Environmental Technology & Innovation 41 (2026) 104740

Contents lists available at ScienceDirect

Environmental Technology & Innovation

journal homepage: www.elsevier.com/locate/eti

Nutrient dynamics and recovery efficiencies in a decentralised faecal sludge and food waste treatment system

Eric Gbenatey Nartey [a,b], Ruben Sakrabani [a,*], Sean Tyrrel [a], Edna Dapaah [c], Noah Adamtey [b]

[a] Faculty of Engineering and Applied Sciences, Cranfield University, College Rd, Cranfield, Wharley End, Bedford MK43 0AL, UK
[b] International Water Management Institute, PMB CT 112, Cantonment, Accra, Ghana
[c] Kwame Nkrumah University of Science and Technology, PMB, University Post Office, Kumasi, Ghana

ARTICLE INFO

Keywords:
Co-composting
Decentralised sanitation systems
Faecal sludge management
Food waste valorisation
Low-cost treatment technologies
Nutrient flow analysis
Nutrient recovery

ABSTRACT

Decentralised faecal sludge (FS) and food waste (FW) treatment systems like co-composting system offer more practical solutions for waste treatment and nutrient recovery in low- and middle-income countries, yet nutrient recovery and losses across this system remain poorly quantified.This study aimed to assess the flows, losses, and recovery efficiencies of nitrogen (N), phosphorus (P) & potassium (K) with the goal of recommending measures to minimize pollution to water bodies. Raw FS, FW, compost, and effluent samples were collected at each treatment stage over three treatment cycles from August 2021 – 2022 in Somanya, Ghana. A total of 108 composite samples were collected and analysed for N,P & K using standard procedures. The N, P & K losses at each stage of the treatment system were calculated using the mass balance principle and the nutrient flow diagrams were created using the Sankey diagram generator. Results show that, 59–86 % N, 8–40 % P and 49–81 % K were lost at the dewatering stages for all cycles. Losses were lumped together as either gaseous losses, adsorption to media surfaces or percolate. The overall nutrient recovery efficiency of the system was 6–17 % N, 20–37 % P & 17–24 % K in co-compost and treated effluent. Despite high removal efficiencies in the facultative ponds, the final effluent did not meet EU standards. Effluent may become a resource in geographies that have scarce water and less stringent regulations. This study recommends strategies and approaches such as biochar use, percolate/leachate recirculation and covering of compost piles to reduce nutrient losses.

1. Introduction

Nutrients from wastewater treatment plants pose significant challenges to local environment and public health (Carey and Migliaccio, 2009). Wastes like faecal sludge (FS) and food waste (FW) contains useful nutrients and organic matter that can be recovered through treatment for fertiliser (Keraita et al., 2015) and other uses. FS contains approximately 50 % carbon (C), 4–5 % N, 2–3 % P, & 2–3 % K dry weight (Onabanjo et al., 2016; Rose et al., 2015). However, in sub-Saharan Africa (SSA) most of these nutrients are not recovered due to poor sanitation and unsustainable waste management practices. Numerous attempts to implement conventional wastewater and FS treatment technologies such as rotating biological contactors and activated sludge systems have generally

* Corresponding author.
E-mail address: r.sakrabani@cranfield.ac.uk (R. Sakrabani).

https://doi.org/10.1016/j.eti.2025.104740
Received 17 October 2025; Received in revised form 29 December 2025; Accepted 30 December 2025
Available online 31 December 2025

proven unsuitable for the SSA context. Key challenges were high installation costs, unreliable energy supply, and limited availability of local technical skills and human resources.

However, decentralised FS treatment systems coupled with FW offer more practical solutions, particularly in urban areas where centralised infrastructure are often not feasible (Nansubuga et al., 2016; Semiyaga et al., 2015). These decentralised systems focus more on treating waste and recovering valuable resources. Examples of such systems include co-composting, vermicomposting, biogas, conversion to animal feed, pyrolysis, and large-scale natural systems like stabilisation ponds and constructed wetlands (Semiyaga et al., 2015). If well suited to the local socio-economic and environmental context, they are often efficient and low-cost.

Despite these advantages, a major challenge persists. There is very little information on the recovery efficiency and long-term sustainability of these systems in developing countries (Strande et al., 2014, 2018). In particular, nutrient recovery efficiency and losses in decentralised systems are not well quantified. This lack of comprehensive data makes it difficult to assess the effectiveness of these systems in terms of resource recovery and environmental impact, occasioning the need for further research. Previous studies focused only on assessing single components of the FS and FW treatment system. For example Getahun et al. (2020); Gold et al. (2018); Stefanakis and Tsihrintzis (2011); and Ward et al. (2019) reported efficiency of different drying/dewatering methods of FS and efficiencies of pollutant removal in constructed wetlands or vertical-flow constructed wetlands (Kengne et al., 2009; Kegne et al., 2011; Koottatep et al., 2006). FS co-composting optimization with various organic wastes has also been reported (Al-Muyeed et al., 2017; Berendes et al., 2015; Cofie et al., 2009; Hashemi et al., 2019; Kone et al., 2007; Mengistu et al., 2018; Nakasaki et al., 2011; Nartey et al., 2017; Thomas et al., 2018). However, an end-to-end N,P & K assessment across combined FS and FW treatment system like dewatering of FS on sand drying beds coupled with co-composting with FW (Nartey et al., 2023; Nikiema et al., 2013) has not been well studied.

While mass balances approaches have been applied previously to individual components of treatment chains for e.g. composting, wetlands (Breen, 1990; Sommer et al., 1999) or full-scale wastewater treatment plants (Ekama et al., 2011; Puig et al., 2008; Venkatesan et al., 2016), fewer studies present empirically sampled, end-to-end N,P & K mass balances for combined FW and FW decentralised treatment system with multi-cycle temporal replication. Therefore, this study aimed to assess the flows, losses, and recovery efficiencies of N,P & K in a decentralised faecal sludge and food waste treatment system. By measuring solids and liquid streams across three full cycles and reporting recovery as product outputs (co-compost and treated effluent) plus residual losses, this study will provide novel, operationally-relevant N,P & K budgets that can directly inform low-cost interventions for nutrient retention and reuse as well as protecting the environment and supporting decision making on sustainable sanitation planning.

2. Materials and methods

2.1. Study location and decentralised treatment system description

The study was carried out at field scale at the Jekora Ventures Ltd – Yilo Krobo Municipal Assembly (JVL-YKMA) Recycling Plant (Fig. 1) in Somanya, Ghana (latitude 6° 6’ 0’’ N and 3° 3’ 0’’ N and between longitude 0° 0’ 30’’ W and 0° 0’ 10’’ W) (Sadiq, 2016). The

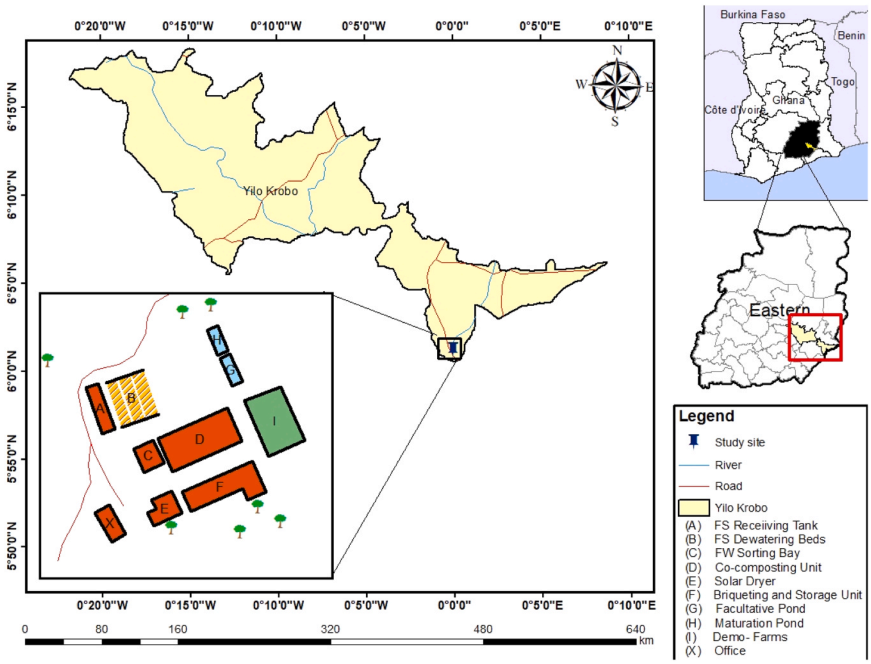

Fig. 1. Map of study location showing study site.

annual rainfall ranges from 750 to 1600 mm and spans from May to October (bimodal). Average temperatures range between 24 and 30°C while relative humidity ranges 60–90 % (Sadiq, 2016). This decentralised treatment system presents a one stop shop for receiving FS from vacuum trucks and FW from markets for treatment (Fig. 2). Treatment proceeds through several sequential stages designed to receive FS and FW, dewater FS on sand drying beds, stabilize organic matter and recover nutrients through co-composting dewatered faecal sludge (DFS) and FW, and treat percolate and leachate in ponds for discharge or potential reuse (Nartey et al., 2024) (Fig. 2).

