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Fertilizer quality and carbon sequestration potential of compost from Municipal organic solid wastes in Uganda

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Abstract

Municipal Organic Solid Wastes (MOSW) remains a major urban challenge in developing countries, yet it is a valuable resource for agricultural production. Large quantities of MOSW cause environmental pollution via greenhouse gas (GHG) emission. A study on nine municipal waste management plants estimated GHG mitigation using the IPCC Tier 1 model and evaluated the quality of compost. Composting MOSW reduced CH_4 emission from 4391.7 Mg year^{-1} by landfill to 516.8 kg year^{-1}. The compost generated added 3886 and 7.8 Mg year^{-1} of organic carbon and stable carbon into the soil, respectively. The plants produced compost with a fertilizer potential of 9,886, 20,247 and 102,892 ha of N, P and K, respectively. The quality of compost significantly varied across the plants and months attribute aligned to different agroecological zones and agricultural seasons, respectively. The concentrations of total nitrogen ranged between 7.06 - 15.44 g kg^{-1}, whereas it was 81.7 - 160.6 g kg^{-1} for organic carbon; with C: N ratio < 12 indicative of matured compost. The concentrations of phosphorus in the CDM compost ranged between 3.03 to 3.37 g kg^{-1} while potassium was 10.30 to 51.42

g kg^{-1}, calcium 12.42 to 55.56 g kg^{-1} and magnesium 1.3 to 5.48 g kg^{-1}. The maximum detected concentration of Pb was 51.1 mg kg^{-1} indicating low risk of Pb accumulation in soil following application of compost. Therefore, composting the MOSW reduced GHG emission and recovered fertilizer resources with low-risk heavy metal contaminants. The MOSW compost could substitute for the imported organic fertilizer forms into the country.

Key words: Composting, compost-quality, greenhouse gas, methane, Municipal Organic Solid Waste

Introduction

There is growing global urbanization, particularly in sub-Saharan Africa (SSA), which has led to increased wastes in cities that have limited land capacity for waste management. Komakech *et al*. (2014) estimated that at least 28 Gg per month of Municipal Organic Solid Wastes (MOSW) was generated in Kampala city, which corresponds to similar quantities of wastes generated in equivalent cities in SSA. Cumulatively, these quantities of MOSW contribute to substantial greenhouse gas (GHG) emissions. The primary disposal method of wastes in SSA is in waste lands or poorly planned and managed landfills (Rotich *et al*., 2006). Most landfills in SSA are poorly constructed and managed causing high greenhouse emissions and environmental degradation (Shimelis *et al.*, 2024). Besides, landfills space is diminishing within or in the vicinity of cities in developing countries, forcing the authorities to seek disposal sites at a long distance out of the cities thereby experiencing increasing costs of transporting the solid wastes.

Incidentally, the MOSW contain at least 90% biodegradable wastes constituted by food and food wastes, garden, yard and park waste, and paper and pulp wastes (Komakech *et al*., 2014; Tibihika *et al*., 2021; Gebrekidan *et al*., 2024; Zhang *et al*., 2024). The high constituent of biodegradable MOSW makes it suitable for circular economy to generate energy (biogas) or organic fertilizer (compost) under the anaerobic and aerobic treatments, respectively. Waste to fertilizer through composting is the most practical in SSA because of its affordable cost of infrastructure and technologies; and research has demonstrated the importance of MOSW compost for improvement of soil fertility and crop yields (Salis *et al*., 2024).

Sub Saharan African has low and declining soil fertility, constraining agricultural productivity and exacerbating high food insecurity and nutrition in the region. Declines in soil organic matter (SOM) in SSA is attributed to continuous cultivation without manure inputs yet the tropical conditions of high temperature and moisture favor rapid organic matter decomposition and mineralization. The decline in SOM is a threat to soil health as it is an indicator of soil health and crop yield (Lal, 2007; Musinguzi *et al*., 2016). SOM influences soil fertility and productivity, biodiversity, soil structure stability and infiltration characteristics. On the other hand, plant nutrients are mined in large quantities through crop harvesting, exacerbating low soil fertility and yields. The most deficient plant nutrients include nitrogen, phosphorus and potassium, which are abundant in MOSW (Tibihika *et al*., 2021; Gebrekidan *et al*., 2024). Negative nutrient balances in Uganda were reported at 35 - 100 kg N, 10 - 20 kg P and 30 - 170 kg K per hectare per year (Kaizzi *et al*. 2004), values far higher than the average negative nutrient balances for SSA at 22 kg N, 2.5 kg P and 15 kg P ha^{-1} yr^{-1} (Smaling *et al*. 1993). The situation is made worse by the average rate of inorganic fertilizer application in Africa stands at less than 20 kg ha^{-1} (FAO, 2023), attributed to high cost and low availability. Yet, Amoding (2007) reported that 47, 7 and 133 Mg $year^{-1}$ of N, P and K, respectively, were being lost in MOSW in Kampala city alone, which must be much more after 20 years given the increasing quantities of MOSW proportional to population growth in Uganda (UBOS, 2016). Thus, there is a high fertilization potential of compost from MOSW to alleviate low soil fertility and reverse perennial negative nutrient balances.

Municipal organic waste composting is globally advocated as a feasible alternative, which carries a benefit of increasing agricultural production. Composting MOSW diverts organic waste from landfills and thus reduces on greenhouse gas emissions, the cost of waste management yet producing compost that is environmentally and economically valuable for improving soil productivity (Wolkowski 2003; Hargreaves *et al*. 2008). Indeed, composting of MOSW as a management option has been used by several urban authorities in developing and developed countries (Otten, 2001; Gebrekidan *et al*., 2024; Zhang *et al*., 2024). Composting has been promoted as a waste management technology because it reduces volume and greenhouse gas emissions, destroys weed seeds, pathogen and malodorous compounds present in plant and animal residue waste (Jakobsen, 1995, Khan *et al*., 2022). Nevertheless, there are reports of MOSW compost containing high concentrations of heavy metals and other organic pollutants that pose a risk to the environment (Yuksel, 2015) such as cadmium, lead, nickel, zinc, chromium, and copper (Cao *et al.*, 2023). Therefore, the quality of compost is essential for its utilization in soil fertility management.

