speed dictate NH_3 emissions (Leytem et al., 2011, Leytem et al., 2013). In the present study, however, wind speed was standardized and was accounted for in the emission rate calculation. Consequently, NH_3 emissions were largely determined by temperature and thus followed a diurnal trend, increasing during the day and decreasing at night as the temperature respectively rose and fell (Figure 5a and Figure 6a). Although the amount of NH_3 emitted from the EFF was considerably less than that of the LAG and INF, emission rates from all three liquids peaked during the afternoon, when ambient temperatures were the highest during the sampling period. These observations agreed with previous studies quantifying ammonia emissions from dairy lagoons (Leytem et al., 2011, Leytem et al., 2013, Moore et al., 2014, Todd et al., 2015).

4.1.2 Nitrous oxide

Among LAG, INF, and EFF, N_2O emissions on a per hour basis (Figure 5b) and on a per day basis (Table 1) were minor (< 10 g d^{-1}), preventing meaningful comparison among these samples. The N_2O emissions from TOP and BOT were higher than that of the wastewaters, with the TOP emissions remaining consistently higher than that of BOT (ranging from 2.7- to 92.6-fold higher) throughout the sampling period (Figure 6b). The sporadic rise and fall of the emission rate may be due to the intermittent application of the INF: the INF was applied for 10 min/hr, causing the TOP to fluctuate between the INF saturating of the media's pores and the INF vacating the pores as gravity pulled the liquid down. As the INF was applied to the TOP, the INF may have displaced the gases trapped in the pores of the media, releasing them into the air.

On a per day basis (Table 1), N_2O emissions from the TOP (134.99 g d^{-1}) and BOT (12.65 g d^{-1}) of the vermifilter were higher, and emission from within the vermifilter was calculated to be -147.26 g d^{-1}. These relatively minor emissions of N_2O coupled with a large reduction in NH_3 emission from the vermifilter system has been observed previously during vermifiltration of swine slurry (Li et al., 2008, Luth et al., 2011). The increase in soluble NO_2^- and NO_3^- from the INF to the EFF coupled with the reduction in total Khejldahl N and minor N_2O emission from the EFF implies that nitrification creates NO_2^- and NO_3^- faster than denitrification removes these compounds, causing them to accumulate in the EFF. Importantly, whatever quantify of NO_2^- and NO_3^- that is denitrified favors complete denitrification to N_2 over incomplete denitrification to N_2O, as implied by the minor increase in N_2O emission from the EFF. Li et al. (2008) also detected a large reduction in NH_3 emission concurrent with minor N_2O emission and also concluded that vermifiltration enhances nitrification and complete denitrification to N_2 as opposed to incomplete denitrification to N_2O. These findings disagree with that of Lubbers et al. (2013), whose meta-analysis showed that earthworms increase emissions of N_2O from soil by 42%; however, Lubbers et al. (2013) focused on earthworms in soil as opposed to in vermifilters, a comparatively more nutrient-rich environment. Luth et al. (2011) proposed that if the N content of the media was lower than that of the earthworm gut, such as in soil, earthworms enhance N_2O emission; however, if the N content of the media exceeded that of the earthworm gut, which was common in vermifilters, the presence of earthworms decreased N_2O emission. Thus, in the present study, the high N content in the vermifilter media likely favored complete denitrification to N_2 as opposed to N_2O, resulting in low N_2O emission.

4.1.3 Carbon dioxide

Carbon dioxide was formed as a byproduct from respiration of both the earthworms and the microbes that inhabit the vermifilter. On an hourly basis, CO_2 emission from the three wastewaters (Figure 5c) and the TOP and BOT of the vermifilter were minute (Figure 6c). Carbon dioxide emission from the three wastewaters (LAG, INF, and EFF) followed a similar trend, beginning with the highest emission rate which rapidly dropped over time. Although the starting emission rates differed among the three wastewaters, emission rates were negligible overall, starting at $< 1,200$ mg h^{-1} then dropping precipitously to and remaining below < 300 mg h^{-1} 12h after the start of sampling. The TOP and BOT emissions were < 300 mg h^{-1} throughout the sampling period, with TOP CO_2 emissions consistently higher than BOT emissions, remaining up to 145-fold higher than that of BOT except when both TOP and BOT emissions were zero. Similar to N_2O emission from the TOP, the erratic emission pattern of CO_2 from the TOP likely resulted from the periodic application of INF.

