Agriculture & Food Security

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Decomposition and nutrient release patterns of municipal solid waste compost in two agro-ecological zones of Uganda

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Abstract

Background: Deteriorating soil fertility is a major constraint to agricultural production and food security among smallholder farmers in Uganda and throughout sub-Saharan Africa, where the majority of the population relies on subsistence farming for its livelihoods.

Unfortunately, inorganic fertiliser used as a significant soil nutrient replenishment is unsustainable, causing adverse environmental effects, including soil acidification and pollution of water bodies. Therefore, finding alternative, more sustainable, low-cost nutrient management systems is vital. This study assessed the decomposition and nutrient release patterns of municipal solid waste compost (MSWC) in a 36 weeks litter bag experiment under field conditions in two agro-ecological zones (AEZs) of Uganda.

Results: We found a higher rate of decomposition in the South-western Grass Farmlands (SGF) agro-ecological zone (0.041 week^{-1}, with 20% of initial compost mass remaining after 36 weeks of decay) compared to Southern and Eastern Lake Kyoga Basin (SEKB) (0.043 week^{-1}, 32% of initial litter mass remaining). The half-life values were 16 and 17 weeks for SGF and SEKB AEZs, respectively. The nutrient release rates differed between the two study sites. The macronutrient release pattern in both sites followed the order K > P > N. The secondary macronutrients release followed the order Ca > Mg in the SGF, while in SEKB, the order was reversed. The micronutrients followed the order Cu > Mn > Fe > Zn and Cu > Mn > Zn > Fe in SGF and SEKB AEZs, respectively. The MSWC mass loss during decomposition was negatively correlated with rainfall in both AEZs and with temperature in SGF AEZ, while it was positively correlated with temperature in SEKB AEZ. However, the relationship with nutrient release rates was inconsistent in both AEZs.

Conclusions: Our results showed consistent release of nutrients in all AEZs throughout the study period, which coincides with the two cropping seasons in Uganda, suggesting that smallholder farmers can use MSWC as a soil amendment to address soil fertility decline and improve crop productivity. However, because most nutrients were released almost right away in both AEZs, planting should be done at the beginning of high rainfall months when soil moisture is high to synchronise nutrient release from MSWC with crop demand and maximise nutrient uptake by crops while minimising losses to the environment. Furthermore, the inconsistent relationships between the climatic variables and nutrient release suggest that other factors, such as site-specific microbial composition, influenced MSWC nutrient release. Therefore, long-term research is needed to examine other factors affecting nutrient release in these AEZs.

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Keywords: Single exponential model, Microbial activity, Mass loss, Nutrient release, Synchronisation, Litterbag

Introduction

Soil fertility decline and increase in the amount of food lost and wasted are among the significant challenges threatening the food security status of smallholder households in sub-Saharan Africa [1–3]. According to FAO [4], as much as 40% of Africa's soils experience moderate to severe degradation as a result of soil erosion and nutrition depletion, with about 28% of the population in sub-Saharan Africa (SSA) living in areas that have experienced degradation since the 1980s [5]. Sanchez et al. [6] estimates that an average of 660 kg of nitrogen, 75 kg of phosphorous and 450 kg of potassium per ha has been lost in the last 30 years from an estimated 202 million ha of cultivated land in 37 African countries due to nutrient mining representing approximately US$ 4 billion loss [7].

In Uganda, agriculture contributes significantly to smallholder farmers' dietary intake and welfare [8]. However, agricultural food production is constrained by accelerated soil fertility reduction, threatening the livelihoods of most farmers in the region [9–11]. Depleting soil nutrients is mostly due to leaching and continuous removal when harvesting crops [6, 12]. Sunday et al. [13] estimated an annual nutrient depletion rate of 87 kg of nutrients (NPK) per hectare for Uganda in 2013. One way of combating soil infertility and sustaining crop production is by using inorganic fertilisers. However, synthetic fertilisers are, in most cases, unaffordable and inaccessible to subsistence. Over-reliance on synthetic fertilisers also contributes to increased production costs, environmental pollution, and global warming [14].

In this regard, finding unexploited, cheap, easily accessible alternative interventions other than commercial fertilisers that promote the reuse and recycling of materials from a green and circular economy perspective are essential [3, 15]. The use of compost from organic agricultural wastes has been recognised generally as an effective means for improving soil fertility and enhancing the contribution of inorganic fertilisers [16–20]. Compost improves soil quality by enhancing aeration, water holding capacity and maintaining a long-term supply of macro- and micronutrients to crops hence boosting crop productivity [21]. The organic resources also supply essential nutrients such as zinc, iron, iodine and boron that are not available in inorganic fertilisers [22]. Compost is also known to suppress soil pathogens and plant diseases [16]. Municipal solid waste compost (MSWC) contains large amounts of organic matter [19] and is a good nutrient source [23–27] which enhances net primary productivity. In addition, MSC produces marketable high-value products that can provide revenues for sustainable and financially viable waste management systems [28]. The ability of compost to provide nutrients to crops largely depends on the synchronisation of the nutrients' availability and the nutrient requirements of crops [29] and successive crops being grown. The synchronisation between nutrient availability and plant nutrient uptake is critical for improving nutrient use efficiency and minimising nutrient losses [30, 31]. A severe short-term nutrient deficiency generated by adding enormous amounts of low-nutrient composts can prove fatal for new crops, and an initial planting might fail [23]. However, compost's slow nutrient release pattern enhances the net primary productivity and reduces the need for constant application of fertilisers [32]. Many studies have been conducted in several countries to assess the decomposition and nutrient release pattern of compost from various sources of organic residues during decomposition, e.g., from composted cattle manure and cowpea haulm [32], composted animal manure [33], composted kitchen and kraal manure [34], cherry residue, cattle manure and sugarcane bagasse [35] and from composted pig manure [36]. For example, Abdou et al. [32] assessed composted manure's decomposition and nutrient release patterns under field conditions in the Sahelian zone of Niger. They found that 57% of the compost mass had decomposed after 84 days (12 weeks). A litterbag study conducted in northeastern Japan by Eusufzei et al. [37] found that 15.4% of compost residues remained after 540-day (77 weeks) incubation at low-temperature conditions.

