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Research article

Nutrient recovery from pineapple waste through controlled batch and continuous vermicomposting systems

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ABSTRACT

The largest portion of pineapple peels and pulp generated from production points is disposed of haphazardly contributing to a number of environmental and health challenges. However, these wastes contain valuable plant nutrients that could be recovered to boost soil fertility, and increase agricultural production. This study evaluated the variation in physico-chemical parameters in batch and continuous vermicomposting systems as potential pathways for nutrient recovery from pineapple waste. The study compared the efficiency of waste reduction and nutrient recovery for batch (B), and continuous (C) vermicomposting systems during a 60-day period. The substrates were pineapple peels (PW), and cattle manure (CM) fed in a ratio of 4:1 (w/w). Control reactors were fed with 100% CM in both the feeding modes. Results indicated that waste degradation was 60%, and 54% while earthworm biomass increased by 57% and 129% for BPW, and CPW, respectively. pH significantly decreased with time in both systems. Total phosphorous increased with vermicomposting time with that of B being significantly higher than C systems. Nitrogen, potassium, and sodium significantly increased in the control experiments while the three elements significantly reduced for BPW, and CPW owing to high leachate production in the latter. The N, P, K, and C retention in vermicompost was 24.2%, 90.4%, 67.5%, 41.1%, and 32.6%, 91.2%, 79.3%, 46.1%, for BPW and CPW, respectively. Continuous systems produced higher earthworm biomass and retained more nutrients in vermicompost than batch systems, and can therefore, be recommended as better systems for pineapple waste vermicomposting.

Credit author contribution statement

Ahamada Zziwa: Principal investigator of the project, fund administrator, experimental design, final manuscript-review & editing. Joseph Jjagwe: Experimental design, data collection and analysis, Writing – original draft of the manuscript. Simon Kizito: Experimental design, Formal analysis, manuscript review & editing. Isa Kabenge: Experimental set up: Formal analysis, manuscript draft writing, review & editing. Allan John Komakech: Experimental design, manuscript preparation and reviews. Henry Kayondo: Data collection, routine monitoring and participation in manuscript preparation.

1. Introduction

Pineapple (*Ananas comosus*) is a tropical fruit that can be grown throughout the year in Uganda. The current annual production of pineapple fruits in the country stands at 3,642 tons, increasing at about 6% per annum (FAO, 2020). The pineapple value chain is equally expanding with more small –to- medium scale fruit processors joining the industry (Nyamwaro et al., 2018). With more production, marketing, and processing, a lot of waste in form of leaves, residual pulp, stems, and peels is generated (Sukruansuwan and Napathorn, 2018). In addition, due to perishability of the fruit, significant postharvest losses (up to 55% of the total harvested) are incurred during long distance transportation from rural farms to urban markets (Upadhyay et al., 2010). The utilization of pineapple wastes similar to other crop residue waste is low in Uganda with about 20% used as animal feed (Kiggundu et al., 2014; Nalubwama et al., 2014). The remainder is openly disposed of or dumped together with municipal solid waste into landfills.

From a circular economy perspective, a lot of nutrients contained in the pineapple waste are lost when the residues are just dumped off into the open environment albeit with negative environment health issues.

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There is also nutrient exportation out of the fruit production area when whole pineapples are harvested and processed away from the farm, and yet commercial pineapple growing is a fertilizer intensive venture. As a matter of fact, recent studies (Nyamwaro et al., 2018; Zziwa et al., 2017) have highlighted low soil fertility as one of the major drawbacks to extensive cultivation of pineapples in the different parts of Uganda. Therefore, finding ways of recovering and recycling the nutrients lost in the harvested fruit will contribute to the minimization of soil fertility losses in the pineapple production areas.

Vermicomposting technology is a well-established method for nutrient recovery from organic wastes (Soobhany, 2019; Huang and Xia, 2018). Vermicomposting has been reported as an affordable technique of processing large quantities of agricultural wastes (Aira and Domínguez, 2008) with the ability to concentrate their nutrients thus producing an organic fertilizer that is superior to traditional compost (Soobhany, 2019). Vermicomposting can be carried out in two modes i.e. in the batch and continuous modes. In the batch mode, all the inputs (earthworms and substrates) are fed once at the start without any additions throughout the vermicomposting period. On the other hand, continuous modes (systems) involve the addition of substrates periodically into vermi-reactors depending on the consumption rate of the earthworms. It is worth mentioning that vermicomposting of wastes in continuous (Tedesco et al., 2019; Částková and Hanč, 2019) and batch (Sharma and Garg, 2019; Fu et al., 2015) systems have been studied in isolation. To the best of our knowledge, only a single study (Hénault-Ethier et al., 2016) has done a comparative assessment of batch and continuous vermicomposting in a single experimental setup. That study mainly evaluated the persistence of *Escherichia coli* in the two systems using fruit and vegetable wastes as substrates. However, the variation of physico-chemical parameters with vermicomposting time for the two systems is not clearly known. Therefore, this study sought to assess the vermicomposting of pineapple waste in both continuous, and batch modes of feeding focusing mainly on the variation of physico-chemical parameters and their retention in the two systems.

2. Materials and methods

2.1. Waste collection and preparation

Pineapple peels used in this study were obtained from fruit processing centers around Kampala city and were mainly of the Smooth Cayenne variety. A mechanical shredder was used to cut the peels into small pieces (15 mm) suitable for biodegradation using vermicomposting technology (Fu et al., 2015). The bedding material was cattle manure and was obtained from a dairy farm at Makerere University Agricultural Research Institute Kabanyolo (MUARIK), located in Gayaza-Kabanyolo (0. 2806″ N, 32. 3624" E).

2.2. Experimental setup

2.2.1. Pre-composting

Prior to feeding into the vermicomposting reactors, both fresh pineapple peels (120 kg) and cattle manure (80 kg) were pre-composted for 3 weeks, and 1 week, respectively. The two pre-composting periods were based on previous studies for pineapple peels (Castillo-González et al., 2019; Mongjam et al., 2018), and cattle manure (Rini et al., 2020). The pre-composting phase aimed at breaking down highly volatile substances, reduce on the volatile acids, and to release the heat that could harm the earthworms (Karwal and Kaushik, 2020; Mainoo et al., 2009). The wastes were pre-composted by heaping and wrapping in a permeable tarpaulin (MOQ, Tents Africa Ltd, Kampala, Uganda) with daily turning throughout the composting period as recommended by Sommer (2001). The pre-composted pineapple peels and cattle manure were then stored in a refrigerator (Thermo Scientific, TSX 400, Italy) at 4 °C until when required for use in the actual vermicomposting experiments.

2.2.2. Vermicomposting

The vermicomposting reactors were made from plastic buckets (50 L, diameter of 0.52 m, a height of 0.63 m) with and a top lid. Holes (16 of 5 mm diameter each) were drilled through the top lid and the bottom of the buckets. Similar holes were drilled in the sides of the bins along the circumference in three equidistant layers to serve as oxygen inlets within the reactors. To avoid escape of earthworms and entry of predators, all holes were sealed off with a nylon mesh of 0.5 mm square perforations.