Scaled up to an entire day, the EFF (43.73 kg d^{-1}) emitted less than half the amount of CO_2 per day than the INF (97.15 kg d^{-1}), but the large difference was likely due to CO_2 loss via the TOP emissions (54.49 kg d^{-1}) rather than adsorption by the vermifilter itself (Table 1). Instead, the vermifilter itself contributed slightly to the CO_2 emissions (5.97 kg d^{-1}) in the EFF. The vermifilter itself had little contribution to CO_2 emissions from the EFF because carbon dioxide emission, a byproduct of decomposition largely driven by microbes (Lubbers et al., 2013), depends on the application rate of organic matter as opposed to the presence of earthworms in the vermifilter (Luth et al., 2011). Thus, the emissions from TOP were determined by the application rate of the INF to the vermifilter, and were largely responsible for CO_2 removal from the INF. The emission of CO_2 from the TOP is not ideal because it is released into the atmosphere instead of being absorbed by the vermifilter.

The vermifilter itself was responsible for contributing 6 kg of CO_2 to the EFF per day, or 14% of the 43.73 kg from EFF. This contribution from the vermifilter was less than half of the estimate by Lubbers et al. (2013), who reported that earthworms have the potential to increase CO_2 emissions by 33%; however their meta-analysis focused on the effect of earthworms on GHGs in soil, which generally has a lower organic matter content than the livestock wastewater applied to vermifilters. Luth et al. (2011) proposed that if C availability in the media exceeds that of the earthworm gut, overall decomposition of the media will mask earthworm-enhanced CO_2 emission. Furthermore, earthworm-induced CO_2 production is not only minor, but is also temporary: Lubbers et al. (2013) noted that earthworms increase CO_2 emissions for up to 200 days, after which their effect becomes negligible.

4.1.4 Methane

Because LAG originated from an anaerobic lagoon, which produces methane as a byproduct of anaerobic decomposition (Casey et al., 2006), LAG was expected to have the greatest rate of methane emission among the liquids. However, all three wastewaters exhibited similar CH_4 emission rates throughout the day (Figure 5d). The unexpected similarity may be attributed to the source from which the LAG was pumped: LAG was collected from a pump floating on the surface of the water, where soluble CH_4 is extremely depleted. Additionally, the emission rate calculations excluded the first 4 h of the sampling period, which may have included a rapid initial spike in CH_4 emission. Irrespective of sample type, all emissions peaked during the afternoon, when ambient temperatures were the highest. The observed influence of temperature on CH_4 emission was similar to the findings of Leytem et al. (2011) and Grant et al. (2015), who found that temperature was strongly correlated with CH_4 production from a dairy lagoon in Idaho and dairy wastewater holding basins in Wisconsin, respectively.

Similar to the trend observed in other gases, CH_4 emission from TOP remained higher than BOT emission during the duration of the sampling period except when both TOP and BOT emissions dropped to zero (Figure 6d). Similar to the emission pattern of N_2O and CO_2, the irregular emission from the TOP was likely due to the intermittent application of INF to the surface of the vermifilter.

4.1.5 Ethanol

For the wastewaters (LAG, INF, and EFF), the EtOH gas concentrations were above the limit of detection, but below the limit of quantification, and thus could not be accurately reported. Ethanol emissions from the TOP were consistently higher than that of the BOT, but even so, these emissions were relatively minor (Figure 6e).

4.2 Winter sampling

Because the majority of gases were expelled within the first 24 hours of sampling during the summer, during the winter sampling, gas concentrations were measured for 24 hours.