The Government of Uganda put a deliberate effort to manage municipal organic solid wastes through composting to reduce on environmental pollution and cost of waste management through the initiatives of Clean Development Mechanisms (CDM) in 18 plants established across the country beginning in 2009. Therefore, this study aimed to: i) evaluate the quality of compost from nine CDM Municipal Composting plants in Uganda over a period of one year, and ii) estimate reductions in greenhouse gas emissions and potential for carbon sequestration as a result of the CDM mechanism. This is important in developing and appreciating the environmental value of CDM composting plants and deriving the compost fertilization potential of these establishments in Uganda.

Material and methods

Sites descriptions and plant operating procedures

The study was conducted in the period 2016-2017 on nine municipal composting plants spread in different part of Uganda, i.e., Kabale, Mbale, Mbarara, Fort Portal, Kasese, Mukono, Jinja, Soroti, and Lira municipalities (Fig. 1); seven years after the composting plants were established. Unsorted MOSW excluding medical and other hazardous wastes were delivered by trucks and loaded into windrows. A few workers were employed to partially sort and remove polyethene, glass and other non-biodegradable wastes at pre-windrow formation and during turning. The characteristics of fresh MOSW was described in Tibihika *et al*. (2021). In brief, the fresh wastes

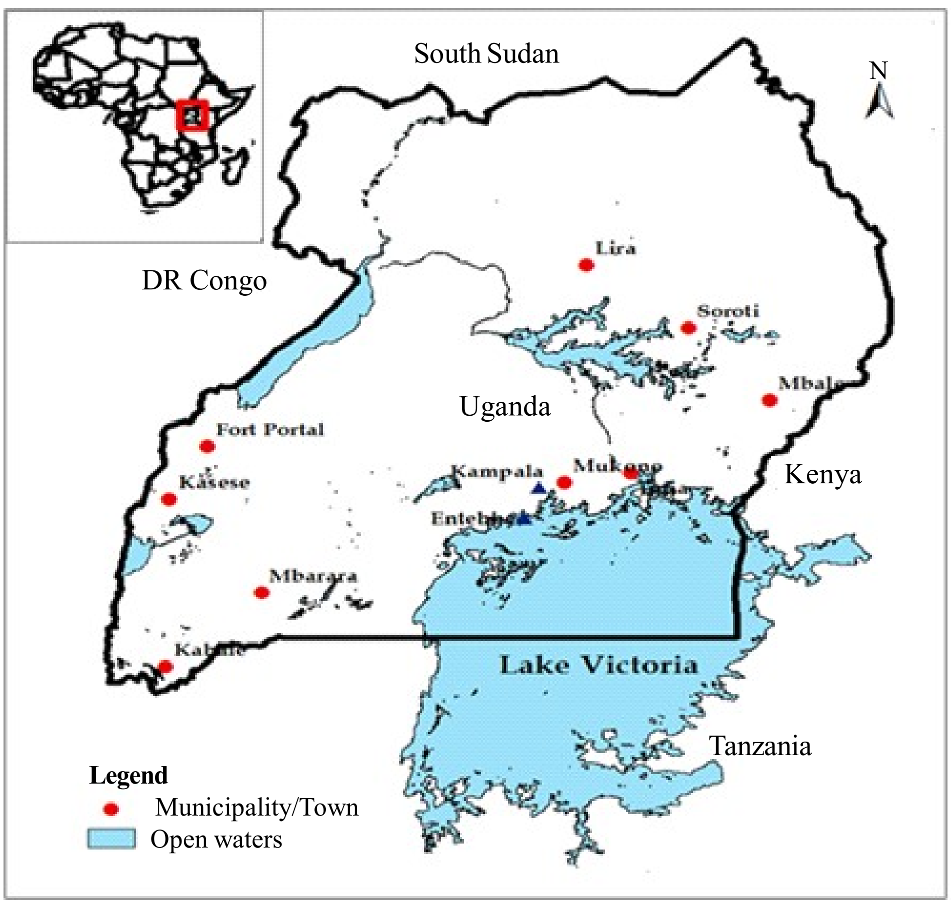

Figure 1. Locations of the Municipal waste composting sites (Tibihika *et al*., 2021).

contained 96% biodegradable organic matter, average pH of 7.7, total organic carbon of 318 gkg^{-1} and nitrogen at 12 gkg^{-1}, and varying concentrations of plant nutrients attributed to economic activities and population lifestyles. These MOSW composting sites were located in different agro-ecological zones of Uganda, which vary in the composition of wastes received and quality of MOSW at the different composting sites. The partially sorted MOSW then was put into the first windrow. The wastes in windrows were turned using a tractor while shifting progressively to maturity windrow. The first windrow (fresh waste windrow) was 27 m long, 4m wide and often heaped to maximum 2.5 m high at full formation. These wastes were transferred to the second, then third windrows after every 10 - 14 days. The second and third windrows were 18 m long, 4 m wide, and also heaped to 2.5 m high. The materials are then transferred to fourth, and fifth windrows, of dimensions 4 m wide 2.5 m high and 18 m long, and then onto the final windrow (4 m wide, 2 m high and 13.5 m long) to mature; followed by drying, sieving to produce the compost. The leachate was collected in an underground tank of 5000 m^3 and reused to moisten materials during composting. Total days from feedstock introduction in the first windrow to mature compost in the last windrows took 60 - 70 days.

Compost sampling and laboratory analysis

The mature compost windrow was divided into five equal parts by area covered. This was followed by sampling from 10 random sampling points using a one-litre cup to scoop compost within each subdivision of the compost windrow. The 10 sub-samples were mixed following the quarter sampling procedures, and was reduced to 1 kg. A total of five composite samples from a matured compost windrow were collected per plant, every four months over a period of 16 months. In the laboratory, compost samples were analysed for pH, total organic carbon, Kjeldahl nitrogen, total phosphorus, calcium, magnesium, lead, cadmium, chromium and electrical conductivity.