The reactors were divided into two sets; one set operated in batch mode, and the other in continuous mode with respective controls. The initial worms (*Eudrilus eugeniae* spp.) and biomass feeding (cattle manure and pineapple waste) rates were calculated based on a study by Ndegwa et al. (2000), who reported optimal stocking density of earthworms as 1.60 kg worms/m^2 and feeding rate as 1.25 kg feed/kg worms/day. During the start of the batch operation, each reactor received a total of 26.25 kg pineapple waste (PW), and cattle manure (CM) in a ratio of 4:1 w/w in addition to 0.35 kg of earthworms. On the other hand, control batch reactors received 100% CM (26.25 kg) with the same earthworm biomass.

In continuous mode, each reactor separately received 0.35 kg of earthworms, and a mix of PW and CM (4.38 kg) in the ratio of 4:1 (w/w) at day-1 (process start) and the same amount of feedstock (4.38 kg and no additional worms) every 10 days till the end of the experiment. The control reactors each received 4.38 kg of CM every 10 days with no additional worms till the end of the experiment i.e. 60 days. All reactors in both systems including their respective controls were set up in triplicates and kept under shade from rain and direct sunshine.

The leachate produced was collected daily into plastic containers, which were put underneath the vermicomposting reactors. The leached volumes were measured in a graduated measuring cylinder (1 L). To ascertain the moisture content of compost within reactors, a sponge test, which involved squeezing a handful of the compost into the hands, was used. When required, the moisture content within the vermicomposting reactors was maintained between 60 and 70% by sprinkling clean water regularly. After the 60 days, all the reactors were closed down and vermicompost was harvested. All tangible inputs and outputs were measured by weighing directly using a portable electronic weighing scale (model A08 50 kg/10g, Singapore) for solids or in a graduated measuring cylinder (1L) for liquids. Earthworms were separated from vermicompost by handpicking and then thoroughly washing with clean water before weighing them.

2.3. Sampling and physicochemical analysis

The physico-chemical properties of substrates were determined before pre-composting, after pre-composting, and thereafter at an interval of 10 days during vermicomposting until the end of the experiment at day 60. On every sampling event, three samples (20 g) were randomly taken from each replicated reactor set for all treatments and then separately mixed to form a composite sample. Throughout the experimental period, the daily volume of leachate produced was measured and a 5 mL sample from each treatment was stored in a refrigerator at 4 °C for future analysis. All the stored daily samples were mixed on the 10th day to form a composite sample of each treatment for analysis. For the solid samples, the following parameters were analyzed; pH, total solids (TS), ash content, volatile solids (VS), total organic carbon (TOC), total Kjeldahl nitrogen (TKN), total phosphorous (TP), total potassium (TK), and Sodium (Na). For the leachates the following parameters were determined; pH, TKN, TOC, Na, TK and TP.

The pH was determined by mixing the sample with in distilled water (1:10 w/v) and the solution was stirred for 2 min, and the mixture was left to stand for 1 h. Then after, pH was read off directly from a digital pH meter (model HI 96107, Italy) by inserting the probe into the solution. The TS were determined as the measured weight after oven drying of a 10 g sample at 105 °C for 16 h (Sluiter et al., 2008a). Ash content was determined as the measured weight after heating 5 g of the oven dried sample in a carbolite muffle furnace (serial number 20–503092, UK) at 550 °C for 6 h (Sluiter et al., 2008b). The VS was calculated as the lost weight after determining the ash content (Sluiter et al., 2008b). TKN was determined following procedures as specified by Okalebo et al. (2002). TOC was calculated from VS by multiplying with a factor of 1.8 (Devi and Khwairakpam, 2020a). TK and Na were determined using a flame photometer (model PFP7, UK) following procedures by Bhat et al. (2017) while TP was determined by Atomic Absorption Spectrophotometer (model 4110 ZL, USA) using procedures by Okalebo et al. (2002).

2.4. Material Flow Analysis

In this study, Material Flow Analysis (MFA) was undertaken to determine the extent of material retention and loss within a vermicomposting waste bioconversion process for the batch and continuously fed systems. Parameter values determined from chemical analyses, and weight measurements were fed into STAN (subSTance flow Analysis, 2.6) to perform the MFA (Guo et al., 2019) of the vermicomposting systems. STAN software was preferred because of its ability to combine all necessary features of MFA in one software product (Cencic and Rechberger, 2008). The model inputs were the weights of the added wastes (pineapple peels, and cattle manure), initial earthworm biomass, and volume of water. The outputs were the weights of vermicompost, harvested earthworm biomass, and volume of leachate collected. Within STAN, substance flows were determined by multiplying measured substance concentrations by the main material flows. Ash content, TP, Na and TK were taken as representatives of non-volatile substances (Jensen et al., 2017) hence their loss into the atmosphere was assumed to be zero. TS, VS, TOC, and TKN were considered as volatile substances and their loss to the atmosphere was determined by STAN software. The standard errors of all the measured parameters were used as uncertainties in the software. The carbon content and nutrient concentrations in water were assumed to be zero in all cases while those of earthworms were based on literature (Lalander et al., 2015; Bernard et al., 1997; Jimenez and Garcia, 1992). A temporal boundary of 60 days was considered corresponding to a vermicomposting experimental period. The spatial boundary was limited to vermicomposting reactor where the decomposition of wastes took place. All mass/substance flows within the study were based on wet weight basis.

2.5. Statistical analysis

The data collected was first checked for normality and homogeneity using the Shapiro-Wilk, and Bartlett's tests, respectively. The produced residual plots were normally distributed about the mean with variances being homogeneous, which meets the assumptions of analysis of variance (ANOVA). The variation of physico-chemical properties of the vermicompost with system type and vermicomposting time was analyzed using a two-way ANOVA. Statistical tests were considered significant at $p < 0.05$. For the significant variations, Posthoc analysis using a Tukey test based on the mean differences was performed. All the analyses were done using GenStat software (GenStat for windows, version 14, VSN Inc. Hemel-Hempstead, UK).

3. Results and discussion

3.1. Feed material characteristics, and mass flows

The physico-chemical characteristics of pineapple peels, and cattle manure before and after pre-composting are shown in Table 1. Pre-composting increased the pH of pineapple peels from 4.47 to 6.86 which lies within the range of 6.07–8.02 optimal for earthworm growth (Tedesco et al., 2019). The pH of cattle manure also increased from 7.53 to 7.9 after pre-composting. Conversely, pre-composting also increased the C/N ratio of the pineapple waste due to the slight loss of TKN. Hanc and Chadimova (2014) also reported an increase in the pH of apple pomace from 4.0 to 6.7 after two weeks of pre-composting, which they attributed to degradation and consumption of organic acids by microorganisms. The same reason could explain the increased pH observed in this study. Physico-chemical parameters are key in assessing the nutrient quality of the final product and the suitability of a substrate for vermiconversion (Karmegam et al., 2019). As shown in Table 1, the physico-chemical parameters of the pre-composted substrates for this study were within ranges suitable for vermicomposting.

Table 1
Physico-chemical parameters of pineapple peels and cattle manure before, and after pre-composting.