4.2.1 Ammonia

Compared to the summer sampling, ammonia emissions from the LAG in the winter sampling were 20-fold lower (Figure 5a and **Error! Reference source not found.**a). This dramatic reduction in NH_3 was likely due to a combination of the seasonal effect (Bjorneberg et al., 2009) and upstream management changes (i.e. the lagoon had been emptied and thus had a lower soluble NH_3 to begin with). The lower NH_3 emission from LAG in turn predisposed all downstream emissions to be lower as well compared to emissions in the summer sampling period. Although emissions from the INF appear higher than that of the LAG, the difference is negligible (~1 mg h^{-1}). The NH_3 emission from EFF consistently remains at ~0.3 mg h^{-1}, save for the last hour (0.5 mg h^{-1}), while the emissions from the LAG and INF rise during the last 5 hours of the sampling period, suggesting that the vermifilter is still effective at reducing NH_3 emission from the INF. The lower INF NH_3 emission predisposed the TOP and BOT to similarly yield lower emission rates. Overall, NH_3 emissions consistently increased throughout the 24-hour sampling period, confounding whether we had captured the majority of emissions to accurately extrapolate daily system-scale emissions. Thus, daily NH_3 emission removal efficiency was not calculated.

4.2.2 Nitrous oxide

Nitrous oxide emissions were similar across the LAG, INF, and EFF, demonstrating that the vermifilter did not increase the production of this GHG from treated wastewater despite the reduction in NH_3 emission. Likewise, emissions from the TOP and BOT also remained low.

4.2.3 Carbon dioxide

Emission of CO_2 from the LAG and INF followed an almost identical trend and remained consistently higher than that of the EFF.

4.2.4 Methane

Across the liquid samples, methane emissions remained low (<1 mg h^{-1}) after the initial spike during the beginning of the sampling period. Notably, the LAG had the highest initial emission of CH_4 among the liquids, followed by INF, and finally EFF. This ranking of emissions was likely because the LAG was from the anaerobic lagoon, conditions that favor the growth of methanogens, while the INF had been subjected to the partially aerobic pre-filters, preventing methanogenic activity. The continued aeration of the wastewater similarly reduced CH_4 emission from the EFF to levels below that of the INF. Methane emission from the BOT remained negligible, ranging from <1 mg h^{-1} to 3 mg h^{-1}, while emission from the TOP was too sporadic to draw any meaningful conclusions.

5 CONCLUSION

Vermifiltration reduced ammonia emissions from dairy wastewater by 90.2% at the expense of producing minor amounts of CO_2 in the summer, suggesting that this technology may be a promising environmental solution for dairies in Central California; however, because previous studies have reported seasonal effects, with summer exhibiting the highest emissions, this study must be replicated across different seasons. The addition of wood shavings filters upstream of the vermifilter did not drastically affect emissions from the resulting influent as compared to the lagoon water, and gas emissions were lower from the effluent as compared to the influent; however, it is unclear whether the reduction in gases is due to the action of the vermifilter itself or emission from the surface or the bottom of the vermifilter. Furthermore, because this vermifilter is currently the only vermifilter used at a commercial dairy, this study must be repeated at future vermifilters built at other dairies for statistical verification of the observed results.

Tables

Table 1. Daily net emissions (Q) from the wastewaters (LAG, INF, and EFF), the TOP and BOT of the vermifilter, and the vermifilter itself during July 2015.

	Daily net emission						Gas removal efficiency of the vermifilter* [%]
	Q_{LAG}	Q_{INF}	Q_{EFF}	Q_{TOP}	Q_{BOT}	$Q_{Vermifilter}$*	
NH_3 [kg d^{-1}]	17.57	17.21	1.54	0.14	0.00	15.53	90.24
N_2O [g d^{-1}]	0.23	1.70	1.31	134.99	12.65	-147.26	-86.85
CO_2 [kg d^{-1}]	74.96	97.15	43.73	54.49	4.90	-5.97	-0.06
CH_4 [kg d^{-1}]	0.45	0.60	0.35	0.76	0.01	-0.51	-0.84

*Negative values indicate that the vermifilter contributed emissions to the wastewater.