Briefly, compost pH and electrical conductivity were measured with hydrogen ion and salt sensor electrodes, respectively in a distilled and deionised water in a ratio of 1:10 (v/v) after mechanical shaking for 1 hour on a rotary shaker. A sub sample of 50g of air-dried compost samples was digested with freshly prepared salicylic acid digestion solution at 360°C until white ash and a clear solution were formed. This extract was used for analysis of total nutrient and heavy metals in compost. The concentration of total nitrogen was determined following Kjeldahl methods and phosphorus using the UV spectrophometer, while total potassium measured on a flame spectrophotometer (Okalebo *et al*., 2002). The same extract was used to determine the concentrations of calcium, magnesium, lead, cadmium and chromium using Atomic Absorption Spectrophotometer. The concentration of total organic carbon was determined based on Walkley and Black method as described in Okalebo *et al*. (2002) where a 5 g of air-dried compost sample was oxidized with 50ml of 0.5M Potassium dichromate catalyzed by concentrated H_2SO_4 at 150^oC for 30 minutes, allowed to cool and then titrated with 0.5M Ferrous ammonium nitrate.

Land fertilization potential of produced compost

The compost fertilization potential was calculated based on the actual nutrient concentration from laboratory analysis of the compost samples and the fertilizer rate recommendation of the main crops in each agroecological site of the compost site. The major crops were potato (*Solanum tuberosum*) for Kabale; banana (Musa x paradisiaca) for Mbale, Mbarara and Fort Portal sites; maize (*Zea mays*) for Kasese, Mukono, Jinja and Lira sites; and sweet potato (*Ipomea batatus*) for Soroti site. The fertilizer rates for banana used were elemental 60 kgN, 30 kg P and 90 kg K ha^{-1}; rates for maize were 60 kgN, 30 kg P and 60 kg K ha^{-1}, sweet potato 50 kgN, 30 kg P and 60 kg K ha^{-1}, and potato 80 kgN, 20 kg P and 60 kg K ha^{-1} per season. Uganda has bimodal rainfall and two season per year. The land fertilization potential of compost produced was estimated using procedures adopted by Shimelis *et al* (2024):

$$LFP = \frac{Qcompost\ x\ compost\ NPK\ x\ Available\ NPK}{NPK\ requirement} \quad \text{.................. Equation 1}$$

Where: LFP is the Land fertilization Potential (hectares), *Q compost* is quantity of compost generated per compost sites (Gg $year^{-1}$, dry weight), *compost NPK* is the content of N, P, K in compost (Gg $year^{-1}$), *Available NPK* is % of N, P and K released in first year (22% for N, 66%P and 93%K), *NPK requirement* is the N, P and K application rate based on the major crop grown in the agroecological zone where the compost site is located.

Estimating greenhouse gas emissions and potential carbon sequestration of composting

The emission of methane during composting was estimated using default IPCC emission factors (IPCC, 2006) of 4kg CH_4 and 0.3kg N_2O per quantity of fresh municipal organic waste (Gg) as delivered to the composting site (wet basis) using equation 2 (Menikpura and Sang-Arun, 2013):

$$eGHG = (eCH_4 \text{ x } GWP_{CH4}) + (eN_2O \text{ x } GWP_{N2O}) \quad \text{.............................. Equation 2}$$

Where: *eGHG* is estimated greenhouse gas emission during composting (Gg $year^{-1}$), eCH_4 and eN_2O are methane and nitrous gas emission (Gg $year^{-1}$) during composting; GWP_{CH4} and GWP_{N2O} are the global warming potential of methane and nitrous IPCC default at 27.2 and 273 (IPCC, 2022).

The potential methane emission if all the MOSW were disposed of in the unmanaged landfills was estimated using equation 3 (IPCC 2006; Tun and Juchelkova, 2019):

$$eCH_4 = \left[\left(MOSW_t \times MOSW_f \times MCF \times DOC \times DOC_f \times F \times \left(\frac{16}{12}\right) - R\right) \times {}^{1\text{-}OX}\right]$$

.... Equation 3

Where: eCH_4 is methane emission from landfilling per site (Gg year^{-1}), $MOSW_t$ is total fresh MOSW received per site (Gg year^{-1}, wet basis), $MOSW_t$ is the fraction disposed in landfill (wet basis), MCF is a methane correction factor, DOC and DOC_t are degradable organic carbon and fraction of degradable organic carbon, respectively; F is fraction of methane generated from landfilling, R is recovered methane from landfilling (zero for unmanaged landfills), $\frac{16}{12}$ is a molecular weight ration of methane to carbon, and ^{OX} is the oxidation factor (zero for unmanaged landfills).

The produced compost was all (100%) used for agriculture as organic fertilizer. The study adopted approach by Shimelis *et al*. (2024) and estimation of annual carbon sequestration (equation 4) was based on the assumption that 38% of total organic carbon is the carbon sequestered (Shimelis *et al*., 2024; Castro-Herrera *et al*., 2021). Secondly, it was assumed that 2% of the sequestered organic carbon is stabilized in soil after application of compost (Boldrin *et al*., 2009):

$$Csq = Qcompost \ x \ TOC \ x \ fSC$$ .... Equation 4

Where: Csq is quantity of sequestered organic carbon following compost application (Gg year^{-1}, dry weight); is the quantity of compost applied Gg year^{-1}, dry weight), TOC is total organic carbon content in compost (quantity applied x % organic carbon), is the fraction of organic carbon stabilized in soil following compost application (2%).

Data analysis

Data were subjected to analysis of variance using Genstat software (24th Edition). Plant site and the different sampling dates were the factors considered. pH data were normalized by logarithm transformation before analysis variance. The means were compared using Least Significant Difference at 5%; and boxplots for visualization of data were synthesized using 27th version of IBM SPSS Statistics.

Results

Compost quality

Electrical conductivity

There were significant variations in the electrical conductivity of compost from different sites ($p< 0.001$) in the different months ($p< 0.001$) and amongst sites at different months ($p< 0.001$). The minimum and maximum EC values of 1580 and 3760 µS cm^{-1} were measured in compost from Soroti and Mbarara plants, respectively in the May 2016 (Table 1). Indeed, compost from Mbarara plant had a consistently and significantly high EC followed by Kasese while Lira and Soroti plants had compost with low EC.