2.2. *Sampling, analysis, and data collection*

The sampling plan followed the treatment value chain of the system described in Fig. 2. A "Phase" referred to a FS dewatering process on a drying bed, typically lasting 3–4 weeks, while a "Cycle" referred to the complete treatment process from start to finish, lasting 4–6 months. Three treatment Cycles were conducted, with the study spanning from August 2021 to June 2022. Sampling points (SP) referred to the sequential stages of treatment where samples were collected.

Raw FS was sampled from vacuum trucks, following methods described by Klingel et al. (2002) and Bassan et al. (2013) at SP1 in Fig. 2. Upon entering the treatment system, FS underwent solid–liquid separation to DFS and percolate. Percolate (at SP2) and leachate (at SP3) from distinct stages were collected and composited. These liquid streams converged (at SP4) before entering the facultative pond (at SP5) and maturation pond (at SP6), where influent and effluent sampling was performed. Food waste (FW) was sampled at the sorting bay (at SP8) and DFS (at SP7), with additional samples taken from DFS and FW heaps before (at SP9) and after co-composting (at SP10). Composite samples were collected in triplicate throughout the process.

The solid samples were air dried and milled (0.5 mm) to homogenize. Total N was determined by the modified Kjeldahl method described by Black (1965). Total P and K were determined by wet digestion (using perchloric acid, nitric acid and sulfuric acid) followed by spectrophotometry for total P and flame photometry for total K as described in Okalebo et al. (2002). For liquid samples the total N,P, & K were determined by same methods mentioned above and described in American Public Health Association-American Water Works Association-Water Environment Federation (APHA-AWWA-WEF, 2001). Masses of N, P & K for each treatment stage were calculated by multiplying measured concentrations (mg·L^{-1} for liquids, mg·kg^{-1} for solids) by corresponding stream volumes or masses and converting to kg. Dry mass was computed using measured total solids (%TS) or moisture content.

2.3. *FS loading of the treatment system*

On average, nine trucks desludged per drying bed in each Phase for Cycle 1, 5 trucks in each Phase for Cycle 2 and 6 trucks in each Phase for Cycle 3 (Table 1). A total of 202, 155 and 128 m^3 of FS were desludged for Cycles 1, 2 and 3, respectively. The sources of raw FS were mostly from homes (predominantly using septic tanks) and public toilets (using pit latrines). Septic tanks and Ventilated Improved Pits (VIP) are the two types of on-site sanitation systems (OSS) frequently used in towns and peri-urban communities in Ghana (Fanyin-Martin et al., 2017; Nayebare et al., 2020). Public toilets use little flush water in contrast to septic tanks, that require much water for their operation (Oppiah-Mensah, 2019). Hence, FS from public toilets were usually more fresh, thick, and concentrated (high strength) while the FS from septic tanks were more stable, watery, and diluted (low strength).

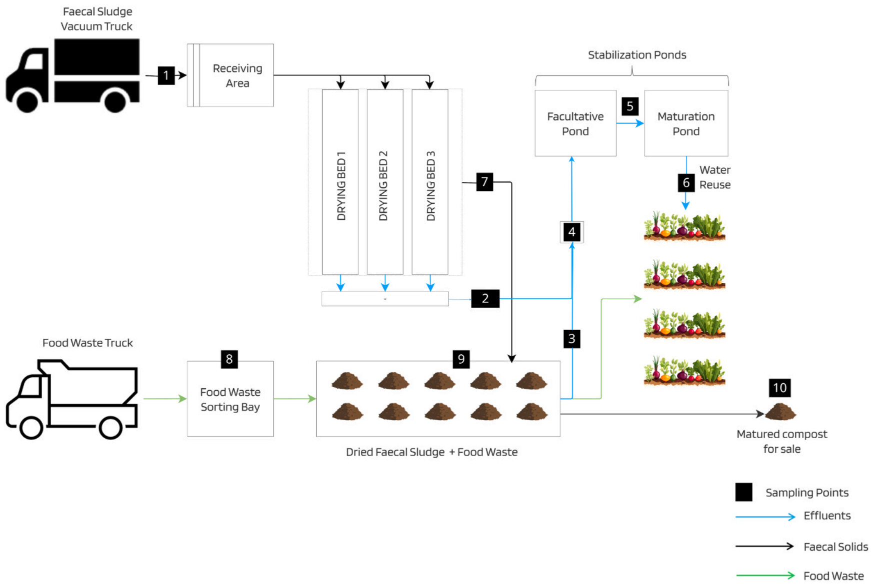

Fig. 2. Schematic of the decentralised FS and FW treatment system.

Table 1
Volumes of raw FS received and processed during the various Phases and Cycles of treatment.

Treatment Cycle	Phase	No. of FS trucks received	Volume of FS received (SP1) (m^3)	Volume of collected percolate after dewatering (SP2) (m^3)	Dislodging time (days)	Fresh weight of DFS collected (SP7) (Kg)	Number of heaps formed with FW
Cycle 1	Phase 1	10	55	25.7	7	2927	1
	Phase 2	9	52	8.0	6	1963	1
	Phase 3	10	45	28.6	8	1401	1
	Phase 4	6	50	22.4	2	1694	1
Cycle 2	Phase 5	7	35	16.3	3	1075	1
	Phase 6	6	44	24.2	32	1384	1
	Phase 7	4	34	7.3	14	1097	1
	Phase 8	4	42	14.2	2	443	1
Cycle 3	Phase 9	7	54	23.3	40	2206	1
	Phase 10	5	25	10.8	4	2546	1
	Phase 11	6	31	20.7	14	3080	1
	Phase 12	7	39	7.0	19	5930	1

2.4. N, P & K loss and flow in FS and FW treatment system

The N,P & K loss for a Cycle and for each treatment stage was calculated using the mass balance principle, as described by Laner and Rechberger (2016). Eqs. 1–7, and the nutrient flow diagrams depicting the various stages in Fig. 2 for the Cycles were created using Sankey diagram generator (SankeyMATIC). The study did not focus on the specific pathways for nutrient losses but lumped all together as either gaseous losses due to evaporation or adsorption of media surfaces or through leaching.

Mass balance for a Cycle:

$$\sum Mx, in = \sum Mx, out + Mx, loss \tag{1}$$

Where:

X = N, P or K

Mx, in = Total mass in Kg of X in input materials/feedstock over the Cycle

Mx, out = Total mass in Kg of X in output products (compost and treated effluent) over the Cycle

Mx, loss = Total mass in Kg of X lumped (gaseous losses + adsorption + uncounted leaching)

Stage-by-stage Mass balance within a Cycle:

– *Dewatering (solid-liquid separation)*

$$Mx, FS = Mx, DFS + Mx, perc + Mx, loss, dew \tag{2}$$

$$\text{Therefore}, \text{Mx}, \text{loss}, \text{dew} = \text{Mx}, \text{FS} - (\text{Mx}, \text{DFS} + \text{Mx}, \text{perc})$$

Where:

Mx, FS =Mass of X in raw FS received (vacuum trucks)

Mx, DFS =Mass of X in DFS (solid after drying bed)

Mx, perc =Mass of X in percolate from drying beds

Mx, loss, dew =Mass of X lost during dewatering (volatilisation, adsorption to media, unmeasured pathways)

– *Composting (co-composting DFS +FW)*

The initial DFS + FW mix is Mx, mix, init = Mx, DFS + Mx, FW

$$Mx, mix, init = Mx, comp, final + Mx, loss, comp \tag{3}$$

$$Therefore, Mx, loss, comp = Mx, mix, init - Mx, comp, final$$

Where:
Mx, mix, init =Mass of X in initial compost mixture (DFS + FW) before composting
Mx, FW = Mass of X in input food waste
Mx, loss, comp =Mass of X lost during composting (gaseous loss, leachate, volatilisation)
Mx, comp, final = Mass of X in final mature co-compost product
Stabilisation pond (facultative and maturation) treatment
Facultative pond

$$Mx, influent, fac = Mx, fac, eff + Mx, loss, fac \tag{4}$$

Where:
Mx, influent, fac = Mass of X in influent entering facultative pond
Mx, fac, eff =Mass of X leaving the facultative pond (effluent to maturation pond)
Mx, loss, facMass of X lost in facultative pond (volatilisation, adsorption to sediment, etc)
Maturation pond

$$Mx, fac, eff = Mx, mat, eff + Mx, loss, mat \tag{5}$$

Where:
Mx, fac, eff = Mass of X in influent entering maturation pond
Mx, mat, eff =Mass of X leaving the maturation pond (effluent to maturation pond)
Mx, loss, matMass of X lost in maturation pond (volatilisation, adsorption to sediment, etc)
Pond system as a whole

$$Mx, influent, fac(Mx, perc + Mx, other\ leac, in) = Mx, mat, eff + Mx, pond, loss \tag{6}$$

Where:
Mx, other leac, in = Mass of X in influent leachate from other sources such as co-composting)
Mx, pond, loss =Mass of X lost inside pond processes (volatilisation, adsorption to sediment, etc.)