Parameter	Pineapple Peels		Cattle manure	
	Initial	Pre-composted	Initial	Pre-composted
pH	4.47 ± 0.08	6.86 ± 0.14	7.53 ± 0.10	7.90 ± 0.19
TS	6.80 ± 0.40	12.43 ± 0.32	23.43 ± 0.20	22.92 ± 0.46
VS (% TS)	90.84 ± 0.54	85.23 ± 0.99	81.42 ± 0.62	80.56 ± 0.59
TKN (% TS)	0.95 ± 0.03	0.78 ± 0.03	1.06 ± 0.08	1.15 ± 0.02
TP (% TS)	0.43 ± 0.03	0.34 ± 0.02	0.60 ± 0.03	0.63 ± 0.03
TK (% TS)	1.80 ± 0.06	1.59 ± 0.06	1.19 ± 0.02	1.23 ± 0.02
TOC (% TS)	41.43 ± 0.64	36.03 ± 0.55	31.57 ± 0.63	30.87 ± 0.70
Na (% TS)	1.53 ± 0.05	1.11 ± 0.03	5.93 ± 0.10	6.11 ± 0.03
C/N ratio	43.46 ± 0.47	48.10 ± 2.23	29.79 ± 2.11	26.92 ± 0.35

TS- total solids, VS – volatile solids, TKN- total Kjeldahl nitrogen, TP- total phosphorous, TK- total potassium, TOC- total organic carbon, C/N- carbon to nitrogen ratio.

The amount of waste (PW, and CM), earthworms, water, leachate and vermicompost added and harvested from the vermicomposting systems for different treatments are shown in Table 2.

The variations in water added into the reactors, and the drained leachate from reactors with time are shown in Fig. S1 of the supplementary material. There was a significant difference ($p < 0.05$) in the amount of vermicompost, and earthworms harvested among the four treatments. In all the treatments, the final earthworm biomass (FEB) was greater than the initial earthworm biomass (IEB). The increase was in the order CCM > BCM > CPW > BPW with percentage increases of 314%, 260%, 129%, and 57%, respectively. Mongjam et al. (2018) reported an 850% increase in *Eudrilus eugenia* biomass when pineapple peels were vermi-composted with cattle slurry (3:1 w/w) in a batch process for 60 days. On the hand, Balachandar et al. (2020) reported an increase of 432% in *Eudrilus eugenia* biomass using only cattle manure in a batch system for 50 days while Jjagwe et al. (2019) reported an increase of 518% for the same earthworm species and substrate operated in a continuous mode for 90 days. The rate of earthworm biomass increase during vermicomposting could be affected by biochemical quality of feeds (Vodounnou et al., 2016) which is influenced by their source and type (Suthar and Ram, 2008), earthworm stocking density (Suthar, 2012), and earthworm species (Suthar and Ram, 2008). These factors could thus explain the variations in earthworm biomass increase for this study, and other previous studies.

The smaller increase in earthworm biomass in batch systems as compared to continuous systems for this study could be due to exhaustion of the readily available nutrients in the substrate as reported by Atiyeh et al. (2000) and Gong et al. (2019). It was observed in this study that earthworms were mainly located in the upper layers (new layers of about 10 cm thick) of the substrate for continuous systems with a high density of hatchlings. This is in agreement with Aira and Domínguez (2008), and Částková and Hanč (2019) who reported a high density of earthworms in the younger layers during vermicomposting of pig slurry and grape marc, respectively, with no earthworms found at the bottom (oldest layers). This was attributed to the movement of earthworms towards fresh and nutritious substrates.

On the other hand, batch vermicomposting systems could have forced the earthworms to move into deeper layers in search of food in an environment that is not ideal for their growth and multiplication (Shak

Table 2
Amounts of substrate and earthworm biomass added, and amounts of vermicompost and earthworm biomass harvested for the different vermicomposting systems.

Treatment	Feedstock composition (w/w)	Total substrate (kg)	Feeding mode	IEB (kg)	Vermicompost harvested (kg)	FEB (kg)	Water added (L)	Leachate collected (L)
BPW	PW:CM (4:1)	26.25	Batch	0.35	10.53 ± 1.01a	0.55 ± 0.03a	1.07	6.80
BCM	PW:CM (0:1)	26.25	Batch	0.35	13.46 ± 0.86c	1.26 ± 0.05c	1.35	0.42
CPW	PW:CM (4:1)	26.25	Continuous	0.35	12.07 ± 1.03b	0.80 ± 0.01b	1.10	4.58
CCM	PW:CM (0:1)	26.25	Continuous	0.35	15.42 ± 0.56d	1.45 ± 0.07d	1.47	0

IEB- initial earthworm biomass, FEB- final earthworm biomass, values with different letters within a column are significantly different ($P < 0.05$, LSD, mean ± SD, n = 3).

et al., 2014). For the case of CPW and BPW, the smaller quantity of earthworm biomass obtained as compared to BCM, and CCM could be attributed to high moisture content of pineapple peels that could have caused anoxic conditions (Hanc et al., 2017) within reactors hence leading to death of some earthworms. In fact, high quantities of leachate were produced in the first 20 days of the experiment for BPW (Fig. S1), which indicated high moisture content within the reactor. This could thus, explain why BPW had the smallest final earthworm biomass.

Waste degradation within the reactors decreased in the order; BPW > CPW > BCM > CCM with mass reduction of 60%, 54%, 49%, and 41%, respectively. The largest cumulative amount of leachate (6.8 L) was obtained from BPW while no leachate was produced from CCM throughout the experimental period. These findings are similar to results by Mongjam et al. (2018) who reported a 56% mass reduction in pineapple peels and cattle slurry (3:1 w/w) vermi-composted in a batch system for 60 days using *Eudrilus euginea*. The absence of leachate from continuous cattle manure systems could be attributed to adding of small layers of cattle manure (which has relatively high total solids) during vermicomposting hence reducing compaction that would enhance leachate production. The high mass reduction and voluminous leachate production from BPW and CPW could be attributed to the low total solids (12.43%), and high volatile matter (85.23%) contents of pineapple peels that could have elevated the degradation process.

3.2. Changes in physio-chemical parameters

3.2.1. pH, total solids, and volatile solids

For all the reactors, pH significantly decreased ($p < 0.05$) with vermicomposting time with an overall percentage decrease of 15.1%, 12.4%, 12.1% and 11.8% for CCM, BCM, CPW, and BPW, respectively. The decrease of pH with time was not significant ($p > 0.05$) between B, and C systems. A decrease in pH during vermicomposting of different substrates has been reported by Balachandar et al. (2020) and Srivastava et al. (2020), and has been attributed to the mineralization of nitrogen and phosphorus into nitrites/nitrates and orthophosphates, as well as to the bioconversion of the organic material into intermediate species of organic acids (Suthar, 2010).

The total solids (TS) content significantly increased ($p < 0.05$) with vermicomposting time for all the reactors (Table 3). The overall increase of 94.9% for BPW was significantly higher ($p < 0.05$) compared to the increase in CPW at 88.6%. TS increased by 42.8% and 40.1% for BCM and CCM respectively. An increasing TS content indicates the progress in composting (Tatàno et al., 2015), which may be attributed to a high consumption rate of the substrate by earthworms, thereby making it friable (Sonowal et al., 2014). Higher TS in B systems could be attributed to uniform degradation of the substrates since these were added once at the start of the experiment. Besides, higher moisture in form of leachate was lost from the B compared to C systems (Table 2). Our results are corroborated by the studies by Lalander et al. (2015) who reported a 50% increase in TS during vermicomposting of cattle manure with food waste using *Eudrilus eugeniae*.

The volatile solids (VS) content of all treatments significantly decreased ($p < 0.05$) with vermicomposting time with an overall reduction of 21.4%, 20.0%, 20.0%, and 19.4% for BCM, CCM, BPW, and CPW, respectively. The decrease between systems was not significant ($p > 0.05$). Our results corroborate recent studies by Che et al. (2020) and Arumugam et al. (2018) who reported a decrease in VS of 27.3%, and 52.99% during vermicomposting of cattle manure, and cow dung with paper cup waste, respectively. The observed VS reduction corresponds to good decomposition efficiency of the organic wastes (Li et al., 2020; Khan et al., 2019) due to the combined effect of microorganisms and earthworms (Che et al., 2020) in the tested reactors.

