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# A vermifilter system for reducing nutrients and organic-strength of dairy wastewater

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ABSTRACT

Vermifiltration is an emerging low-cost and environmentally sustainable technology for the treatment of wastewater and recovery of nutrients. This study evaluated, for six months, the efficacy of a pilot-scale vermifilter for the treatment of a side-stream of dairy wastewater at a commercial dairy farm in Washington State. Samples of dairy wastewater were collected at the upstream and downstream of the vermifilter during these six months and analyzed for reductions in the solids contents (total solids (TS) and total suspended solids (TSS)), chemical oxygen demand (COD), pertinent nitrogen species (total nitrogen (TN), total ammonia-nitrogen (TAN), nitrate-nitrogen ($NO_3$–N), and phosphorus species (total phosphorus (TP) and orthophosphate (Ortho-P)). The respective reductions were 81 ± 7.1% for TAN, 77 ± 8.4% for TN, and 74 ± 9.5% for $NO_3$–N. Total solids reduction was, generally, low at 21 ± 7.0% but the reduction of TSS was significantly high at 68 ± 10%. Results indicated modest reductions of TP (48 ± 6.0%) and COD (45 ± 4.1%) but relatively lower Ortho-P reduction (3.9 ± 19.2%). Regression modeling showed that ambient temperature has a significant influence on the reduction efficiencies of TAN (by as much as 50%) and COD (by as much as 59%). Overall, this study demonstrated that vermifiltration has great potential in alleviating nutrients contents and simultaneously reducing the organic strength of the vermifilter effluents.



## 1. Introduction

Over the last several decades, the dairy industry has seen tremendous growth due to the increased demand for milk and milk products (USDA, 2019). This has concurrently led to the production of more and more dairy manure. The industry has also seen significant changes in recent years, including a decrease in the number of dairy farms but an increase in the size of individual operations and regional concentrations of dairy operations (Von Keyserlingk et al., 2013; Zeb et al., 2019). The regional concentrations of large dairies have led to the production of large volumes of manure in small geographical areas, leading to concerns about their impacts on local air, land, and water resources (Jiang et al., 2014; Tao et al., 2016).

Traditionally, manure management relied on the basic agronomic approaches, where dairy wastewater is stored in lagoons and subsequently applied in fields for the production of pasture and forage crops (Owusu-Twum and Sharara,

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2020). Although this approach is effective for nutrient recycling, this management system has potential risks to the air, land, water resources. This situation further worsens if the producer does not have an adequate land base to utilize all nutrients in an environmentally safe manner. Technologies such as aerobic treatment (Zhao et al., 2015), anaerobic treatment for energy recovery (Yao et al., 2017; Zhang et al., 2018), membrane filtration (Carretier et al., 2015; Gerardo et al., 2015; Soler-Cabezas et al., 2018), struvite precipitation (Capdevielle et al., 2013; Tao et al., 2016), ammonia stripping (Jiang et al., 2014; Yao et al., 2017) have been well researched and suggested as technically viable alternatives, but they are not deemed uneconomical due to high energy and labor demands required for either aeration or managing the sludge.

Vermifiltration is an emerging low-cost (Arora and Kazmi, 2016; Ghasemi et al., 2020; Manyuchi et al., 2018; Wang et al., 2016a, 2017) and environmentally sustainable technology for the treatment of domestic and industrial wastewater (Jiang et al., 2016; Singh et al., 2017, 2021b). Vermifiltration is fundamentally an aerobic wastewater treatment system using a consortium of microorganisms and earthworms in a filter bed media (Singh et al., 2019b). The basic bed media is mainly a combination of coarse gravel, fine gravel, sand, and an organic layer with earthworms, all acting in concert as a hub for microbial growth, filter, and adsorbent unit. The earthworms enhance biochemical reactions in the system through the ingestion and digestion of wastewater organics and nutrients (Samal et al., 2017b; Singh et al., 2019b). Zhong et al. (2017) reported higher microbial diversity in vermifilters than in conventional biofilters, attributing this phenomenon to the presence of earthworms. The vermifilter system recovers nutrients from wastewater in two ways: earthworm biomass and vermicasts (earthworm's excreta). A major feature of this technology is that it does not need external energy other than the pumping of the manure, which implies lower operation costs (Li et al., 2013a). The economics of the system can further be enhanced by the sale of the earthworms and vermicasts as animal feed and soil amendment, respectively.

Numerous studies have been carried out evaluating vermifiltration technology for the treatment of municipal wastewater (Kumar et al., 2016; Lourenco and Nunes, 2017a,b), domestic wastewater (Furlong et al., 2015, 2014; Wang et al., 2016b), and industrial effluents (Lim et al., 2014; Singh et al., 2018a). Although the effectiveness of this technology in the treatment of municipal, domestic, and industrial wastewater is evident, its effectiveness in the treatment of dairy wastewater is not well studied. Singh et al. (2018b) studied the intricacies of vermifilter clogging using dairy manure and reported that high organic loading rates activate a higher number of microbial sites, in turn causing a higher degree of clogging. Samal et al. (2018b) studied the effect of the hydraulic loading rate of synthetic dairy wastewater on the vermifiltration technology. Two other vermifiltration studies using dairy wastewater have been conducted, but their focus was on the energy requirement and the microbiome populations of the system (Lai et al., 2018; Pasha et al., 2018). More research is needed to understand further the performance and efficiency of this technology for the treatment of dairy wastewater. The goal of this study was to evaluate the efficacy of this technology on the reduction of solids, organic strength, and nutrients (nitrogen and phosphorus) in dairy wastewater from a dairy operation with a manure-flush system. The ultimate goal of the treatment was: (1) to reduce the nutrient load of the wastewater to enable its recycle via irrigation on nearby land-base, (2) for reuse to flush fresh manure from the barns, and (3) to recover the nutrients in the form of earthworm biomass and vermicasts.