– *Overall system balance (Cycle)*

$$Mx, FS + Mx, FW = Mx, comp, final + Mx, mat, eff + Mx, total\_loss \tag{7}$$

2.5. N, P & K treatment efficiency, recovery efficiency and loss of FS and FW treatment system

The treatment efficiency of the treatment system was calculated based upon the influent and the effluent concentrations (Eq. 8) at the different stages according to the procedure described by Gross (2005):

Treatment system removal efficiency:

$$\text{Removal Efficiency} = ([(\text{Cin} - \text{Cout})]\text{x}100\%)/\text{Cin} \tag{8}$$

Where:
C_{in} = Influent concentration (mg/L)
C_{out} = Effluent concentration (mg/L)
100% = Efficiency expressed as a percentage

In addition to the treatment performance, the system is considered regulatory compliant when N, P & K values are/or below N = 10.0 mg/L, P = 1.0 mg/L and K= NA according to European Union (EU) standards (Preisner et al., 2020).

The recovery efficiencies and loss percentages of the system were calculated by Eqs. 9–11 as follows:

$$\text{Recovery in compost(as\%of total input)} = \frac{[\text{Mx, comp, final}]\text{x}100\%}{\text{Mx, FS} + \text{Mx, FW}} \tag{9}$$

$$\text{Recovery in treated effluent(as\%of total input)} = \frac{[\text{Mx, mat, eff}]\text{x}100\%}{\text{Mx, FS} + \text{Mx, FW}} \tag{10}$$

$$\text{Loss in the system(as\%of total input)} = \frac{[\text{Mx,} \quad \text{total}_{\text{loss}}]\text{x}100\%}{\text{Mx, FS} + \text{Mx, FW}} \tag{11}$$

3. Results

3.1. Effect of decentralised FS and FW treatment system on nutrient flow

3.1.1. N, P & K flow in Cycles 1–3

Results for the distribution of total N, P & K for Cycles 1–3 are shown in Figs. 3–5(a, b & c). In Cycle 1, results show that for every

1 kg of total N input from raw FS (vacuum truck), 41 % was distributed in DFS, 31 % trapped in percolate that collect in the stabilisation ponds and 28 % considered as loss. This amount of N in DFS is co-composted with N in FW (food waste truck) which led to only 27 % of it being recovered in the mature co-compost (Fig. 3a). Total P distribution in Cycle 1 showed a higher percentage of 67 % in DFS and only 3 % trapped in percolate and 30 % as loss for every 1 kg of total P in raw FS. Only 31 % of the combined total P in DFS with FW is recovered in the mature co-compost (Fig. 3b). Total K distribution in Cycle 1 from raw FS was 22 % in DFS, 20 % in percolate and 58 % as loss. When DFS was co-composted with FW, 53 % of the combined total K was recovered in mature co-compost (Fig. 3c). Further distribution of total N, P & K through the treatment system is shown in Fig. 3(a, b and c).

The distribution of nutrients in Cycle 2 was different from what pertained in Cycle 1. In Cycle 2, the distribution of total N input from raw FS (Vacuum truck) was 14 % in DFS, 39 % trapped in the percolate and 28 % accounted for as losses. This amount of total N in DFS when co-composted with total N from FW (food waste truck) led to only 26 % recovered in the mature co-compost and 74 % lost (Fig. 4a). Total P distribution in Cycle 2 still showed a higher percentage of 61 % in DFS and only 2 % trapped in percolate and 37 % as loss for every 1 kg of total P in raw FS. About 46 % of the combined total P in DFS and FW is recovered in the mature co-compost (Fig. 4b). Total K distribution in Cycle 2 from raw FS was 20 % in DFS, which was similar to Cycle 1 however, 40 % was trapped in percolate and 40 % as loss. When DFS was co-composted with FW, 33 % of the combined total K was recovered in mature co-compost (Fig. 4c). Further distribution of total N, P & K through the treatment system is shown in Fig. 4(a, b and c).

In Cycle 3, the distribution of total N input from raw FS (Vacuum truck) was 15 % in DFS similar to Cycle 2. A much lower amount (9 %) was trapped in the percolate and 76 % accounted for as losses. Similar to the first two Cycles, only 21 % was recovered in the mature co-compost and 79 % lost (Fig. 5a). Total P distribution in Cycle 3 showed a much higher percentage recovery of 91 % in DFS and a minimal 3 % trapped in percolate and a 5 % loss for every 1 kg of total P in raw FS. About 21 % of the combined total P in DFS and FW is recovered in the mature co-compost (Fig. 5b). Total K distribution in Cycle 3 from raw FS was 51 % in DFS, however, 31 % was trapped in percolate and 18 % as losses. When DFS was co-composted with FW, 28 % of the combined total K was recovered in mature co-compost (Fig. 5c). Further distribution of total N, P & K through the treatment system is shown in Fig. 5(a, b and c).

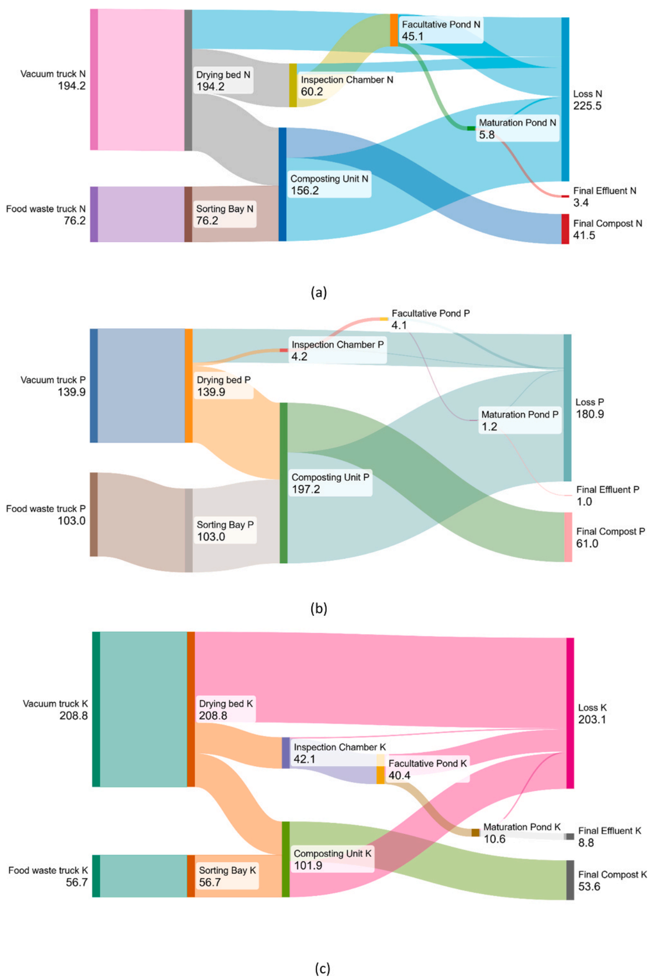

Fig. 3. Total N (a), P (b) and K (c) distribution in kg dry weight of the different stages of FS and FW treatment system during Cycle 1.

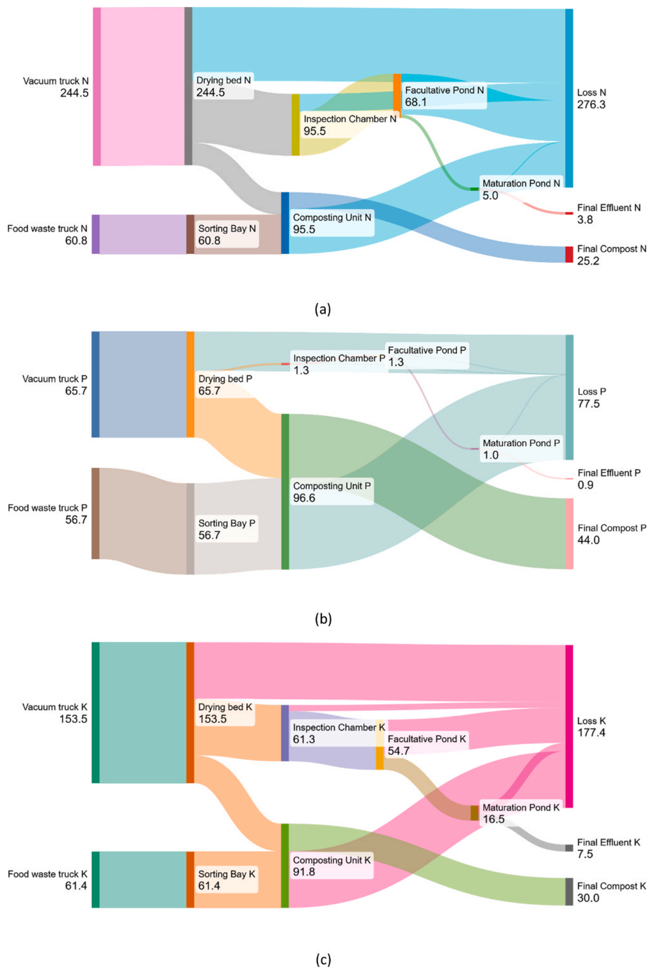

Fig. 4. Total N (a), P (b) and K (c) distribution in kg dry weight of the different stages of FS and FW treatment system during Cycle 2.