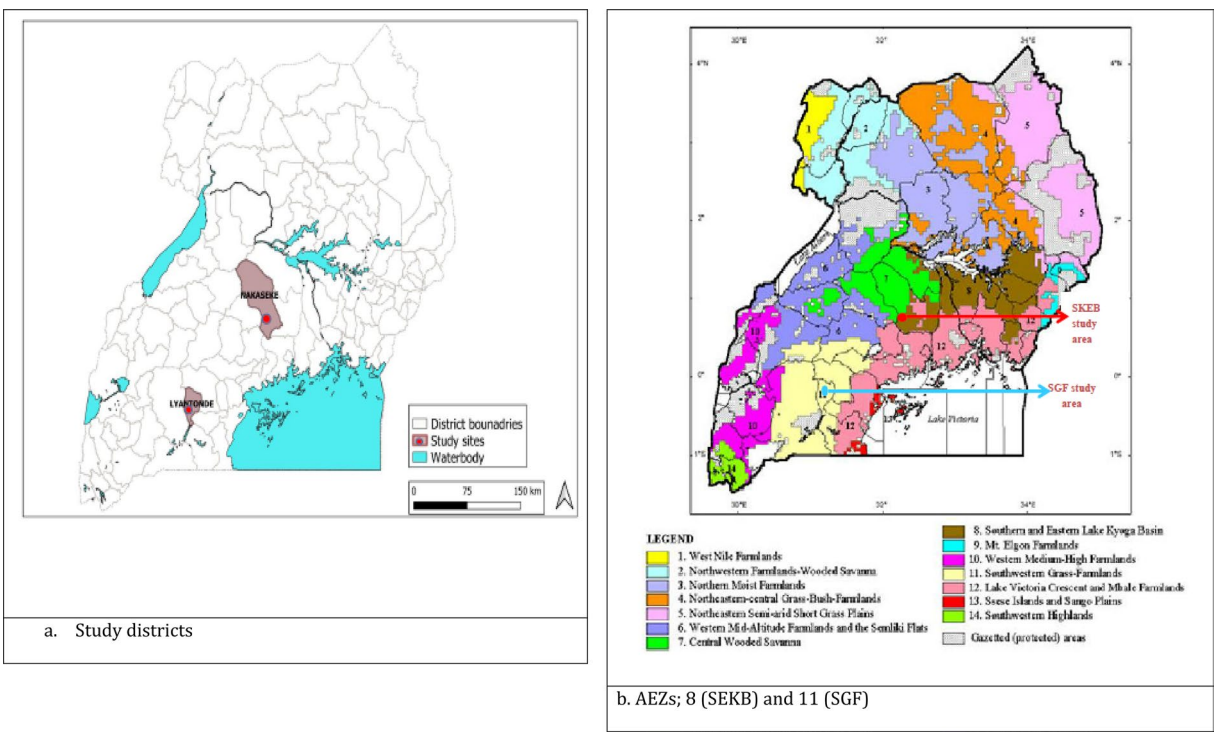
In Uganda, MSWC is currently generated in 12 urban councils under the Clean Development Mechanism (CDM) project. However, studies on the decomposition and nutrient release patterns of MSWC have not been conducted. Understanding the kinetics of decomposition and nutrient release of MSWC generated at the CDM plants when applied is necessary for assessing their potential for soil fertility restoration, predicting the organic matter dynamics in the soil [38] and providing a theoretical basis for its rational use in soil nutrient management. An accurate assessment of nutrient release from organic amendments and decomposition dynamics is also essential in deciding the optimal rates, frequency and timing of application of organic soil amendments, synchronisation with crop requirements [27, 39], optimising crop yields, improving food security and minimising environmental pollution. Many studies have demonstrated that organic material decomposition dynamics can be a function of

its quality, biota and microclimate and other edaphic factors [29, 40–43]. According to Briggs [44] and Antil et al. [45], the rate of release of nutrients from organic amendments in soil depends on many factors, including the efficiency of uptake by crops, losses of nitrogen, the timing of planting, and climatic factors, particularly temperature and amounts of rainfall at the site. Our study: (i) assessed decomposition and nutrient release patterns of MSWC with respect to time under field conditions in Southern and Eastern Lake Kyoga basin and Southern Grass Farmlands AEZs of Uganda and (ii) examined whether these patterns are associated with local climatic conditions (rainfall and temperature) in the respective AEZs.

Materials and methods

Study sites

The field studies were conducted from April 2019 to December 2019 in Lyantonde (0°23′32.02”S; 31° 08′ 27.76”E, altitude 1285 m asl) and Nakaseke (0°41′03.11”N; 32°13′41.54”E; altitude 1098 m asl) districts, representing Southern Grass Farmlands and Southern and Eastern Lake Kyoga basin AEZs of Uganda, respectively (Fig. 1a). These two AEZs were purposively selected because of their contrasting climates, land use types, soil types, population and cropping patterns [46]. These variables are among the strong determinants of decomposition and nutrient release patterns of MSWC [44, 45]. The 2 study sites are located approximately 234 km apart, and both had been under fallow for nearly 2 years after a maize/bean intercrop. According to Okello et al. [47, 48] and Nkonya et al. [11, 49], the Southern Grass Farmlands (SGF) AEZ (Fig. 1b) is drier and is characterised by bimodal rainfall pattern with an average annual rainfall of less than 1000 mm per year with a distinct dry season during June–July, and average annual temperatures greater than 20 °C. This area is famous for dairy cattle, millet and sorghum production. Meanwhile, the Southern and Eastern Lake Kyoga basin (SEKB) AEZ (Fig. 1b) is sub-humid. It is characterised by rainfall of greater than 1200 mm per year which is relatively reduced and unreliable during June–August with temperatures greater than 20 °C. Major crops grown include finger millet, sorghum, maize and bananas. Both AEZs are characterised by high soil nutrient mining, leaching and soil erosion [50, 51]. The mean rainfall received in SGF during the study period (April to December 2019) was 53.17 ± 8.08 while the temperature was 27.33 ± 0.21. The mean rainfall received in SEKB was 81.99 ± 10.58 while the temperature was 28.49 ± 0.21.



a. Study districts

b. AEZs; 8 (SEKB) and 11 (SGF)