## 2. Materials and methods

### 2.1. Site of the current study

This study was conducted on a commercial dairy farm in Yakima county, Washington state. The dairy, which comprises approximately 3000 milking cows, operates free-stall barns and manure-flush systems coupled with screw-press solids-liquid separators. A side stream of the liquid from the solid-liquid separators was used in the study. The initial characteristics of the dairy wastewater are shown in Table 1. A pilot-scale vermifilter Biofiltro BIDA®, installed on-site and operated under the prevailing local environmental conditions, was used for this research. The study spanned six months and three seasons (Summer, Fall, and Winter) from July to December 2019. The summers in this region are hot and arid with mostly clear skies, while the winters are relatively cold, dry, and the skies partly cloudy. The temperature typically varies from 26 °F to 94 °F. During the 6-months study period, ambient temperatures ranged between 0 and 102 °F, the area received between 0.1–0.8 inches of rain monthly, wind speeds ranged from 0 to 37 mph, and humidity levels were between 15%–100%. The first three months were generally hotter, received more rainfall, and had lower humidity than the last three months.

### 2.2. The vermifilter system design

The vermifilter system used in the current study was a vertical flow subsurface flow type which consisted of an influent-holding tank, a pump station to deliver the influent from the influent reservoir to the vermifilter-bed via an overhead sprinkler system, and an effluent reservoir to receive treated wastewater. Fig. 1a is a schematic of this system, while Fig. 1b is a photograph of the actual unit. The vermifilter-bed was constructed out of an ordinary shipping container (L × W × H: 6.1 m × 2.4 m × 2.6 m) with polyethylene linings on the inside. The top layer (0.2 m of a mixture of wood shavings and chips) of the unit was inoculated with approximately 300 kg of *Eisenia fetida* to obtain an earthworm density of approximately 12,000 worms $m^{-3}$. Earthworm densities ranging between 10,000 to 15,000 worms $m^{-3}$ were documented in previous studies (Samal et al., 2017b; Singh et al., 2021b). The selection of earthworm species *Eisenia*

**Table 1**
Dairy wastewater characteristics.

| Category | Parameter | Concentrations (Mean ± SD) |
|---|---|---|
| Solids | Chemical oxygen demand (g $L^{-1}$) | 2.9 ± 0.5 |
| | Total solids (g $L^{-1}$) | 7.7 ± 1.4 |
| | Total suspended solids (g $L^{-1}$) | 2.5 ± 0.8 |
| Nitrogen | Total nitrogen (mg $L^{-1}$) | 857.9 ± 246.8 |
| | Total ammonia-nitrogen (mg $L^{-1}$) | 322.2 ± 69.2 |
| | Nitrate nitrogen (mg $L^{-1}$) | 203.2 ± 93.3 |
| Phosphorus | Total phosphates (mg $L^{-1}$) | 92.4 ± 27.7 |
| | Orthophosphates (mg $L^{-1}$) | 24.0 ± 7.2 |

**Table 2**
Technical specifications of the pilot vermifilter system.

| Specifications | Values |
|---|---|
| Length × Width × Depth (m) | 4.9 × 2.4 × 1.2 |
| Flow rate ($m^3$ $d^{-1}$) | 5.7 |
| Earthworm density (worms $m^{-3}$) | 12,000 |
| Total volume ($m^3$) | 0.9 |
| Surface area ($m^2$) | 11.9 |
| Hydraulic loading Rate ($m^3$ $m^{-2}$ $d^{-1}$) | 0.5 |
| Organic loading rate (kg COD $m^{-2}$ $d^{-1}$) | 1.4 ± 0.2 |
| Solids loading rate (kg TSS $m^{-2}$ $d^{-1}$) | 1.2 ± 0.5 |
| Nitrogen loading rate (kg TN $m^{-2}$ $d^{-1}$) | 0.4 ± 0.1 |
| Hydraulic retention time (h) | 4 |