3.2. Effect of decentralised FS and FW treatment system on nutrient recovery and losses

3.2.1. Nutrient recovery and losses in Cycle 1–3

The total N, P & K received as input in Cycle 1 was 270.4, 242.9 and 265.6 Kg. In terms of feedstock, Raw FS contributed 72, 58 and 77 % of that N, P & K, respectively (Table 2). Results from FS dewatering (primary treatment) showed nutrient recovery of only 41, 67and 22 % of total N, P & K in DFS while losses ranged from 33 % to 78 % through percolate and other non-specific pathways (Table 2). The percent N, P & K recovered after co-composting were 27, 31 and 53 %, respectively. Losses encountered after co-composting were 73, 69 and 43 %, respectively. Only 8, 24 and 22 % of total N, P and K were recovered in treated effluent leaving treatment system in Cycle 1. In Cycle 2, the total input of total N, P & K received was 305.3, 122.4 and 214.9 kg, respectively (Table 2). Results from FS dewatering showed nutrient recovery of only 14, 61and 20 % of total N, P and K in DFS while losses ranged from 39 % to 86 % through percolate and other non-specific pathways. The percent N, P & K recovered after co-composting were 26, 45.5 and 33 %, respectively.

While in Cycle 3, the amount of total N, P & K recovery from FS dewatering were 15, 91 and 51 %, respectively. The losses were 85, 9, and 49 % for total N, P & K, respectively. The percent N, P & K recovered after co-composting were 26, 45.5 and 33 %, respectively. Losses encountered after co-composting were 74, 54.5 and 67 %, respectively. In all cycles, total N recovery during dewatering was less than 50 %. The highest recovery of 41 % was obtained in Cycle 1 while recoveries of 14 and 15 % were obtained for Cycles 2 and 3, respectively. Total N recovery from co-composting was less than 30 % for the system (27 % in Cycle 1, 26 % in Cycle 2 and 21 % in Cycle 3). Total P recovery in DFS were above 60 %, ranging between 61 % and 91 % during dewatering However, for co-composting, total P recovery ranged between 21 % and 45.5 %. Total K recovery in DFS during dewatering was similar for Cycles 1 and 2 but was 30 % more in Cycle 3. After co-composting, total K recoveries were 53, 33 and 28 % for Cycles 1, 2 and 3, respectively. Nutrient losses were more than 50 % for total N during dewatering and more than 70 % during co-composting.

Overall, between 6 % and 15 % of total N was recovered from the input feedstock in the form of co-compost and between 0.2 – 1 % in the form of treated effluent leaving the treatment system. For total P, between 21 % and 36 % of it was recovered in co-compost and

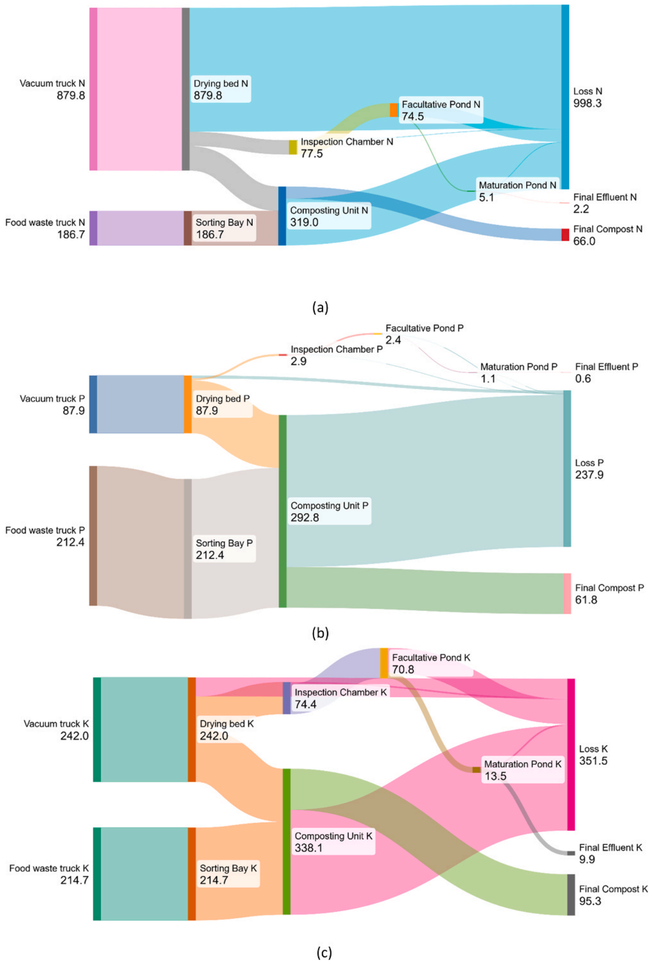

Fig. 5. Total N (a), P (b) and K (c) distribution in kg dry weight of the different stages of FS and FW treatment system during Cycle 3.

Table 2
Nutrient recovery and loss in the different stages of FS and FW treatment system during Cycle 1–3 (Kg).

Nutrient	Input (kg)		FS dewatering (kg)			Co-composting (kg)			Effluent treatment (kg)		
Cycle 1											
	FS	FW	DFS	Percolate	loss	Initial	Final	loss	Influent	facultative	Maturation
Total N	194.2	76.2	80.0	60.2	54.0	156.2	41.6	114.7	45.1	5.8	3.4
Total P	139.9	103.0	94.2	4.2	41.5	197.2	61.0	136.2	4.1	1.2	1.0
Total K	208.9	56.7	45.2	42.1	121.5	101.9	53.6	48.3	40.4	10.6	8.8
Cycle 2											
Total N	244.5	60.8	34.7	95.5	114.4	95.4	25.2	70.2	68.1	5.0	3.8
Total P	65.7	56.7	39.9	1.3	24.5	96.6	44.0	52.7	1.3	1.0	0.9
Total K	153.5	61.4	30.4	61.3	61.9	91.8	30.0	61.7	54.7	16.5	7.5
Cycle 3											
Total N	879.8	186.7	132.3	77.5	670.0	319.1	66.0	253.0	74.5	5.1	2.2
Total P	87.9	212.4	80.4	2.9	4.6	292.8	61.8	231.0	2.4	1.1	0.6
Total K	242.0	214.7	123.4	74.4	44.2	338.2	95.3	242.9	70.8	13.5	9.9

FS = faecal sludge, FW = food waste, DFS = dewatered faecal sludge.

between 0.2 % and 0.7 % was recovered in treated effluent. Finally, between 14 % and 25 % of total K was recovered in co-compost while between 2 % and 3 % was recovered in treated effluent. The rest of the nutrients were lost either through gaseous losses, adsorption to treatment surfaces and accumulation in the treatment system.

3.3. Decentralised treatment system efficiency and pollution mitigation

3.3.1. Treatment efficiency of the treatment stages

The total N concentration in raw FS measured ranged between 821 – 5056 mg/L for the three cycles (Table 3). There were significant differences at $p < 0.05$ between total N and P concentrations of the cycles. Total P ranged between 60 – 519 mg/L. Differences in total K concentrations in the raw FS were not statistically significant between cycles. After dewatering, differences in total N and P concentrations between raw FS and percolate were significant at $p < 0.05$. Similarly, differences in nutrient concentrations of percolate between cycles were statistically significant at $p < 0.05$.

The results of the treatment efficiency for the sand drying beds per Cycle is shown in Table 4. The efficiency of total N removal in Cycle 3 was 63 % and 91 % greater ($p < 0.05$) than those from Cycles 1 and 2, respectively. The N removal was negative in Cycle 2. The P removal relatively high and ranged from 16 % to 94 %. In contrast, K removal was below 50 % in Cycle 1 and negative for Cycles 2 and 3 (-528 to −46 %). The treatment efficiency for total K removal not significant at $p < 0.05$ and was the least removed from the raw FS.

The results of the treatment efficiency for the stabilisation ponds (facultative and maturation ponds) are shown in Table 5. The efficiency of total N removal in facultative pond was remarkably high and ranged between 88 % and 96 %. Removal efficiency for total P in Cycle 1 was 43 % and 9 % greater than Cycles 2 and 3. Total K removal in Cycle 1 increased by 7 % and 20 % in Cycles 2 and 3, respectively. For the maturation ponds, total N removal efficiencies were below 50 %. Total P removal efficiency was greater in Cycle 3 than in Cycles 1 and 2 whiles greater removal efficiency in Cycle 2 was recorded for total K.

3.3.2. Treatment performance against discharge standards

The total N, P and K characteristics of the final treated effluent leaving the maturation pond over the different treatment cycles is described and compared with EU discharge standards in Table 6. The final concentrations did not meet the EU standards for release into receiving waters (Table 6). In Cycle 1, the total N and P content of the discharged effluent exceeded EU threshold values by 3.4 and 7.8 times, respectively. In Cycle 2, the levels were 3.4 times higher for N and 7.5 times for P, while in Cycle 3, they were 2.5 and 5.3 times higher, respectively. Indicating that the FS and FW treatment system is not compliant to discharge standards.