Fig. 1 Maps showing the study areas (districts and AEZ) in Uganda

MSWC collection and analyses

We sampled the MSWC used in this experiment from a CDM Compost plant in Mbarara Municipality in 2019. Samples randomly collected in triplicate from different parts and depths of the compost windrows were mixed thoroughly to form a composite sample (about 20 kg) as recommended by Bary et al. [50] and Brinton et al. [51]. Three samples (approximately 1 kg of the composite sample) were separately packed in air-tight labelled polythene bags, transported in an icebox to the MetLab East Africa Ltd laboratory in Kampala, and stored at 4 °C until further analysis. At the laboratory, the samples were air-dried at room temperature to terminate biological activities, ground in a mechanical motor and pestle and sieved through a 2 mm screen to ensure a homogeneous mixture. We then analysed 100 g of each of the samples for pH, electrical conductivity (EC), total nitrogen (N), total phosphorous (P), total potassium (K), organic carbon (OC), calcium (Ca), magnesium (Mg) and heavy metals; boron (B), copper (Cu), iron (Fe), zinc (Zn), lead (Pb), cadmium (Cd), chromium (Cr) and manganese (Mn). The pH and EC of the compost samples were determined using a portable digital pH meter (Palin test pH pocket meter PT1550) in aqueous suspensions at a compost-to-distilled water ratio of 1:10 (w/v). The solution was allowed to settle for 1 h and the supernatant solution's electrical conductivity (EC) was then measured using an EC meter (Palin test Conductivity Sensor PT 157). The total OC was estimated using the Walkley–Black method [52–54]. Briefly, concentrated sulphuric acid was initially added to a mixture of compost and 0.167 M aqueous potassium dichromate ($K_2Cr_2O_7$). The heat of dilution raised the temperature (120 °C) sufficiently to induce substantial oxidation by the acidified dichromate. Residual dichromate was back-titrated using 0.5 M ferrous sulphate ($FeSO_4$). The difference in added $FeSO_4$ was compared with a blank titration which determined the amount of easily oxidisable OC. The organic matter (OM) content of compost was calculated using the formula; OM (%) = 1.724 × OC (%). Total N was determined using the Kjeldahl distillation method described by Okalebo [55]. Briefly, a homogeneous sample was heated in concentrated sulphuric acid to liberate reduced nitrogen in the form of ammonium sulphate. Thereafter, 45% sodium hydroxide was added to the digestion product to convert the ammonium salt to ammonia which was recovered by distilling the reaction product; where the distilled vapours were trapped in a solution of hydrochloric acid and water. The amount of ammonia or the amount of nitrogen present in the sample was then determined by back titration. Total P was determined by the ascorbic method [56] using a Hach Lange direct reading Spectrophotometer (DR 1900 Spectrophotometer at a wavelength of 880 nm). Total potassium (K) was extracted with 1 M ammonium acetate (NH_4OAc), and the amount was determined using a flame photometer (425; Spring Instrument Equipment Co., Ltd., Shanghai, China) [57]. Ca and Mg were estimated by titration method, i.e. using an ammonium acetate (1:5) extract with standard EDTA solution using Eriochrome Black-T indicator and Patton–Reeder's indicators. The concentrations of heavy metals (Zn, Pb, Cd, Cu, Cr and Ni) in MSWC were determined by atomic absorption spectrophotometer (AAS 3100, Perkin-Elmer, USA) [58] using acetylene gas as the fuel (at 8 psi) and air as an oxidiser. Moisture content (MC) was determined gravimetrically by drying 10 g of the sample to constant weight at 105 °C in an oven for 24 h [59–61].

Litter bag experiment

The fine mesh litterbag technique developed by Bocock and Gilbert [54] was used to study the decomposition and nutrient release patterns of the MSWC under field conditions over time. The technique remains the most widely used method for studying the decomposition processes of green manure and plant residues in terrestrial ecosystems [34, 57–59]. The technique assumes that all the mass losses from litterbags are mineralised. In this technique, fresh litter is enclosed in fine mesh bags, buried in the soil and collected at periodic intervals to measure the remaining mass. Mesh size is generally chosen to optimise access by all organisms to the litter while minimising excessive particle loss. To determine the litter decomposition rate, a total of 54 litter bags (20 cm × 30 cm) made from nylon mosquito nets were filled with litter. To minimise spillage and allow entry of below-ground macroorganisms such as earthworms, we placed 1.0 mm and 2 mm mesh sizes at the bottom and the top of the litterbags, respectively. Each litter bag was filled with 100 g of MSWC, labelled and placed underground of each sample plot at a depth of 0.05 m and located 0.1 m apart in each study area in order to simulate compost residue assimilation when the land is ploughed. The experiment was arranged in a randomised complete block design (RCBD) with three replications of plot sizes 0.05 m × 1 m. Three litterbag samples (one per plot) were retrieved at 2-week intervals (i.e. 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34 and 36 weeks) for nine subsequent months (April to December 2019) after burying of the compost at both AEZs. A total of 18 litter bags were left in the laboratory as control. Each litter bag was carefully removed, put inside a paper bag, and taken to the MetLab East Africa Ltd laboratory in Kampala for analysis. The content of each retrieved litterbag was emptied in a sieve and extraneous materials, e.g., soil particles, plant roots and visible organisms were taken off. The retrieved compost

samples from each litterbag were oven-dried for 48 h at 65–70 °C and weighed to determine compost weight loss (expressed as a percentage of the initial weight), and afterwards ground by mortar and pestle [60]. The ground materials were then sieved with a mesh sieve of size 0.5 mm. The sieved samples were kept in an air-tight polythene zip pouch for nutrient analysis using the aforementioned analytical methods. To describe the seasonal variation of MSW compost decomposition and nutrient release in the two AEZs, climatic variables, e.g., monthly temperature and rainfall data (for January–December 2019) for the study areas were obtained from the Uganda National Meteorological Authority. We used the mass of MSWC (g) and nutrients (%) lost during the experiment to determine decomposition and nutrient release dynamics. The percentage of dry biomass remaining (%DM) in each bag was calculated using the following formula:

$$\%DM = (M_t/M_o) \times 100, \quad (1)$$

where M_t = mean oven dry weight remained after sampling time t in weeks (g), M_o = initial oven dry weight (g), which is potentially decomposable.

To describe the decomposition pattern of MSW compost in litter bags, data for dry mass remaining were fitted to a negative exponential model [60, 61] as follows:

$$M_t = M_o.e^{-kt}, \quad (2)$$

where M_o = initial oven dry weight (g) at time zero, M_t = mean oven dry weight (g) of litter remaining after a given time t (weeks), t = time interval of sampling expressed in weeks, k = the rate constant (the decomposition rate constant per week), e = base of natural logarithms. Therefore, mass loss = M_o-M_t. The nutrient content of decomposing MSWC released over time was determined using the following equation:

$$\text{Nutrient release } (\%) = ((C_o \times M_o) - (C_t \times M_t)/C_o \times M_o)) \times 100\%, \quad (3)$$

where C_o = initial concentration of the nutrient in percentage; C_t = concentration of the nutrient in percentage at the time t (in weeks) of sampling; M_o = initial weight of the litterbag (g); and M_t = the mass of compost (g) in litterbag at time t (in weeks) [33, 60].

The difference between the initial mass and those remaining in the litterbags (M_o-M_t) after each sampling time (2 weeks interval) was used to calculate the total nutrients released during the 0–36 weeks of decomposition as shown by the following equation:

Nutrient remaining (%) = 100-% nutrient released.