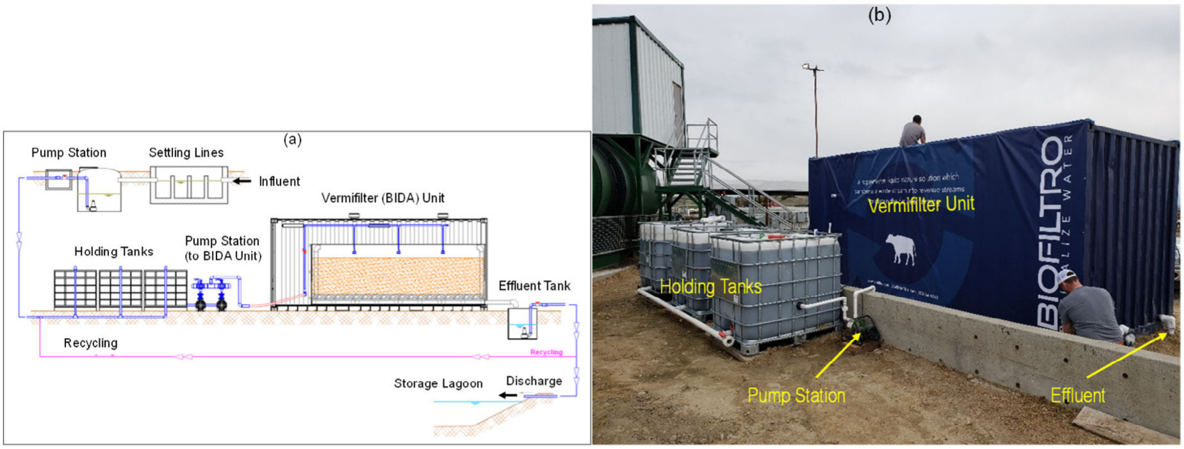



**Fig. 1.** A schematic (a) and a photo (b) of the vermifiltration system used in this study.

*fetida* was also based on previous studies. *Eisenia fetida* is the most commonly used earthworm species in vermifiltration systems due to its high reproductivity and survival in high moisture or waterlogged conditions (Arora and Kazmi, 2015), while also performing well under a wider temperature range (Kumar et al., 2016; Wang et al., 2016b).

The top layer provided a medium for the formation of a biofilm, consisting of microbes and bacteria that feed off of the organic matter and nutrients in the wastewater. Fine crushed stones and cobblestones (10–20 cm) were also incorporated into the unit for improved filtration. The bottom drainage basin consisted of thick pallets lining the floor of the vermifilter. Permeable textile material was placed between each media layer to prevent either the migration of worms and shavings into the rock layer or the rocks into the drainage basin. A recycle line of effluent was also included to maintain TSS below 3 g $L^{-1}$ in the influent wastewater to minimize the clogging of the vermifilter. After setting up the vermifilter, an acclimation period of 3 months was provided. Dairy wastewater was applied during this period to enable the formation of biofilms and for microbial growth in the vermifilter. After the acclimation period, wastewater from the equalization tank was intermittently irrigated uniformly from the top of the vermifilter-bed via rotary head sprinklers every 30 min. The specifications and design parameters (Table 2) of the vermifilter were as per the patent AU2013397276A1 (Fuentes, 2009).

### 2.3. Wastewater sampling and analysis

To evaluate the efficacy of the vermifiltration technology for nutrients solids and organics reduction, influent and effluent wastewater samples were collected every two weeks, at the inlet and outlet of the vermifilter system, for six months. The samples were collected in 5-gallon sealable buckets and transported in cooler boxes to the wastewater laboratory on the Washington State University's main campus in Pullman. The samples were stored at 4 °C until the day of analysis to minimize biodegradation Cui et al. (2020). The influent and effluent wastewater samples, while taken at the same time of the day, had an actual time-lag of approximately 4 h based on the vermifilter design hydraulic retention time (BioFiltro, 2017). During the collection of the wastewater samples, the prevailing ambient temperatures were also recorded using a digital thermometer (B07JBW8VPX, BTMETER, Zhuhai, China). The temperature data would later be used to investigate the effect of ambient temperature on the vermifilter performance.

During laboratory analysis of the wastewater, TS and TSS were analyzed by evaporation to dryness at 105 °C of unfiltered and filtered (Whatman GF/C) samples, respectively. For the determination of the COD concentration of the wastewater, the digestion colorimetric method (HACH Reactor Digestion Method 8000) was used. For the determination of the TN concentration, the persulfate method was used, Nessler's method was used for TAN concentration (sum of ammonium and ammonia nitrate), while the HACH s-TKN (Method 10242) method was used for nitrate-nitrogen concentration (Fellah and Elektorowicz, 2020). For the determination of total phosphorus and orthophosphate concentrations, the ascorbic acid method was used (APHA, 2017). For quality control, all analyses for the samples, in this study, were performed in triplicates, while the calibrations of equipment with standard solutions were also performed quarterly or according to manufacturers' recommendations. The respective final reduction efficiencies were then calculated as the percent reduction for each parameter using (Eq. (1)). Reduction rates were also computed using (Eq. (2)).

$$\mathit{Efficiency}\,(\%) = \left(1 - \frac{C_e}{C_i}\right) \times 100 \tag{1}$$

where: $C_i$ and $C_e$ were influent and effluent concentrations, respectively, in mg $L^{-1}$ or g $L^{-1}$

$$\mathit{Reduction\ Rate}\ (\mathrm{kg\ d^{-1}}) = F \times (C_i - C_e) \tag{2}$$

where:
F is flow rate, in $m^{-3}$ $d^{-1}$
$C_i$ and $C_e$ were influent and effluent concentrations, respectively, in kg $m^{-3}$

### 2.4. Data analysis

R-software was used in the data analysis. Descriptive statistical parameters included the means and standard deviations of the solids, nitrogen, phosphorus, and organic concentrations. Outliers were identified by applying Grubbs' test on the influent, effluent characteristics, and the reduction efficiencies data. Outlier values were substituted with the residual means. Principal component analysis and correlation analyses were also performed on the influent and effluent characteristics to determine the effects of temperature, solids, nitrogen, phosphorus, and organic concentrations of the wastewater on the performances of the vermifilter system. ANOVA was used for hypothesis testing, while the separation of means, when the ANOVA indicated significant differences, was performed using Tukey's HSD test. Significant differences among the means of interests were inferred if $p \leq 0.05$ (i.e., $\alpha = 0.05$). Linear regression was used to model the relationships within or amongst the wastewater characteristics.