3.2.2. Total nitrogen, phosphorous, potassium, and sodium

For BPW and CPW, TKN significantly decreased ($p < 0.05$) with vermicomposting time and between systems ($p < 0.05$) with overall percentage decrease of 51.3%, and 43.6%, respectively. On the other hand, TKN for BCM and CCM significantly increased ($p < 0.05$) with vermicomposting time with an overall increase of 111.3%, and 104%, respectively. Similar results were reported by Mainoo et al. (2009) during vermicomposting of pineapple waste with *Eudrilus eugeniae*. Mainoo et al.(2009) attributed this loss to the solubility of NH_4^+-N and loss of NH_3 through volatilization as well as the leaching of NO_3–N. Fu et al. (2015) attributed the decrease of total nitrogen during vermicomposting of dewatered sludge to its consumption by earthworms during their growth and reproducing of the next generation. It is worth noting that the net earthworm biomass gain in this study was observed to be minimal in BPW and CPW (Table 2) which could have slowed worm activity leading to lower TKN in the vermicompost (Devi and Khwairakpam, 2020a). These two factors could thus explain why BPW with more leachate produced, and less earthworm biomass harvested (Table 2) portrayed a more decrease in TKN than CPW.

Total phosphorous (TP) significantly increased ($p < 0.05$) with vermicomposting time and between systems ($p < 0.05$) (Table 3) with overall percentage increase of 132.4%, 131.8%, 120.6% and 106.4% for BPW, BCM, CPW, and CCM, respectively. Close range results were reported by Rini et al. (2020) and Balachandar et al. (2020) who reported TP increases of 128.2%, and 98.7% during vermicomposting of cow dung, and green manure with cow dung, respectively. The increase in TP may be attributed to the presence of earthworm gut phosphatase, and phosphorous solubilizing microorganisms in the worm casts that enhance the release of phosphorus in various forms (Deka et al., 2011). This argument is corroborated by Ghosh et al. (2018) who reported the presence of phytase enzymes in vermicompost that enhances mineralization of phosphorus as time progresses. In addition, mineralization and mobilization of organic matter by the combined effect of microorganisms and fecal excretion of phosphate by earthworms could have increased the TP content in the final vermicompost (Yadav and Garg, 2019). The reduction of pH could also have enhanced the solubilisation of phosphorous and release of organically bound phosphate and thus increasing its concentration in the final product (Devi and Khwairakpam, 2020a). A higher TP content in B as compared to C systems could

Table 3
Physico-chemical parameters of BPW BCM, CPW, and CCM samples at different stages of vermicomposting (mean ± SD, n = 3).

Parameter	BPW					
	Vermicomposting days					
	10	20	30	40	50	60
pH	6.81 ± 0.02e	6.69 ± 0.01d	6.62 ± 0.04d	6.49 ± 0.01c	6.31 ± 0.02b	6.05 ± 0.03a
TS	14.36 ± 0.25a	16.03 ± 0.12b	19.31 ± 0.06c	21.25 ± 0.57d	22.49 ± 0.07e	24.23 ± 0.03f
VS (%DM)	82.11 ± 0.37f	79.24 ± 0.09e	75.57 ± 0.21d	72.44 ± 0.03c	70.18 ± 0.13b	68.26 ± 0.16a
TKN (% DM)	0.73 ± 0.02f	0.68 ± 0.01e	0.55 ± 0.02d	0.48 ± 0.01c	0.43 ± 0.02b	0.38 ± 0.01a
TP (%DM)	0.36 ± 0.01a	0.40 ± 0.02b	0.49 ± 0.01c	0.59 ± 0.01d	0.66 ± 0.02e	0.79 ± 0.01f
TK (%DM)	1.48 ± 0.02f	1.41 ± 0.01e	1.33 ± 0.02d	1.12 ± 0.02c	0.99 ± 0.01b	0.79 ± 0.01a
TOC (% DM)	32.15 ± 1.23e	30.01 ± 0.83de	28.17 ± 0.91cd	26.75 ± 0.91c	23.62 ± 1.05b	21.41 ± 0.78a
Na (%DM)	0.88 ± 0.01d	0.83 ± 0.02cd	0.78 ± 0.01c	0.69 ± 0.01b	0.57 ± 0.03a	0.54 ± 0.01a
C/N ratio	44.25 ± 0.12a	43.93 ± 0.03a	51.56 ± 0.01b	55.75 ± 0.13b	54.94 ± 0.15b	55.86 ± 0.17b
	CPW					
pH	6.75 ± 0.02e	6.64 ± 0.01d	6.44 ± 0.01d	6.34 ± 0.02c	6.28 ± 0.05b	6.03 ± 0.02a
TS	15.11 ± 0.17a	17.16 ± 0.21b	18.95 ± 0.04c	20.47 ± 0.09d	21.47 ± 0.03e	23.44 ± 0.25f
VS	81.15 ± 0.13f	78.46 ± 0.35e	76.21 ± 0.07d	73.44 ± 0.22c	70.29 ± 0.42b	68.72 ± 0.21a
TKN	0.75 ± 0.01d	0.72 ± 0.02d	0.65 ± 0.02c	0.52 ± 0.01b	0.47 ± 0.02a	0.44 ± 0.01a
TP	0.38 ± 0.01a	0.46 ± 0.01b	0.53 ± 0.02c	0.60 ± 0.02d	0.69 ± 0.01e	0.75 ± 0.02f
TK	1.51 ± 0.01f	1.46 ± 0.02e	1.39 ± 0.03d	1.19 ± 0.01c	1.04 ± 0.02b	0.86 ± 0.02a
TOC	31.45 ± 0.57d	29.36 ± 0.68c	27.27 ± 0.06b	26.01 ± 0.31b	25.59 ± 0.33b	21.60 ± 1.04a
Na	0.91 ± 0.03e	0.82 ± 0.01d	0.74 ± 0.01c	0.66 ± 0.01b	0.61 ± 0.02 ab	0.58 ± 0.01a
C/N ratio	41.94 ± 0.14a	41.00 ± 0.07a	41.75 ± 1.36 a	49.71 ± 0.18b	54.87 ± 0.22b	49.13 ± 0.37b
	BCM					
pH	7.78 ± 0.03e	7.69 ± 0.01e	7.36 ± 0.04d	7.24 ± 0.03c	7.04 ± 0.02b	6.92 ± 0.04 a
TS	24.28 ± 0.09a	25.46 ± 0.12b	27.43 ± 0.22c	29.41 ± 0.13d	31.24 ± 0.05e	32.76 ± 0.26f
VS	77.33 ± 0.12f	73.46 ± 0.29e	70.12 ± 0.11d	67.43 ± 0.02c	65.45 ± 0.07b	63.33 ± 0.05a
TKN	1.43 ± 0.01a	1.75 ± 0.03b	1.94 ± 0.02c	2.17 ± 0.01d	2.32 ± 0.03e	2.43 ± 0.03f
TP	0.68 ± 0.01a	0.73 ± 0.02b	0.83 ± 0.01c	1.15 ± 0.02d	1.41 ± 0.03e	1.46 ± 0.01f
TK	1.37 ± 0.02a	1.41 ± 0.03a	1.53 ± 0.02b	1.77 ± 0.04c	2.06 ± 0.04d	2.23 ± 0.02e
TOC	28.92 ± 1.02f	26.24 ± 0.34e	24.15 ± 0.44d	23.12 ± 0.22c	21.03 ± 0.48b	19.48 ± 0.19a
Na	6.36 ± 0.02a	6.87 ± 0.12b	7.24 ± 0.31c	7.52 ± 0.03d	7.95 ± 0.04e	8.19 ± 0.03f
C/N ratio	20.18 ± 0.19f	14.97 ± 0.08e	12.47 ± 0.21d	10.64 ± 0.18c	9.04 ± 0.11b	8.03 ± 1.12a
	CCM					
pH	7.83 ± 0.03a	7.51 ± 0.19 ab	7.27 ± 0.14bc	7.13 ± 0.03cd	6.89 ± 0.07de	6.71 ± 0.01e
TS	25.18 ± 0.04a	26.45 ± 0.03b	28.14 ± 0.13c	29.75 ± 0.22d	31.26 ± 0.13e	32.54 ± 0.04f
VS	76.44 ± 0.09f	72.33 ± 0.18e	70.35 ± 0.10d	68.38 ± 0.05c	66.69 ± 0.07b	64.44 ± 0.13a
TKN	1.54 ± 0.02a	1.62 ± 0.04a	1.85 ± 0.03b	2.03 ± 0.02c	2.21 ± 0.02d	2.35 ± 0.03e
TP	0.67 ± 0.01a	0.71 ± 0.02b	0.78 ± 0.01c	0.99 ± 0.02d	1.25 ± 0.01e	1.30 ± 0.02f