To provide independent estimates of k and r squared (R^2) for each treatment, the regressions of ln (M_t/M_o) over time were performed separately for each set of litter bags in each plot. Furthermore, the time (in weeks) required for 50% ($t_{0.5}$) of the initial mass of MSWC to decay (or half the nutrients in the compost to be released) was estimated either from the graph or from the equation:

$$T_{0.5} = 0.693/k(36). \quad (4)$$

Data analyses

Descriptive statistics were applied for the calculation of means and standard errors. An independent samples t-test was used to compare differences in mean weight loss, decomposition rate constants, nutrient release rates and nutrient release rate constants (response variables) between the two AEZs (independent variable). We used bivariate analysis (Pearson's correlation) to determine the association between local climatic variables (mean monthly rainfall and temperature) and mass loss and nutrient release rates of MSWC in both AEZs. All tests were two-tailed, and p-values ≤ 0.05 were considered statistically significant. All data were analysed using the Statistical Package for the Social Sciences (SPSS) software version 24 (IBM Cop., Armonk, New York, United States).

Results

The chemical composition of the MSWC used in the study vis-a-vis the UNBS and African Standards is shown in Table 1.

MSWC decomposition dynamics

The percentages of the remaining dry matter (mass) from compost over time for the two AEZs are shown in Fig. 2. The single exponential model explained the pattern of decomposition, which was between 80 and 96% of the observed variation in residual MSWC dry matter over time. Over the 36 weeks of study, the MSWC decomposition gradually decreased the mass remaining in the litterbags over both AEZs. After 36 weeks of decay, 20% and 32% remaining masses were observed in SEKB and SGF AEZs, respectively. By the 16th week and 17th week, 50% of the MSWC had decomposed in the SEKB and SGF AEZs, respectively. Decomposition in both AEZs showed an initial exponential decrease in mass after 2 weeks followed by a constant decrease in SEKB (Fig. 2). The decomposition in SGF stabilised after the initial exponential decline and decreased again after 18 weeks. The decomposition then stabilised after 26 weeks in both AEZs (Fig. 2).

The results of the single exponential model parameters estimated from the linear regression equations (Table 2) showed that the decomposition coefficient (k) in SGF

Table 1 Chemical composition of the MSWC used for the decomposition and nutrient release study at the Southern and Eastern Lake Kyoga Basin (SEKB) and South-western Grass Farmlands (SGF) study sites, April 2019 to December 2019

Parameter	Content (mean ± SE)	UNBS standards[a] [85]	African standards for organic fertilisers [86]
OC (%)	17.6 ± 0.058	12	
C:N ratio	26.96 ± 0.006	12–15	≤ 20
Moisture content (MC) (%)	12.6 ± 0.058	30–35	10–35
Total N (%)	0.65 ± 0.006	1	> 1
Total P (%)	0.4 ± 0.058		
Total K (%)	2.46 ± 0.006		
Ca (%)	3.16 ± 0.006		≥ 1.0
Cu (%)	0.00421 ± 0.000	0.03	0.008
Fe (%)	0.78 ± 0.006		
Mg (%)	0.87 ± 0.006		≥ 0.5
Mn (%)	0.072 ± 0.001		
Zn (%)	0.031 ± 0.001		0.03
pH	9.61 ± 0.017	6–10	6.5–7.5
Electrical conductivity (µS/cm)	4362 ± 5.774	5000	5000

[a] UNBS: Uganda National Bureau of Standards: US 1584: 2017

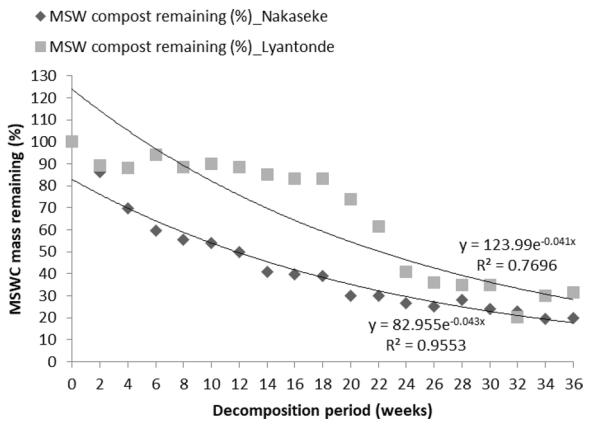


Fig. 2 Dry matter weight (% of original content) remaining during decomposition of MSWC in the two AEZs

Table 2 Differences in decomposition rate constant, mass loss and half-life of MSWC between the two AEZs in Uganda (April–December 2019)

Location	Decomposition rate constant, k	Mass loss (g)	R^2	Half-life (t1/2)
SGF	− 0.041 ± 0.000145	68.39 ± 0.006	0.8193	17
SEKB	− 0.043 ± 0.000058	79.99 ± 0.006	0.9653	16
F	1.923	0.001		
n	3	3		
t	− 11.393	− 1420.7		
p	0.000	0.000		
df	4	4		

was 0.041 week^{-1} which was higher than that of SEKB, 0.043 week^{-1}.

The results of the independent sample t-test which compared the differences in the mean decomposition rate constant between the two AEZs showed that the SEKB AEZ (M = 0.0431, SD = 0.001 had higher decomposition rate constant than SGF AEZ (M = 0.0412, SD = 0.00025 [t (4) = -11.939, $p < 0.001$]. The SEKB AEZ (M = 79.99, SD = 0.01) also demonstrated a significantly higher loss in mean mass compared to the SGF study site (M = 68.39, SD = 0.01 [t (4) = − 1420.7, $p < 0.001$, Table 3].

We investigated the association between the MSWC mass loss and climatic variables. We found a highly significant, negative correlation between MSWC mass loss and total annual rainfall received in both SGF ($r = -0.502$, n = 54, $p < 0.01$) and SEKB AEZs (Pearson's correlation, $r = -0.282$, $n = 54$, $p = 0.039$). There was also a significant negative correlation between MSWC mass loss and mean monthly temperature in SGF AEZ ($r = -0.341$, $n = 54$, $p = 0.013$). However, MSWC mass loss was significantly and positively correlated with mean monthly temperature in SEKB AEZ ($r = 0.533$, $n = 54$, $p < 0.01$).

Nutrient release patterns of MSWC during decomposition

The nutrient release rates of MSWC for the 2 AEZs are shown in Fig. 3. When the amount of the nutrients and heavy metals released from the MSWC and that remaining were assessed in the SGF AEZ, N (25.9%), P (23%), K

Table 3 Percentage OC and nutrients released during decomposition between the two AEZs in Uganda (April to December 2019)

Study site				
Variable	**SGF**	**SEKB**	***t***	***p***
	%	**%**		
Organic carbon	10.34 ± 0.006	10.37 ± 0.005	-41.211	**0.000**
N	74.13 ± 0.006	74.05 ± 0.006	9.798	**0.001**
P	74.67 ± 2.340	81.64 ± 0.006	-2.982	**0.041**
K	89.93 ± 0.006	94.1 ± 0.058	-71.868	**0.000**
Ca	73.29 ± 0.006	76.79 ± 0.005	-417.63	**0.000**
Cu	99.7 ± 0.350	99.7 ± 0.350	0.000	1.000
Fe	67.01 ± 0.006	77.91 ± 0.006	-1334.9	**0.000**
Mg	72.28 ± 0.006	89.86 ± 0.006	-2153.1	**0.000**
Mn	78.49 ± 0.006	82.77 ± 0.006	-524.19	**0.000**
Zn	46.98 ± 0.006	81.93 ± 0.006	-4280.5	**0.000**