4. Discussions

4.1. Effect of decentralised FS and FW treatment system on nutrient flow

The design of wastewater treatment plants has been primarily to treat effluents to required legal standards (Wild and Siegrist, 1999). For decentralised FS systems which offer more than just treating waste, a comprehensive understanding and management considering all involved flows and processes is necessary to reach optimal plant performance. The result from this study gives a comprehensive overview of the flow of total N, P & K distributed at various stages and in the different forms they exit the system. There is limited published data on an end-to-end N,P & K flow assessment of FS treatment systems to compare these results with, as few studies have been conducted on nutrient flows especially in FS treatment systems (Levira et al., 2023). However, a study by Montangero and Belevi (2007) on nutrient flow in OSS found that only 5–14 % N and 11–27 % P of the waste input are removed from septic tanks in the FS/sludge. The remaining fraction left the tanks in liquid effluent which usually ends up in rivers and lakes. For urine diversion latrines, 21 – 53 % Nand 41 – 73 % P of inputs were removed in the dried faeces and the remaining fraction in the urine. Making these latrines contribute to reducing nutrient load in the environment more than septic tanks (Montangero and Belevi, 2007).

In this study, 6 – 15 % N, 20 – 36 % P and 14 – 30 % K fractions of the input nutrients were left in the co-compost (fertiliser) for agricultural purposes while 0.2 – 1 % N, 0.2 – 0.8 % P and 2 – 4 % K left the system in treated effluent. A substantial fraction (83 – 94 % N, 63 – 79 % P and 77 – 83 % K) was estimated as losses in the system through adoption to media surfaces or to the atmosphere through volatilisation. Implying that, the decentralised FS and FW system is effective at pollutant removal but ineffective for nutrient recovery. Losses to the atmosphere could be an air quality concern, however this study could did not estimate the exact amounts. The nutrient flows differed between the cycles and could be attributed to factors such as the varying characteristics and quantities of input waste, climatic conditions, and plant operations (the loading and the dewatering times on the drying beds). Yaser et al. (2022) confirms this, that sludge properties vary depending on where it is produced, how it is generated, the seasonal variation, and the type of OSS in place etc. In this study, cycles 1, 2 and 3 flows coincided with the minor rainy, dry, and major rainy seasons, respectively (Ministry of Food and Agriculture, 2023) indicating the possible climatic effect.

The nutrient flow analysis carried out in this study provides several important engineering insights for the design and optimisation

Table 3
Mean ± SD concentrations of NPK in FS before and after dewatering on sand drying beds.

Treatment Cycle	FS (mg/L)			Percolate after dewatering (mg/L)		
	Total N	Total P	Total K	Total N	Total P	Total K
Cycle 1	821 ± 73	60 ± 9	895 ± 291	719 ± 89	50 ± 5	895 ± 105
Cycle 2	1346 ± 266	367 ± 30	857 ± 479	1546 ± 343	22 ± 4	857 ± 213
Cycle 3	5056 ± 75	519 ± 59	1449 ± 1475	1256 ± 131	41 ± 19	1449 ± 1334

SD: standard deviation, FS: faecal sludge

Table 4
Mean ± SD efficiency of **sand drying beds** in FS and FW treatment system.

Treatment Cycle	Treatment efficiency (%)		
	Total N	Total P	Total K
Cycle 1	12.3 ± 8.9	16.1 ± 7.6	41.2 ± 27.8
Cycle 2	-15.3 ± 19.3	93.9 ± 1.1	-46.4 ± 62.5
Cycle 3	75.2 ± 2.3	91.7 ± 4.6	-528.2 ± 953.6

Note: the (-) negative treatment efficiency means accumulation of nutrients.

Table 5
Mean ± SD efficiency of **stabilisation ponds** in FS and FW treatment system.

Treatment Cycle	Treatment efficiency of facultative pond (%)			Treatment efficiency of maturation pond (%)		
	Total N	Total P	Total K	Total N	Total P	Total K
Cycle 1	87.9 ± 0.0	64.3 ± 0.1	65.8 ± 0.0	40.8 ± 0.9	13.2 ± 4.0	16.2 ± 17.1
Cycle 2	94.5 ± 0.1	21.0 ± 0.0	72.8 ± 0.5	24.2 ± 2.7	10.1 ± 3.6	54.3 ± 0.5
Cycle 3	95.5 ± 0.1	55.5 ± 0.2	85.3 ± 0.4	18.9 ± 32.7	42.4 ± 1.5	27.0 ± 0.1

Putting all the components together, the overall treatment efficiencies of the treatment system for Cycles 1 – 3 were 94 – 99 % for total N, 14 – 98 % for total P and 4 – 88 % for total K.

Table 6
Comparison of treated effluent of FS and FW treatment system to discharge guidelines.

Nutrient (mg/L)	Treatment cycles			EU
	Cycle 1	Cycle 2	Cycle 3	
Total N	51.4 ± 1.6	65.0 ± 1.0	37.8 ± 0.7	15.0[a] 10.0[b]
Total P	15.5 ± 0.8	15.8 ± 0.1	10.5 ± 0.5	2.0[a] 1.0[b]
Total K	133.0 ± 20.2	128.1 ± 0.9	168.0 ± 5.0	-

Source: Preisner et al# (2020), a = 10,000 – 100,000 PE; b = <100,000 PE

of decentralised FS and FW treatment systems as the goal of such systems is to maximise nutrient recovery. The results highlight the importance of aligning engineering design with local climatic conditions, waste characteristics, and operational capacity. Systems that perform adequately under temperate or controlled conditions may behave sub-optimally in tropical, high-rainfall environments like Ghana.

4.2. Effect of decentralised FS and FW treatment system on nutrient recovery and loss

By design, N,P & K recovery was expected to be maximised in DFS during dewatering and in co-compost of the treatment system to enhance reuse into agriculture as fertiliser. However, results show less than half of total N and K received from raw FS was recovered in DFS and the rest lost in the system around the dewatering stages. While this study did not investigate the specific routes for the nutrient losses, it was probable that losses occurred in percolate, atmospheric gaseous losses, and/or adsorption to surfaces of filtering media. According to Montangero and Belevi (2007), faeces contain both water-soluble and insoluble nutrients combined in larger particles. Some 50 % of the N in faeces are water-soluble, exiting the solid -liquid separation process in the percolate. This could explain why less than 50 % of total N was recovered in the DFS. Manga et al. (2016) observed similar losses of total N during dewatering and attributed to higher NH_3-N volatilisation due to longer dewatering times and extended exposure of dewatering FS to high ambient temperatures.

The substantial total P and K losses, although relatively lower for total P compared to others during dewatering could also be linked to the high solubility and mobility of these nutrients under the warm, moisture-rich conditions typical of the FS and FW treatment system. During dewatering, K probably leached into percolate possibly due to its high soluble ionic form and the low adsorption capacity of the sand drying beds (Ward, 2022). Whereas the drying beds may have adsorbed to soluble P through phosphate binding to its surfaces (Altamira-Algarra et al., 2022). Sand drying beds (unplanted sludge drying beds) have proven to be technically feasible FS treatment technology with the recovery of nutrient and biosolids for agriculture. However, it has been associated with some limitations such as generation of low-quality dewatered solids in terms of N,P & K and organic matter; percolate with high contaminant loads; longer dewatering periods and high required footprint (Heinss et al., 1998; Cofie at al. 2006; Manga et al., 2016). Previous studies have addressed the longer dewatering periods (Gold et al., 2016; Seck et al., 2015) but not so much on the quality of the solids and the very high percolate contamination load (Manga et al., 2016).

Though total K is not typically considered an important pollutant in the same way that N and P, because it has fewer identified environmental concerns (Sutton et al., 2013), K plays a more important role than other elements in improving crop quality and reducing environmental pollution caused by loss of N and P fertiliser (Li et al., 2019). Hence its recovery is equally important for balanced nutrient management in fertiliser. In this study, recoveries in co-compost as measured were minimal for total N (less than 30 %), moderate for total P (less than 50 %) and total K (less than 60 %). Losses of N, P and K were over 70, 50 and 40 %, respectively during co-composting. Losses of P and K may have been due to mineralised P and soluble K draining from compost piles through gravitational percolation that could not be captured (Chatterjee et al., 2013). Regardless, these results are within typical ranges of 44–73 % for N losses and 82–88 % for P losses reported in earlier studies (Cofie et al., 2009; Nartey et al., 2017). Many studies have shown that, when there is sufficient K, K ions significantly promote the absorption and utilization of N and P by crops in the form of compensation charges (Barnes et al., 1976), improve the utilization rate of N and P fertilizers (Reid et al., 2016) and thus reduce pollution. Managing these losses is crucial and from an engineering perspective, this underscores the need to integrate leachate management features, such as, low-permeability compost pads, leachate collection systems, and leachate recirculation loops to reduce losses.

