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Advancing Composting Needs and Options: Assessing the Co-composting Potential of Feacal Sludge and Selected Yard Waste Fractions

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ABSTRACT: Composting is a nature's way of recycling soil conditioners and nutrients, and the value of the resulting compost depends on the efficiency of the composting process. This study sets out to investigate the effectiveness of co-composting feacal sludge (FS) and selected fractions of yard waste (YW). Laboratory-scale aerobic composting batch experiments were designed and operated according a predefined schedule for mixing and aerating (turning) the substrates for co-composting. To measure the effectiveness of the co-composting process, evolution of temperature, moisture content, pH, organic matter and nutrients were monitored through direct measurement and laboratory analysis. A maximum temperature of 63℃ (lasting for 74hours) was attained by a treatment with substrates mixed at 1:3 (FS: YW) in the first ten days of composting. The analysis of the results indicated that a mix of FS and selected yard waste fractions that forms an average initial moisture content of 63.2% and C-N ratio of 14.1 can efficiently decompose to reduce the mass of the composting substrates by at least 26% in 30 days. The results indicated further that the concentration of nutrients (N and P) and organic matter content in the co-composting substrates decreased with composting time while the measured values of C-N ratio and non-volatile solids (NVS) were increasing with increase in composting duration. Based on the physicochemical quality attained in the current study, the compost resulting from co-composting of feacal sludge and selected fractions of yards waste has a promising potential for soil conditioning.

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In the past two decades, rapid increase in urban population has led to a dramatic increase of municipal solid waste (MSW) and feacal sludge (FS) management challenges (Chen *et al.*, 2020). In the wake of inadequate management of stormwater runoff, which is prevalent in many cities of the developing world, MSW and FS management challenges are becoming even more stringent (Justin *et al.*, 2018; Xu *et al.*, 2023). Environmental pollution caused by improper management of MSW and FS is increasingly alarming especially in fast urbanizing cities like Dar es Salaam in Tanzania (Justin *et al.*, 2018). To this end, it is critical to keep exploring new techniques for safe management of both MSW and FS which continues to threaten the public and environmental health. In many cities, improper management of the increasing organic fraction of municipal solid waste (OFMSW) is becoming a challenge of concern (Xu *et al.*, 2023).

Yard waste as a component of OFMSW is largely biodegradable (Osikabor *et al.*, 2022). However, it is characterized by high water content which impairs its biodegradability potential (Zamri *et al.*, 2021). Despite being a reservoir of energy and nutrients, when inadequately managed, yard waste cause challenges in MSW management chain leading to adverse environmental and public health impacts (Alibardi and Cossu, 2015). In recent past, the focus of yard waste management options has concentrated at yard waste reduction at source using different technologies, based on either thermal (e.g., incineration) or on biological processes (composting, anaerobic digestion) (Brown, 2016; Thengane, 2019). While incineration of yard waste is limited by low heating value of its contents (Nelles *et al.*, 2010), composting is often challenged by several shortcomings in term of air pollution and

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uncertainties associated with its compost quality (Meyer-Kohlstock *et al.*, 2013).

Like what happens with OFMSW, FS management silently presents another growing challenge in many low-income and rapidly growing cities of Africa (Klinger *et al.*, 2019; Singh *et al.*, 2017). Manageability and treatability of FS is highly impeded by its high-water content behaviour (Qian *et al.*, 2016; Syed-Hassan *et al.*, 2017). Technically, many FS treatment options demand relatively expensive primary and secondary treatment components for dewatering and treatment of the thickened sludge respectively. In practice however, a bigger population in many rapidly growing Africa cities rely on poorly operated and inadequately managed onsite sanitation systems (Klinger *et al.*, 2019).

Consequently, a small fraction of FS is properly contained and adequately managed (Klinger *et al.*, 2019). Among others, the latter is exaggerated by long haulage distances, lack of proper disposal sites and elevated disposal fees of sludge (Semiyaga *et al.*, 2015). Taking the advantage of their differences in physical-chemical characteristics, FS and yard waste present a promising co-composting potential for recovery of nutrients and other soil conditioning elements.

Despite the advancement in science and technology, the adoption and prevalence of sludge management options in cities of the developing world remains a growing challenge and the need for alternative FS treatment techniques continues to loom wide. This paper therefore, sets out to examine the co-composting effectiveness of FS and selected yard waste fractions as a means to address both FS and yard waste management challenges while enhancing the utility of the resulting compost.