(10.1%), Ca (26.7%), Cu (0.001%), Fe (33.0%), Mg (27.7%), Mn (21.5%), Zn (53%) remained after the 36 weeks of the litterbag study and could therefore be available for the subsequent crop. In the SEKB AEZ, N (26%), P (18.4%), K (6.0%), Ca (23.3%), Cu (0%), Fe (22.1%), Mg (10.1%), Mn (17.2%), and Zn (18.1%) remained at the sites after the experiment and could be available for the subsequent crop. The macronutrient release in SGF and SEKB AEZs followed the order K (89.9%) > *P* (77%) > N (74.1%) in SGF and K (94%) > *P* (81.6%) > N (74%) in SEKB AEZ. The secondary macronutrients released followed the order Ca (73.3%) > Mg (72.3%) in SGF. However, in the SEKB AEZ, the order was Mg (89.9%) > Ca (76.7%). The micronutrients (heavy metals) in SGF followed the order, Cu (99.9%) > Mn (78.5%) > Fe (67%) > Zn (47%) while in SEKB the order was Cu (100%) > Mn (82.8%) > Zn (81.9%) > Fe (77.9%). The contents of N in SEKB AEZ increased markedly in the first 24 weeks and remained constant until the end of the experiment (Fig. 3). In the SGF AEZ, N increased gradually in the first 16 weeks, increased sharply between the 18th and 32nd week and then sharply declined until the end of the experiment (Fig. 3). Whereas the release of K increased markedly in SEKB AEZ in the first 20 weeks and then remained almost constant until the end of the experiment. The release of K in SGF, increased sharply in the first 16 weeks, slightly dropped in the 18th week and gradually increased until the 32nd week when it remained constant till the end of the experiment (Fig. 3). There was a gradual increase in P release in the first 10 weeks which declined in the 12th week and increased sharply until the 18th week when it declined again. It then increased again in the 22nd week and levelled off until the end of the experiment in SEKB. In SGF, P release slightly increased until the 12th week, declined in the 14th week and increased until the 20th week when it declined again. The release then increased till the 32nd week when it levelled off until the end of the experiment. Ca release in SEKB increased gradually from the first week until the end of the experiment. In SGF, Ca slightly increased until the 16th week, then declined until the 20th week. The Ca release sharply increased until the 26th week after which it declined again to the 30th week and then increased until the end of the experiment. Mg release in SEKB and SGF followed a similar trend, where there was a gradual increase until the 26th week when it declined; Mg release increased again in the 32nd week and then levelled off until the end of the experiment. Mn release in SGF and SEKB followed the same trend. It increased gradually in the first 26 weeks, declined until the 30th week, increased in the 32nd week in SGF, and finally levelled off until the end of the experiment in both study sites. Fe release in SEKB increased gradually until the 26th week, then decreased in the 28th week and increased from the 30th week until the end of the experiment. In SGF, Fe was retained in the first 6 weeks, gradually increased until the 32nd week, and then declined until the end of the experiment. There was the gradual release of Cu in the first 6 weeks, then a decline in the 8th week in all study sites. In SGF, Cu release increased gradually until the 16th week and declined again in the 18th week after which it sharply increased and then declined after the 32nd week until the end of the experiment. In SEKB AEZ, Cu release increased gradually until the 22nd week, decreased in the 28th week and increased until the end of the experiment. Zn release in SEKB increased sharply in the first 20 weeks and gradually until the experiment's end. In SGF, Zn release slightly increased until the 6th week and declined sharply until the 12th week. The release then gradually increased until the end of the experiment. The OC release steadily increased throughout the study in all the study areas.

The independent *t*-test showed that generally, there was a significant difference in the nutrient release rates between the two AEZs (Table 3). The SGF AEZ had significantly higher N and P release rates than the SEKB study site (Table 3). However, the K, Ca, Fe, Mg, Mn, Zn release rate was significantly higher in the SEKB study site than in the SGF AEZ (Table 3). The Cu nutrient release rate did not differ significantly between the 2 AEZs.

Nutrient release rate constants, k (week^{-1}) and their half-lives are presented in Tables 4, 5. Generally, the half-lives of nutrients in the SGF AEZ were shorter than those in the SEKB (Table 4). The results of the independent sample *t*-test showed that the nutrient release rate constants differed significantly between the 2 AEZs (Table 6)