## 3. Results and discussions

### 3.1. Total solids and total suspended solids

The TS concentrations of the influent wastewater during the sampling period ranged from 6–10 g $L^{-1}$, while reduction efficiencies were 21 ± 7.0% (Fig. 2a) during the treatment through the vermifiltration system. The vermifilter removed the TS at the rate of 5.7–14.2 kg [TS] $d^{-1}$. There were no significant differences ($p < 0.05$) in the influent TS contents in the warmer months compared to the colder months. However, the differences in the influent and effluent TS concentrations were significant and positively correlated. The TSS in the influent wastewater, on the other hand, ranged between 1.4–3.8 g $L^{-1}$, which was reduced by 68 ± 10% (Fig. 2b) in the effluent; translating into reduction rates of 6.4–16.2 kg [TSS] $d^{-1}$ during the treatment in the vermifiltration system. There were also no significant differences ($p < 0.05$) in the influent TSS concentrations between warmer months and colder months. The differences in TS concentrations between influent and effluent were not only significant but also indicated strong positive correlations. The fluctuations in TS reduction efficiencies were attributed to flooding on some days, which may have promoted more anoxic environments with negative effects on organic degradation. Results also revealed that influent solids concentrations had significant ($p < 0.05$) positive influences on both influent-TN and -TP concentrations.

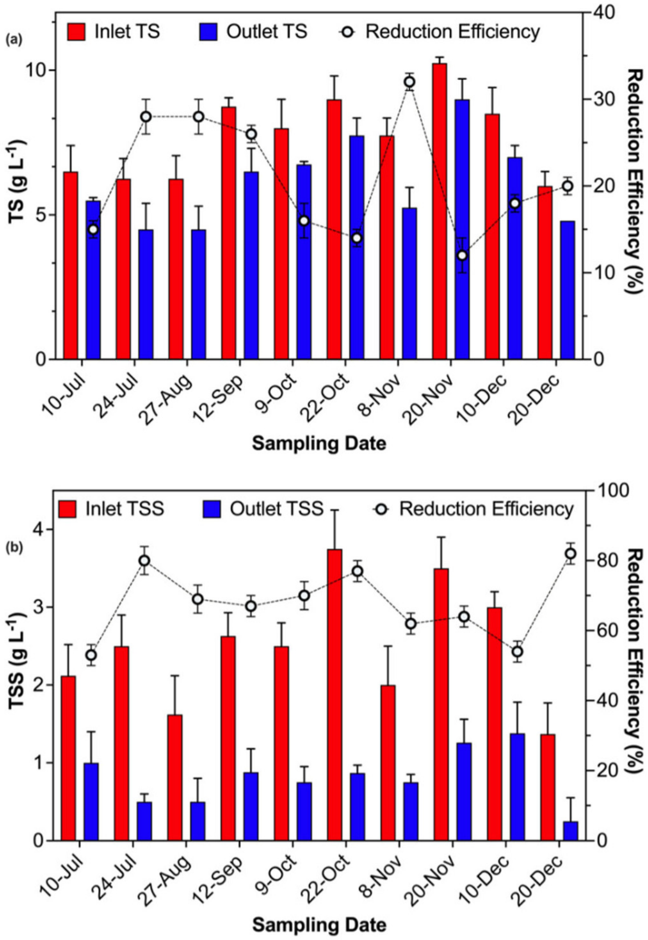



**Fig. 2.** Bar graphs present influents and effluents solids concentrations: (a) total solids (TS) and (b) total suspended solids (TSS), while line graph presents the corresponding reduction efficiencies, during each sampling event.

Higher reduction efficiencies were observed in TSS compared to the TS, which was attributed to significantly more suspended solids component of TS being trapped and adsorbed in the vermibed than the dissolved solids component of the TS. The reduction rates in the vermifilter, however, were not significantly different between TS and TSS concentrations. The variations in influent TS and TSS concentrations did not have significant ($p < 0.05$) effect on the reduction efficiencies. The TS and TSS reduction efficiencies in vermifiltration are attributed to the combined action of the earthworms and microorganisms, and the filtration capacity of the vermifilter. According to Singh et al. (2019b), reduction of suspended solids during vermifiltration is mainly due to the solids being trapped in the pores and capillaries of the bedding, from where it is devoured by earthworms and later excreted as castings. The castings are highly rich in organic matter, microbial activity, and plant available nutrients, which if incorporated into soils tend to boost soil productivity. In the current study, castings manifesting as compact and granulated round pellets on the surface of the vermifilter were observed. According to Arora and Saraswat (2021), the dissolved solids are degraded biologically by the action of microbes in the vermifilter.