MATERIAL AND METHODS

To achieve the intended objectives, this study was proceeded by a series of preliminary lab-scale experiments to establish suitable baseline conditions necessary for co-composting the intended feed materials. The FS and yard wastes used in experiments were collected from around Ardhi University campus in Dar es Salaam -Tanzania.

Experimental Setup: Four units of raised composting bins each with 1.3m. x 1.5m x 1.50m (H x W x L) internal dimensions were designed and assembled. To limit moisture losses, the walls of the composting bins were made from cement-sand blocks while the bottom was made of reinforced concrete (Figure 1 left). Besides being raised, twelve equally spaced holes (Ø = 25mm) were drilled at the bottom of each composting bin to enhance aeration of the composting materials.

Processing of feed materials: Since effective composting requires some initial conditions, both FS and yard wastes had to be processed before feeding them into the composting bins. After the removal of visible non-biodegradable debris from both sludge and yard waste, FS was stored into a sludge drying bed for 24 hours reducing its moisture content to around 70%. Since yard waste was also serving as balking agent, to achieve the initial moisture conditions of feed materials, dry yard wastes with (moisture content ≤ 45.8%) was used. Table 1 summarizes the characteristics of other feed materials. For further processing, a mechanical lab-scale waste shredder (Mercodor, type ZM1) was used to improve the surface area of yard waste by chopping it into smaller pieces (about 2cm long). The same shredder was also used to refine the final compost to meet the needed texture and improve its utility.

Fig 1: Typical appearance of composting bins

Table 1: Characteristics of co-composting feed materials

Parameter Monitored	Yard Waste	Feacal Sludge
Moisture content (%)	45.8 ± 0.14	70 ± 0.21
Organic carbon (g/kg)	71.2 ± 2.5	58.2 ± 1.70
Total nitrogen (g/kg)	7.68 ± 0.41	22.05 ± 0.91
Total phosphorus (g/kg)	8.62 ± 1.8	159 ± 4.70
Nitrate nitrogen, NO3 – N (g/kg)	10.5 ± 0.2	9.8 ± 0.85
NH4 - N	8.21 ± 0.81	3.4 ± 0.34
Ration of carbon to nitrogen (C/N Ratio)	12.31 ± 0.26	18.33 ± 0.87
pH	63 ± 0.12	6.7 ± 0.24

NB: The values reported are mean ± standard deviation of three replicates

Experimental design: To achieve the study objectives, the influence of feedstock mixing ratios (MR) and turning frequency (TF) of the co-composting materials had to be monitored as they are necessary in attaining initial composting characteristics. As such, each experimental batch was designed to have four treatments (T): the control experiment (C) and treatments- T1, T2, & T3 (Table 2) in two replicates. With reference to Table 2, the rows of experiment batches and their replicates meant to test the influence of feedstock mixing ratios where MR varies while TF was kept constant, and the columns of each treatment meant to test the effect of turning frequency where TF varies while MR is kept constant. The feed materials in the control experiment were similar to that of other treatments but neither TF nor MR was varied.

Table 2: Experimental design for feedstock turning frequency and mixing ratios

Experiments conducted		Treatments (T) of the Experiments conducted							
Batch	Replications	Control (C)		Treatment (T1)		Treatment (T2)		Treatment (T3)	
		MR	TF	MR	TF	MR	TF	MR	TF
Batch 1	R1	1:2	0	1:2	4	1:3	4	1:4	4
	R2	1:2	0	1:2	4	1:3	4	1:4	4
Batch 2	R1	1:2	0	1:2	7	1:3	7	1:4	7
	R2	1:2	0	1:2	7	1:3	7	1:4	7
Batch 3	R1	1:2	0	1:2	9	1:3	9	1:4	9
	R2	1:2	0	1:2	9	1:3	9	1:4	9

NB: R = Replications, MR = Mixing ratio (feacal sludge: Yard waste), TF = Turning frequency (in days).

Operation and monitoring of the experiment: Loading of feed materials into the composting bins was governed by two main factors- mixing ratios of the feed materials and their initial moisture content. Co-composting however, was preceded by the analysis of the initial phyco-chemical characteristics of the feed materials (Table 1). Following the design of the experiment, a known fraction of FS was thoroughly mixed with a known ratio of compacted yard waste and loaded into the composting bins. The composting mixture was then covered by a 2mm thick black plastic sheet to prevent moisture losses through evaporation (Figure 1 right). As an indicator of microbial activities, temperature was monitored onsite. The ambient temperature and that of the feed materials were measured twice a day (around 7.30 am and 6.30 pm). Temperature monitoring continued until the temperature in the composters was almost equal to that of ambient temperature.