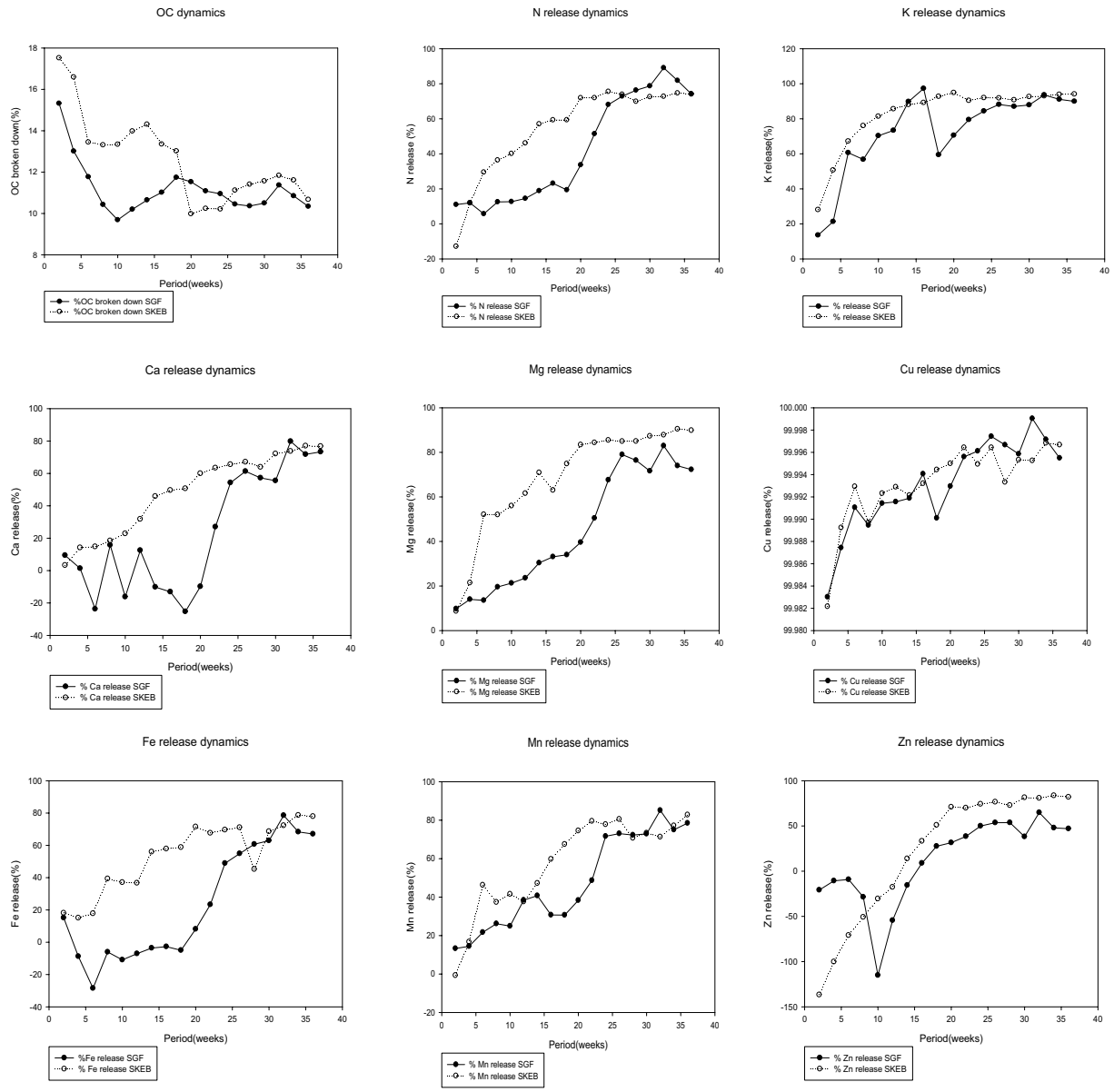


Fig. 3 Nutrients remaining (% of original contents) during decomposition of MSWC

with SGF (Mean, M = 0.0794 week^{-1}, SD = 0.00001) having higher mean decomposition rate constant k value than the SEKB study site (M = 0.0444 week^{-1}, SD = 0.00003) [N t (4) = 1917.029, $p < 0.05$]. The P, K, Ca, Mg, Fe and Mn decomposition rate constants were significantly higher in the SGF study site than in the SEKB study site (Table 6).

Correlation between climatic variables and MSWC nutrient release

The correlation between climatic factors (mean monthly rainfall and mean monthly temperatures) and nutrient release in the 2 AEZs (Table 6) showed that mean monthly rainfall significantly and positively affected N, P, K, Ca, Cu, Fe, Mg and Mn releases. In contrast, Zn was not affected by the mean monthly rainfall. Mean monthly temperature significantly and positively impacted the K, Cu, Mg and Mn releases but did not affect Zn, Fe, Ca, N and P in SGF. In the SEKB AEZ, mean monthly rainfall significantly and positively affected the releases of N, P, Ca, Mg, Cu, Fe and Mn, whereas it significantly and negatively affected K release. Zn was not affected by mean monthly rainfall. Mean monthly temperature significantly and positively impacted the release of N, P, Ca, Cu,

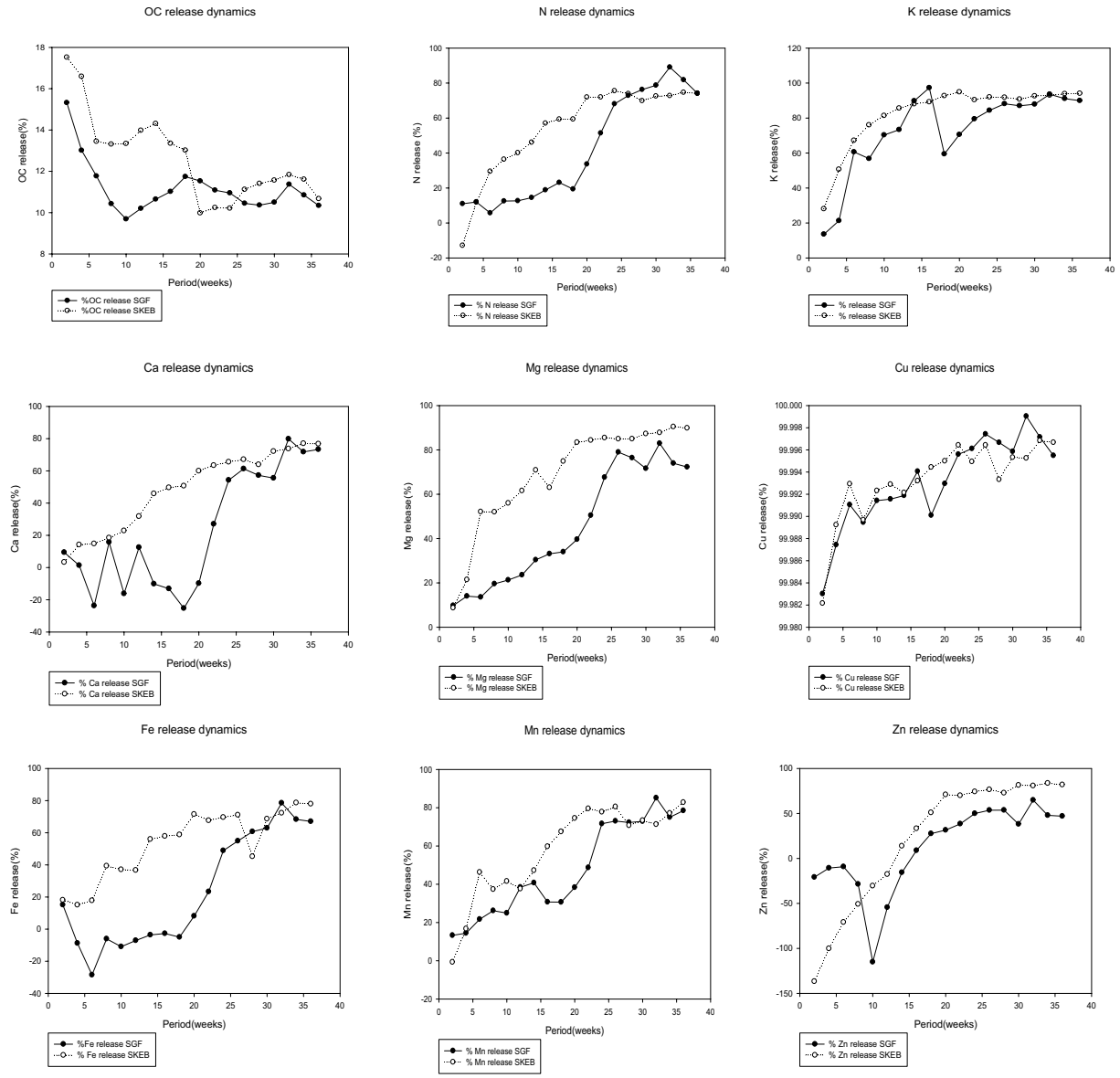


Fig. 3 continued

Mn, and Mg release. However, mean monthly temperature significantly and negatively affected the release of K. Mean temperatures did not affect Zn and Fe release in SEKB study area (Table 6).