The significant N,P & K losses observed in this study highlight important trade-offs. While decentralised FS and FW systems reduce reliance on sewer networks, they may underperform in nutrient recovery unless carefully designed and operated. Compared with centralised treatment plants, the decentralised FS and FW approach is low-cost but more vulnerable to nutrient losses through volatilisation, leaching and inefficient composting. Therefore, achieving the environmental and resource-recovery benefits of decentralised systems require context-specific optimisation such as improved dewatering design, leachate capture, and enhanced composting practices rather than simple replication of these systems in many locations. These findings are relevant not only to Ghana but to many countries globally seeking sustainable waste management solutions under resource, infrastructure, and climatic constraints.

4.3. Decentralised treatment system efficiency and pollution mitigation

Total K concentrations of raw FS were found not to be statically significant between cycles. This could be attributed to the huge variation in the characteristics of the FS. The high variability of FS observed in this study is corroborated by results of earlier studies in West Africa (Bassan et al., 2013; Heinss et al., 1999). This variability could be attributed to differences in pH, sludge storage period, presence of oxygen and type of OSS installation (Eliyan et al., 2021). The total N in this study was higher than the total N of 350 – 400 mg/L reported by the National Institute of Urban Affairs (NUIA), 2022 in India for FS and septage or the total P of 140 – 350 mg/L reported in India (NIUA 2022).The higher total N concentrations measured during Cycle 3 could be due to increased volume of public toilet FS received in comparison to septage. Kuffour et al. (2019) reported similar observations that, public toilet FS was usually fresh and undigested. It had very high concentrations for all parameters while septage had comparatively lower concentrations of parameters analysed.

Dewatering beds removed very little N and often increased K as shown by the negative removals for total N and K obtained. This may have been due to enrichment from the sand filtering medium especially for total K concentrations. According to Kumar et al. (2022) negative removal is a commonly found phenomenon in all wastewater treatment facilities irrespective of the pollutants, amount of wastewater, capacity of the treatment plants, and regions. Even the most efficient pollutants separation techniques will have negative removal efficiency for more than one pollutant (Kumar et al., 2022). Additional factors such as accumulation from treatment components (e.g., sand drying bed), operating parameters such as varying retention times and climatic conditions (ambient temperature, rainfall etc.) (Dodane and Ronteltap, 2014; Samal et al., 2022) could account for the negative removals. The efficiency for total N removal in this study for Cycles 1 – 3 was lower compared to planted drying beds (constructed wetland systems), which achieved efficiencies of 80–90 % for total N (Kegne et al., 2011; Koottatep et al., 2005) and 75.9 – 81.6 % by unplanted drying bed (Kuffour et al., 2019). This confirms that sand drying beds are designed for water removal not nutrient removal.

Nutrient treatment and removal were expected to be greater at the dewatering and facultative pond stages of treatment by total N and P particulate bounded to DFS during dewatering and also by sedimentation and algal uptake in the facultative pond (Heinss et al., 1999; von Sperling, 2007). Although the maturation pond was also assessed in Table 5, less nutrient treatment was anticipated compared to the facultative as it was for pathogen reduction. Findings reported in Table 5 confirms this. Overall, total K is the least removed nutrients observed in the study as also reported by Heinss and Strauss (1999) and Nyenje et al. (2010). Despite the high removal efficiencies in the facultative ponds, the final effluent did not meet EU standards, highlighting the difference between internal treatment performance and regulatory compliance. In this study, FS is naturally concentrated in nutrient and variable in characteristics making it different from other wastewater types. FS treatment systems may require a different set of regulatory schemes and discharge standards commensurate with their characteristics. It also emerged that discharge standards for total N and K concentrations in effluent were non-existent for countries like Ghana and Uganda. The absence of total N and K discharge standards for wastewater can lead to severe environmental issues, including eutrophication from nutrient pollution.

4.4. Limitations and uncertainties of data

Although the mass-balance approach provided a robust framework for quantifying nutrient flows across the decentralised FS and FW treatment system, several limitations introduce uncertainty into these estimates. First, gaseous emissions particularly ammonia volatilisation during dewatering and composting were not directly measured and are therefore captured only as part of the lumped losses. This also included unmeasured leachate and adsorption to media surfaces, which may vary with weather conditions and operational practices. Second, percolate and leachate volumes were estimated from periodic sampling rather than continuous monitoring, contributing to potential under- or overestimation of soluble nutrient losses. Third, FS and FW characteristics exhibited high temporal variability; although three treatment cycles were sampled, the results may not capture the full range of seasonal or operational fluctuations. Finally, analytical and volumetric measurement errors propagate through the mass balance, affecting closure accuracy. These uncertainties do not undermine the overall conclusions but should be considered when interpreting nutrient loss magnitudes and recovery efficiencies.

5. Conclusions and recommendations

In conclusion, the study successfully characterised the end-to-end N, P & K flow in a decentralised FS and FW treatment system. N,P & K recovery efficiency of the system was low, characterised by huge losses. Findings revealed that, 59–86 % N, 8–40 % P and 49–81 % K were lost at the dewatering stages for all cycles. Treated effluent quality for total N, P & K did not meet minimum EU standards compared. There is the need for countries in SSA to prioritize setting discharge standards for total N and K. However, the effluent may become a great irrigation water source in geographies that have scarce water resources. The current FS treatment system infrastructure support solids (organic matter) recovery more than nutrient recovery in co-compost for agriculture.

The study recommends strategies and approaches such as biochar use, percolate/leachate recirculation and covering of compost piles for their low-cost, simple, and environmentally friendly nature to reduce nutrient losses specifically at dewatering and co-composting stages. Further study is needed to assess the specific routes of nutrient losses in the treatment system. Findings from this study can be used to build nutrient flow dashboards or decision support tools on nutrient recoveries and losses in FS treatment in low- and middle-income countries.

CRediT authorship contribution statement

Noah Adamtey: Writing – review & editing, Visualization, Validation, Methodology. **Edna Dapaah:** Writing – review & editing, Formal analysis, Data curation. **Sean Tyrrel:** Writing – review & editing, Supervision, Conceptualization. **Ruben Sakrabani:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Nartey Eric:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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.

Acknowledgements

We would like to acknowledge the Sue White Fund, Cranfield University and the International Water Management Institute for funding this work.

Data availability

Data will be made available on request.

References

Al-Muyeed, A., Oko-williams, A., Islam, K., Ali, L., Nath, S.K., Sanyal, P.R., 2017. Co-composting of faecal sludge with solid waste to improve FSM practice in Sakhipur municipality. Proceedings of the 40th WEDC International Conference, pp. 0–7. ⟨https://wedc-knowledge.lboro.ac.uk/resources/conference/40/Al-Muyeed-2684.pdf⟩. Loughborough, UK.

Altamira-Algarra, B., Puigagut, J., Day, J.W., Mitsch, W.J., Vymazal, J., Hunter, R.G., García, J., 2022. A review of technologies for closing the P loop in agriculture runoff: contributing to the transition towards a circular economy. Ecol. Eng. 177, 106571. https://doi.org/10.1016/j.ecoleng.2022.106571.

APHA-AWWA-WEF, 2001. Standard Methods for the Examination of Water and Wastewater, twenty-second ed. American Public Health Association.

Barnes, A., Greenwood, D.J., Cleaver, T.J., 1976. A dynamic model for the effects of potassium and nitrogen fertilizers on the growth and nutrient uptake of crops. J. Agric. Sci. 86 (2), 225–244. https://doi.org/10.1017/S002185960005468X.

Bassan, M., Tchonda, T., Yiougo, L., Zoellig, H., Mahamane, I., Mbeguere, M., Strande, L., 2013. Characterization of faecal sludge during dry and rainy seasons in Ouagadougou, Burkina Faso. 36th WEDC International Conference, Nakuru, Kenya, 2013, 0–6.

Berendes, D., Levy, K., Knee, J., Handzel, T., Hill, V.R., 2015. Ascaris and Escherichia coli Inactivation in an Ecological Sanitation System in Port-au-Prince, Haiti. PLOS ONE 10 (5), e0125336. https://doi.org/10.1371/journal.pone.0125336.

Black, C.A., 1965. Methods of soil Analysis, Part 2 -Chemical and microbiological properties. Agronomy monograph No. 9. American Society of Agronomy.

Breen, P.F., 1990. A mass balance method for assessing the potential of artificial wetlands for wastewater treatment. Water Res. 24 (6), 689–697. https://doi.org/10.1016/0043-1354(90)90024-Z.

Carey, R.O., Migliaccio, K.W., 2009. Contribution of wastewater treatment plant effluents to nutrient dynamics in aquatic systems: a review. Environ. Manag. 44 (2), 205–217. https://doi.org/10.1007/s00267-009-9309-5.

Chatterjee, N., Flury, M., Hinman, C., Cogger, C.G., 2013. Chemical and physical characteristics of compost leachates. A Review Report prepared for the Washington State Department of Transportation Washington State University. WA-RD 819.1. Accessed on 02/12/25 from: ⟨https://www.wsdot.wa.gov/research/reports/fullreports/819.1.pdf⟩.

Cofie, O.O., Agbottah, S., Strauss, M., Esseku, H., Montangero, A., Awuah, E., Kone, D., 2006. Solid-liquid separation of faecal sludge using drying beds in Ghana: implications for nutrient recycling in urban agriculture. Water Res. 40 (1), 75–82. https://doi.org/10.1016/j.watres.2005.10.023.