The reduction efficiencies of TSS in the current study were similar to those reported in Samal et al. (2017a) ranging between 73.8–84.8%, while treating synthetic dairy wastewater with in a vermifilter system. In comparison to other wastewater streams treated via vermifiltration systems, Singh et al. (2018b) also reported TSS reduction efficiencies of 82.17 ± 0.65% while treating synthetic brewery wastewater. Singh et al. (2019b), in another study, also observed suspended solids reduction efficiencies of up to 95% with domestic wastewater streams. The variability in the solids reduction rates in the various studies may be attributed to the differences in rates of ingestion by earthworms (Lourenco and Nunes, 2017b), filtration efficiency of the filter media (Samal et al., 2018b), as well as the differences in microbial degradation rates of the solids in each wastewater (Singh et al., 2019b).

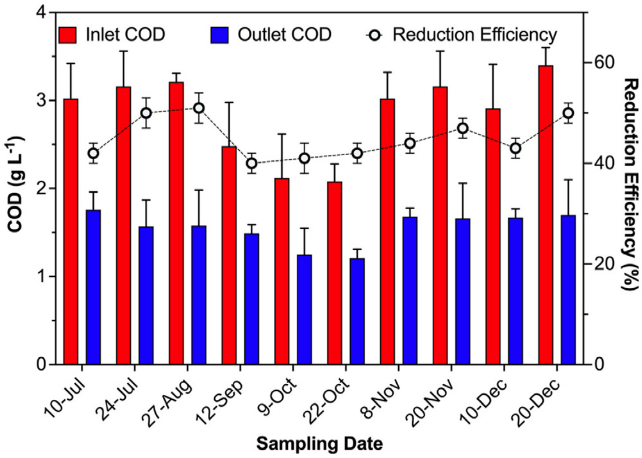



**Fig. 3.** Bar graphs present influents and effluents chemical oxygen demand concentrations, while line graph shows the corresponding reduction efficiencies, during each sampling event.

### 3.2. Chemical oxygen demand

The COD concentrations of the influent wastewater during the sampling period ranged from 2.1–3.4 g $L^{-1}$, while reduction efficiencies of 45 ± 4.1% (Fig. 3), and reduction rates ranging from 7.2 to 9.7 kg [COD] $d^{-1}$ were observed during treatment through the vermifiltration system. There were no significant differences ($p < 0.05$) in the influent COD concentrations between warmer months and colder months. The effluent COD concentrations, however, significantly and positively correlated with the influent COD concentrations. Results also revealed that the COD concentrations, in the influent, was significantly and positively correlated with solids and nitrogen concentrations. The COD reduction efficiencies were similar to those reported by Li et al. (2013b) and Arora et al. (2014) while treating domestic sewage sludge and municipal wastewater, respectively, but higher than 10–37.1% reported in Samal et al. (2018a) while treating dairy wastewater via a macrophyte-assisted vermifilter. The reduction efficiencies, however, were lower than 80%–86% reported in Samal et al. (2018b) in a two-stage hybrid macrophyte assisted vermifiltration system. The variation in the efficiencies was attributed to the differences in hydraulic loading rates (0.3 $m^3$ $m^{-2}$ $d^{-1}$) in the different systems and the usage of macrophytes by Samal et al. (2018b) as lower hydraulic loading rates (HLR) typically result in better pollutants reduction. The reduction of COD in vermifiltration systems has, overall, been attributed to the joint action of earthworms and microbes in the vermifilter system (Manyuchi et al., 2013). These oxidative processes enhance the degradation of the organics in the wastewater streams. According to Singh et al. (2017, 2019b), earthworms enhance COD reduction by maintaining aerobic conditions that promote the activity of aerobic microbes which oxidize organics.

### 3.3. Total nitrogen, total ammonia, and nitrate nitrogen

The total nitrogen (TN) concentrations in the influents during the sampling period ranged from 408–1231 mg $L^{-1}$, the mean reduction efficiencies were 77 ± 8.4% (Fig. 4a), and reduction rates spanned from 2.0–5.6 kg [TN] $d^{-1}$, during the treatment through the vermifiltration system. Ambient temperature conditions had no significant effect ($p < 0.05$) on the influent TN concentrations, but the influent and effluent TN concentrations were strongly correlated. The observed TN reduction efficiencies were generally higher than either the 32.4% reported in Wang et al. (2016b) in a vermifilter system treating domestic wastewater, or the 18.13% reported in Singh et al. (2019a), during treatments of brewery wastewater. The reduction efficiency, however, was close to that observed in studies by Wang et al. (2014, 2013) that reported reduction efficiencies of 63%–65% during treatments of domestic wastewater. The variations in TN reduction efficiencies, in different studies are attributed to variations in pH, bedding materials, hydraulic loading rates, and retention times in the respective systems. The reduction in TN has been attributed to the joint effects of potential ammonification, nitrification, denitrification, filtration, adsorption, and ammonia volatilization in the vermifilter (Lai, 2017). During ammonification, organic nitrogen is hydrolyzed to total ammonia-nitrogen, which may either volatilize or nitrified to nitrates (Singh et al., 2017). Earthworms facilitate these processes via their burrowing activities, which enhance aeration in the vermifilter (Kumar et al., 2015). According to Singh et al. (2019b), several factors affect the performance of vermifilters, and these range from organic and hydraulic loadings, the earthworm density, and the influent characteristics. Under field conditions, maintaining all these factors constant or in control is a big operational challenge. The variability in the TN reduction efficiencies in this study could thus also be attributed to changes in these parameters during the study period.