Discussion

After the 36 weeks of decomposition, 20% and 32% of the original mass remained in SEKB and SGF, respectively, confirming the long-term residual effect of MSWC in the soil. Our result contrast with the findings of Eusufzai et al. [37], who found that 15.4% of compost residues remained after 540 days (77 weeks) of incubation in low-temperature condition of north Eastern Japan and of Abdou et al. [32] who found that 40.3 and 56.3% of compost mass losses remained, respectively, in 2013 and 2014 after only 12 weeks of decomposition under field conditions in Niger. However, by the 16th week and 17th week, 50% of the MSWC had decomposed in the SEKB and in SGF, respectively. The decomposition in the SEKB corroborates the findings of Abdou et al. [32], who found that 57% of the compost mass in the Sahelian zone of Niger had decomposed after 84 days (12 weeks). The observed variations in mass loss between the two AEZs, likely reflected site-specific differences in the climatic

Table 4 Half-lives of nutrients during decomposition of MSWC in the two AEZs

Study site				
Variable	**SGF**	**SEKB**	***t***	***p***
N	9 ± 0.058	16 ± 0.580	− 12.064	**0.000**
P	10 ± 0.867	13 ± 0.350	− 3.216	**0.032**
K	20 ± 0.173	35 ± 0.173	− 61.237	**0.000**
Ca	8 ± 0.577	10 ± 0.404	− 3.456	**0.026**
Mg	11 ± 0.173	16 ± 0.115	− 24.019	**0.000**
Fe	231000 ± 69002	231000 ± 69002	212.352	**0.000**
Mn	144 ± 0.577	16 ± 0.173	− 11.642	**0.000**

Significant values (at $p < 0.05$) are highlighted in bold

Table 5 Nutrient release constants during decomposition of MSWC in the two AEZs

Study site				
Variable	**SGF**	**SEKB**	***t***	***p***
N	0.0794 ± 0.0000057	0.0444 ± 0.0000173	1917.029	**0.000**
P	0.0667 ± 0.000057	0.0527 ± 0.0000231	225.144	**0.000**
K	0.0345 ± 0.0000057	0.0196 ± 0.000029	506.128	**0.000**
Ca	0.091 ± 0.0000057	0.0681 ± 0.000040	560.933	**0.000**
Mg	0.063 ± 0.000057	0.0421 ± 0.0000116	354.969	**0.000**
Fe	0.0048 ± 0.0000057	0.0423 ± 0.000057	− 4592.79	**0.000**
Mn	0.0529 ± 0.0000057	0.0431 ± 0.0000116	759.105	**0.000**

Significant values (at $p < 0.05$) are highlighted in bold

Table 6 Correlation between nutrient release variables of MSWC in SEKB and SGF and climatic variables (temperature and rainfall) from April to December 2019

Variable	SEKB		SGF	
	Rainfall	**Temperature**	**Rainfall**	**Temperature**
OC (%)	− 0.452[b]	− 0.446[b]	− 0.320[a]	− 0.717[b]
C:N ratio	− 0.650[b]	− 0.672[b]	0.162	− 0.069
MC (%)	0.591[b]	0.109	0.624[b]	− 0.119
N (%)	0.355[b]	0.381[b]	0.554[b]	0.249
P (%)	0.396[b]	0.314[a]	0.594[b]	0.209
K (%)	− 0.396[b]	− 0.992[b]	0.286[a]	0.520[b]
Ca (%)	0.392[b]	0.341[b]	0.570[b]	0.084
Cu (%)	0.396[b]	0.991[b]	0.344[b]	0.990[b]
Fe (%)	0.475[b]	0.207	0.542[b]	0.097
Mg (%)	0.411[b]	0.495[b]	0.481[b]	0.316[a]
Mn (%)	0.386[b]	0.436[b]	0.499[b]	0.365[b]
Zn (%)	0.22	0.001	0.206	0.049
pH	− 0.358[b]	-0.531[b]	0.166	− 0.495[b]
EC (µs/cm)	− 0.339[b]	-0.604[b]	0.309[a]	− 0.454[b]

[a] $p < 0.05$

[b] $p < 0.001$

and other site-related environmental factors [62, 63], latitude [62] and soil biota [63, 64]. This finding is similar to studies of Pries et al. [64] and Jacob et al. [65] which found overall effects on decomposition to be site-specific, raising the issue of the extent to which climate affects MSW compost decay at large scales. Furthermore, previous studies, e.g., [29, 40–42, 66], have shown that organic material decomposition dynamics can be a function of its quality, biota and microclimate and other edaphic factors. The positive association between rainfall and organic matter loss has also been documented in mass loss studies conducted in northeastern Japan, by Eusufzai et al. [37], in Shaanxi, China by Du et al. [67] and in Southern California by Glassman et al. [68]. Therefore, it was expected that the higher mean monthly rainfall and mean monthly temperature received in SEKB compared to those received in SGF could explain the higher mass loss in SEKB. However, the negative correlation between mean monthly precipitation and mean monthly temperature and the MSWC mass loss could imply that factors other than climate influenced MSWC decomposition (mass loss). For example, Glassman et al. [68] found that decomposition responses to changing temperature and precipitation depended on the composition of a microbial decomposer community, implying that when conditions favour the microbes in the soil, decomposition increases. This might explain the negative correlation of mass loss with the climatic factors in this study. Additionally, the negative association of mass loss to precipitation observed in this study could be attributed to the relatively narrow precipitation regimes in the AEZs (22.6–303.9 mm and 25–293 mm in SGF and SEKB, respectively (Additional file 1 Fig. S1) and shorter decomposition time (36 weeks) as also indicated by Glassman et al. [68]. The decomposition rate constants (k) in both AEZs, SEKB AEZ ($M = 0.0431$ week^{-1}, $SD = 0.001$) and SGF AEZ ($M = 0.0412$ week^{-1}, $SD = 0.00025$) were also generally lower compared to results of studies conducted by Bloukounon-Goubalan et al. [33] in Niger who found that decomposition coefficient of compost was 0.07 week^{-1}. The MSWC had a half-life (50% of material mass loss) of 16 weeks and 17 weeks, respectively. This is higher than the half-life of 50–60 days (about eight weeks) of compost made from agro-processing by-products in a study conducted in Benin [69]. Nevertheless, it is lower than what was reported in a survey by Gadelha et al. [70] who found that the half-life of compost decomposition under different irrigation systems in semi-arid Brazil varied from 26 to 49 weeks. The macronutrient release in SGF and SEKB followed the order K > P > N in SGF and K > P > N in SEKB. This is consistent with the