Table 3 (*continued*)

Parameter	BPW					
	Vermicomposting days					
	10	20	30	40	50	60
TK	1.33 ± 0.01a	1.43 ± 0.03b	1.57 ± 0.01c	1.80 ± 0.02d	1.99 ± 0.01e	2.14 ± 0.02f
TOC	27.98 ± 0.06f	25.48 ± 0.42e	23.25 ± 0.01d	21.20 ± 0.11c	19.45 ± 0.03b	18.77 ± 0.46a
Na	6.32 ± 0.02a	6.84 ± 0.04b	7.07 ± 0.06c	7.36 ± 0.09d	7.72 ± 0.02ef	7.81 ± 0.05
C/N ratio	18.17 ± 0.21f	15.77 ± 0.71e	12.55 ± 0.16d	10.43 ± 0.11c	8.80 ± 0.09b	8.00 ± 0.04a

Means with different letters across a row are significantly different (*$P < 0.05$, LSD*), BPW- batch pineapple peels vermicomposting system, CPW- continuous pineapple peels vermicomposting system, BCM – batch cattle manure vermicomposting system, CCM – continuous cattle manure vermicomposting system.

be attributed to a lower vermicompost yield (Table 2) that could have concentrated this nutrient.

Total potassium (TK) for BPW and CPW significantly decreased (*$p < 0.05$*) with vermicomposting time and between the two systems (*$p < 0.05$*) with overall decrease of 47.3%, and 42.7% respectively. To the contrary, TK contents for BCM and CCM significantly increased (*$p < 0.05$*) with vermicomposting time and between systems with overall increase of 81.3%, and 74.0%, respectively. The same trend was observed for sodium (Na) where by it decreased with vermicomposting time for BPW and CPW while increased for BCM and CCM. The overall decrease in Na for BPW and CPW was 51.4%, and 47.8%, respectively while its overall increase for BCM and CCM was 34.0% and 27.8%, respectively. Sharma et al. (2011) reported a decrease in TK and Na during vermicomposting of spinach waste with cow dung. On the other hand, an increase in TK and Na during vermicomposting of cattle manure either solely or mixed with other substrates has been previously reported (Balachandar et al., 2020; Rini et al., 2020; Sharma and Garg, 2019). The reduction of TK and Na, could be attributed to a large quantity of leachate (Huang et al., 2016) which could have flushed out these elements together with other nutrients (Sharma et al., 2011; Mainoo et al., 2009). This could thus explain why BPW with higher amount of leachate produced had significantly lower TK and Na in the vermicompost than CPW.

Conversely, the increase in TK could be attributed to the solubilizing of organically bound potassium as a result of acid production by microorganisms (Garg et al., 2006). In addition, the gut of an earthworm has a big population of symbiotic microflora which could enhance the release of potassium in vermicompost (Khatua et al., 2018; Pramanik et al., 2007). These factors could thus have contributed to an overall increase in TK over time for BCM and CCM.

Much as N, K, and Na reduced in the final vermicompost of BPW and CPW, this was mainly through the leaching of these nutrients as a result of excess leachate produced. However, recycling of the produced leachate could ensure a closed system which would otherwise increase the nutrient concentration in the vermicompost (Hanc et al. (2017).

3.2.3. *Total organic carbon, and C/N ratio*

Total organic carbon (TOC) significantly reduced (*$p < 0.05$*) with vermicomposting time for all systems with overall decrease of 40.6%, 40.1%, 39.2%, and 36.9% for BPW, CPW, CCM and BCM, respectively. TOC reduction between systems was not significant (*$p > 0.05$*). An overall reduction in TOC of 23.8%, and 24.9% were reported by Rini et al. (2020) and Esmaeili et al. (2020) during vermicomposting of cow dung. Carbon is metabolized by microorganisms (earthworms and bacteria) to derive energy for the respiratory activities (Arumugam et al., 2018; Ravindran et al., 2015; Esmaeili et al., 2020). Therefore, a reduction in the TOC content indicates biodegradation and mineralization of organics in the reactor with release of CO_2 due to microbial activity (Khatua et al., 2018). Likewise, earthworms also fragment large particles within the vermicompost pile which accelerates the decomposition of carbon (Yang et al., 2017).

A reduction in C/N ratio with vermicomposting time was observed for BCM, and CCM with overall reduction of 70.17% and 70.28% respectively. On the contrary, C/N ratio for BPW and CPW increased with vermicomposting time with overall increases of 16.13% and 2.27% respectively. The C/N ratio indicates the maturity of vermicompost since it reflects stabilization and mineralization rates during vermicomposting (Srivastava et al., 2020; Arumugam et al., 2018). Therefore, low C/N ratios of 8.03, and 8 for BCM and CCM, respectively (Table 3) indicated maturity of cattle manure vermicompost. The decrease of C/N ratio over time is also due to the enhanced nitrogen content and organic matter degradation (Devi and Khwairakpam, 2020b). This could thus explain why C/N ratios of BPW, and CPW increased with time due to reduction in nitrogen content over time (Table 3). Our results are corroborated by previous studies by Karmegam et al. (2019) and Biruntha et al. (2020) who reported up to 50.86% and 48.8% reduction in C/N ratio during vermicomposting of cow dung, and cow dung with vegetable waste, respectively.

3.2.4. Nutrient composition of leachate

The nutrient composition of leachate with vermicomposting time for different treatments is shown in Table S1 of supplementary material. All the measured parameters of leachate (pH, TKN, TP, TK, Na, TOC) for all the treatments increased with vermicomposting time. The increase in pH could be attributed to the presence of K^+, Na^+ and NH_4^+ in the leachate. In fact, Varma et al. (2016) reported that excess organic nitrogen is released as ammonium nitrogen in leachates which leads to increased pH. All the produced leachate contained high concentrations of TKN, TP and TK which mostly occurred as NO_3^-, PO_3^{3-} and K^+, respectively implying that this leachate could be used as a fertilizer for crop production (Gutiérrez-Miceli et al., 2008).

