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A vermifiltration system for low methane emissions and high nutrient removal at a California dairy

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ABSTRACT

Liquid storage of manure is a leading cause of methane emissions from the dairy sector and an important source of air and water pollution. This study monitored the effect of vermifiltration on methane emissions and water quality at a California dairy that uses an anaerobic lagoon. Methane fluxes and wastewater removal rate of volatile solids, N species, salinity, major ions, and trace elements were monitored for 12 months. Vermifiltration reduced methane emissions relative to an anaerobic lagoon by 97–99% and removed 87% of the volatile solids, contaminants such as salts and trace elements, P (83%) and N (84%) from the wastewater. Vermifiltration of dairy wastewater demonstrated to be a useful tool to mitigate methane emissions, regulate excess nutrients and improve water quality at dairy farms.

1. Introduction

The livestock sector is responsible for about 14.5% of total anthropogenic greenhouse gas (GHG) emissions worldwide (Gerber et al., 2013), and manure is a significant source of both agricultural CH_4 and N_2O emissions (Chadwick et al., 2011). Between 1990 and 2022 in the United States (US), CH_4 emissions from cattle manure increased 122%, reflecting the increased use of emission-intensive liquid systems over this time period (USEPA, 2022). Nearly 98% of CH_4 emissions caused by management of manure occur during storage (Aguirre-Villegas and Larson, 2017; Grossi et al., 2019), an essential practice that enables farmers flexibility in the timing of land applications to optimize crop production and protect environmental quality. Anaerobic lagoons are the primary source of storage GHG emissions (Kaffka et al., 2016), as they provide anaerobic conditions ideal for CH_4-producing microorganisms and are also a source of N_2O and NH_3 emissions. The NH_3 eventually redeposits or transforms to N_2O or particulate matter, contributing to both eutrophication and climate change (Hristov et al., 2002). The management of dairy manure has a high potential for GHG emissions mitigation, making it an essential target for reducing anthropogenic global warming from agriculture (Grossi et al., 2019).

Since the 1950s, US dairies have experienced intensification and agglomeration (Vanotti et al., 2020). This has resulted in increased problems associated with the utilization and disposal of animal waste, as in many areas the concentration of manure nutrients exceeds the capacity of the land to receive them (Burkholder et al., 2007). The livestock sector is one of the top contributors to the most serious environmental problems, including water-quality degradation, globally (FAO, 2006). Because of these high environmental risks, the use of livestock wastewater stored in anaerobic lagoons is often subject to regulations, and off-farm manure export requirements are increasing (Vanotti et al., 2020).

Manure nutrients can be recovered and used for crop production using solid-liquid separation, where manure nutrients are removed and/or treated with a variety of technologies to generate value-added products (Gollehon et al., 2016; Vanotti et al., 2020). These technologies vary in operational costs, use of additives, complexity, energy input, and production of sludge requiring disposal.

As animal production has intensified, offensive odors are increasingly a concern (Stowell et al., 2005). Also, livestock water use can represent a large proportion of total agricultural water use in areas with intensive dairy farming (Le Riche et al., 2017). The reuse of dairy wastewater provides a potential means for farmers to reduce the demand for high-quality water (Pimentel et al., 2004).

Vermifiltration offers the opportunity to reduce the dairy GHG emissions (both N_2O and CH_4), remove organics and excess nutrients from wastewater, increase flexibility in water use, avoid odors, and recover the manure nutrients in the treated wastewater and vermicompost. A vermifilter serves simultaneously as a solid-liquid separator, a treatment system for wastewater and separated solids, and a nutrient

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recovery technology. The practice consists of spreading wastewater over a filtering system containing earthworms (Arora and Saraswat, 2021). The method uses the joint action of earthworms and microorganisms to aerobically treat the wastewater. Although microorganisms biochemically degrade the organic waste, the earthworms aerate and fragment the substrate and modify its physical and chemical characteristics, promoting microbial activity and decomposition (Manyuchi and Phiri, 2013).

Vermifiltration can be used to treat wastewater containing high organic matter from variable sources, including livestock liquid manures (Samal et al., 2018; Singh et al., 2021). The performance of a vermifiltration system is affected by the earthworm loads (Wang et al., 2015), hydraulic loading rates (Singh et al., 2019), filter materials used (Adugna et al., 2019), and conditions affecting the survival of the earthworms, such as toxicity, humidity, temperature, and pH (Sinha et al., 2010). Other characteristics reported in the literature are low technology and power requirements to operate (Sinha et al., 2010), lack of odor during treatment (Arora and Saraswat, 2021), the ability to remove solids, excess nutrients, and contaminants, including pathogens, from wastewater (Arora and Saraswat, 2021), and allowing on-farm recycling of waste and water. The technique doesn't produce sludge (Yang et al., 2008) but vermicompost, which has beneficial effects on soils and crops. It is a source of plant macro-and micronutrients (Hussain and Abbasi, 2018), increases soil microbial biomass and diversity (Saha et al., 2022), enhances soil health (Lazcano and Domínguez, 2011; Hussain and Abbasi, 2018), and has the potential to sequester carbon.

Industrial-scale dairy vermifiltration systems in the US range in size from 45 m^2 to 29,000 m^2 and treat wastewater from up to 6000 dairy cows and 2,840,000 L of wastewater per day (BioFiltro personal communication).

Very little is known about GHG emissions from vermifiltration systems. Only a very limited number of studies are available (Luth, 2011; Lai et al., 2018). Quantification of the annual CH_4 emissions from vermifilters is needed to help establish the technique as a recognized tool to mitigate agricultural GHG emissions and can spur the process by allowing dairy farmers to participate in the carbon market. In addition, most vermifiltration studies have focused on the efficiency of removing organics and nutrients from wastewater and have consisted of small-scale laboratory experiments and short-term observations (Singh et al., 2019; Wang et al., 2015). This study monitored a commercially available vermifiltration system (BIDA system, BioFiltro) for one year, operating on a typical Central Valley California dairy farm with an anaerobic lagoon. The study focused on quantifying the CH_4 emissions of a vermifiltration system treating dairy wastewater. The study also aimed to address vermifiltration effects on the wastewater nutrient contents. Further research is needed to assess the vermifiltration GHG life cycle, including GHGs emitted for building and operating the vermifilter and the potential GHG sequestration from land application of vermicompost.