The total ammonia-nitrogen (TAN) concentrations in the influents during the sampling period ranged from 213–464 mg $L^{-1}$, the mean reduction efficiency was 81 ± 7.1% (Fig. 4b), and reduction rates were from 0.9 to 2.3 kg [TAN] $d^{-1}$ during

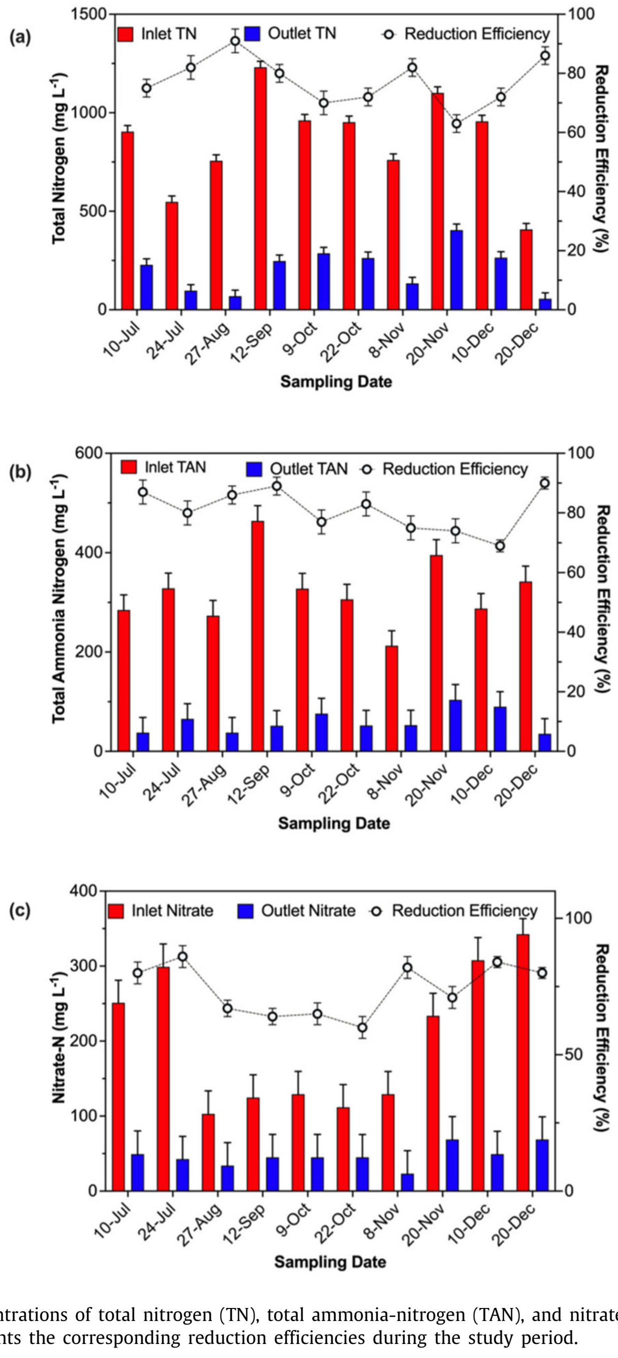



**Fig. 4.** Bar graphs present the concentrations of total nitrogen (TN), total ammonia-nitrogen (TAN), and nitrate-nitrogen (nitrate-N) in the influents and effluents, while line graph presents the corresponding reduction efficiencies during the study period.

the treatment through the vermifilter. Results indicate that ambient temperature conditions had no significant effect ($p < 0.05$) on TAN concentrations in the influent wastewater. The reduction efficiencies of TAN, in the vermifilter, were similar to the 98.4% reported in a similar system for dairy wastewater (Pasha et al., 2018). The reduction efficiencies were also consistent with the 70.5%–86% reported in Kumar et al. (2016) and Wang et al. (2014, 2013), during treatment of domestic wastewater using vermifilters. The reduction in TAN in a vermifilter is attributed partly to nitrification in the aerobic zones, denitrification occurring in the anoxic lower layers of the system, and also via volatilization as ammonia gas. The microbial nitrification process is oxidative and is thus boosted by earthworms via improved aeration. Samal et al. (2018b) reported sufficient oxygen transfer rates (OTR) in vermifilters, which enhanced nitrification. Singh et al. (2021a) further expounded on the nitrogen pathways in vermifiltration and reported on the occurrence of both nitrification and denitrification in a vermifilter system.