Table 1. Electrical conductivity (µS cm^{-1}) of compost generated at different municipality composting sites in Uganda

Composting plant	Month of sampling					Mean[1]
	May 2016	Sept 2016	Jan 2017	May 2017	Sept 2017	
Fort Portal	2340	2600	2860	2700	2816	2663
Kasese	2460	2640	2780	2860	2800	2708
Mbarara	3760	3420	2860	2640	2804	3097
Kabale	1580	2258	2640	2740	2590	2362
Mukono	2520	2660	2820	2840	2668	2702
Jinja	2220	2920	2860	2760	2800	2712
Mbale	1880	2660	2780	2840	2700	2572
Soroti	1580	2080	2640	2940	2660	2380
Lira	1600	2160	2660	2660	2808	2378
Mean[1]	2216	2600	2767	2776	2738	2619

[1]Amongst the sites ($P< 0.001$; $LSD_{0.05} = 146.9$); months ($p< 0.001$; $LSD_{0.05} = 109.5$); and sites*months ($p< 0.001$; $LSD_{0.05} = 328.6$).

pH

The pH of compost obtained from the municipal plants was alkaline but varied significantly amongst municipalities ($p< 0.001$), months ($p< 0.001$) and amongst sites by months ($p< 0.001$). Compost generated in September 2017 was most alkaline (average pH = 10.09) while the least alkaline compost was noted in May 2016 (average pH = 9.00). The minimum and maximum pH of 8.72 and 10.36 were noted in compost produced at Lira and Fort Portal plants, respectively (Table 2).

Table 2. The pH of compost generated at different municipality composting sites in Uganda

Composting plant	Month of sampling					Mean[1]
	May 2016	Sept 2016	Jan 2017	May 2017	Sept 2017	
Fort Portal	9.12	9.57	9.74	9.40	10.36	9.64
Kasese	9.02	9.39	9.70	9.31	9.72	9.43
Mbarara	9.31	9.83	10.02	9.10	10.08	9.67
Kabale	8.83	9.18	10.14	9.74	10.03	9.58
Mukono	9.17	9.69	9.56	9.94	10.35	9.74
Jinja	9.02	9.17	9.94	9.48	10.15	9.55
Mbale	8.99	9.45	9.69	10.00	9.89	9.61
Soroti	8.84	9.31	9.39	10.18	9.99	9.54
Lira	8.72	9.23	9.54	9.78	10.21	9.50
Mean[1]	9.00	9.43	9.75	9.66	10.09	9.58

[1]Amongst the sites ($p< 0.001$; $LSD_{0.05}$ =0.135), months ($p< 0.001$; $LSD_{0.05}$ = 0.101); sites*months ($p< 0.001$; $LSD_{0.05}$ = 0.303)

Total organic carbon concentration

Total organic carbon in the compost was significantly different at the sites (p<0.001) and month of sampling (p<0.001) and across all sites irrespective of the month ((p<0.001). MOSW compost from Fort Portal, Jinja and Lira maintained high total organic carbon concentrations across the evaluation period. The least and highest concentration of total organic carbon was 81.7 and 160.6 g ka^{-1} obtained from Kabale and Jinja, respectively (Fig. 2a). The average minimum and maximum total organic carbon across the sites during the evaluation duration was 119.32 and 140.26 g kg^{-1} across the sites, respectively.

Total nitrogen concentration

There were significant variations in the concentration of total nitrogen at different composting sites (p< 0.001) and months (p< 0.001) during the period of evaluation (Table 3). It should be noted that there were significant differences at various composting plants for even the same months over the study duration (p<0.001). For example, the least and most total nitrogen concentrations were 7.06 and 15.44 g kg^{-1} obtained at Soroti and Mbarara, respectively (Fig. 2b). The average of minimum

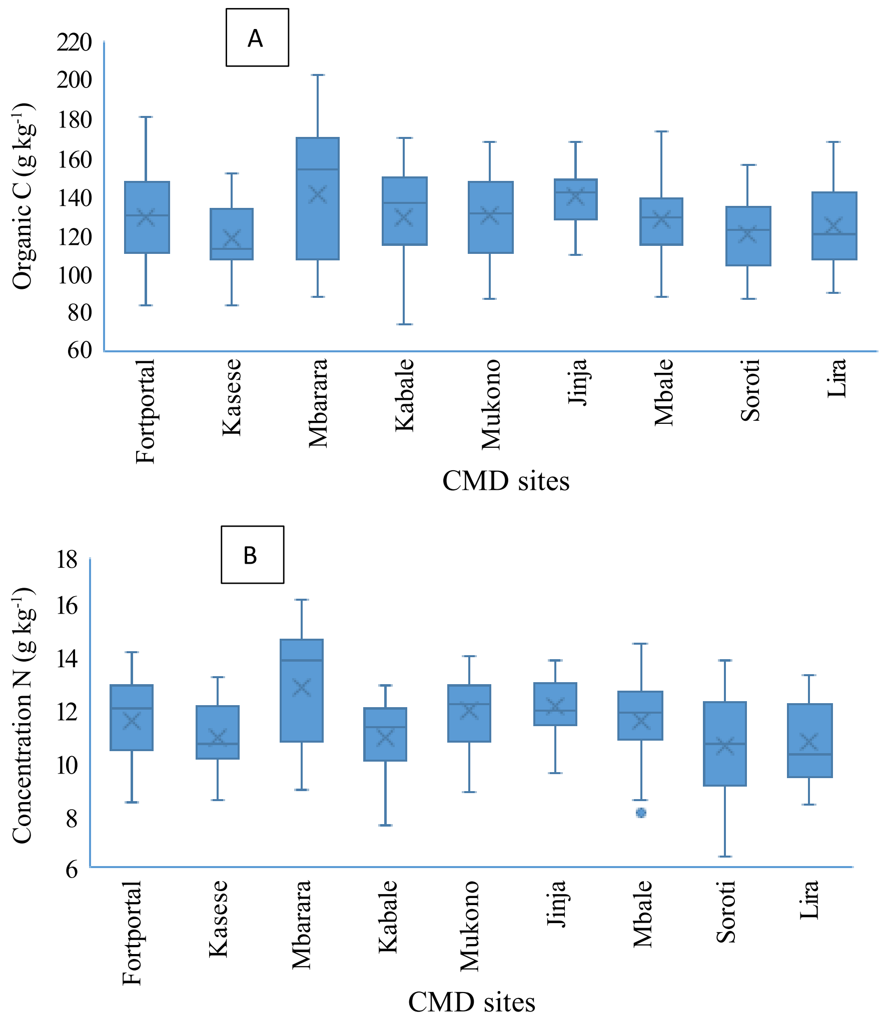

Figure 2. Boxplots showing compost quality variations of (A) organic carbon ($p<0.001$; $LSD_{0.05} = 5.446$), (B) nitrogen ($p< 0.001$; $LSD_{0.05} = 0.498$).