Table 2. Water chemistry analysis of INF and EFF

		Sample Location	
Constituent	Units	INF	EFF
NH_3	mg L^{-1}	361	56
NO_3^--N	mg L^{-1}	7.81	48.3
NO_2^-	mg L^{-1}	*	79.4
NO_2^--N	mg L^{-1}	N/A	24.1**
Total Kjeldahl N	mg L^{-1}	498	129

*Below limit of detection

**Empirically calculated from NO_2^- concentration

Figures

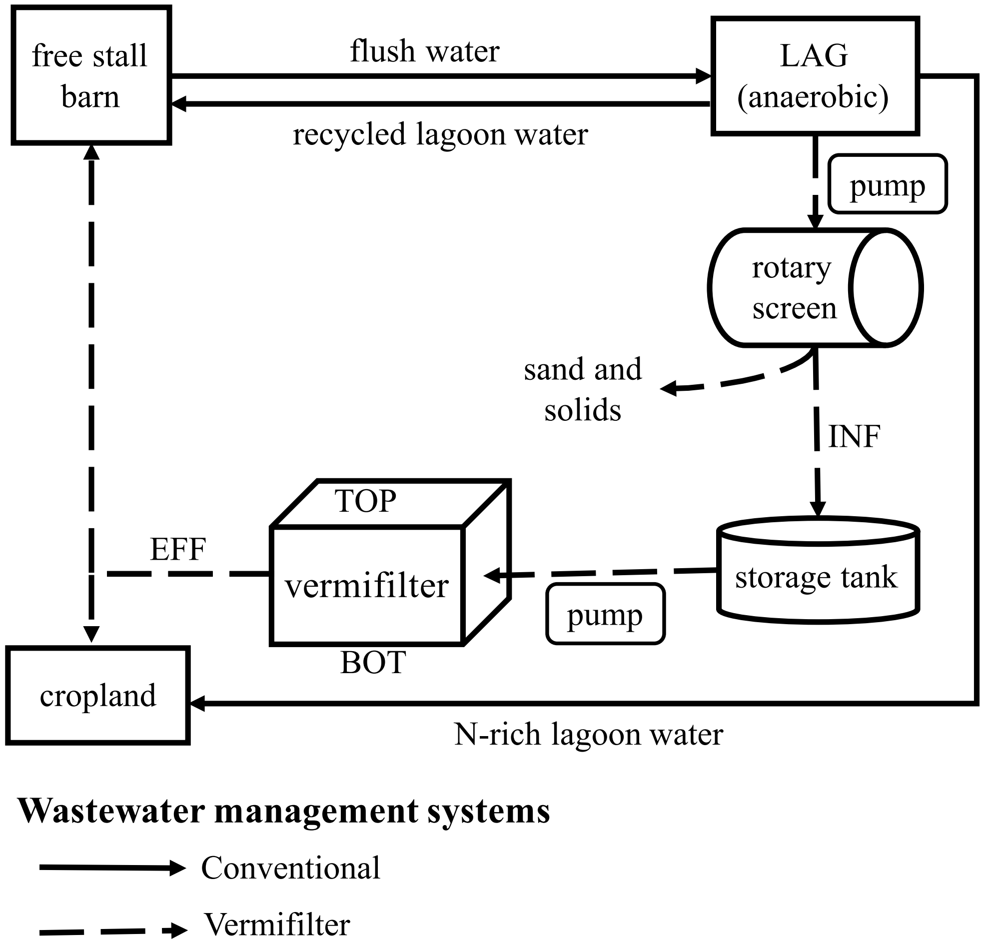

Figure 1. Overview of conventional and vermifiltration wastewater management systems on the dairy of the present study.

In the conventional system at the dairy of the present study, the free stall barn is flushed 2 or 3 times a day, and the flush water is sent to the anaerobic lagoon. The lagoon water (LAG) is then recycled back to the free stalls as flush water, or applied to cropland. In the vermifiltration system, LAG is pumped through a rotary screen to remove sands and solids, and the resulting liquid, the influent (INF), is stored in the storage tank. For the first 15 minutes of every hour, the INF is sprinkled over the top of the vermifilter (TOP). The INF percolates to the bottom of the vermifilter (BOT) via gravity, and the resulting effluent (EFF) is stored in a storage tank until it is used as flush water or applied to cropland.