Quantification of CH_4 emissions from manure management for national and regional GHG inventories as well as carbon market methodologies are based on IPCC equations which include a treatment-specific parameter denoted as *methane conversion factor* (MCF; IPCC, 2006). The factor allows estimation of CH_4 emissions from the different manure management systems without monitoring CH_4 fluxes annually.

The study objectives were to 1) quantify CH_4 emissions of a dairy vermifilter and compare vermifilter and anaerobic lagoon CH_4 emissions; 2) determine the methane conversion factor; and 3) assess the effects of vermifiltration on dairy wastewater constituents such as organic solids, nutrients, trace elements, and EC.

2. Materials and methods

The study was conducted on a commercial dairy (Fanelli Dairy) located in Hilmar, in the California Central Valley, that housed 800 milking cows and 700 replacements. The farm had 1500 animals, a typical herd size for the Central Valley of California, which hosts 90% of the dairy cows in the State (CDRF, 2020). Manure was flushed from the barn floors and stored in an anaerobic lagoon. The vermifilter was built in 2015 for a pilot project studying vermifiltration effects on dairy N dynamics and GHG emissions. The pilot vermifilter was approximately 10% of an estimated full-size plant for the farm and treated circa 2500 tons of manure and 15,000–45,000 L of dairy wastewater per day. The hydrologic rate of raw influent was regulated by recirculating wastewater in order to maintain total suspended solids concentration below 10,000 mg L^{-1}.

Milking cows were housed in free-stall barns and replacements in open lots. The free-stall barns and the feeding areas of the open lots were flushed three times daily for 10 min using recycled wastewater from an anaerobic lagoon built with a holding capacity of ~5.7 million L and a surface area of 10,800 m^2. Flushing water from the barns flowed through a vibrating screen primary separator and then to the anaerobic lagoon. The separated solids were air-dried and used for bedding. Water from the lagoon was used for crop irrigation or recycled for flushing (as described in Lai et al., 2018).

The vertical flow vermifiltration system treated wastewater collected after the first separator (Fig. 1). The vermifiltration system included a second rotary separator that removed manure fibers with diameters larger than 0.8 mm to prevent clogging of the sprinkler system used to apply the wastewater on the vermifilter bed. The resulting influent water was then directed into a holding tank. Every 30 min, influent was applied for 2 min to the vermifilter surface by the sprinkler system. The applied influent percolated through the vermifilter to the underlying drainage space and drained under gravity in about 4 h. Treated water was then used for flushing.

The analysis assumed flushing collected 100% of the VS excreted by milking cows housed in free-stalls, where the cows spent all of their time, and 30% of the replacement excreted VS in open lots, where manure was collected exclusively from regularly flushed feeding areas. The screen separator VS removal was 17% (CARB, 2019; Pain et al., 1978). The daily production rates of 7.6 kg VS per milking cow and 3.4 kg VS per replacement and the maximum methane producing capacity for the specific type of animal manure (B_o) of 0.24 m^3 CH_4 kg VS^{-1} are values currently used in the GHG US inventory for California (USEPA, 2022). A cow population of 895 animals, obtained by weighting the VS contribution of milking and replacement cows, was used when determining emissions rates (or other metrics) per animal.

The vermifilter consisted of a concrete rectangular enclosure (49 × 11 × 1.5 m) inhabited by worms (*Eisenia fetida*) within the top 30 cm of the 0.5 m layer of woodchips. A 30-cm deep space at the bottom of the vermifilter bed collected drainage and provided aeration through 20 peripheral PVC exhaust pipes (15 cm diameter) that allowed air exchange (passively) with ambient air (Fig. 1A, B). Monthly tilling of the vermifilter surface layer increased aeration in the woodchips and avoided ponding of water. The handheld tiller required less than three hours and was pulled by a winch powered by a car battery.

2.1. Methane emissions

CH_4 emissions were measured from the vermifilter and the anaerobic lagoon at the Fanelli Dairy using the chamber technique and a dynamic closed measurement system (Pavelka et al., 2018). Fluxes from 16 locations on the vermifilter and 12 locations on the lagoon were measured monthly from December 2019 to November 2020.

2.1.1. Gas flux measurement system

The portable Trace Gas Analyzer used Optical Feedback-Cavity Enhanced Absorption Spectroscopy (Li-7810, LI-COR) to measure CH_4 and CO_2 concentrations once per second in the volume enclosed by a chamber positioned on the media surface. The instrument has a measurement range 0 to 100 ppm and precision of 0.60 ppb at 2 ppm with 1 s averaging. A 5 L min^{-1} pump circulated the air in a closed loop between

