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ORIGINAL ARTICLE

Enhancing the economic potential of organic waste by co-composting using ratio modelling toward a circular economy

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Abstract

Co-composting, a circular economy approach to waste management, has economic potential and environmental benefits through nutrient recycling and waste minimization. This research is based on the hypothesis that co-composting municipal organic waste, chicken manure, and faecal sludge feedstocks using ratio modelling will yield compost with economic potential. The study therefore investigated the quality of compost produced by co-composting municipal organic waste, chicken manure, and faecal sludge via ratio modelling in terms of the compost nutrient levels, microbial activities, compost maturity and heavy metals as a cheaper alternative for farming purposes. Nine compost piles of different substrate ratios were prepared. The pristine moisture content of feedstocks was maintained, however, moisture content of the piles was adjusted during the composting process to obtain optimal levels. Compost maturity was 91 days. pH and organic matter ranged from 7.7 to 8.4 and 19.75 to 28.10% respectively. C/N ratio, N, P, and K levels were satisfactory. Micronutrients such as Ni, Zn, Cu, and Pb were within acceptable European Union standards. Germination indices were > 80% implying that composts were mature and phytotoxin free. Respiration rate was 0.2 to 1.2 mg CO_2•C/g organic carbon/day and acceptable. Self-heat was at 30 °C ambient temperature. Although the optimum moisture content of 50 to 60% was not achieved, the overall compost quality was satisfactory. The contribution of moisture content, organic matter, organic carbon, C/N ratio, germination index, respiration rates, and self-heat to variations in compost quality was statistically significant at $p < 0.05$. Three principal components (PC) explained 71.5% of the variations in compost quality. PC1 explained 33.3%, PC2 23.9%, and PC3 14.3%. The substrate ratios applied through ratio modelling, suggest the feasibility of large-scale production and safe use of co-compost from organic waste, chicken manure and faecal sludge. It is recommended that further studies should explore varying the moisture content to achieve the optimum range.

Extended author information available on the last page of the article

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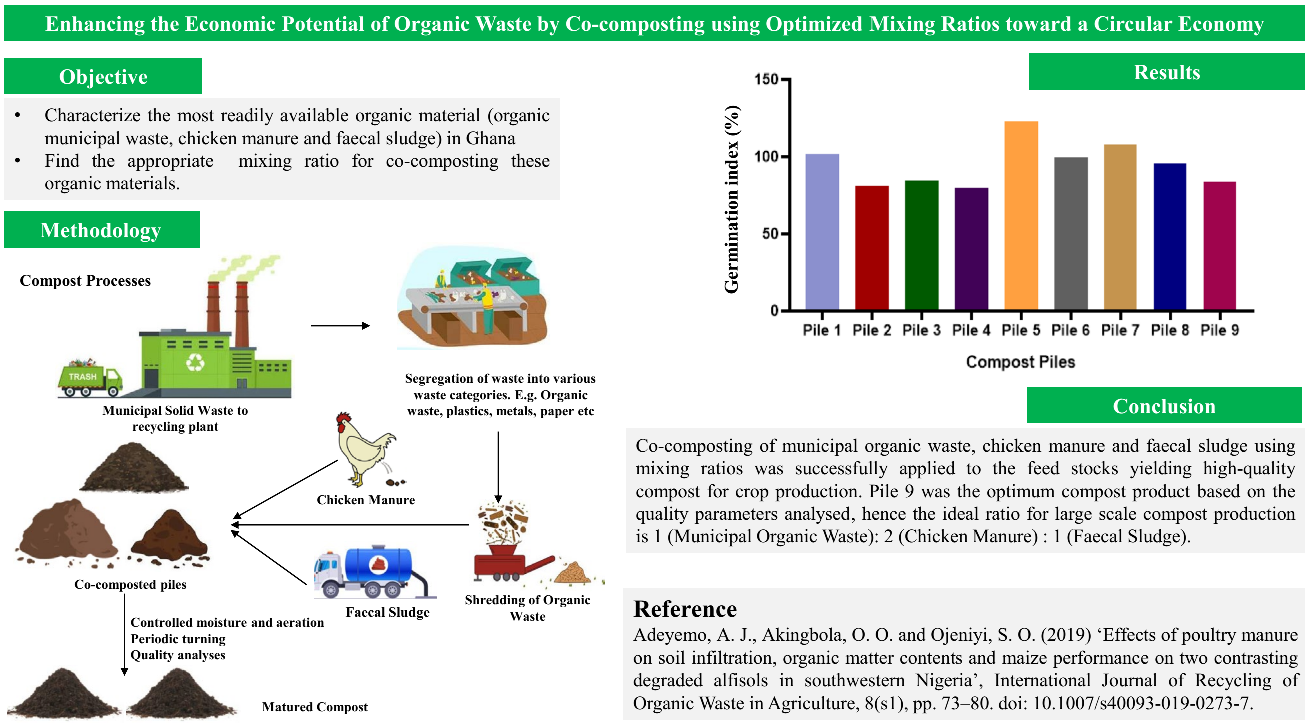
Graphical Abstract