findings of Kolahchi et al. [71] in the study of the kinetics of nutrient release from different organic residues in Iran, where the per cent release of some macronutrients was in the order K > P. This behaviour could be explained by the fact that P forms stable Ca-bound compounds in organic amendments [72], caused by the high pH of MSWC. P is also involved in cell membrane formation for microbes, which slows down its release [73]. A literature review by Prasad and Foster [74] on the availability of P from compost indicated that composting reduces the availability of P. The initial decline of N could have been caused by its initial immobilisation by the microbial populations present in the MSWC [75]. Dhanya et al. [66] describes the initial decline of N as being caused by leaching of soluble forms of N. The second phase of increase may be attributed to mineralisation of N when the microbial population present in the MSWC dies off. Also, N mainly exists in organic form [76] which gets released slowly from organic materials. These findings are partly consistent with Dey et al. [38] and Li et al. [72] in a study of time dependent release of some plant nutrients from different organic amendments in India and Iran, respectively. The secondary macronutrient release followed the order Ca > Mg in SGF, similar to the study carried out in Iran on the kinetics of nutrient release from different organic residues [72]. However, in the SEKB, the order was Mg > Ca. The micronutrients (heavy metals) in SGF followed the order, Cu > Mn > Fe > Zn while in SEKB the order was Cu > Mn > Zn > Fe. The findings suggest that location had a significant effect on nutrient release patterns of the composts in these 2 study sites. Several previous studies have shown that the regulation of nutrient release rates of organic matter may be due to nutrient quality, biota, microclimate and other edaphic factors [29, 40–42, 66] and these could explain the differences in the nutrient release patterns between the two AEZs in our study. Overall, Zn and Fe were the most persistent micronutrients in both study sites. This persistence or reduced Zn and Fe solubility could be due to their tendency to chelate on surfaces of organic compounds [77, 78], rendering them less likely to be leached out of the material even after the decay has occurred.

In SGF, the nutrient release was fastest for K. Similar findings have been reported by Dey et al. [38] while assessing the dependency of nutrient release from organic materials with time in India. The high release of K may result from the fact that K is not a structural element in organic materials and usually exist in ionic form in the cytoplasm. Therefore, as soon as the cell membrane disintegrates, the K is released. Consequently, as organic residues decompose, most of the potassium is quickly released [77]. Whereas climatic factors are known to affect nutrient release from organic matter [79–82], the effect of these climatic factors are inconclusive. The differences in the release patterns of nutrients from the organic matter between the 2 AEZs could instead be due to factors such as site-specific microbial composition [39, 83, 84]. Overall, OC, Zn, Mn, K, P and N were the least sensitive to variations in temperature and rainfall in both AEZs. Although the average percentage of most nutrients (P, K, Ca, Mg, Fe, Mn and Zn) remaining in the MSWC were lower in SEKB than in SGF, the nutrient release constants were higher in SGF than in SEKB. Furthermore, the nutrients in SGF showed shorter half-lives than those in SEKB. The finding means that there could be an increased release of nutrients in the early stage of MSWC application in the SGF study site compared to the SEKB study site, although nutrients would stay longer in the soil after application in the SGF AEZ than in the SEKB study site. Our results is consistent with a study of mineralisation rate constants and half-lives of cow dung and swine manure by Uzoh et al. [84], which indicated that as nutrient release rate constants increase, half-lives of nutrients decrease.

Conclusions

Our results showed consistent release of nutrients in all AEZs throughout the study period, which coincides with the two cropping seasons in Uganda, suggesting that MSWC can be used by smallholder farmers as a soil amendment to address soil fertility decline, improve nutrient availability and crop productivity. Furthermore, considerable amounts of organic material and nutrients remained at the end of the study indicating that they could be available for the first cropping season in the next year. Whereas this could have been a result of the slow-release nature of the MSWC, other environmental factors could have been at play. Most nutrients were immobilised at application time but peaked at the beginning of the wet seasons, which coincide with the planting seasons in most parts of Uganda. Since decomposition and nutrient release dynamics showed different trends between the AEZs, farmers should apply different fertilisation programme management, aiming to synchronise the release of nutrients with the time of greatest nutritional demand for the crops. For example, nutrients such as N, P, K, Ca and Mg are released faster in SGF than in the SEKB and therefore MSWC should be applied at least a week to planting compared to SEKB where compost application can take place at least two weeks to planting. Cu and Zn were released almost right away, and none was left by the end of the study period in both AEZs. Therefore, farmers should take care to ensure that crops are planted in such a time to utilise the micronutrients (heavy metals) immediately after application and avoid leaching into the soil or being washed away by erosion. Because plant

nutrient requirements and uptake vary during the cropping season, careful timing of MSWC applications in the periods of active crop growth is needed to maximise the agronomic benefit in crop nutrient uptake, while minimising environmental impacts in losses of released nutrients by leaching and runoff. This balanced crop nutrition is crucial in the development of sustainable food systems. To improve fertiliser management strategies in Uganda, there is a need to conduct research on the application time recommended from this study in the different AEZs as well as application rates for improved crop productivity. Finally, the inconsistent relationships between the climatic variables and nutrient release suggest that other factors such as site-specific microbial composition influenced MSWC nutrient release. Therefore, long-term research is needed to examine other factors other than climate that affect nutrient release in these AEZs. This will help to understand the nutrient dynamics in these areas and therefore be able to synchronise between nutrients availability and uptake and improve nutrient use efficiency and minimise nutrient losses.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40066-022-00392-3.

Additional file1: Figure S1 Rainfall and temperature of the study sites.

Acknowledgements
This work was partially supported by the Regional Universities Forum for Capability Building in Agriculture (RUFORUM) and Biofertiliser Africa (U) Ltd. We are grateful to the Gulu University Research and Ethics Committee (GUREC) and the Uganda National Council for Science and Technology (UNCST) for permission to undertake this study and MetLab Uganda Ltd, Kampala, for laboratory analysis of the samples.

Author contributions
All authors have participated sufficiently in the work and take responsibility for the content, including participation in the concept, design, analysis, writing or revision of the manuscript. KJK, EO and GMM were involved in the study conception and design, KJK and GMM were responsible for setting up the field experiments, data collection, analysis and its interpretation. KJK and GMM are responsible for drafting the manuscript, KJK and GMM, EO and ES are responsible revising the manuscript critically for important intellectual content. All authors read and approved the final manuscript.

Funding
This work was partially supported by the Regional Universities Forum for Capability Building in Agriculture (RUFORUM) (Experimental design and data collection) and Biofertiliser Africa (U) Ltd (Laboratory analysis).

Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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Received: 24 January 2022 Accepted: 10 September 2022
Published online: 05 November 2022

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