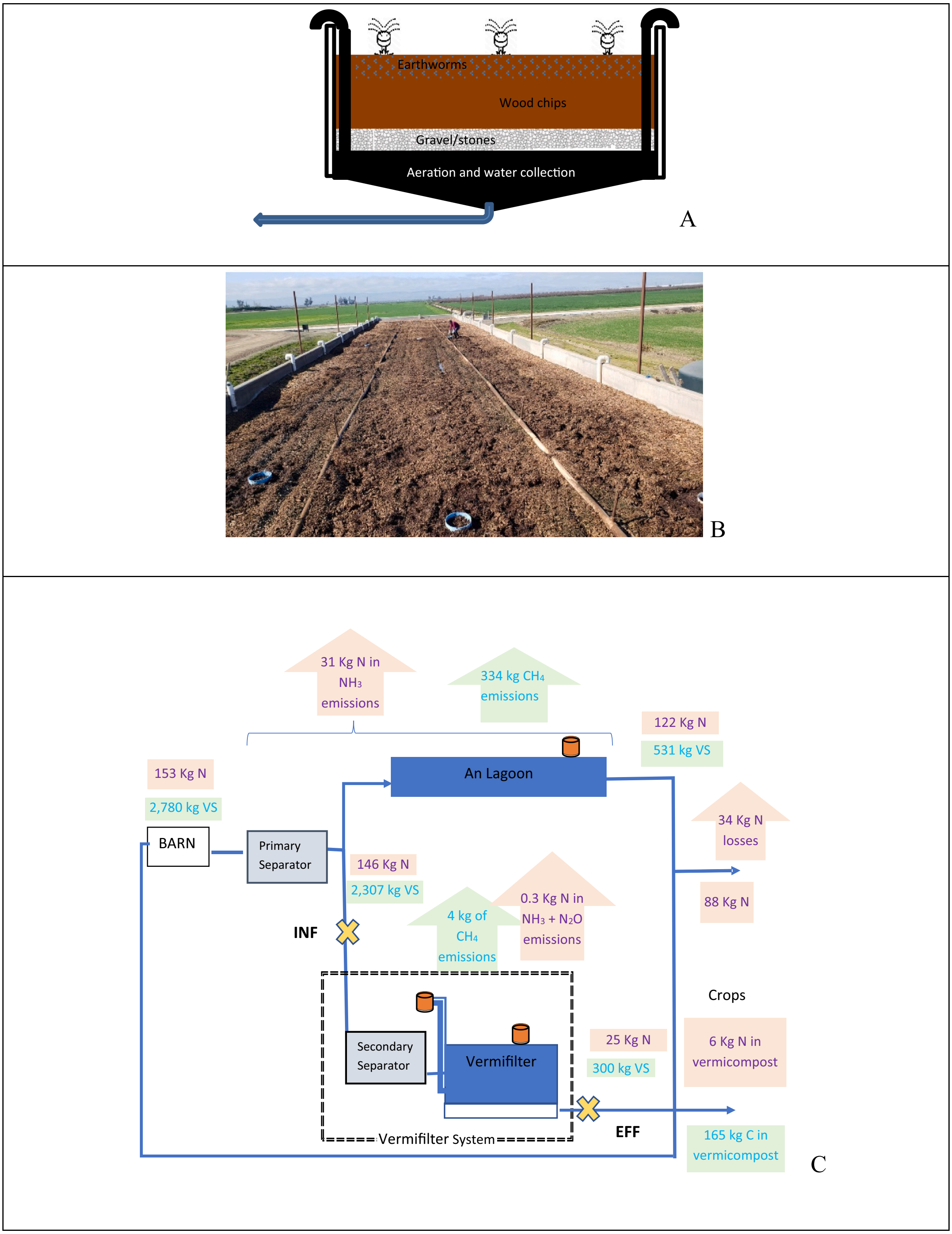

Fig. 1. Overview of the vermifiltration wastewater management system at the Fanelli Dairy. A) Schematic diagram of the vermifilter. B) The vermifilter bed with vents, irrigation lines, and CH_4 fluxes measurement collars C) The manure treatment process at the Fanelli Dairy. Water flushed from the free-stall barn was stored in the anaerobic lagoon (An Lagoon). The lagoon water was recycled as flush water or to irrigate crops. The wastewater (INF) passed through a secondary separator to remove sand and large manure fiber before it was applied over the top of the vermifilter. The effluent wastewater (EFF) was recycled as flush water. The yellow symbols show sampling locations for water quality and the orange cylinders for flux measurements. The shaded boxes follow the pathway of the volatile solids (VS) and nitrogen (N) produced by one typical California cow over one year, assuming all water was used for crop irrigation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the chamber and the analyzer, and fluxes were calculated from the changes in CH_4 concentrations over time (Parkin and Venterea, 2010). Flux calculation was limited to the initial linear increase in CH_4 concentration. Before positioning the chamber, the CH_4 concentration inside the chamber was allowed to equilibrate with ambient concentration to ensure that the analyzer chamber and tubing were free of CH_4 from previous measurements. Measurement on each of the 28 measured locations lasted less than 5 min. The order of the measurement changed during each site visit, and fluxes were measured mid-morning in less than 4 h to reduce the effects of daily temperature fluctuations.

The chamber was built using non-emitting CH_4 materials (PVC and HDPE) and included a vent to avoid pressure effects (Pavelka et al., 2018). The ratio of surface to volume of the chamber was determined by the need to avoid a rapid CH_4 build up, which leads to an insufficient number of readings before exceeding the analyzer measurement range. The size of the lagoon chamber was limited by the need for floating the chamber and positioning it without disturbance using a 6 m pole on the lagoon surface.

The vermifilter chamber had a diameter of 31 cm and a volume of 39 or 54 L. The lagoon chamber had a diameter of 25 cm and a volume of 49 L. The chambers were tested for leaks before deployment in the field following guidelines in Pavelka et al. (2018), and leaks were less than 0.006 μmol CH_4 m^{-2} s^{-1}.

2.1.2. Vermifilter measurements

In the vermifilter, sources of CH_4 emissions were the vermifilter bed and potentially the underlying drainage and aeration space. Therefore, CH_4 fluxes at 12 locations on the vermifilter bed and four vents connected to the underlying space were monitored (Fig. 1B). On the vermifilter bed, measurements were located on three equidistant transects and in areas of varying moisture content and distances from sprinkler heads and walls. During measurements, the chamber was fastened to a PVC collar (17 cm high, 30 cm diameter, permanently inserted 10 cm into the woodchip layer (Fig. 1). A tight seal was obtained by a locking mechanism pressing the chamber on a rubber gasket attached to the top of the collar. The collars didn't interfere with the spraying of the wastewater or the periodic, hand-operated tilling. The collars ensured repeated measurements at the same locations and prevented disturbance to the media surface and below-surface air exchange during measurement. On each date, measurements were repeated on each of the vermifilter locations two times and three times when increase in CH_4 concentration over time was irregular. Repeated measurements were averaged for each location. At each monitoring location, temperature at a depth of 15 cm was measured. To measure CH_4 emissions from the vents, the chamber sampling area was reduced to the size of the vent (15 cm diameter) by placing a 5-cm thick foam layer on the bottom of the chamber. The modified chamber was pushed onto the vents to form a tight seal.

The vermifilter CH_4 emissions are equal to the sum of the CH_4 emissions from the vermifilter bed and the vents. These were calculated by scaling up measured vermifilter bed and vent flux densities (μmol CH_4 m^{-2} s^{-1}) for the corresponding surface area. CH_4 fluxes for a full-size vermifilter were also calculated. The full-size was defined as the scale required to treat the entire Fanelli Dairy animal population minimizing the need for long-term manure storage. The 4630 m^2 full-size was determined using the ratio between cow population and size of a full-size vermifilter currently operating in Washington State, US (circa 5 m^2 per cow, BioFiltro personal communication).

2.1.3. Anaerobic lagoon measurements

For the 12 measurement locations on the lagoon, a floating chamber was attached to a 6 m pole and was lowered onto the lagoon surface, about 5 m from the lagoon edge. The chamber opening was sealed to and floated upon a 1 × 1 m, 5-cm thick foam board. This created an air-tight seal on the lagoon surface. It was not possible to replicate measurements in the same location because lifting the chamber at the end of the measurement cycle disturbed the lagoon surface and would have likely affected gas exchanges. The lagoon water temperature was measured at each sampling event. Measurement locations were at varying distances from the lagoon inlet and outlet and included areas of open water and areas covered by a scum layer. Lagoon CH_4 emissions were calculated by multiplying the mean fluxes densities (μmol CH_4 $m^{-2}s^{-1}$) by the total surface area of the lagoon (10,800 m^2).