Sampling and analytical procedures: Laboratory analysis of physico-chemical characteristics involved the measurement of temperature, moisture content (MC), pH, total phosphorus (TP), total organic matter (TOM), and water soluble total Kjeldahl nitrogen (TKN), C-N ratio, ammonium nitrogen (NH_4-N) and nitrate nitrogen (NO_3-N). Samples of about 250 g were collected after every 24 hours and dried in an oven at 105°C for 24 hours; the weight loss was considered as moisture content. For pH measurement, the samples were mixed with distilled water at a weight ratio of 1:10. The mixture was then shaken for thirty minutes and later allowed to settle under quiescent conditions. Having the supernatant settled, a pH meter (HQ30d Flex LDO) was used to measure the pH of the top clear liquid. Both NO_3-N and phosphorous (as PO43-P) were measured by HACH Spectrophotometer (DR/4000). Based on the standard methods (APHA, 1992), TKN and TOM were measured using a TKN analyzer (Model: DX-VA-TS) and a TOM analyzer (Hach-QbD1200-TOC) respectively, on samples that had been centrifuged at 2000 rpm for 15 minutes and filtered through a 12.7mm Whatman filter paper (model: WHA-10311862). The enumeration of Helminth eggs (cyst) in final compost as an indicator of pathogenic microorganisms was done following the Moodley *et al.* (2008) methodology.

RESULTS AND DISCUSSION

In this study, results from laboratory analysis indicated that evolution of feedstock physicochemical properties was insignificantly influenced by turning (mixing) frequency of co-composting feedstock. Analysis results of changes in feedstock physico-chemical properties during the composting process are summarized in Table 3. The observed changes were mainly influenced by preliminary processing and mixing ratios of co-composting feedstock. Using temperature as an indicator of microbial processes, no significant microbial activity was observed beyond day 28. As such, changes in feedstock physico-chemical properties presented in Table 3, is a difference between the initial characteristics (day 1) of the composting feedstock and that of the final compost (day 30). With reference to Table 3, results indicate that little changes in physical chemical characteristics (including mass loss) were observed in control experiments. Results indicate further that while the measured values of C-N ratio and non-volatile solids (NVS) were increasing with increase in composting duration, measured values of the remaining monitored parameter were comparatively decreasing. Added to the above observations, the analysis of the results denotes that a mix of FS and selected yard waste fractions that forms an average initial moisture content of 63.2% and C-N ratio of 14.1 can effectively decompose to reduce the TVS of the composting substrates by 26% in 30 days.

Table 3: Changes of physico-chemical characteristics of the feedstock and resulting compost

Parameter	Time (days)	Control (C)	Treatment (T1)	Treatment (T2)	Treatment (T3)
MC (% d.w)	1	73.1±0.21	66.8±0.14	65.33±0.30	63.2±0.51
	30	72.21±0.35	54.78±0.34	58.01±0.47	51.05±0.07
TOM (% d.w)	1	63.22±1.70	72.98±0.10	67.6±3.00	70.2±2.50
	30	64.13±1.60	69.25±1.80	65.83±3.00	67.09±2.80
TKN (% d.w)	1	1.98±0.08	3.37±0.01	2.05±0.07	2.90±0.09
	30	2.08±0.10	2.13±0.04	1.73±0.01	2.17±0.07
TP (mg/Kg)	1	154±4.70	118.6±1.8	135.7±4.10	120.3±6.9
	30	142±3.70	105±2.40	116.5±3.70	102.5±5.10
C-N ratio	1	15.89	10.49	15.2	12.31
	30	14.5	14.11	16.38	14.34
NO3-N (mg/Kg)	1	9.80±2.70	10.5±4.2	12.6±1.98	14.2±4.6
	30	10.50±0.80	8.5±1.70	20±0.90	18±2.101
NH4-N (mg/Kg)	1	0.22±0.03	0.28±0.09	0.22±0.001	0.27±0.01
	30	0.19±0.04	0.10±0.01	0.13±0.09	0.15±0.06
NVS (g/g)	1	0.22	0.26	0.24	0.19
	30	0.25	0.51	0.48	0.51
pH	1	6.8±0.3	6.7±0.01	6.30±0.20	6.40±0.01
	30	7.20±0.1	7.1±0.01	6.8±0.22	6.9±0.07
Mass loss (% of Initial)	30	3.8%	20.3%	31.5%	25.9%

NB: The numbers in the table are mean values followed by standard deviation.