Cofie, O., Kone, D., Rothenberger, S., Moser, D., Zubruegg, C., 2009. Co-composting of faecal sludge and organic solid waste for agriculture: Process dynamics. Water Res. 43 (18), 4665–4675. https://doi.org/10.1016/j.watres.2009.07.021.

Dodane, P.H., Ronteltap, M., 2014. Unplanted drying beds. In: Strande, L., Ronteltap, M., Brdjanovic, D. (Eds.), Faecal Sludge Management: Systems Approach for Implementation and Operation. IWA Publishers, pp. 141–154.
Ekama, G.A., Mebrahtu, M.K., Brink, I.C., Wentzel, M.C., 2011. Mass Balances and Modelling Over Wastewater Treatment Plants. Water Research Commission. WRC Report No. 1620/1/11. Accessed on 01/12.25 from: ⟨https://www.wrc.org.za/wp-content/uploads/mdocs/1620-1-111.PDF⟩.
Eliyan, C., Vinneras, B., Zurbrügg, C., Koottatep, T., Sothea, K., Mcconville, J., 2021. Factors influencing physicochemical characteristics of faecal sludge in Phnom Penh, Cambodia. J. Water Sanit. Hyg. Dev. 12 (1), 129–140. https://doi.org/10.2166/washdev.2021.193.
Fanyin-Martin, A., Tamakloe, W., Antwi, E., Ami, J., Awarikabey, E., Apatti, J., Mensah, M., Chandran, K., 2017. Chemical characterization of faecal sludge in the Kumasi metropolis, Ghana. Gates Open Res. 1, 12. https://doi.org/10.12688/gatesopenres.12757.1.
Getahun, S., Septien, S., Mata, J., Somorin, T., Mabbett, I., Buckley, C., 2020. Drying characteristics of faecal sludge from different on-site sanitation facilities. J. Environ. Manag. 261 (October 2019), 110267. https://doi.org/10.1016/j.jenvman.2020.110267.
Gold, M., Dayer, P., Faye, M.C.A.S., Clair, G., Seck, A., Niang, S., Morgenroth, E., Strande, L., 2016. Locally produced natural conditioners for dewatering of faecal sludge. Environ. Technol. 37 (21), 2802–2814. https://doi.org/10.1080/09593330.2016.1165293.
Gold, M., Harada, H., Therrien, J., Nishida, T., Cunningham, M., Semiyaga, S., Fujii, S., Dorea, C., Nguyen, V.-A., Strande, L., 2018. Cross-country analysis of faecal sludge dewatering. Environ. Technol. 39 (23), 3077–3087. https://doi.org/10.1080/09593330.2017.1374472.
Gross, M.A., 2005. Wastewater Characterization Text. In: Gross, N.E., Deal, M. (Eds.), University Curriculum Development for Decentralized Wastewater Management (Issue September). National Decentralized Water Resources Capacity Development Project. University of Arkansas, Fayetteville, AR, pp. 1–5.
Hashemi, S., Boudaghpour, S., Han, M., 2019. Evaluation of different natural additives effects on the composting process of source separated feces in resource-oriented sanitation systems. Ecotoxicol. Environ. Saf. 185 (April), 109667. https://doi.org/10.1016/j.ecoenv.2019.109667.
Heinss, U., Larmie, S.A., Strauss, M., 1998. Solids Sep. Pond Syst. Treat. Septage Public Toilet Sludges Trop. Lessons Learn. Recomm. Prelim. Des.
Heinss, U., Larmie, S., Strauss, M., 1999. Characteristics of Faecal Sludges and their Solids-Liquid Separation. In EAWAG/SANDEC (Issue January). ⟨http://www.sswm.info/sites/default/files/reference_attachments/HEINSS et al 1994 Characteristics of Faecal Sludges and their Solids-Liquid Seperation.pdf⟩.
Heinss, U., Strauss, M., 1999. Co-treatment of Faecal Sludge and. Wastewater Trop. Clim.
Kengne, I.M., Dodane, P.-H., Akoa, A., Koné, D., 2009. Vertical-flow constructed wetlands as sustainable sanitation approach for faecal sludge dewatering in developing countries. Desalination 248 (1–3), 291–297. https://doi.org/10.1016/j.desal.2008.05.068.
Kengne, I.M., Kengne, E.S., Akoa, A., Bemmo, N., Dodane, P.-H., Koné, D., 2011. Vertical-flow constructed wetlands as an emerging solution for faecal sludge dewatering in developing countries. J. Water Sanit. Hyg. Dev. 1 (1), 13–19. https://doi.org/10.2166/washdev.2011.001.
Keraita, B., Drechsel, P., Cofie, O.O., Nikiema, J., 2015. Productive and safe use of urban organic wastes and wastewater in urban food production systems in low-income countries. In: de Zeeuw, H., Drechsel, P. (Eds.), Cities, Food and Agriculture; Towards Resilient Urban Food Systems. Earthscan, Routledge, Abingdon.
Klingel, F., Montangero, A., Koné, D., Strauss, M., 2002. Fecal Sludge Management in Developing Countries: A planning manual. In SANDEC/EAWAG (Issue April).
Koné, D., Cofie, O., Zurbrügg, C., Gallizzi, K., Moser, D., Drescher, S., Strauss, M., 2007. Helminth eggs inactivation efficiency by faecal sludge dewatering and co-composting in tropical climates. Water Res. 41 (19), 4397–4402. https://doi.org/10.1016/j.watres.2007.06.024.
Koottatep, T., Polprasert, C., Hadsoi, S., 2006. Integrated faecal sludge treatment and recycling through constructed wetlands and sunflower plant irrigation. Water Sci. Technol. 54 (11–12), 155–164. https://doi.org/10.2166/wst.2006.846.
Koottatep, T., Surinkul, N., Polprasert, C., Kamal, A.S.M., Koné, D., Montangero, A., Heinss, U., Strauss, M., 2005. Treatment of septage in constructed wetlands in tropical climate: lessons learnt from seven years of operation. Water Sci. Technol. 51 (9), 119–126. https://doi.org/10.2166/wst.2005.0301.
Kuffour, R., Awuah, E., Koné, D., 2019. Effect of physical conditioners (sawdust) on the dewatering of faecal sludge using unplanted filter beds. Applied Journal of Environmental Engineering Science, 4, 321–333.
Kumar, M., Ngasepam, J., Dhangar, K., Mahlknecht, J., Manna, S., 2022. Critical review on negative emerging contaminant removal efficiency of wastewater treatment systems: Concept, consistency and consequences. Bioresour. Technol. 352 (February), 127054. https://doi.org/10.1016/j.biortech.2022.127054.
Laner, D., Rechberger, H., 2016. Material flow analysis. In: Finkbeiner, M. (Ed.), Special types of life cycle assessment. LCA Compendium - The Complete World of Life Cycle Assessment, pp. 293–332.
Levira, B., Bright-Davies, L., Carmargo, J., Duma, L., Fettback, T., Lazaro, A., Mahundo, C., Matwewe, F., Mrimi, E., Schmidt, A., Thomas, J., 2023. Decentralised treatment solutions for on-site faecal sludge: quantifying the removal efficiencies of two novel systems in an East African city. Environmental Science Water Research Technology 9 (2), 603–619. https://doi.org/10.1039/D2EW00718E.
Li, Z., Zhang, R., Xia, S., Wang, L., Liu, C., Zhang, R., Fan, Z., Chen, F., Liu, Y., 2019. Interactions between N, P and K fertilizers affect the environment and the yield and quality of satsumas. Glob. Ecol. Conserv. 19, e00663. https://doi.org/10.1016/j.gecco.2019.e00663.
Manga, M., Evans, B.E., Camargo-Valero, M.A., Horan, N.J., 2016. Effect of filter media thickness on the performance of sand drying beds used for faecal sludge management. Water Sci. Technol. 74 (12), 2795–2806. https://doi.org/10.2166/wst.2016.451.
Mengistu, T., Gebrekidan, H., Kibret, K., Woldetsadik, K., Shimelis, B., Yadav, H., 2018. Comparative effectiveness of different composting methods on the stabilization, maturation and sanitization of municipal organic solid wastes and dried faecal sludge mixtures. Environ. Syst. Res. 6 (1), 5. https://doi.org/10.1186/s40068-017-0079-4.
Ministry of Food & Agriculture. (2023). Eastern Region. Ministry of Food & Agriculture. Accessed on 20/03/23 from: ⟨https://mofa.gov.gh/site/directorates/47-regional-directorates/eastern-region/83-eastern-region⟩.
Montangero, A., Belevi, H., 2007. Assessing nutrient flows in septic tanks by eliciting expert judgement: A promising method in the context of developing countries. Water Res. 41 (5), 1052–1064. https://doi.org/10.1016/j.watres.2006.10.036.
Nakasaki, K., Ohtaki, A., Takemoto, M., Fujiwara, S., 2011. Production of well-matured compost from night-soil sludge by an extremely short period of thermophilic composting. Waste Manag. 31 (3), 495–501. https://doi.org/10.1016/j.wasman.2010.11.011.
Nansubuga, I., Banadda, N., Verstraete, W., Rabaey, K., 2016. A review of sustainable sanitation systems in Africa. Rev. Environ. Sci. Bio/Technol. 15 (3), 465–478. https://doi.org/10.1007/s11157-016-9400-3.
Nartey, E.G., Amoah, P., Ofosu-Budu, G.K., Muspratt, A., Pradhan, S. kumar, 2017. Effects of co-composting of faecal sludge and agricultural wastes on tomato transplant and growth. Int. J. Recycl. Org. Waste Agric. 6 (1), 23–36. https://doi.org/10.1007/s40093-016-0149-z.
Nartey, E.G., Sakrabani, R., Tyrrel, S., Cofie, O., 2023. Assessing consistency in the aerobic co- composting of faecal sludge and food waste in a municipality in Ghana. Environ. Syst. Res. 12 (33). https://doi.org/10.1186/s40068-023-00323-6.
Nartey, E.G., Sakrabani, R., Tyrrel, S., Cofie, O., 2024. Storage duration and temperature affect pathogen load, heavy metals, and nutrient levels in faecal derived fertiliser. Environ. Technol. 45 (27), 5827–5837. https://doi.org/10.1080/09593330.2024.2309479.
National Institute of Urban Affairs (NUIA). (2022). Characterization of Faecal Sludge, Dewatered and Dried Sludge from Select Faecal Sludge and Sewage Treatment Plants. ⟨https://scbp.niua.org/download.php?fn=capacity_needs_assessment⟩.pdf.
Nayebare, J.G., Owor, M.M., Kulabako, R., Campos, L.C., Fottrell, E., Taylor, R.G., 2020. WASH conditions in a small town in Uganda: how safe are on-site facilities? J. Water Sanit. Hyg. Dev. 10 (1), 96–110. https://doi.org/10.2166/washdev.2019.070.
Nikiema, J., Cofie, O., Impraim, R., Adamtey, N., 2013. Processing of Fecal Sludge to Fertilizer Pellets Using a Low-Cost Technology in Ghana. Environ. Pollut. 2 (4), 70–87. https://doi.org/10.5539/ep.v2n4p70.
Nyenje, P.M., Foppen, J.W., Uhlenbrook, S., Kulabako, R., Muwanga, A., 2010. Eutrophication and nutrient release in urban areas of sub-Saharan Africa — A review. Sci. Total Environ. 408 (3), 447–455.
Okalebo, J.R., Gathua, K.W., & Woomer, P.J., 2002. In: Laboratory Methods of Soil and Plant Analysis: A Working Manual (2nd ed.).
Onabanjo, T., Patchigolla, K., Wagland, S.T., Fidalgo, B., Kolios, A., McAdam, E., Parker, A., Williams, L., Tyrrel, S., Cartmell, E., 2016. Energy recovery from human faeces via gasification: A thermodynamic equilibrium modelling approach. Energy Convers. Manag. 118, 364–376. https://doi.org/10.1016/j.enconman.2016.04.005.
Oppiah-Mensah, J., 2019. Faecal sludge disposal and health implications in Ejura - Sekyedumase Municipality. University of Cape Coast (UCC).