2.1.4. Methane emission calculation

The CH_4 emissions were calculated as 1) flux densities, i.e., the CH_4 flux per unit area of lagoon and vermifilter (in μmol CH_4 m^{-2} s^{-1}), and 2) to account for the different footprints of the vermifilter (4630 m^2) and lagoon (10,800 m^2), as total CH_4 fluxes for a full-size vermifilter and lagoon. The full-size vermifilter was the size required to treat the dairy's entire animal population. The total surface area of the lagoon was determined using satellite imagery. To calculate GHG emissions in CO_2 equivalent (CO_2eq), the GWP of 25 for CH_4 was used, following the IPCC (2007) Fourth Assessment Report.

The vermifilter emission reduction was calculated for each measurement event as the difference between lagoon and vermifilter CH_4 emission, divided by the lagoon CH_4 emissions. The monthly emission reductions values were averaged to estimate the mean effect (±standard error) of the vermifilter on the dairy lagoon CH_4 emissions.

Daily CH_4 emissions were estimated by linearly interpolating data between measurement dates. Daily values were summed to calculate monthly and annual CH_4 emissions from vermifilter and lagoon. Uncertainty in the annual CH_4 emissions for the lagoon and the vermifilter was estimated as the standard error of the mean of the 12 annual sums obtained by linearly interpolating fluxes for each of the 12 measurement locations.

The CH_4 emissions of the solids separated by the vermifiltration separator (CH_4f) were calculated using IPCC quantification guidelines (IPCC, 2006) as:

$$CH_4f = VS_{yr} \cdot B_o \cdot 0.66 \cdot MCF \cdot MS \tag{1}$$

where VS_{yr} is the annual VS production after primary separation, B_o is 0.24, 0.66 is the density of CH_4 at 25 °C (kg $CH_4 \cdot m^{-3}$ CH_4), MS is the fraction of livestock manure handled by the secondary separator and was 0.1 (BioFiltro personal communication). The MCF of 0.01 is the IPCC value for composting manure in passive windrow. The CH_4 emissions of these separated solids were added to the CH_4 emissions measured on the vermifilter to quantify the CH_4 emissions of the vermifiltration system.

The IPCC guidelines (IPCC, 2006) base the calculation of CH_4 emissions from manure management on treatment specific MCF parameter values. The MCF quantifies the percentage of VS that each management system converts to CH_4 compared to a maximum methane-producing capacity for the specific type of animal manure (B_o) in a particular climate. A MCF for vermifiltration is currently not available. The Fanelli Dairy emission data were used to determine the vermifiltration system MCF for climatic conditions of the study site (average air temperature of 16 °C) by applying the method described in Mangino et al. (2001):

$$MCF = \frac{CH_{4yr}}{Bo\ x\ VS_{yr}} \tag{2}$$

where the $CH_{4\ yr}$ is the annual sum of the CH_4 emissions of the full-size vermifilter and the vermifiltration separator; B_o was 0.24 m^3 $CH_4 \cdot$(kg VS^{-1}); and the VS_{yr} was the VS produced annually by the dairy cow population, excluding the 17% VS retained by the solid-liquid separator.

The MCF for the vermifilter was based on monthly monitoring. Monthly CH_4 emissions was the timescale used by Mangino et al. (2001) to determine the anaerobic lagoon MCF for the US and adhered to the IPCC recommendation for the determination of MCFs to include the effects of seasonal changes in VS, temperature, and VS retention time.

2.2. Water quality

The quality of the wastewater effluent determined the residual capacity of the treated wastewater to produce GHG emissions and the amount of macro and microelements provided to crops from land application. To determine the effect of the vermifilter on water quality, the vermifilter influent and effluent were sampled monthly from March 2019 to March 2020. Grab samples were kept refrigerated after collection and delivered in less than 24 h to an accredited laboratory for testing (BSK Associates, Fresno, CA). Data were assessed to ensure that laboratory quality assurance/control measures (duplicates, matrix spikes, matrix spike duplicates, and blanks) were within the prescribed limits. Samples were analyzed for solids (total solids, total dissolved solids, total suspended solids, total volatile solids, total volatile suspended solids), N species (ammonia, nitrates, nitrites, total nitrogen, total Kjeldahl nitrogen), dissolved and total organic carbon, other nutrients (calcium, magnesium, potassium, chloride, sulfate, phosphorous, sodium), trace elements (boron, cadmium, chromium, copper, iron, lead, manganese, nickel, zinc) pH and electrical conductivity. Frequency of the analysis varied from monthly to seasonal. Frequency of sampling and analysis methods for each constituent are listed in Table 2.

Constituent removal rates were calculated monthly as the ratio of the difference between influent and effluent concentrations divided by the influent concentration. Mean removal rates were calculated as the averages (±standard error) of all available values. We quantified the N recovered over one year by comparing the annual N produced by the cows with the sum of the N contained in the wastewater and in the vermicompost.

2.3. Vermicompost analysis

The vermicompost is the product of the action of the worms and microbes on the organic matter removed from wastewater and the wood chips. Vermicompost is typically removed after an 18-month period, during which no chips are added. The mass of vermicompost produced was quantified from the volume of material in the vermifilter at extraction and its bulk density. In 2021 the Fanelli Dairy vermicompost was analyzed by Prof. W. Horwath's research group at UC Davis. Samples were dried at 45 °C, for 48 h. A subsample was acidified with 3 M HCl to prevent N loss and dried at 45 °C for 48 h. Samples were ground to <0.25 mm using a ball mill. After, 10 mg of each sample was analyzed for total C and N by dry combustion (AOAC Method 972.43). Wet bulk density was determined for a 10 L composite sample. A subsample was dried at 105 °C for 48 h to determine moisture content by mass difference.