The nitrate-nitrogen ($NO_3$–N) concentrations in the influents during the sampling period ranged from 103–343 mg $L^{-1}$. The respective reduction efficiencies were 74 ± 9.5% (Fig. 4c), translating into reduction rates of 0.4–1.6 kg [$NO_3$–N] $d^{-1}$, during treatment through the vermifiltration system. Results also showed that ambient temperature conditions had no significant effect ($p < 0.05$) on $NO_3$–N concentrations in the influent wastewater. Most of the past studies have not reported on nitrate-nitrogen reduction efficiencies because $NO_3$–N concentrations are usually negligible in fresh dairy wastewater. Adugna et al. (2019), however, reported similar $NO_3$–N reduction efficiencies (62.2%), while treating greywater. The reduction in $NO_3$–N in vermifilters is attributed to the denitrification of the nitrates in the system, which invariably occurs in the anoxic pockets that exist in the vermifilter. The reduction rates of $NO_3$–N were low in the system, which was attributed to enhanced aeration and thus depressed denitrification rates in the vermifilter system. The utilization of upstream anoxic zones could further enhance the denitrification of the nitrates in dairy wastewater.

### *3.4. Total phosphorus and Ortho-P*

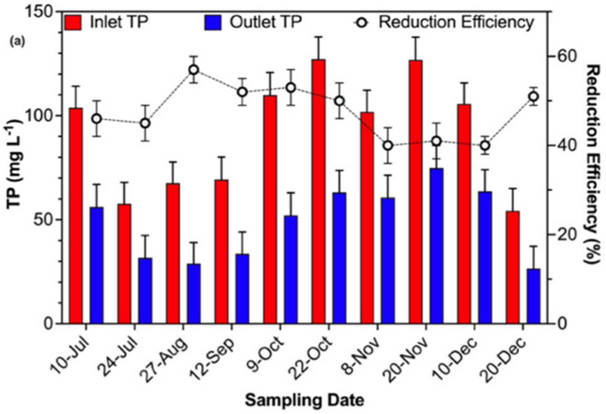
The influent total phosphorus (TP) concentrations during the sampling period ranged from 54–127 mg $L^{-1}$. The efficiency of TP reduction, in the vermifilter, averaged 48 ± 6.0% (Fig. 5a), while the reduction rates ranged from 0.1 to 0.4 kg [TP] $d^{-1}$. Results also showed that the prevailing temperatures had no significant effect ($p < 0.05$) on TP concentrations in the influent wastewater. The concentrations of TP in the influent and the effluent, however, were strongly and positively correlated. The observed TP reductions were similar to the 32.4–50.6% values reported in Singh et al. (2021b) and Wang et al. (2016b), during treatment of feedlot runoff and domestic wastewater, respectively. Wang et al. (2016a), also reported TP reductions of up to 38.6% during the treatment of municipal wastewater in a vermifiltration system.

The TP reduction efficiencies, however, were higher than the 9.0–13.7% reported in Pasha et al. (2018) during treatment of dairy wastewater in a vermifiltration system, or the 13.0–40.0% reported in Samal et al. (2017a) in a macrophyte-assisted vermifilter but were lower than reductions of 60.0–88.8% reported in Kaur and Cheema (2018), during treatment of dairy wastewater. The variability in the TP reduction efficiencies was attributed to the differences in wastewater streams, the season, and the operational set-up of the vermifilter. The effect of seasonal variability has been reported in a previous study and has been linked to seasonal variations in the metabolism of microorganisms in accumulating or utilizing phosphorus (Wang et al., 2010). According to Singh et al. (2019b), reduction of TP in the vermifiltration process is mainly due to adsorption on the filter-media surfaces and sequestration in Polyphosphate-accumulating organisms (PAOs). The significantly lower TP reduction rates as compared to other wastewater characteristics in the dairy wastewater could, however, be improved by incorporation of a more efficient phosphorus reduction or removal process, such as struvite precipitation.

Orthophosphate (Ortho-P) is fundamentally the reactive phosphorus species and hence a good indicator of potential phosphorus pollution. The Ortho-P concentrations in the influents during the sampling period ranged from 12.4–35.6 mg $L^{-1}$, while reductions of 3.9 ± 19.2% (Fig. 5b), and reduction rates of −26–61 g [Ortho-P] $d^{-1}$ were achieved in the vermifilter system. Ambient temperature conditions had no significant effect ($p < 0.05$) on the Ortho-P concentrations in the incoming wastewater. The Ortho-P concentrations of the effluent were strongly correlated to the concentrations of Ortho-P in the influent. The reduction rates of Ortho-P through the vermifilter, however, were significantly lower than those of total phosphorus. Some concentrations of Ortho-P in the influent on 27 Aug, (08 Nov and 10 Dec) were lower than corresponding concentrations at the outlet during the six-month sampling events. These increases in Ortho-P concentrations through the vermifilter were attributed to possible organic phosphorus mineralization occurring in the vermifilter system. Similar increases in Ortho-P during vermifiltration were reported by Kumar et al. (2014), who attributed the increase to the same phenomena, i.e., potential mineralization of organic-P due to enzymatic and microbial activities. Singh et al. (2021b), however, reported Ortho-P reduction efficiencies of 53.9 ± 1.7% while treating feedlot runoff and attributed the reduction to the burrowing activities of earthworms, which created more adsorption sites in the vermifilter. Low Ortho-P reduction efficiencies, in the current study, suggest that there may be a need for integration with a more efficient Phosphorus reduction technology like struvite precipitation.