The efficiency of co-composting FS and selected fractions of yard waste was mainly assessed in terms of humification and sanitation of composting feedstock resulting from microbial processes and temperature rise respectively. Loss of mass due to structural breakdown of organic compound and organic matter mineralization is an important composting attribute as a solid waste management option (Xu *et al.*, 2023). Change in mass and volume of the composting feedstock was measured in terms of non-volatile solids (NVS) and presented in Table 3.

Among the studied parameters, monitoring of moisture content (MC) was critical and it was controlled before, during and after the composting process. According to Kumar *et al.* (2010), excess moisture in the feedstock affects the microbial activity, the composting temperature, and the rate of decomposition in general. In the current study the moisture content was generally decreasing, dropping by 16% from an average of 65.1% to 54.8% for compost feedstock and final compost respectively. The initial moisture of feedstock was highly governed by the water content of FS remaining after the preliminary dewatering processes and the amount of yard waste added in the mix. Water content of the feedstock decreased with an increase of both composting time and fraction of yard waste in the mixture. No helminth eggs were observed in final compost despite the fact that excessive moisture loss was checked by springling the liquid collected from dewatering of FS. Figure 2 and 3 summarizes the performance results of co-composting FS and selected fractions yard waste in terms of temperature rise and mineralization of feedstock organic matter respectively. With reference to Figure 2, it can be observed that maximum temperature of 63 °C (T2), 55 °C(T1), and 46 °C (T3) for the 1:3, 1:2, and 1:4 (FS: YW) mixtures respectively, was attained in the first ten days of composting and a slight drop in temperature was also observed after every feedstock turning session. It can also be observed in Figure 2 that with exception of the control experiment (in which excessive moisture might have limited microbial activity), in the remaining experiments the temperature sharply rose showing the advantage of using FS which comes with a good population of microorganism for instant action on the feedstock.

Despite a sharp rise in temperature during the mesophilic phase, the actual thermophilic temperature (63°C) did not last long (about 72 hours) and the compost attained equilibrium with ambient temperature in 30 days (Figure 2). This observation demonstrates the effects of microorganism in FS causing faster microbial activity in preliminary stages of composting leading to quick depletion energy sources (Liu *et al.*, 2011). High and long-lasting temperature is often crucial for sanitation and safety of the resulting compost (Papale *et al.*, 2021). According to Manga *et al.* (2022), practical applicability of the compost is defined by the level of the remaining pathogens, nutrients and other pollutants including heavy metals and carcinogens. Drop in temperature stems from various causes including aeration of the feed materials, energy loss and decrease in moisture content all of which results into a decreased rate of microbial activity. However, Fan *et al.* (2021) asserts that drop in temperature can also be caused by the death by temperature sensitive microorganisms.

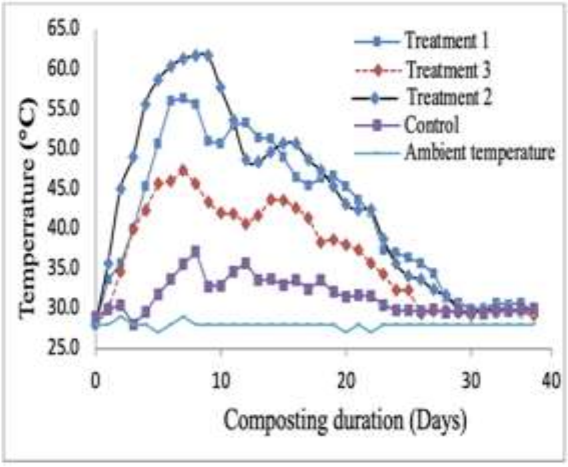

Fig 2: Recorded temperature profiles in pile composting chambers

Generally, the organic matter content of the feedstock decreased during the co-composting of FS and yard waste (Table 3 and Figure 3). Normally, as organic materials decompose, both volume and mass of the feedstock decrease due to the mineralization of organic matter into CO_2 and H_2O (Kumar *et al.*, 2010).