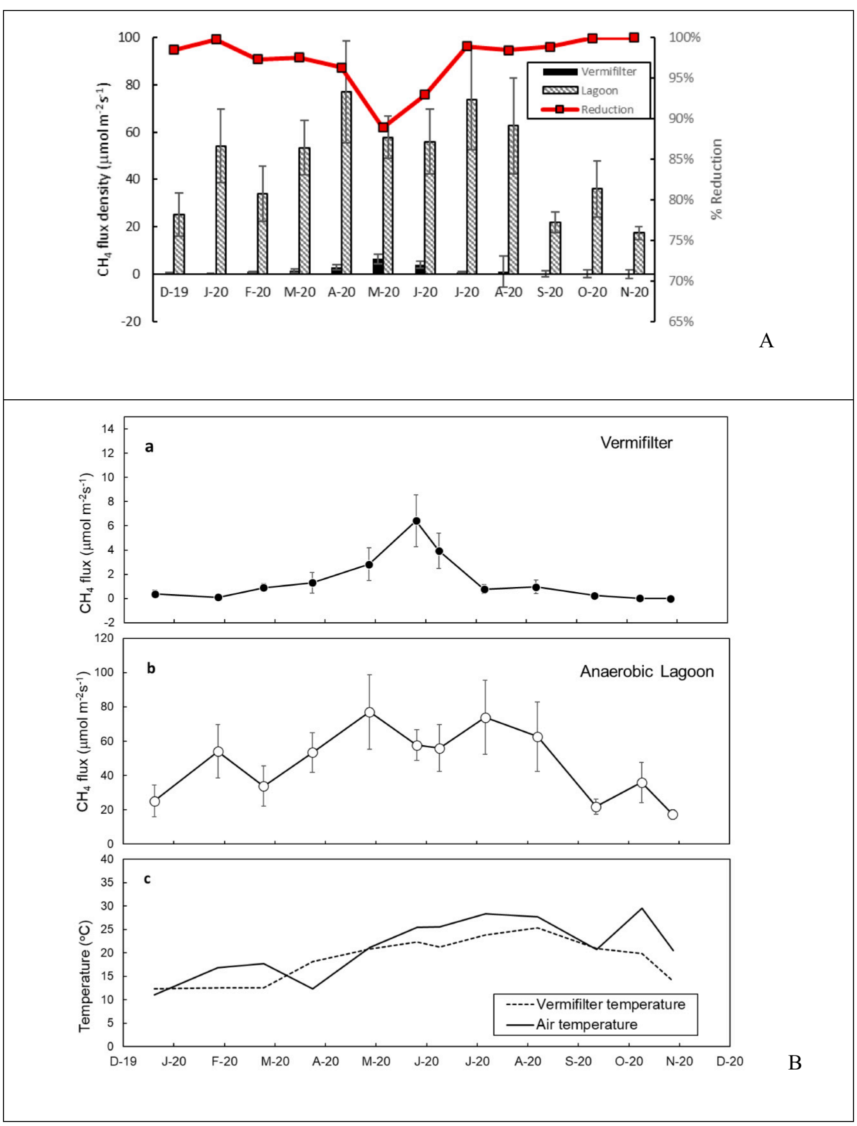

Fig. 2. A: Comparison of the vermifilter and the anaerobic lagoon CH_4 emissions measured monthly between December 2019 and November 2020. Columns represent the average of 12 locations (± standard errors). The red line represents the reduction in CH_4 emissions (%) of the vermifilter compared to the anaerobic lagoon. B: Seasonal trends of CH_4 flux densities (μmol CH_4 $m^{-2}s^{-1}$) from a) the vermifilter and b) the anaerobic lagoon in a California Dairy from December 2019 to November 2020. Symbols are the average of 12 locations (±standard errors). c) Average air and vermifilter bed temperatures (at 15 cm). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Results and discussion

3.1. Methane fluxes

The effects of the vermifilter on the dairy wastewater CH_4 emissions were evaluated using 1) the comparison of CH_4 emissions from the vermifilter with the lagoon CH_4 emissions and 2) the efficacy of the vermifilter to remove VS from the wastewater.

Methane emissions from the vermifilter were substantially lower than emissions from the lagoon throughout the year (Fig. 2, Table 1). Over a year, the vermifilter emitted 97% less CH_4 than the lagoon over the same unit area and 99% less CH_4 at the full-size scale ($p < 0.01$). The vermifilter reduction of the lagoon CH_4 flux density ranged between 89% and 100% (Fig. 2). Even extrapolating the vermifilter maximum measured CH_4 flux rate of 6.4 μmol CH_4 $m^{-2}s^{-1}$ over the year resulted in vermifilter CH_4 emissions 94% lower than the lagoon CH_4 emissions.

Methane emissions from the vermifilter increased steadily between December 2019 and May 2020, and from June 2020 declined gradually through November 2020 (Fig. 2).

Air temperature didn't explain any of the observed variation in CH_4 emissions ($r^2 < 0.1$), and soil (or water) temperature explained only 17% of the vermifilter ($p < 0.001$) and 28% of the lagoon seasonal variations in CH_4 fluxes ($p < 0.001$). The temperature in the vermifilter bed varied by only 13 °C over the year (Fig. 2), in part due to the consistent wastewater application. The vermifilter homogeneous design and consistent operation, the limited variations in humidity and temperature, and the weak relationship with temperature support the reliability of the monthly flux monitoring. Even with a low temporal resolution, the monitoring provided the first quantification of the annual CH_4 emissions of an industrial-scale dairy vermifilter and its MCF.

Table 1
Emissions of CH_4 from manure management systems (MMS) at the Fanelli Dairy. Monthly CH_4 emissions are calculated by linearly interpolating the fluxes between consecutive sampling dates. CH_4 emissions of the lagoon are compared to emissions from a vermifilter of the size required to treat all VS produced in the dairy.

Date		Vermifilter	Lagoon
Year	Month	(kg CH_4 $month^{-1}$)	(kg CH_4 $month^{-1}$)
2019	December	38	20,981
2020	January	114	17,999
	February	236	21,723
	March	422	30,141
	April	948	30,769
	May	708	26,850
	June	195	32,578
	July	163	25,766
	August	57	12,628
	September	7	13,724
	October	21	8763
	November	61	11,931
Annual CH_4 emissions (kg CH_4 yr^{-1})		Vermifilter 2970 (±631) + Solids from vermifiltration separator 308 (±154) = Total vermifilter system 3278 (±649)	253,854 (±35,423)
Potential manure CH_4 emissions (kg CH_4 yr^{-1})		327,951	
MCF		1%	77%
Emission per animal: (kg CH_4 yr^{-1} cow^{-1} yr^{-1})		3.7[a]	284
(t CO_2eq yr^{-1} cow^{-1} yr^{-1})		0.1[a]	7.1
Emission per unit-area of MMS (kg CH_4 m^{-2})		0.7[a]	23.5

[a] Including emissions from the vermifiltration separator;

Furthermore, the methods to determine CH_4 emissions in this study were similar to those reported in the literature. Of the 17 studies included in a review of all available publications on CH_4 emissions measurements from liquid manure storages (Leytem et al., 2017), only four monitored uncovered lagoons and provided annual CH_4 emissions. The reported annual estimates were based on gas measurements made monthly or seasonally for 1–3 days.