and maximum total nitrogen concentrations in the MOSW compost during the study duration were 10.68 and 12.97 g kg^{-1}, respectively.

Total potassium concentration

Total potassium is a constituent nutrient in most crop based organic wastes. The concentrations of total potassium significantly varied by month ($p< 0.001$), site ($p< 0.001$) and amongst sites ($p< 0.001$) during the study duration. The municipalities of Mbarara, Fort Portal, Kabale and Mbale maintained consistently and significantly higher total potassium than Kasese, Jinja, Soroti and Lira. The least and highest concentrations of total potassium were 10.30 and 51.42 g kg^{-1} recorded at Soroti and Mbarara plants, respectively (Fig. 2c). The mean average minimum and maximum

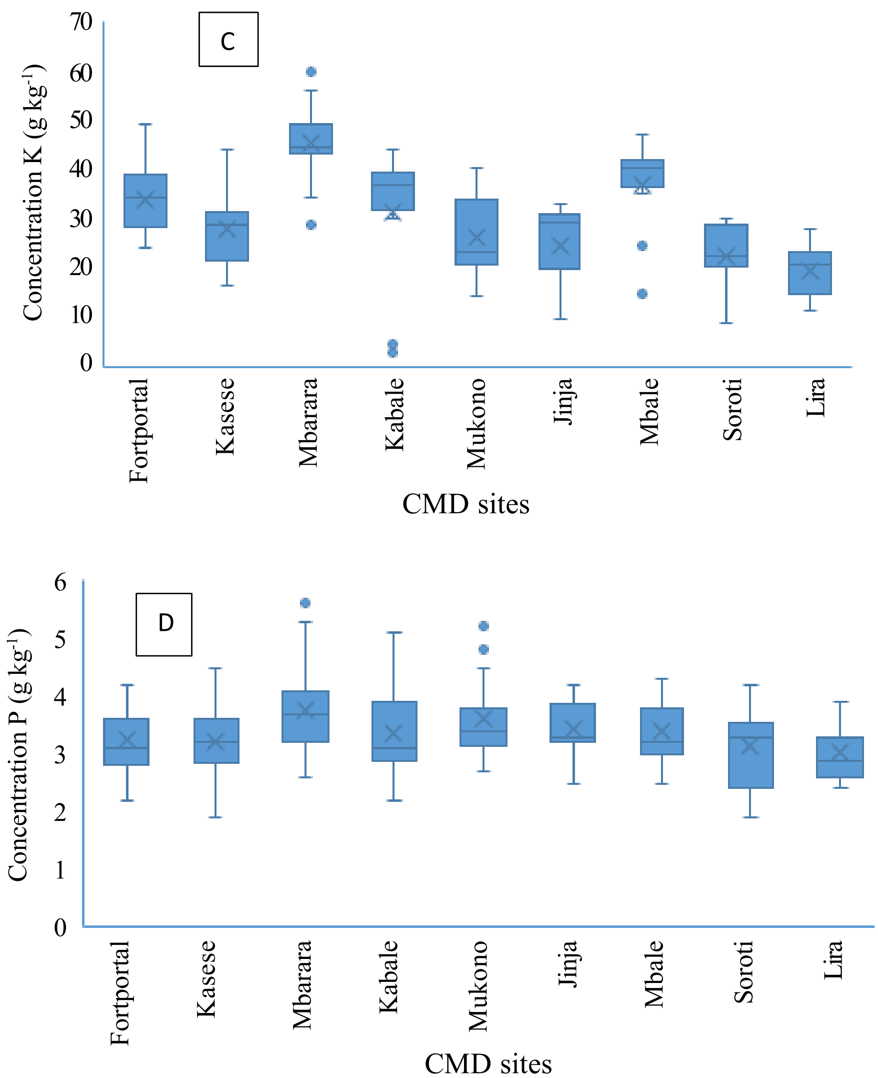

Figure 2. Boxplots showing compost quality variations of (C) potassium ($p < 0.001$; $LSD_{0.05} = 1.250$), and (D) phosphorus ($p < 0.001$; $LSD_{0.05} = 0.1887$) from the different CDM composting sites.

highest total potassium concentrations across the plants during the study were 22.4 and 45.33 g kg^{-1}, respectively.

Total phosphorus concentration

Total phosphorus concentrations in the compost significantly differed across the composting sites ($p < 0.001$) and month ($p < 0.001$) and therefore varied amongst the sites by months of evaluation ($p < 0.001$). The monthly minimum and maximum total phosphorus concentrations were 2.23 and 4.78 g kg^{-1} both obtained within the

Table 3. Calcium concentrations (gk g^{-1}) in compost generated at different municipality composting sites in Uganda

Composting plant	Month of sampling					Mean[1]
	May 2016	Sept 2016	Jan 2017	May 2017	Sept 2017	
Fort Portal	21.48	49.96	38.86	23.46	24.40	31.63
Kasese	18.42	32.50	40.18	25.42	31.74	29.65
Mbarara	27.80	34.08	35.04	21.30	29.28	29.50
Kabale	21.30	23.00	28.94	18.74	28.98	24.19
Mukono	29.94	29.14	21.92	32.80	38.86	30.47
Jinja	35.62	38.40	37.04	32.04	29.38	34.50
Mbale	23.96	37.84	32.46	26.18	23.80	28.85
Soroti	12.42	48.14	43.94	55.56	34.80	38.97
Lira	20.72	39.06	32.88	46.10	35.56	34.85
Mean[1]	23.85	36.90	34.58	31.29	38.97	31.40

[1]Amongst the sites ($p < 0.001$; $LSD_{0.05} = 2.470$); months ($p < 0.001$; $LSD_{0.05} = 1.841$); sites*months ($p < 0.001$; $LSD_{0.05} = 5.523$)

month of May 2016 at Soroti and Mbarara sites, respectively (Fig. 2d). The average mean concentrations across the plants and months were 3.03 and 3.75 g kg^{-1} during the evaluation duration. Consistently high concentrations of total phosphorus were observed in plants in Mbarara, Mukono and Jinja Municipalities while Soroti had the least concentration (Fig. 2d).