Preisner, M., Neverova-Dziopak, E., Kowalewski, Z., 2020. An Analytical Review of Different Approaches to Wastewater Discharge Standards with Particular Emphasis on Nutrients. Environ. Manag. 66 (4), 694–708. https://doi.org/10.1007/s00267-020-01344-y.

Puig, S., van Loosdrecht, M.C.M., Colprim, J., Meijer, S.C.F., 2008. Data Evaluation of Full-Scale Wastewater Treatment Plants by Mass Balance. Water Res 42 (18), 4645–4655. https://doi.org/10.1016/j.watres.2008.08.009.

Reid, J.B., Trolove, S.N., Tan, Y., Johnstone, P.R., 2016. Nitrogen or potassium preconditioning affects uptake of both nitrate and potassium in young wheat (Triticum aestivum). Ann. Appl. Biol. 168 (1), 66–80. https://doi.org/10.1111/aab.12243.

Rose, C., Parker, A., Jefferson, B., Cartmell, E., 2015. The Characterization of Feces and Urine: A Review of the Literature to Inform Advanced Treatment Technology. Crit. Rev. Environ. Sci. Technol. 45 (17), 1827–1879. https://doi.org/10.1080/10643389.2014.1000761.

Sadiq, M.A., 2016. Vulnerability of Smallholder Maize Farming Households to Climate Variability in the Eastern Region of Ghana. Msc Dissertation, University of Ghana.

Samal, K., Moulick, S., Mohapatra, B.G., Samanta, S., Sasidharan, S., Prakash, B., Sarangi, S., 2022. Design of faecal sludge treatment plant (FSTP) and availability of its treatment technologies. Energy Nexus 7 (May), 100091. https://doi.org/10.1016/j.nexus.2022.100091.

Seck, A., Gold, M., Niang, S., Mbéguéré, M., Diop, C., Strande, L., 2015. Faecal sludge drying beds: increasing drying rates for fuel resource recovery in Sub-Saharan Africa. J. Water Sanit. Hyg. Dev. 5 (1), 72–80. https://doi.org/10.2166/washdev.2014.213.

Semiyaga, S., Okure, M.A.E., Niwagaba, C.B., Katukiza, A.Y., Kansiime, F., 2015. Decentralized options for faecal sludge management in urban slum areas of Sub-Saharan Africa: A review of technologies, practices and end-uses. Resour. Conserv. Recycl. 104, 109–119. https://doi.org/10.1016/j.resconrec.2015.09.001.

Sommer, S.G., Dahl, P., 1999. Nutrient and Carbon Balance during the Composting of Deep Litter. J. Agric. Eng. Res. 74 (2), 145–153. https://doi.org/10.1006/jaer.1999.0446.

von Sperling, M., 2007. Waste Stabilisation Ponds. IWA Publishing.

Stefanakis, A.I., Tsihrintzis, V.A., 2011. Dewatering mechanisms in pilot-scale Sludge Drying Reed Beds: Effect of design and operational parameters. Chem. Eng. J. 172 (1), 430–443. https://doi.org/10.1016/j.cej.2011.05.111.

Strande, L., Ronteltap, M., Brdjanovic, D., 2014. Faecal Sludge Management. In L. Strande, M. Ronteltap, & D. Brdjanovic (Eds.), Water Intelligence Online (Vol. 13). IWA Publishing. https://doi.org/10.2166/9781780404738.

Strande, L., Schoebitz, L., Bischoff, F., Ddiba, D., Okello, F., Englund, M., Ward, B.J., Niwagaba, C.B., 2018. Methods to reliably estimate faecal sludge quantities and qualities for the design of treatment technologies and management solutions. J. Environ. Manag. 223 (February), 898–907. https://doi.org/10.1016/j.jenvman.2018.06.100.

Sutton, M.A., Bleeker, A., Howard, C.M., Bekunda, M., Grizzetti, B., de Vries, W., Van Grinsven, H.J.M. Abrol, Y.P., Adhya, T.K., Billen, G., Davidson, E., Datta, A. Diaz, R., Erisman, J.W., Liu, X.J., Oenema, O., Palm, C., Raghuram, N., Reis, S., Scholz, R.W., Sims, T., Zhang, Y., 2013. Our Nutrient World: The challenge to produce more food and energy with less pollution. Centre for Ecology and Hydrology (CEH) on behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative.

Thomas, A.R., Kranert, M., Philip, L., 2018. In-vessel co-composting – a rapid resource recovery option for septage treatment in Indian cities. J. Water Sanit. Hyg. Dev. 8 (4), 688–697. https://doi.org/10.2166/washdev.2018.046.

Venkatesan, A.K., Hamdan, A.H.M., Chavez, V.M., Brown, J.D., Halden, R.U., 2016. Mass balance model for sustainable phosphorus recovery in a US wastewater treatment plant. J. Environ. Qual. 45 (1), 84–89. https://doi.org/10.2134/jeq2014.11.0504.

Ward, B.J., 2022. Settling and dewatering of faecal sludge: building fundamental knowledge for improved global sanitation. Doctoral Dissertation. ETH Zurich. https://doi.org/https://doi.org/10.3929/ethz-b-000581228.

Ward, B.J., Traber, J., Gueye, A., Diop, B., Morgenroth, E., Strande, L., 2019. Evaluation of conceptual model and predictors of faecal sludge dewatering performance in Senegal and Tanzania. Water Res. 167, 115101. https://doi.org/10.1016/j.watres.2019.115101.

Wild, D., Siegrist, H., 1999. The simulation of nutrient fluxes in wastewater treatment plants with EBPR. Water Res. 33 (7), 1652–1662. https://doi.org/10.1016/S0043-1354(98)00402-3.

Yaser, A.Z., Lamaming, J., Suali, E., Rajin, M., Saalah, S., Kamin, Z., Safie, N.N., Aji, N.A.S., Wid, N., 2022. Composting and anaerobic digestion of food waste and sewage sludge for campus sustainability: a review. Int. J. Chem. Eng. 2022, 1–14. https://doi.org/10.1155/2022/6455889.