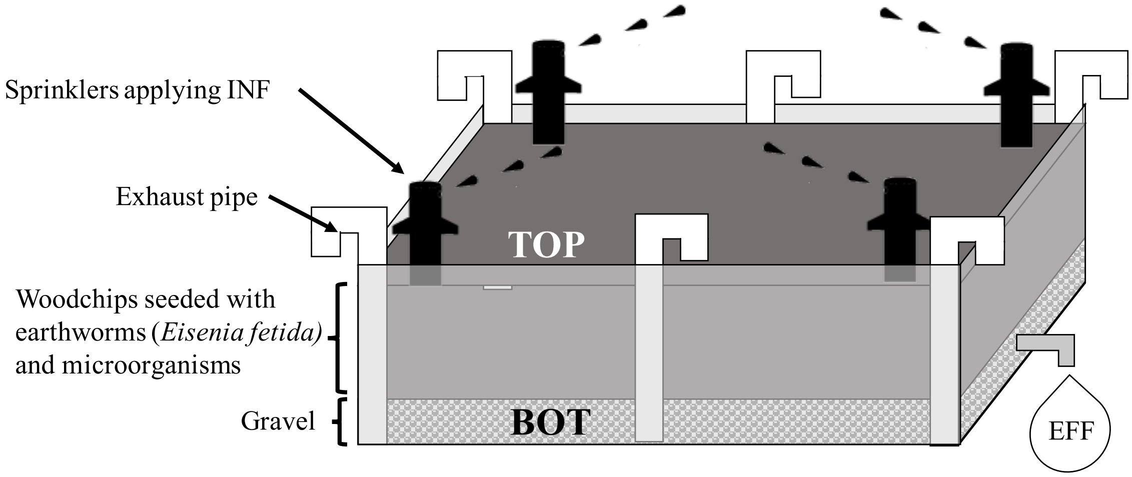

Figure 2. Vermifilter design. The vermifilter is a concrete container (49 x 11 x 1.5 m) filled with woodchips seeded with earthworms and microbes to enhance solid and contaminant removal. The large particle size of the woodchips, the bottom layer of gravel, and the exhaust pipes that line the perimeter of the vermifilter enhance aeration of the vermifilters. Sprinklers apply the INF over the TOP of the vermifilter. The INF filters to the BOT of the vermifilter, resulting in the EFF. (Figure not to scale.)