A weak relationship between CH_4 fluxes and temperature for an anaerobic lagoon was also reported by Safley and Westerman (1992) and Leytem et al. (2017). In the Leytem et al. (2017) study, CH_4 emissions had a stronger relationship with wind and lagoon physicochemical properties such as total solids, chemical oxygen demand, and VS than temperature.

The water level in the lagoon was constant until June 2020, followed by a gradual decrease until November 2020 due to the use of lagoon water for irrigation. The VS availability in the lagoon decreased with water levels and because of the increased consumption of VS due to the high temperatures as described by Mangino et al. (2001). The decreased VS availability offset the effect of the increased temperature and resulted in lower CH_4 emissions. Because the vermifilter received the lagoon water recycled for flushing, the vermifilter received less VS during the summer. Thus, the decreasing CH_4 emissions from the vermifilter during summer could in part be due to the decreasing lagoon VS content.

The vermifilter was tilled monthly to increase porosity and aeration and thus eliminate conditions generating CH_4 emissions. Anoxic conditions built up gradually after each tilling event. Therefore, the length of the interval between tilling and measurements could also explain part of the observed temporal variability in the vermifilter CH_4 fluxes.

Estimated annual emissions of CH_4 from the lagoon were 253,854 kg CH_4 compared to 2970 kg CH_4 from the vermifilter and the additional 308 kg CH_4 from the solids separated by the separator in the vermifiltration system. Even though CH_4 emissions from the solids separated by the second separator were not directly measured in the study, their contribution to the total vermifilter emissions was minimal (10%).

In one year, the full-size vermifilter system could reduce CH_4 emissions by 6264 t CO_2eq (Table 1). The results are consistent with the low vermifiltration CH_4 emissions reported by Luth (2011) and Lai et al. (2018).

The lower vermifilter CH_4 emissions compared to the lagoon were due both to a lower emission rate per unit area (CH_4 flux density) and the smaller surface area of the vermifilter, as the full-size vermifilter was 43% of the lagoon. The vermifilter system emitted annually 3.66 kg CH_4 yr^{-1} per cows (or 0.1 t CO_2eq cow^{-1} yr^{-1}), and 0.7 kg CH_4 m^{-2} yr^{-1} per unit area of vermifilter, compared to 284 kg CH_4 cow^{-1} yr^{-1} (7.1 tCO_2eq cow^{-1} yr^{-1}) and 23.5 Kg CH_4 m^{-2} yr^{-1} of the lagoon (Table 1).

The large size of the lagoon and the inability to reach the lagoon center increased uncertainty in the estimate of the lagoon CH_4 emissions (Fig. 2b). However, this was not the case for the vermifilter CH_4 emissions. Also, the lagoon CH_4 flux rates measured in this study are comparable with the emissions rate of 20 kg CH_4 m^{-2} yr^{-1} reported by Owen and Silver (2014) for dairy anaerobic lagoons. They are also within the range of 0.4–37 kg CH_4 m^{-2} yr^{-1} (12–1030 kg CH_4 ha^{-1} day^{-1}) summarized by Leytem et al. (2017) and also reported by Kupper et al. (2020).

CH_4 fluxes for the same vermifilter were previously measured by Lai et al. (2018). This study also observed low CH_4 emissions from the vermifilter, but the authors reported CH_4 emission rates from the vermifilter higher than from the lagoon (0.8 compared to 0.4 kg CH_4 day^{-1} per 50,000 L of daily treated wastewater, respectively). The emission rates reported in the study did not account for the size of the lagoon. Scaling up the lagoon emissions from the sampled volume to its total volume would increase the reported lagoon CH_4 emissions well above the vermifilter emission. In fact, the vermifilter CH_4 emission rates measured using a triangular sampling tunnel covering a section of the surface of the vermifilter during July by Lai et al. (2018) were lower than the 1.9 kg CH_4 day^{-1} measured in the month of July in this study.

The vents contributed minimally to the total vermifilter CH_4 fluxes. The 20 vents were connected to an air volume similar in size to the vermifilter bed. The low vent CH_4 (on average 0.12 ± 0.1 μmol CH_4 m^{-2} s^{-1}) and high CO_2 (on average 521 ± 175 μmol CO_2 m^{-2} s^{-1}) emission rates provided evidence that aerobic conditions predominated at depth in the vermifilter. Because the maximum contribution of the vents to the vermifilter CH_4 emissions was 0.3% (data not shown), they were excluded from the annual CH_4 flux estimation.

Additional research is needed to improve understanding of how vermifilter design, animal type, climate, and system performance affect emissions of CH_4.

The VS left in treated wastewater determines its capacity to produce further CH_4 emissions. On average, the vermifilter system removed 87% of the VS (Table 2) from the wastewater. Combined with the VS removed by the first separator (17%), only 11% of the total VS produced was present in the vermifilter effluent (Fig. 1). The VS reduction was continuous during the year (Fig. 3) and ranged from 77% to 96%. Even if all treated water was stored in the existing lagoon under current management, CH_4 emissions would be 87% lower than without vermifiltration.

The influent VS content was variable. Similar fluctuations observed by Wilkie et al. (2004) were explained by the way in which the manure particulates moved through the system and not by changes in wastewater characteristics. Fluctuations were also measured by Miito et al. (2021) in a Washington State dairy deploying the same vermifilter. The authors sampled total solids and total suspended solids every two weeks between July and December. The study found no difference in solid content during warmer months compared to winter months. These results suggest seasonality has little effect on dairy wastewater quality and that the monthly sampling sufficiently accounted for the existing temporal variation.

The determination of the MCF coefficient can facilitate the ability of the dairy vermifiltration practice to access the carbon market and other incentive programs aiming to reduce agricultural GHG emissions. The methane conversion factor (MCF) for the vermifiltration system determined during this study was 1%, the same value suggested by the IPCC guidelines for composting for similar climatic conditions (IPCC, 2006). The vermifilter system MCF was much lower than the lagoon MCF of 77% (Table 1). The IPCC suggests a MCF of 75% for an anaerobic lagoon in the region, consistent with our measured values. The higher estimated lagoon MCF relative to the IPCC value suggests that the vermifilter CH_4 emissions reduction was not due to an underestimation of the lagoon CH_4 emissions.