### *3.5. Effects of ambient temperature and influent characteristics*

Regression analyses between the prevailing ambient temperature and the respective reduction efficiencies of solids, organics, and nutrients showed significant and positive correlations between ambient temperature and: TS ($r = 0.4$), TN ($r = 0.5$), TAN ($r = 0.7$) and TP ($r = 0.5$) (see supplementary files #5). Results further revealed ambient temperatures accounted for 14, 23, 50, and 23% of the variations in the reductions of TS, TN, TAN, and TP, respectively, during the treatment of dairy wastewater in the vermifilter system. Earlier studies by Singh et al. (2021a) had reported on the positive effects of the ambient temperature on oxygen diffusion rates, which in turn would positively influence the bioprocesses occurring in the vermifilter system, such as nitrification and denitrification. The strong positive linear relationships were thus attributed to increased microbial activity at higher temperatures than at lower temperatures, within the temperature range (50–83 °F) experienced in this study. According to Singh et al. (2017), higher temperatures also tend to boost the metabolic activity of earthworms. Enhanced microbial and earthworms' activities would naturally improve reductions of nitrogen and solids in the wastewater stream. The results, in the current study, were similar to the findings from previous



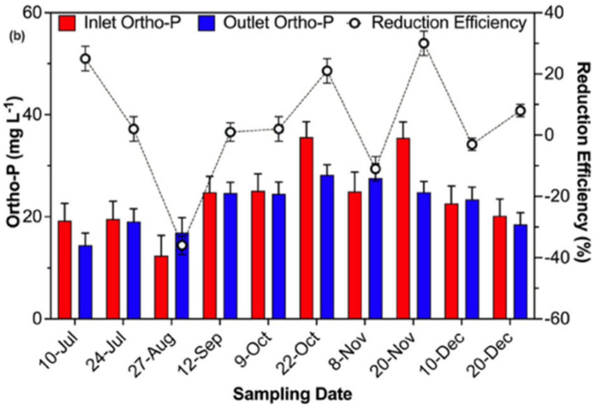




**Fig. 5.** Bar graphs present influent and effluent concentrations of total phosphorus and orthophosphates, while the line graph shows the corresponding reduction efficiencies, during the study-period.

studies by Arora and Kazmi (2015) and Krzeminski et al. (2012), which attributed this phenomenon to increased biological activity and increased oxygen diffusivity at higher temperatures.

Significant ($p < 0.05$) positive correlations were also observed between the influent concentrations of COD, nitrate-nitrogen, and Ortho-P and the respective reduction efficiencies. The correlation coefficient of the COD reduction efficiency as a function of influent COD concentration was 0.8, nitrate-nitrogen reduction efficiency against influent concentration was 0.8, and Ortho-P reduction efficiency versus influent Ortho-P concentration was 0.7 (see supplementary files #5). Results further indicated that the variations in the influent COD, nitrate-nitrogen, and Ortho-P concentrations, explained 59, 57, and 46% of the respective reduction efficiencies, during the treatment in the vermifilter (see supplementary files #6). The results suggest that higher values of influent COD, nitrate-nitrogen and ortho-phosphates of the dairy wastewater between 2.1–3.4 g $L^{-1}$, 103–343 mg $L^{-}$ and 12.4–35.6 mg $L^{-1}$ respectively, result in higher removal efficiencies in the vermifilter. The effect of influent characteristics on reduction efficiencies, beyond the ranges examined in this study, requires further investigation.

## 4. Conclusions and future prospects

The overall goal of this study was to assess the potential of treating dairy wastewater using a vermifiltration system with the ultimate goal of nutrient recovery, wastewater recycle and reuse. A comparison of influent and effluent solids, organics, and nutrients characteristics of the dairy stream showed that a vermifilter system can treat dairy wastewater from a manure-flush system. High reduction rates of organics (COD), solids (TS and TSS), and nitrogen forms (TN, TAN, and nitrate N) were observed. The reduction rates of TP and ortho-P, however, were relatively low. Based on the solids, organics, and nutrients reduction rates in the current study, vermifiltration is a technically viable low-cost alternative for on-site treatment of dairy wastewater to enable effluent reuse via irrigation in nearby crop lands and for recycle to flush out fresh manure. There may be need for integration with a more efficient phosphorus removal technology i.e., struvite precipitation. Ambient temperature and the influent concentrations of the wastewater had a significant effect on the reduction efficiencies. The higher the temperature or the higher the influent concentration, the higher the respective removal efficiencies. There is need to put into consideration the ambient temperature and influent characteristics during design of vermifilter systems. Further studies are required to determine the effect of the earthworm density on the treatment efficiencies in vermifiltration units. There is also a need to optimize the vermifilter performance parameters i.e., hydraulic retention time, hydraulic loading rate and loading rates as they greatly influence the treatment efficiency of the vermifiltration system.

## CRediT authorship contribution statement

**Gilbert J. Miito:** Investigation, Writing - original draft, Validation, Software. **Pius Ndegwa:** Conceptualization, Methodology, Supervision, Writing - review & editing. **Femi Peter Alege:** Investigation, Writing - review & editing. **Sifolo Seydou Coulibaly:** Investigation, Writing - review & editing. **Russ Davis:** Resources, Writing - review & editing. **Joe Harrison:** Methodology, Writing - review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eti.2021.101648.

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