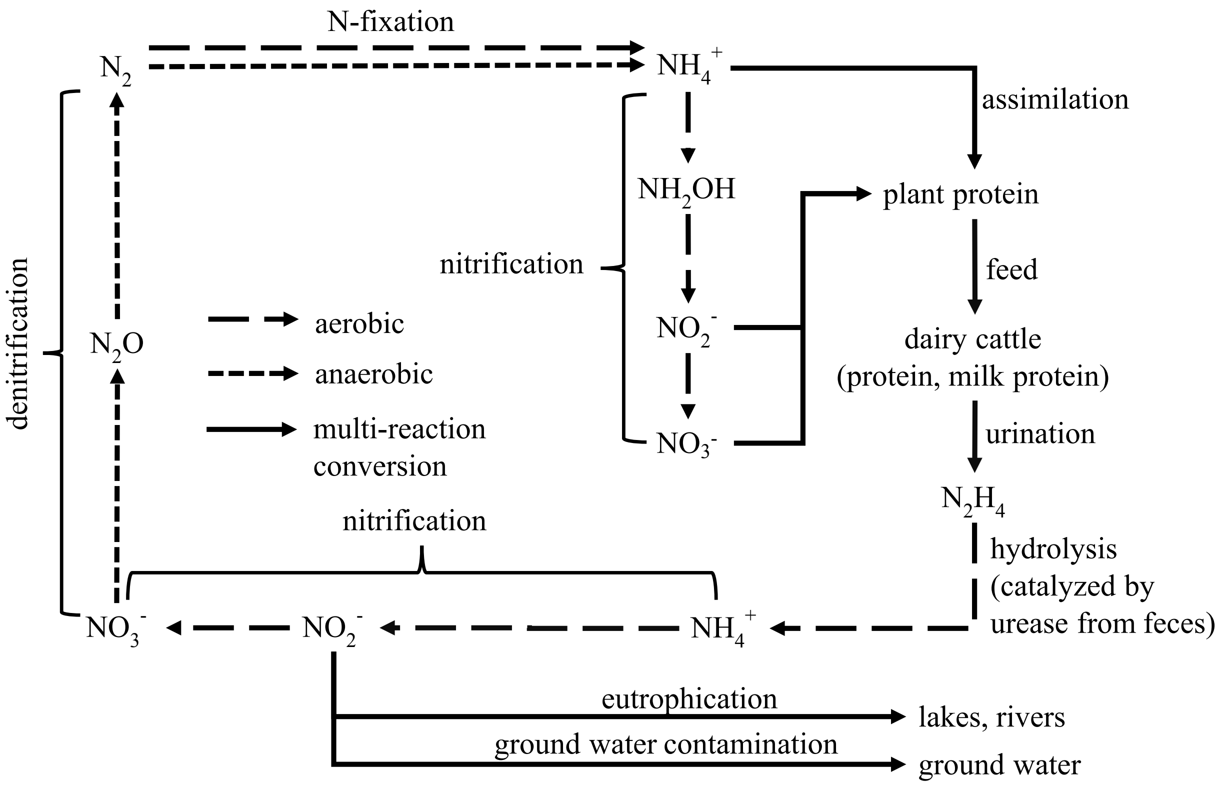

Figure 3. The nitrogen cycle in dairy production

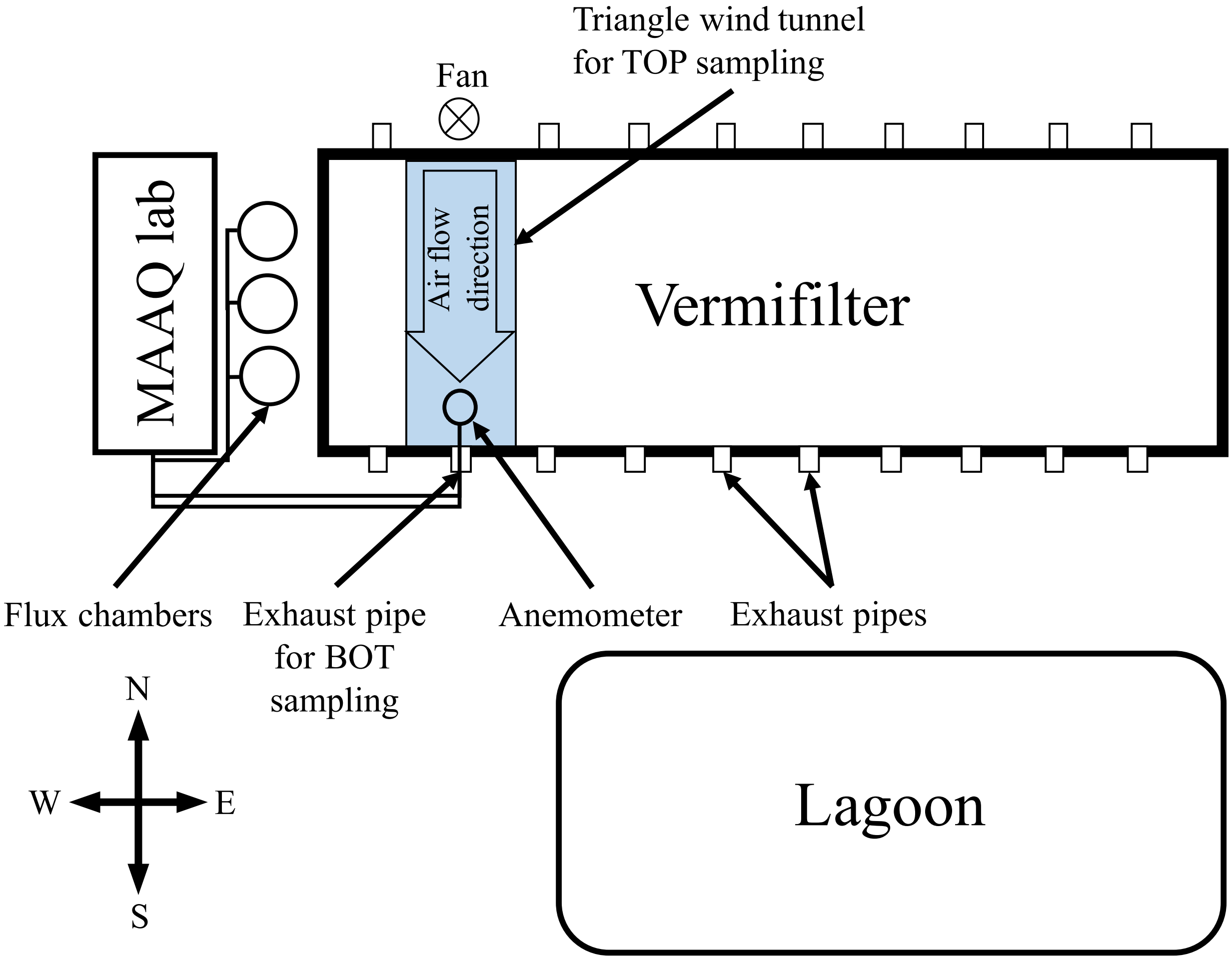

Figure 4. Overview of gas sampling setup.

Flux chambers were used to measure gas concentrations from the liquids (LAG, INF, EFF). A triangle wind tunnel was used to measure gas concentrations from the TOP. A fan was placed on the north end of the triangle wind tunnel, creating a constant airflow from north to south to avoid contamination from the lagoon nearby. The anemometer placed on the south end measured wind speed and wind direction for subsequent emission rate calculations. BOT gas concentrations were measured from the indicated exhaust pipe. (Figure not to scale.)