3.3. Material flow analysis

Material flows for BPW, BCM, CPW, and CCM are shown in Fig. 1 (mass flows), Fig. 2 (TKN flows), and Fig. 3 (TOC flows). The rest of material flows are shown in Fig S2-S4 of the supplementary material. A total of 27.7 kg materials (wet weight) were input into BPW, and CPW rectors and distributed as follows: 38%, and 43% to vermicompost, 36%, and 37% lost as various gases, 24% and 16% formed leachate, 2% and 3% converted into earthworms for the two systems, respectively. For BCM, and CCM, 28 kg materials (wet weight) were fed into the vermireactors and were distributed as follows: 59%, and 60% lost as various gases, 35% for both in vermicompost, 5% in both for earthworms, 1% and 0% in leachate for BCM, and CCM, respectively. The distribution of carbon and nutrients (N, P, K, and Na) for different systems is shown in Table 4. CCM registered the greatest N retention in vermicompost (75.45%) and its least loss to the atmosphere (3.17%). The greatest loss of N to the atmosphere (49.23%) and its least retention in vermicompost (24.21%) were registered by BPW. In case of C, the highest loss to atmosphere (64.4%) was from CCM with the least loss of 50.59% from CPW.

Nigussie et al. (2016) reported up to 46% C, and 30.21% N losses as

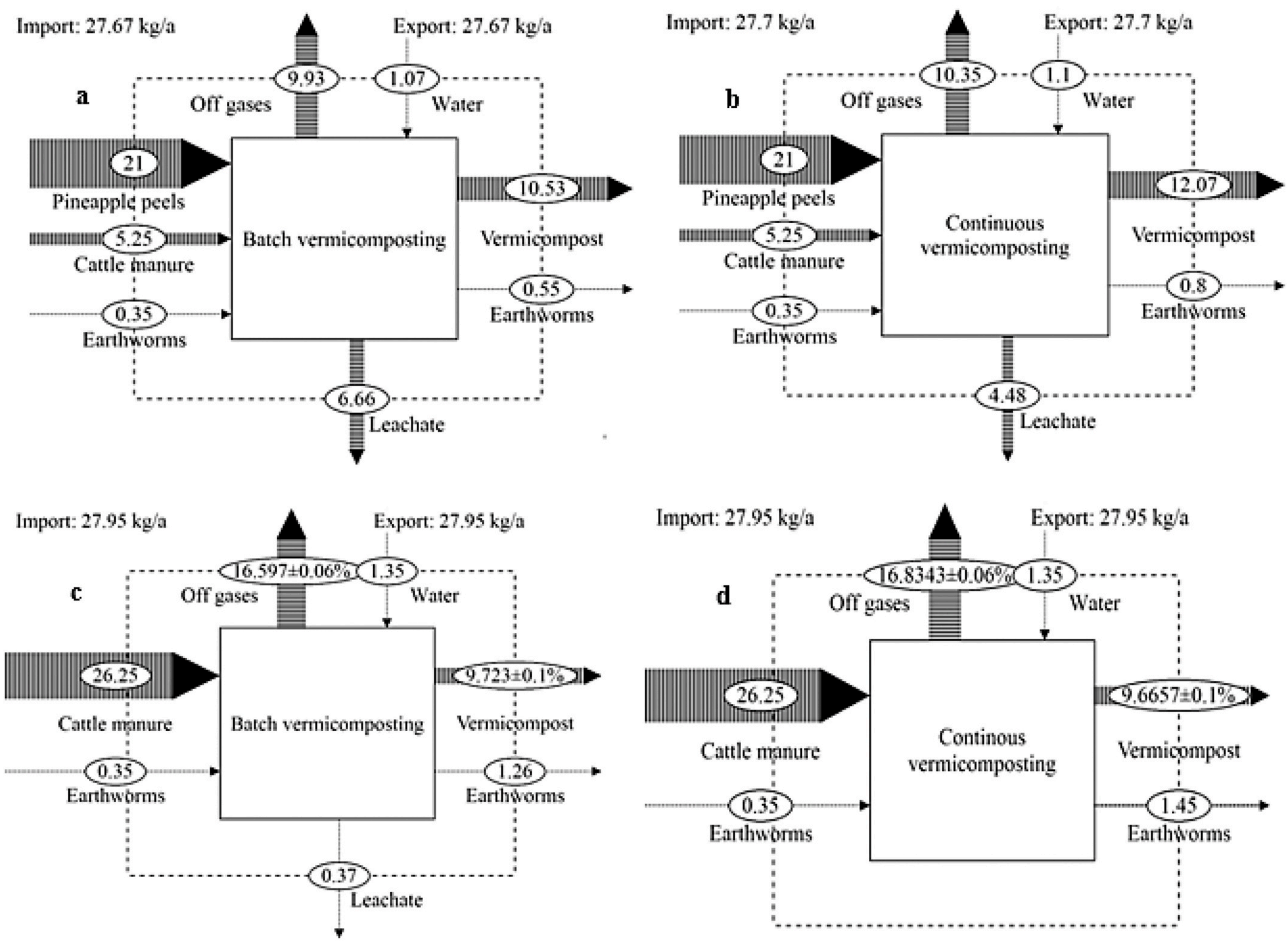

Fig. 1. Mass flows for (a) BPW (b) CPW, (c) BCM, and (d) CCM vermicomposting systems all based on wet weight basis.