Total calcium concentration

A significant variability in concentration of calcium was observed at different sites ($p< 0.001$), during the months ($p< 0.001$), and amongst the sites by month ($p< 0.001$), during the study. Soroti compost plant had the highest (38.97 g kg^{-1}) while Kabale plant had the least average concentration (24.19 g kg^{-1}) of calcium across the duration of study. The minimum and maximum concentrations were 12.42 and 55.56 g kg^{-1}, respectively (Table 3).

Total magnesium concentration

Magnesium concentration significantly varied between the months ($p< 0.001$), within sites ($p< 0.001$) and amongst sites by months ($p< 0.001$). Fort Portal and Mbarara composting plants had the highest concentration of magnesium while Soroti and Lira plants realized the least concentrations (Table 4). The minimum and maximum

Table 4. Magnesium concentrations (gkg^{-1}) in compost generated at different municipality composting sites in Uganda

Composting plant	Month of sampling					Mean[1]
	May 2016	Sept 2016	Jan 2017	May 2017	Sept 2017	
Fort Portal	5.48	3.10	2.90	2.88	2.40	3.35
Kasese	3.50	2.46	2.60	2.48	2.18	2.64
Mbarara	4.44	3.22	3.00	3.06	2.44	3.23
Kabale	4.16	3.40	3.34	2.88	2.36	3.23
Mukono	2.22	3.22	2.86	3.04	2.88	2.84
Jinja	4.10	1.98	3.26	3.06	2.82	3.06
Mbale	1.94	3.14	2.82	2.42	2.74	2.61
Soroti	1.90	2.12	2.76	3.18	2.94	2.58
Lira	1.30	2.48	2.88	2.96	2.50	2.42
Mean[1]	3.24	2.79	2.94	2.88	2.58	2.87

[1]Amongst the sites ($p< 0.001$; $LSD_{0.05} = 0.194$); months ($p< 0.001$; $LSD_{0.05} = 0.144$); sites*months ($p< 0.001$; $LSD_{0.05} = 0.433$)

concentrations of magnesium observed were 1.30 and 5.48 g kg^{-1} at Lira and Fort Portal sites, respectively.

Concentration of Cadmium, Lead and Chromium

Cadmium results are not presented in this paper because they were only detected in 44 out of 225 samples, with an average of 0.069 mgkg-1. The concentrations of Pb significantly varied across the sites ($p< 0.001$), months ($p< 0.001$) and amongst sites by month ($p< 0.001$). The minimum and maximum Pb concentrations were 3.08 and 51.1 mg kg^{-1} noted at Mbarara and Jinja municipality plants, respectively (Table 5). The average minimum and maximum concentrations of Pb were 5.83 and 23.90 mg kg^{-1}. Jinja (13.14 - 51.10 mg kg^{-1}) and Mukono (9.98 - 36.5 mg kg^{-1}) compost maintained consistently and significantly high concentrations of Pb while Soroti (< 10 mg kg^{-1}) and Lira (4.52 – 14.22 mg kg^{-1}) had comparatively lower Pb concentration. The concentration of Chromium varied significantly ($p<0.001$) across the sites and month. The average Chromium concentration was 8.14 $mgkg^{-1}$ across the sites while the highest averages were observed in Jinja and Fort portal cities at 14.68 and 10.72 $mgkg^{-1}$, respectively (Table 6).

Table 5. Lead concentrations (mg kg^{-1}) in compost generated at different municipality composting sites in Uganda

Composting plant	Month of sampling					Mean[1]
	May 2016	Sept 2016	Jan 2017	May 2017	Sept 2017	
Fort Portal	17.54	1.97	2.56	7.00	10.76	7.97
Kasese	27.64	17.18	10.22	4.06	4.34	13.09
Mbarara	19.18	11.40	11.74	3.08	4.48	9,98
Kabale	19.44	18.28	14.92	6.64	9.06	13.67
Mukono	36.50	19.22	10.10	10.50	9.98	17.26
Jinja	51.10	20.12	24.90	10.22	13.14	23.90
Mbale	21.70	12.20	8.88	6.96	4.70	10.89
Soroti	5.40	6.70	14.22	4.52	8.58	7.88
Lira	8.38	3.7	9.06	1.78	6.24	5.83
Mean[1]	22.99	12.31	11.84	6.08	8.14	12.27

[1]Among the sites ($p< 0.001$; $LSD_{0.05}$ = 1.351); months ($p< 0.001$; $LSD_{0.05}$ = 1.007); sites*months ($p< 0.001$; $LSD_{0.05}$ = 3.020)

Table 6. Chromium concentrations (mgkg^{-1}) in compost generated at different municipality composting sites in Uganda (missing values 36)

Composting plant	Month of sampling					Mean[1]
	May 2016	Sept 2016	Jan 2017	May 2017	Sept 2017	
Fort Portal	22.10	12.96	10.00	2.88	5.67	10.72
Kasese	12.34	15.26	12.54	3.92	0.09	8.83
Mbarara	14.68	9.86	9.20	1.98	2.62	7.67
Kabale	11.70	13.24	10.98	5.50	2.14	8.71
Mukono	13.02	14.70	5.92	4.56	3.24	8.29
Jinja	16.20	20.66	19.12	6.68	10.72	14.68
Mbale	8.62	10.80	7.62	2.72	1.13	6.18
Soroti	4.36	8.30	8.10	2.36	1.00	4.82
Lira	2.88	6.12	4.90	2.65	0.06	2.26
Mean	11.77	12.43	9.82	3.11	2.96	8.02