However, unexpected increase of TOM was noticed in Treatment 2 and in the control experiment (Figure 3). Breitenbeck and Schellinger (2004) argue that hydrolysis of solid organic materials to water soluble organic matter by microorganisms may explain the minor increase in TOM concentration in early stages of composting process. Moreover, it was surprisingly noted that there was no strong correlation (r = 0.33) between the percentage of organic matter initially present in the feedstock and loss of organic matter occurred during the composting process. This observation accentuates that organic matter content of the feedstock is less decisive in estimating the quantity of the final compost than the differences of the feedstock biodegradability potential. According to Breitenbeck and Schellinger (2004) many other inert constituents of the feedstock such as metals, minerals, and other inorganics persist beyond decomposition processes forming a part of the finished compost. It is worth noting, however, that TOM governs the stability of compost (Sharma and Yadav, 2018) and in dry weight basis ≥60% of organic matter content is recommended in finished compost to achieve a wider application as soil conditioner (Paradelo *et al.*, 2010).

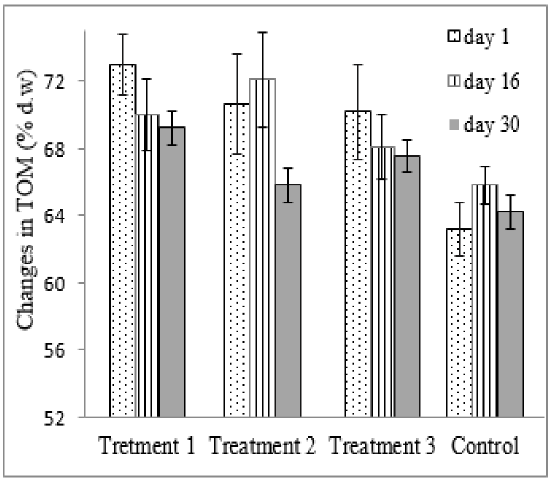

Fig 3: Transformation of total organic matter (TOM) during co-composting

Figure 4 and 5 present concentration trends of nutrients (N & P) during the co-composting of FS and yard waste in different mixing ratios. There was a general increase of total nitrogen in preliminary stages of composting which may be caused by weight reduction in the compost bins (Manga *et al.*, 2022). Unlike the phosphorus trend (Figure 5), a slight decrease in TKN concentration (Figure 4) was observed in the second week of composting and a slight increase was also noted towards the compost maturation phase (day 30). Decrease in total nitrogen in the second week (day 16) of composting, presumably caused by decomposition of proteins and amino acids, volatilization of ammonia and nitrification of NH_4-N into nitrate. This observation has also presented in several composting studies (Fan *et al.*, 2021; Kumar *et al.*, 2010). Statistical analysis of the total nitrogen in all treatments indicated further that TKN was significantly affected by feedstock mixing ratios in the final compost (P=3.71x10-4). With reference to Table 3, Treatment 3 with feedstock mixing ratio of 1:4 (for FS: Yard waste) attained the highest average TKN of 2.17 (% d/w) in finished compost. Analysis of the results signified further that regardless of the intermittent rising and falling of total carbon in the composting substrates, C-N ratio in all treatments was relatively increasing with composting time (Table 3). Similar observation is also reported by Manga *et al.* (2022) and Kumar *et al.* (2010). With reference to Figure 5, the transformation of total Phosphorus (TP) in all experiments revealed comparatively a similar trend. Except for the control experiment, where very little mass loss was revealed (Table 3), the concentration of TP remained relatively unchanged in the first two weeks of composting and a minor decrease was observed towards the maturation phase. Statistical analysis of total Phosphorus data, in all compost piles showed no significant effect on the TP turnover in the final compost (measured at day 30 of composting). Looking at trends of data analysis, TP results for this study could not agree with findings described by Zhong *et al.* (2023) and Huang *et al.*

(2016) reporting a rise in TP during composting process due to mineralization organic matter and overall mass loss of compost feedstock.