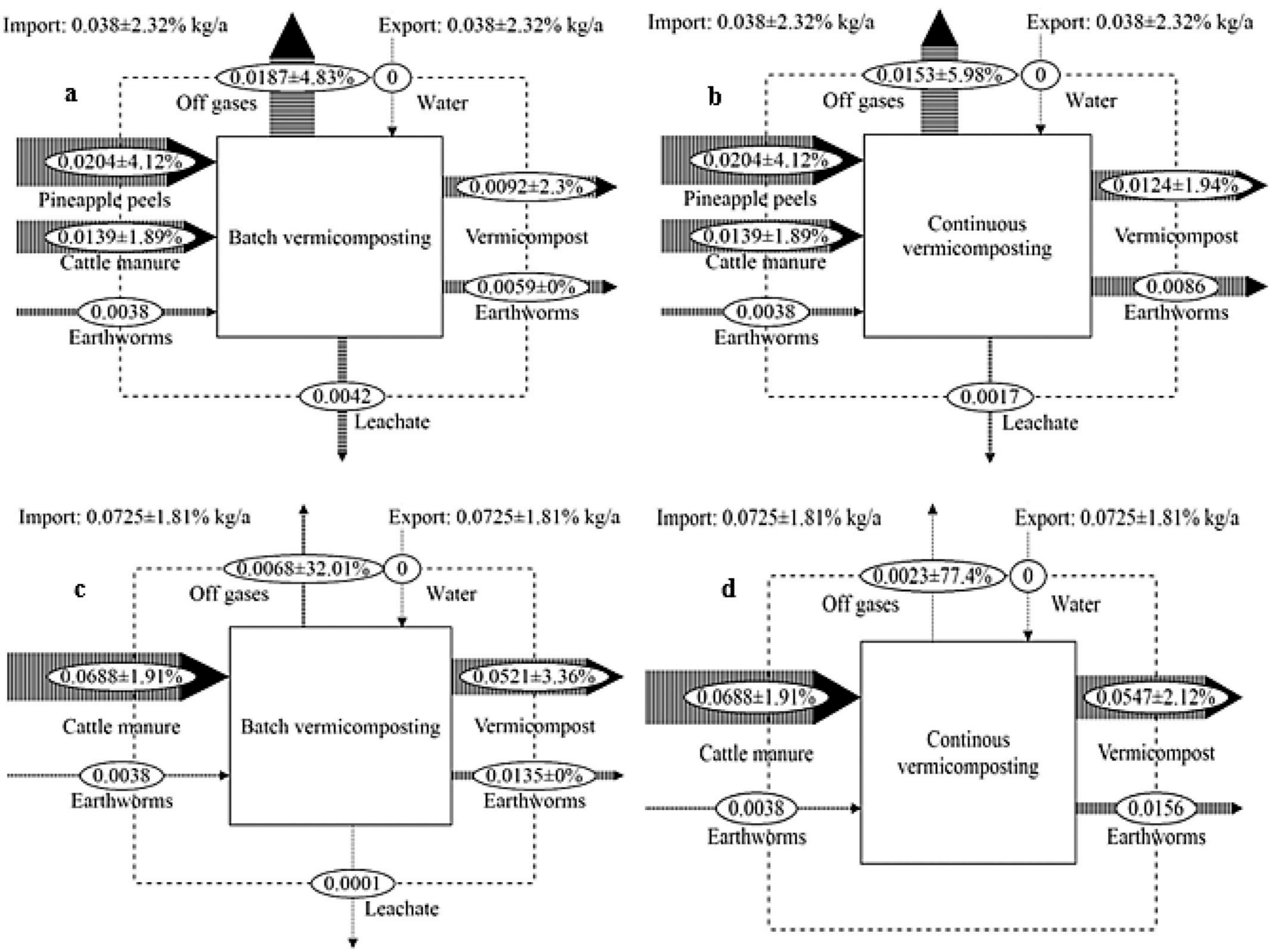

Fig. 2. Nitrogen flow analysis for (a) BPW, (b) CPW, (c) BCM and (d) CCM based on wet weight.

off gases during continuous vermicomposting of vegetable waste while Yang et al. (2017) reported up to 53.2% C, and 15.5% N losses during vermicomposting of tomato stems and cow dung. On the other hand, Jjagwe et al. (2019) reported up to 68.49% C loss and 18.18% N loss to the atmosphere when cattle manure was vermicomposted by *Eudrilus euginea*. Nitrogen losses mainly occur through two main processes: 1. Enzymatic conversion of urea to NH_3 and ammonium (NH_4^+), and volatilization of NH_3, and 2. Nitrification and denitrification, conversion of NH_4^+ to NO_3^-, and NO_3^- to N_2 with volatilization of NO and N_2O (Yang et al., 2017; Vries et al., 2015). Carbon losses mainly occur through the anoxic and anaerobic conversion of organic matter to CH_4 and CO_2, and volatilization of these gases (Li et al., 2020; Nigussie et al., 2016). About 45% of TKN exists as NH_4^+-N which is very soluble in liquid (Vu et al., 2016) and can thus be lost by leaching. The N and C losses are dependent of the nature and quantities of substrates vermicomposted (Nigussie et al., 2016). The high carbon loss from BCM and CCM may be attributed to easily degradable initial C content in cattle manure (Jjagwe et al., 2019). The N, C, and P losses can reduce the agronomic value of a fertilizer (Shan et al., 2019) causing low nutrient use efficiencies by crops. In general, continuous systems (CPW and CCM) retained more nutrients inside the vermicompost than batch systems (BCM and CCM).

3.4. Techno-economic and environmental implications of the vermicomposting systems

Assessment of techno-economic and life cycle analyses are essential to indicate the sustainability for any process (Wainaina et al., 2020). The feasibility of a wider application of vermicomposting technology can only be ascertained by analyzing the performance from environmental and economic perspectives (Hussain et al., 2018)

3.4.1. Environmental implications of vermicomposting pineapple waste

Like previous studies (Swati and Hait, 2018; Nigussie et al., 2016; Lim et al., 2016) have indicated, treating fruit and vegetable wastes (which include pineapple waste as well) solely or in combination with other organic wastes results into reduction of adverse environmental hazards that could emanate from open dumping. Such hazards include; smelly odors, vector transmission through breeding houseflies, blockage of drainage systems and contamination of surface water sources for peri-urban populations (Lv et al., 2018; Nigussie et al., 2016). There is also an advantage of closing up the nutrient loop and creation of a circular economy for pineapples whereby there is zero waste moreless generated and the nutrients within the vermicompost are recycled back into the production cycle (Soobhany, 2019). Morever, the portion of greenhouse gases emitted from huge heaps of openly decaying waste can be greatly reduced through vermicomposting which will in turm reduce acidification, eutrophication and global warming potentials (Yang et al., 2017; Komakech et al., 2016).

3.4.2. Techno-economic analysis

Table 5 shows the overall economic evaluation for starting up, implementation, monitoring and product utilization of