Among the site ($p<0.001$; LSD0.05 = 0.836); months ($p< 0.001$; LSD0.05 = 0.623); sites*months ($p< 0.001$; LSD0.05= 1.868)

Table 7. Compost fertilization potential and carbon sequestration of the CDM compost

Site	Compost applied (Gg year^{-1})	Compost fertilization potential (ha)			Content of organic carbon into soil (Mg year^{-1})	Content of stable carbon in soil (Mg year^{-1})	Estimated greenhouse gas emissions		
		N fertilization potential	P fertilization potential	K fertilization potential			CH_4 (kg year^{-1}) from compost	CH_4 (Mg year^{-1}) if the wastes were landfilled	Estimated GHG emission (Mg year^{-1}) by compost plant
Kasese	2.88	593.6	1320.2	6506.0	342.2	0.68	49.6	421.5	2.37
Fort Portal	3.83	1595.4	2774.2	14140.2	498.4	1.00	67.2	571.1	3.20
Mbarara	5.65	2543.2	5886.4	33405.0	796.8	1.59	100.8	856.6	4.81
Kabale	3.17	606.0	1655.4	8808.8	411.0	0.82	56.0	475.9	2.67
Mukono	3.48	1435.4	2585.0	10942.6	453.4	0.91	59.2	503.1	2.82
Jinja	2.09	526.6	879.0	3737.0	292.6	0.59	36.8	312.7	1.75
Mbale	4.08	1195.6	2774.4	15964.0	521.6	1.04	67.2	571.1	3.20
Soroti	2.25	532.0	934.8	3930.4	272.5	0.55	38.4	326.3	1.83
Lira	3.38	858.0	1437.2	5458.4	297.3	0.59	41.6	353.5	1.98
Total	33.29	9885.6	20246.6	102892.4	3885.8	7.77	516.8	4391.7	24.63

Compost fertilization potential and carbon sequestration

A total of 33.3 Gg year^{-1} of compost was produced from the nine CDM composting plants. The average compost per CDM plant varied from 2.1 to 5.7 Gg year^{-1} depending on the city population and quantity of fresh waste received. All the compost produced was used for agricultural purposes applied on major crop within the crop systems of agroecological zone adding a total of 3885.8 Mg year^{-1} of carbon content into the soil (Table 7). It was estimated that this would lead to 7.77 Mg year^{-1} of stable (passive) carbon in the soil. The CDM composting plants reduced greenhouse emission by about 99%. If the received fresh wastes were disposed of in the landfills, an estimate of 4.39 Gg year^{-1} of CH_4 would have been emitted, compared to 25.15 Mg year^{-1} from the compost at the composting plant.

Discussion

Compost quality

The results from laboratory analysis of compost samples from the selected nine CDM windrow composting plants in Uganda indicated rich nutrient content, minimal heavy contamination and matured compost in the clearing windrow. The nutrient concentrations of total nitrogen, phosphorus and potassium observed across the nine plants were within the ranges reported also in Ethiopia (Castro-Herrera *et al*., 2021). It is important to appreciate that compost has been used historically to improve agricultural production by farmers but the emphasis has been on farm level composted wastes (crop residues and animal manure) because these have posed row risk of contamination. MOSW compost has been used with reservation and regulatory restrictions because of potential human and environmental hazards. However, application of MOSW compost in agricultural field has ripple effects including improved soil health and fertility, reduced use of inorganic fertilizers and carbon sequestration (Berendes *et al*., 2018; Cao *et al*., 2023; Häfner *et al*., 2023) and mitigating environmental contamination from poor disposal of MOSW (Li *et al*., 2023). The chemical and biological qualities of compost especially produced from municipal solid waste are of major environmental concern whether compost is to be landfilled or directly applied to the soil. Consequently, countries or regions have developed limits of concentrations of heavy metals and pathogenic microorganism in compost.

Results of the municipal compost analysis from the nine composting plants in Uganda conformed to the international quality standards for application to both soil and landfilling. For example, the maximum detected concentration of lead was 51.1 mg kg^{-1} and Chromium at 14.68 mg kg^{-1}, which are less than the maximum acceptable range. The average maximum Pb concentration was 36.5 mg kg^{-1} and though the overall average of 12.27 mg kg^{-1} indicated a low of risk of lead accumulation in soil following application of the compost, it raises a caution for continuous monitoring of heavy metals. For instance, with the current concentrations, it would require cumulative application of 417 Mg ha^{-1} of the compost to cause alarming levels of Pb and Cr in the agricultural soils of Uganda, which cannot easily be achieved even if the compost was to be applied at a rate of 10 Mg ha^{-1} per year. Equally, there were very low concentrations of cadmium and chromium detected, which fall below the international minimum concentrations permissible for compost quality standards. Heavy metals have globally been detected in MOSW compost but in very low concentration from sorted wastes compost (Kupper *et al*., 2014; Zhao *et al*., 2024). The most probable sources of heavy metals are waste and expired Pb and Cr batteries used by the residents but these were limited in the waste received at the composting plants, perhaps because most of the city residents used electricity as source of energy for most appliances/tools.