3.2. Nutrient removal and recovery

The effect of the vermifilter on water quality not only determines the residual capacity of treated wastewater to emit GHG gases and pollutants, but also to provide nutrients to crops when land applied. During 2019–2020, vermifiltration reduced wastewater NH_3 concentrations by 97% (±5%) and total N by 84% (±8%) (Fig. 3, Table 2). High rates of N and NH_3 reduction by vermifiltration were reported in several studies (Adugna et al., 2019; Dey Chowdhury and Bhunia, 2021). Our results were consistent with the Lai et al. (2018) study on the Fanelli Dairy vermifilter N dynamics. The vermifilter removed most of the N from the wastewater, and this was transformed into benign N_2 gas through

Table 2
Average concentration of key water quality constituents in influent and effluent samples and percent reduction in concentration for the vermifiltration system at the Fanelli Dairy. Data are averages of monthly or seasonal values between March 2019 and March 2020.

Constituent	Units	Method	Average concentration				Reduction	Range	N
			Influent	SE	Effluent	SE	%	%	
Nitrogen									
Ammonia ($NH_3 + NH_4^+$ as N)	mg l^{-1}	EPA 350.1	494	25	13	6	97%	87–100	13
Nitrate (as N)	mg l^{-1}	EPA 300	ND		54	12			13
Total Kjeldahl Nitrogen	mg l^{-1}	EPA 351.2	810	80	74	15	92%	88–100	13
Total N	mg l^{-1}	CALC	810	80	134	17	84%	72–100	13
Solids									
Total Solids	mg l^{-1}	SM 2540B	19,258	1737	4250	454	79%	72–95	9
Total Dissolved Solids	mg l^{-1}	SM 2540C	5333	410	3300	316	42%	12–64	10
Total Suspended Solids	mg l^{-1}	SM 2540D	13,969	1966	666	174	95%	84–96	13
Total Volatile Solids	mg l^{-1}	SM 2540E	14,127	1344	1798	240	87%	82–96	13
Total Volatile Suspended Solids	mg l^{-1}	SM 2540E	11,392	1716	525	155	95%	85–98	10
Carbon									
Dissolved Organic Carbon	mg l^{-1}	SM 5310C	373	126	127	24	55%	17–85	4
Total Organic Carbon	mg l^{-1}	SM 5310C	640	160	163	28	68%	33–86	4
Conductivity	μS cm^{-1}	SM 2510B	8700	241	4518	345	48%	30–72	11
pH		SM 4500-H+ B	7.8	0.08	8.4	0.04	Incr.* 8%	Incr.*1–15%	12
Calcium	mg l^{-1}	EPA 200.7	530	56	84	4	83%	79–89	4
Magnesium	mg l^{-1}	EPA 200.7	320	39	89	15	70%	56–89	4
Potassium	mg l^{-1}	EPA 200.7	2324	977	1679	673	26%	82–91	11
Chloride	mg l^{-1}	EPA 300.0	435	99	358	75	12%	27–37	4
Sulfate	mg l^{-1}	EPA 300.0	ND		62	24			
Phosphorous	mg l^{-1}	EPA 365.4	233	19	39	7	84%	83–91	8
Sodium	mg l^{-1}	EPA 200.7	295	10	223	25	25%	9–37	4
Boron	μg l^{-1}	EPA 200.8	1875	250	395	75	76%	57–9	4
Cadmium	μg l^{-1}	EPA 200.8 DRC	1.1	0.1	ND		100%		4
Chromium	μg l^{-1}	EPA 200.8 DRC	39	9	1	1	97%	90–100	4
Copper	μg l^{-1}	EPA 200.8 DRC	770	147	100	18	86%	75–92	4
Iron	μg l^{-1}	EPA 200.8 DRC	22,750	5422	913	97	95%	92–98	4
Lead	μg l^{-1}	EPA 200.8 DRC	18	7	1	0	94%	82–99	4
Manganese	μg l^{-1}	EPA 200.8 DRC	4550	712	468	53	89%	83–92	4
Nickel	μg l^{-1}	EPA 200.8 DRC	94	16	19	3	78%	63–89	4
Zinc	μg l^{-1}	EPA 200.8 DRC	3750	746	446	107	91%	85–94	4

Measured increase (Incr.).

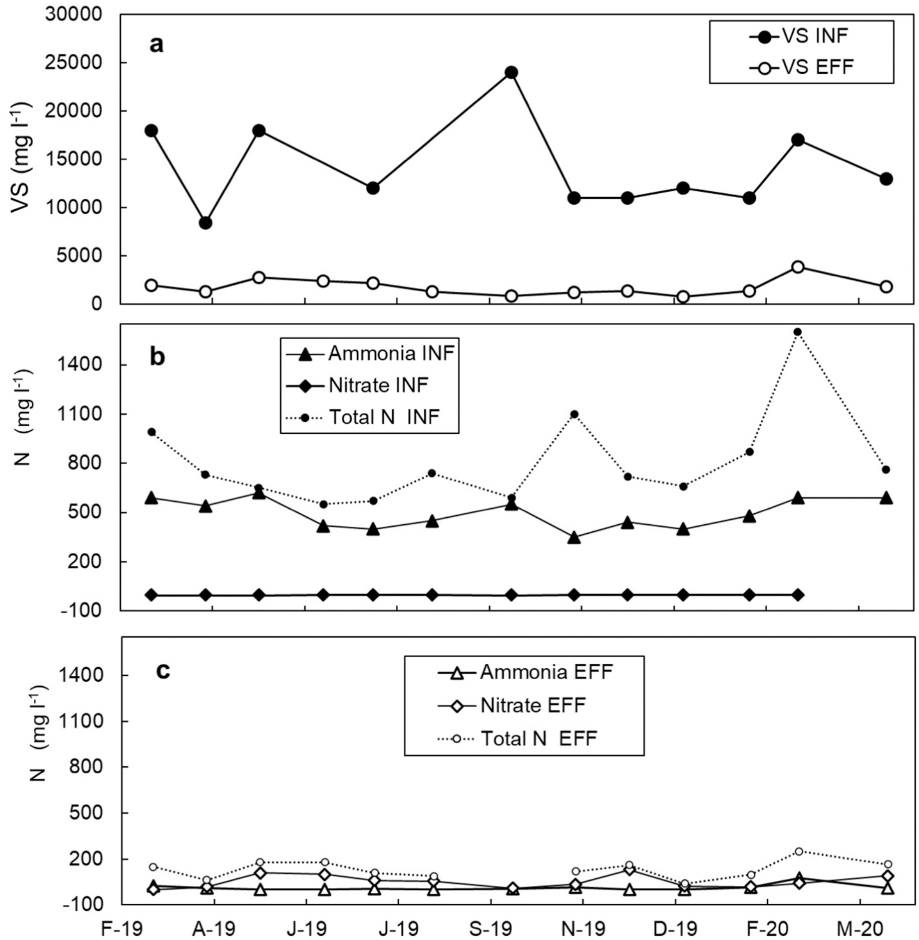

Fig. 3. Concentration of a) volatile solids (VS); ammonia, nitrate, and total nitrogen in the dairy wastewater b) before (INF) and c) after (EFF) the vermifiltration system. Concentrations were measured monthly from March 2019 to March 2020.