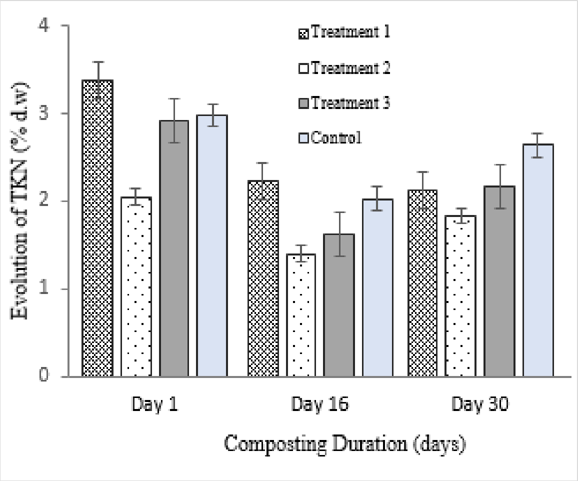

Fig 4: Transformations of Total Kjeldhal nitrogen (TKN) during co-composting

According to Lanno *et al.* (2021), while FS is widely known for its richness in TP, green waste is commonly low in phosphorus content. This argument might demonstrate why compost piles with many parts of yard waste (1:3 and 1:4 for Treatment 2 and Treatment 3 respectively) had lower TP concentration as compared to those with smaller parts of the same. It is worth noting however that, the majority forms of phosphorus in the FS are often bound to iron (Fe) and aluminum (Al) an aspect that may reduce the availability of phosphorus to plant uptake when the final compost is used as fertilizer (Lanno *et al.*, 2021; Yan *et al.*, 2020).

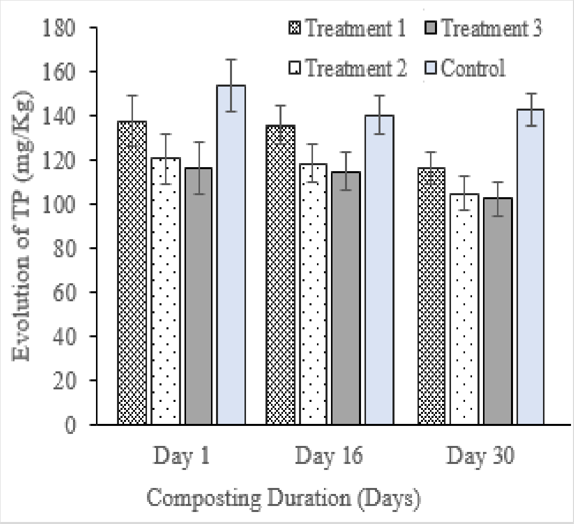

Fig 5: Transformation of total phosphorus (TP) trends during co-composting

Based on the proceeding discussion, the study results demonstrate the possibility and effectiveness of co-composting FS and selected yard waste. Results suggest further that in terms of mass/volume reduction, humification and nutrients condensation (Figure 3 & 4), co-composting of FS and yard waste fractions mixed at 1:3 (other composting necessities abided) performs acceptably well to save as an additional means to abate both FS and yard waste management problems. According to Campuzano and González-Martínez (2016) and Manga *et al.* (2022) the strength of composting as a method of waste management is judged by its ability to recycle soil conditioning elements and essential plant nutrients in the soil (Chen *et al.*, 2020). Knowledge on decrease in mass and volume of composting feedstock is an important consideration in decisions about compost operation and management (Breitenbeck and Schellinger, 2004). Findings of the current study demonstrate that characteristics of FS and selected yard waste fractions complements well to form amenable substrates suitable for humification and sanitation of compost feedstock. The study has demonstrated further that as long as FS and yard waste are mixed to achieve initial moisture content between 50 and 60% can decompose to reduce the TSV of the composting substrates by at least 20%. However, a number of other factors such as stability of FS, types and bulkiness of yard waste may need to be considered for field operationalization of the presented results. Practical applicability of composting as a waste management alternative is governed by the versatility of compost uses and is highly influenced by its security to public health and the environment (de Souza and Drumond, 2022). Despite having the study objectives achieved, the knowledge about the quality of compost in terms of heavy metals mobilization and pathogen contamination, in addition to the nature and forms of nutrients (N and P), is equally important for a candid applicability recommendation of the final compost (Huang *et al.*, 2016). While the latter factors are deserving more investigation efforts, in virtual of the findings presented in the current study the physicochemical quality of the reported compost (Table 3) has a good potential to be applied as a soil conditioner.

Conclusion: In this study the feasibility of co-composting feacal sludge and yard waste fractions is positively testified. It is indicated that when feacal sludge and yard waste fractions are blended to achieve initial moisture content between 48 and 64% and C-N ratio between10.5 and 15.4 can effectively decompose to lessen the mass of the composting substrates by more than 20%. Based on findings, the compost resulting from co-composting of feacal sludge and yard waste fractions has a soil conditioning potential.

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