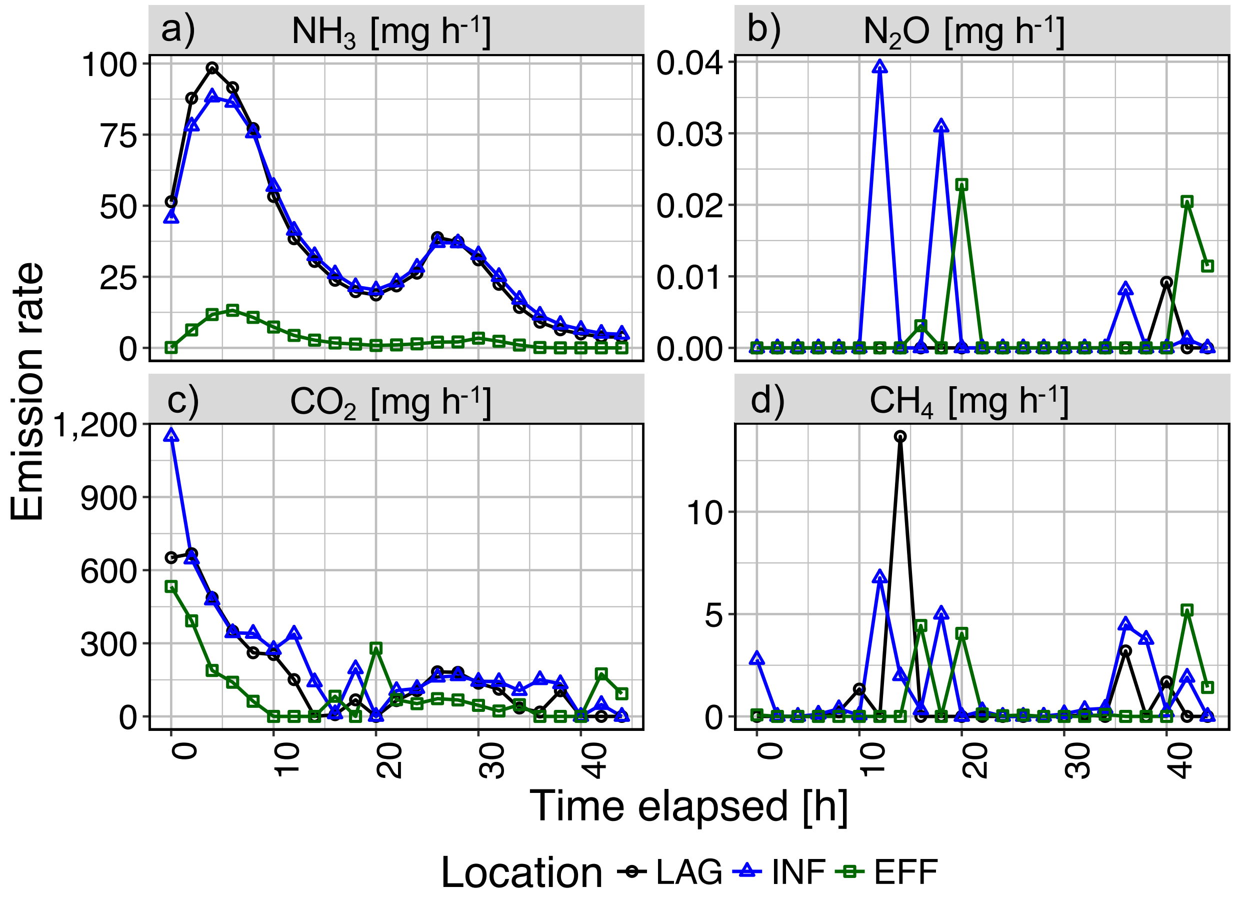

Figure 5. Gaseous emissions on a bihourly basis of (a) NH_3, (b) N_2O, (c) CO_2, and (d) CH_4 from wastewater samples (LAG, INF, and EFF) in each flux chamber during July 2015. Hour 0 corresponded to 12:00 PM.

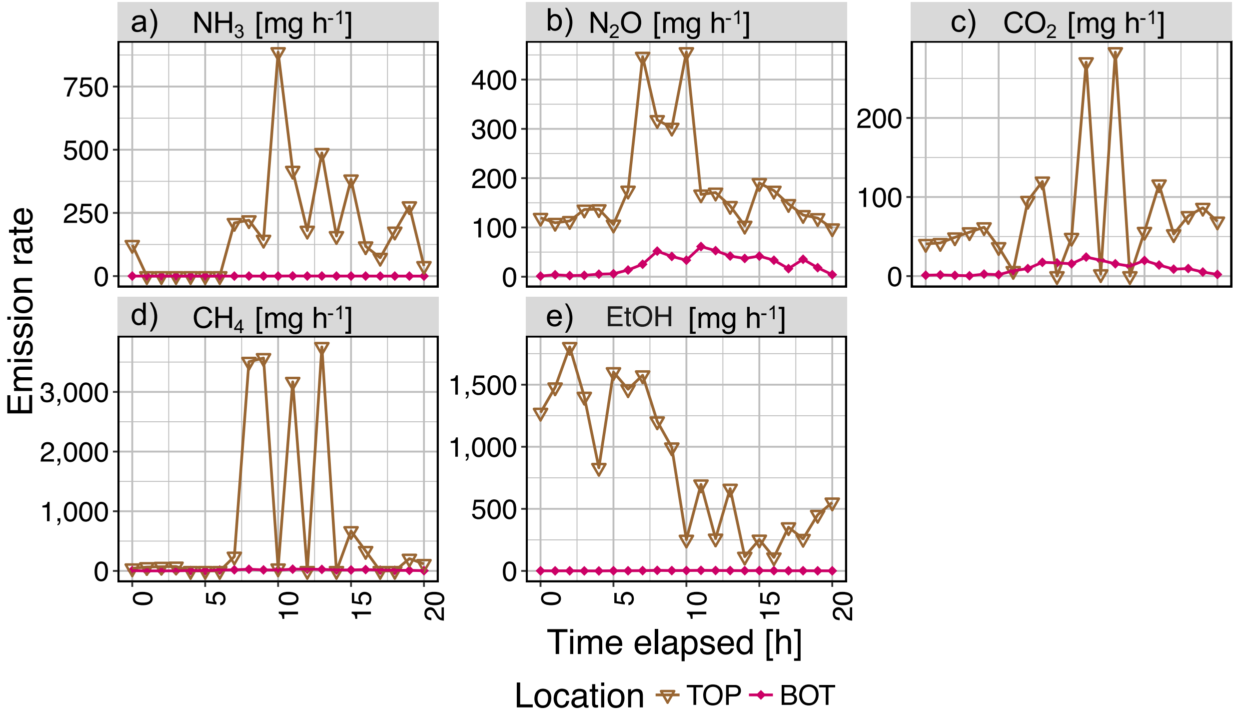

Figure 6. Gaseous emissions on an hourly basis of (a) NH_3, (b) N_2O, (c) CO_2, (d) CH_4, and (e) EtOH from a subsection of the vermifilter surface (TOP) and an exhaust pipe (BOT) during July 2015. Hour 0 corresponded to 1:30 PM.

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