denitrification. The study measured minimal N_2O emissions (0.14 kg N_2O day^{-1}) during vermifiltration. Volatilization of NH_3 from the vermifilter was 0.1 kg NH_3 day^{-1}and was 90% lower than from the lagoon.

The vermifiltration reduction of the N load in dairy wastewater reduces the potential losses to the atmosphere, surface, and groundwater. When regulations limit the maximum load of N to apply with irrigation to land, vermifiltration results in the reduction in the amount of land required by a farmer to dispose of the dairy wastewater. Also, the improved quality of the treated wastewater relative to the lagoon increases the options for recycling treated water and can result in the reduction of the farm's demand for high-quality water.

Vermifiltration can still provide N for crops in both the treated water and vermicompost (Table 2). Water treated by a full-size vermifilter (460,000 L day^{-1}) at the Fanelli Dairy would provide annually 22 t N, 50% of which is plant available ammonia and nitrate (Table 2). Considering a generic N fertilization rate of 150 Kg N per hectare, the treated wastewater would provide N fertilization to 147 ha.

Vermicompost produced at the Fanelli Dairy after circa 18 months of use had 1.4% N content, 42% C, and a bulk density of 190 kg$_{dw}$ m^{-3}. Thus, a full-size vermifilter at the Fanelli Dairy would produce 563 t of vermicompost (wet weight and 60% humidity), with 148 t of C (165 kg C cow^{-1}) and 5 t of N (6 kg N cow^{-1}) that can be applied to soils.

The life cycle of the N produced annually from one cow was followed until the dairy wastewater stored in the anaerobic lagoon was used for irrigation (Fig. 1c). In addition to the data resulting from this study, N production and loss rates estimated regionally by Pettigrove and Eagle (2009) were used. Of the 153 kg N produced annually by one typical cow in the region, on average 31 kg N are lost during storage in anaerobic lagoons. The 20% loss included the N removed by the first separator, as N is minimally affected by separators because soluble nutrients and salts predominantly remain in the liquid system (Harter, 2007). The researchers reported a typical 28% loss (34 kg N) after land application. This leaves 88 kg N for use by the crop. In contrast, the use of the vermifilter resulted in 25 kg N remaining in the treated wastewater and an additional 6 kg N in the vermicompost. Losses of N as emissions of N_2O and NH_3 during vermifiltration measured by Lai et al. (2018) were minimal (<1 kg N). Thus, the vermifilter recovered in both the treated water and vermicompost 20% of the initial N that can be applied to crops. This was lower than the 60% of initial N provided by applying lagoon water. However, this can help mitigate the excess nutrients associated with intensive dairies operation. Also, losses from soils after land application of vermifiltration-treated wastewater are unknown but likely reduced compared to the lagoon because of the lower amount applied, higher microbial activity able to cycle and store nutrients (Saha et al., 2022), and low initial concentrations of NH_3. The difference between N excreted, N_2O emitted during vermifiltration, and left in the effluent/vermicompost was emitted as N_2. This loss may represent a missed opportunity to recover nutrients that are a valuable resource. A cost-benefit analysis can determine the most appropriate strategy for a dairy. However, the analysis should assess not only cost and feasibility of the nutrient-recovering technologies but also their effects on GHG emissions and air and water quality.

The vermifilter removed additional constituents from the dairy manure wastewater. Phosphorous was reduced by 84% (±8%). Total dissolved solids and electrical conductivity decreased by 42% (±14%) and 48% (±11%), respectively. There were also reductions from the wastewater in most major ions and all trace elements (Table 2). Only sulfates and nitrates increased compared to pre-treatment conditions, and concentrations in the effluent were low (Table 2).

Among other available studies Miito et al. (2021) and demonstrated the efficacy of vermifiltration as a technically viable alternative for on-site dairy wastewater treatment. A 68% wastewater reduction in total suspended solids (TSS), 81% reduction in total nitrogen, 48% reduction in phosphorus were reported on a Washington State dairy using a similar vermifiltration system (Miito et al., 2021). These authors reported higher reduction efficacy of the vermifilter at higher temperatures and higher influent concentrations. This can in part explain our study's higher TSS and phosphorus wastewater reduction rates (95% and 84%, respectively). At the California dairy, the annual average air temperature was circa 10 °C higher, and the influent phosphorus concentrations were higher than at the Washington dairy (190–290 mg L^{-1} compared to 54–127 mg L^{-1}).

4. Conclusions

Vermifiltration of dairy wastewater caused minimal CH_4 emissions of 0.7 Kg CH_4 m^{-2} yr^{-1} or 3.7 kg CH_4 m^{-2} $yr^{-1}cow^{-1}$ and greatly reduced the CH_4 emissions of an anaerobic lagoon. The emissions were only 1% of the CH_4 emissions potentially produced by the liquid manure. Vermifiltration significantly decreased the wastewater nutrient load, increasing opportunities to recycle wastewater. Thus, vermifiltration can be a useful tool to mitigate agriculture CH_4 emissions and manage excess nutrients. Further research is needed to assess factors controlling GHG fluxes, GHG life cycle of vermifiltration, and the potential for carbon sequestration from land application of vermicompost and treated water.

CRediT authorship contribution statement

Sabina Dore: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Steven J. Deverel:** Resources, Writing – review & editing, Supervision, Project administration. **Nicholas Christen:** Investigation, Formal analysis.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sabina Dore, Steven Deverel, and Nicholas Christen report financial support was provided by BioFiltro. Sabina Dore, Steven Deverel and Nicholas Christen reports a relationship with BioFiltro that includes: consulting or advisory.

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Appendix A. Supplementary data

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