A major limitation associated with municipal waste compost is high salt content and accumulating electrical conductivity in soil. In this study, EC ranged between 1580 and 3760 µS cm^{-1} with an average of 2619.2 µS cm^{-1}. This indicates a salty compost. This was further shown by the pH of the compost that ranged between 8.72 and 10.36. Ashes were observed in some fresh skips delivered at the composting plant, which may have contributed to the EC and alkalinity of compost. The electrical conductivity of non-saline agricultural soils ranges between 0 and 4000 µS cm^{-1} and the compost values observed fall below the upper limit in soil. Soils with EC greater than 4000 µScm^{-1} are considered saline and degraded. Therefore, compost from the agrarian economy where the major fresh waste composition are crop residues in unlikely to increase soil EC. On the contrary, other studies have shown that compost produced from municipalities of developed countries have higher EC than soil, reaching 7490 µScm^{-1} and proportionately increasing soil EC where applied (Hargreaves *et al*., 2008). An earlier study also showed alkalinity in matured compost from municipal market crop wastes, irrespective of the composting method (Tumuhairwe *et al*., 2009). This may be attributed to processes of oxidizing fats and composition (Mkhabela and Warman, 2005). Alkalinity of municipal compost is a required attribute in the typical acidic tropical soil (due to weathering and leached cations). Previous studies have indicated liming attributed to compost as a major advantage where municipal solid waste has been used (Mkhabela and Warman, 2005). Therefore, this alkaline compost is suitable for a typical tropical soil and can be targeted for liming by release of OH- during carbon mineralisation and chelating of Aluminium in the soil. It should be noted that high acidic levels in most tropical soils such as Ferrallisol, Acrisol and Andosol are due to high exchangeable aluminium saturation, and organic carbon in compost chelates the reactive exchangeable Al and consequently reduces its negative effect on plant root and nutrient uptake.

Fertilization potential of compost and circular economy from CDM plants

Manure remains the most affordable and accessible soil input in SSA and the nine CDM composting plants can produce at least 33 Gg $year^{-1}$ of matured compost (C/N≤ 12.0) with high fertilization value to improve soil fertility based on the nutrient compositions. The total concentrations of N, P and K in compost from all the study sites exceeded 50 gkg^{-1}, which is the minimum acceptable standard by Uganda National Bureau of Standards (UNBS DUS 1584, 2017). The C: N value ≤ 12 is an indicator of compost maturity in various composting studies of different organic wastes (Bernal *et al*., 1998; Benito *et al*., 2003; Castaldi *et al*., 2008; Tumuhairwe *et al*., 2009). Compost from all the composting plants had declarable essential plant nutrient (N, P and K) to contribute to improved soil productivity. The significant variability of the nutrients in compost at different composting plants can be attributed to fluctuating composition of MOSW during the cropping seasons of year. Nevertheless, it is important to note that irrespective of the month of the year, compost quality across the different plants in Uganda was suitable for application to agriculture in soil productivity management with limited environmental risk. The higher concentrations of potassium in compost produced at Mbarara, Kabale and Mbale was attributed to banana wastes (peelings and fiber) that were dominant in the MOSW from the surrounding banana-based farming systems. Bananas accumulate potassium in the plant biomass. Secondly, potassium is not a structural element but kept in the cell cytoplasm and intercellular solutions. Therefore, potassium is easily released during composting without requiring residue mineralization like the structural nutrients. It was noted that sieved compost (< 5 mm) recovered from the mature windrow ranged between 60 - 90% of total biomass, indicating high proportion of partially composted plant residues. The other source of cation nutrients in compost could be ashes from restaurant and residence homesteads within the municipality, which were observed in the fresh wastes received at the composting plants.

A typical tropical soil under continuous subsistence cultivation in Africa has low organic matter (< 3%), nitrogen (< 0.02%) and low available P, yet fixing the P applied in inorganic fertilizers (Sanchez *et al*., 1997). Most soils in Uganda have low soil fertility depicted by deficiencies of essential plant nutrients and low organic matter. The average concentration of organic C in cultivated soils of Uganda is about 1.5 g kg^{-1} (Musinguzi *et al*., 2015) and therefore below critical values for crop productivity. The compost produced was sufficient for at least 4942 ha based on the N fertilization potential. All the manure was available for sale to farmers for agricultural use and thus adding substantial organic carbon (3886 Mg $year^{-1}$), which contributes to soil health and biodiversity. Previous studies have demonstrated the importance of compost for integrated soil fertility management and agricultural sustainable intensification in SSA (Kihara *et al*., 2022; Tittonell *et al*. 2008). The challenge has been and remains the availability and accessibility of compost to farmers. Therefore, the composting plants located in different parts of the country help to recover plant nutrients in MOSW and provide source of compost. Production and accumulation at the composting plant may increase compost availability to interested farmers. Unfortunately, the CDM has fallen into disrepair of late, which is a shame given the demonstrated potential.

Carbon sequestration and greenhouse gas mitigation potential

Municipal organic solid wastes globally disposed of in landfills contribute substantial quantities of methane and nitrous greenhouse gases. It has been estimated landfills can generate about 780kg CO_2-equivalent Mg^{-1} of fresh MOSW (Verma and Borongam, 2022). The nine selected municipality plants generate at least 129 Gg $year^{-1}$ of fresh MOSW containing high fraction (at least 90%) of biodegradable materials (Komakech *et al*., 2014; Tibihika *et al*., 2021,), and can thus contribute about 10 CO_2-equivalent $year^{-1}$. The operations at the CDM composting plants reduced emission by about 99% of the potential greenhouse gas (CH_4) that would have been emitted per annum by disposing of the wastes into landfills. The landfills in Uganda are poorly managed thus expressing full capacity greenhouse gas emissions given the high fraction of biodegradable wastes. Composting stabilizes the biodegradable fraction thus the generated compost (33 Gg $year^{-1}$) increases the labile and passive organic matter fractions in the soil enhancing carbon sequestration without disrupting the soil biome. It has been demonstrated in this study that biosolid compost can increase organic carbon storage and sequestered carbon. The compost had substantial concentration of organic nitrogen and its application can substitute inorganic nitrogenous fertilizers needed for farm use thus reducing on nitrous emissions from agricultural land.

Conclusion

The CDM municipal plant windrow composting generated high quality compost with high fertilization potential and resource nutrient cycling. The compost used for agriculture saves the environment from contaminations by wastes in landfills and leachate spills to the environment. The compost from the CDM plants had low heavy metal concentrations that were below the national and international limits, which poses limited risk of soil contamination. The composting at CDM sites reduced methane emissions from 4391.7 Mg $year^{-1}$ to 516.8 kg $year^{-1}$ contributing to climate smart technology for municipal organic solid waste management. Besides, the compost generated can substitute for organic fertilizer imports into the country saving foreign exchange while improving soil fertility and productivity, justifying the importance of the circular economy.

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