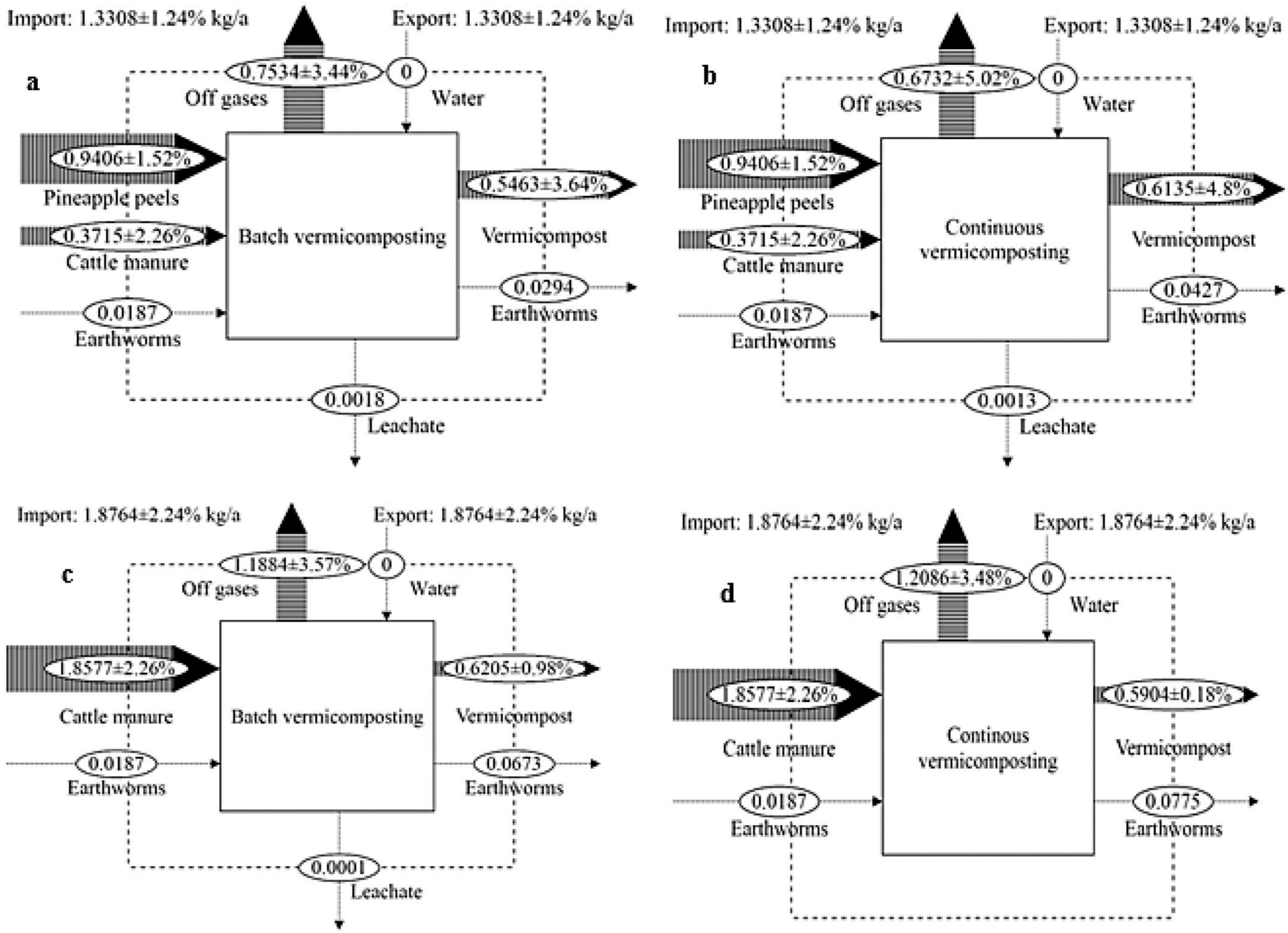

Fig. 3. Carbon flow analysis for (a) BPW (b) CPW, (c) BCM, and (d) CCM based on wet weight.

Table 4
Distribution of nutrients and total organic carbon within materials of the different vermicomposting reactors.

Variable	BPW					CPW				
	TOC	N	P	K	Na	TOC	N	P	K	Na
Input material (kg)	1.33	0.04	0.02	0.03	0.03	1.33	0.04	0.02	0.03	0.03
Vermicompost (%)	41.05	24.21	90.37	67.54	74.90	46.10	32.63	91.19	79.29	79.35
Earthworms (%)	2.21	15.53	4.29	2.20	9.88	3.21	22.63	5.45	2.96	12.32
Leachate (%)	0.14	11.05	5.34	29.84	15.22	0.10	4.47	2.65	17.75	8.33
Off gases (%)	56.60	49.23	0	0	0	50.59	40.27	0	0	0
Sum (%)	100	100	100	100	100	100	100	100	100	100
	BCM					CCM				
Input material (kg)	1.88	0.07	0.05	0.07	0.28	1.88	0.07	0.05	0.07	0.28
Vermicompost (%)	33.07	71.86	95.82	97.53	97.96	31.46	75.45	94.90	97.40	97.67
Earthworms (%)	3.57	18.62	3.76	2.19	1.94	4.13	21.52	5.10	2.60	2.33
Leachate (%)	0.03	0.14	0.63	0.28	0.10	0	0	0	0	0
Off gases (%)	63.33	9.38	0	0	0	64.41	3.17	0	0	0
Sum (%)	100	100	100	100	100	100	100	100	100	100

vermicomposting systems. The monetary expenses of the systems were normalized to 1 ton of waste per vermicomposting period (2 months), which implies a treatment of 6 tons of waste per year. Using the same waste proportions as outlined in section 2.2.2 of this study, and up scaling the reactor volume and the initial earthworm biomass stock, a reactor of 1,905 L and initial earthworm biomass of 13 kg were considered for both the batch and continuous systems. The investment cost for both systems was estimated at USD 247 (Table 5) and included local cost for construction materials, cost of labour as well as cost of the initial earthworm stock. Water cost in maintaining the moisture level of the vermicomposting pile was considered negligible due to rather low water charges in Uganda (USD 0.95/1000 L for domestic use according to NWSC (2020)). The conversion factors for waste into vermicompost (0.40 and 0.51), and earthworm biomass multiplication factors (1.57 and 2.29) for BPW, and CPW, respectively were based on results from Table 2. The cash inflow included the following:

Savings from landfill disposal: If all the waste considered (1 ton for every 2 months) were to be disposed to landfill, with the gate fee at USD

Table 5
Techno-Economic analysis based on pineapple waste treatment capacity of 6 tons/year using either a batch or continuous vermicomposting system.

Description of parameters	Treatment system	
	BPW	CPW
Volume of reactor (L) needed to vermicompost 1 ton waste per 2 months	1905	1905
Cost of constructing the reactor (USD)[a]	134	134
Initial earthworm biomass (kg)[b]	13	13
Cost of acquiring earthworm biomass (USD)[a]	247	247
Total investment cost (USD)[a]	378	378
Savings from vermicomposting 6 tons of waste per year (USD)[a]	1584	1584
Total vermicompost produced per year (kg)[b]	2400	3060
Total earthworm biomass produced per year (kg)[b]	122.46	178.62
Value of yearly generated vermicompost (USD)[a]	192	306
Value of yearly produced earthworm biomass (USD)[a]	2297	3351
Total yearly profits (USD)[a]	4073	5241

[a] Computed based market prices in Uganda as per October 2020.
[b] Measured on a wet weight basis.

7/ton (KCCA and IFC, 2020), and waste collection fee at USD 37/ton (Kinobe et al., 2015) in Uganda, vermicomposting 6 tons of waste/year would achieve a saving of USD 1584/year.

Selling the generated vermicompost; vermicompost can be used to replace the inorganic fertilizer for maize growth in Uganda (Komakech et al., 2015) and according to Lalander et al. (2015) vermicompost is valued at USD 4 per 50 kg bag in Uganda. Therefore, selling the generated vermicompost (Table 5) would generate USD 192, and USD 306 for BPW and CPW, respectively. Lastly, the earthworm biomass is a potential poultry feed due to its high protein content. The average price of 1 kg of *Eudrilus eugeniae* in Uganda is USD 19 (Jjagwe et al., 2020). Therefore, the generated earthworm biomass (Table 5) would raise USD 2297, and USD 3351 for BPW and CPW, respectively if sold off as an animal protein feed. From the total annual cash inflows, CPW generates more profits than BPW owing to the high earthworm biomass and vermicompost generated.

4. Conclusions

This study compared the batch and continuous vermicomposting of pineapple waste on various process factors and nutrient retention efficiency. A continuous vermicomposting system performed better than a batch in terms of nutrient retention in the vermicompost as well as reduction of nitrogen and carbon losses to the atmosphere. A higher degree of waste degradation and earthworm multiplication was achieved in continuous systems. Owing to the reasonable nutrient content, the vermicompost produced from pineapple peels in both batch and continuous systems could be used as a crop fertilizer especially in cases where phosphorus is the limiting crop nutrient. Moreover, recycling the produced leachate back into the vermicompost stockpile could also enhance the nutrients retention otherwise the leachate could also be used directly as a liquid fertilizer. The economic analysis showed that both systems are viable with benefits such as replacing chemical NPK by 40% for maize and common short term rotation crops. Compared to open disposal or landfilling, treating the pineapple waste was economically viable with a projected revenue of USD 264 per ton of waste valorized.

Declaration of competing interest

The authors declare no potential conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.111784.

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