Keywords Chicken manure · Circular economy · Co-composting · Faecal sludge · Organic waste · Ratio modelling

Introduction

Circular economy is a regenerative sustainable alternative to the traditional linear take-make-dispose of economic model [9, 37, 65] The philosophy of circular economy presents a sustainable alternative to global environmental problems associated with the burden of uncollected municipal solid waste (MSW) [9, 36, 71]. Co-composting, an emerging circular economy approach amplifies the advantages of composting and improves compost quality [125]. It disposes of at least two waste streams at a time and increases nutrient recycling through microbial activity [45, 56]. However, having good composting feedstocks and bulking agents is not a recipe for obtaining high-quality compost. Good feedstocks have resulted in low-end composts due to poor mixing ratios [112]. Literature further conveys that an optimized combination of feedstocks is critical to yielding high-quality compost [51, 83]. Ghana, like any other developing economy has its peculiar challenges with MSW and faecal sludge management. It is estimated that 3400 tons of solid waste and 36,685 m^3 of faecal sludge are generated on a daily basis in Accra, Ghana [88, 100]. Only 10% of solid waste is collected in Ghana [80] and faecal sludge is discharged into the environment untreated [63]. Out of the MSW generated daily in Ghana, it is estimated that 60% are organic fractions [85]. Chicken manure is also very abundant in peri-urban areas of southern Ghana [86].

Research has demonstrated that faecal sludge, farm manure, chicken manure, organic waste and green waste, for example, are feedstocks that yield high-end compost when conditions are properly managed [41]. Organic feedstocks for instance are good bulking agents [118, 126]; faecal sludge has high nitrogen content [15], chicken manure has high nitrogen and low moisture content [23, 101] whereas green waste has rehabilitation properties for soils affected by mining activities and metalliferous wastes [46]. Particularly, the trio of organic wastes, chicken manure, and faecal sludge have good physical and chemical properties for co-composting. Their composite physical and chemical properties tend to accelerate microbial action to degrade organic fractions of waste. Chicken manure has successfully been co-composted with feedstocks such as pineapple leaves and barley to yield high-end composts [22, 42, 64, 94]. Furthermore, research has demonstrated that when chicken manure is co-composted with organic solid waste, it improves soil quality: increases soil organic matter, improves porosity, aeration, water holding capacity, structural stability, and nutrient availability [56]. Similarly, faecal sludge has been co-composted successfully with other substrates [31, 36, 41, 48]. Though chicken manure and faecal sludge yield high-end composts with other substrates, it remains unknown what compost quality will be yielded if both are mixed with organic waste. Additionally, the mixing ratios of organic waste, chicken manure, and faecal sludge for co-composting is unknown.

Undoubtedly, gaps exist in literature regarding the use and appropriate mixing ratios of chicken manure, faecal sludge, and organic waste to yield high-end co-compost. It is, therefore, hypothesized that municipal organic waste, chicken manure, and faecal sludge which are readily available in Ghana can yield good compost quality through ratio modelling. This study, therefore, aimed to co-compost organic waste, chicken manure, and faecal sludge using ratio modelling. The compost quality is assessed by (1) germination index for maturity and phytotoxicity of compost products; (2) self-heating test for compost stability as a function of microbial activity; and (3) respiration test to determine compost maturity in terms of microbial metabolic activities and population [49].

It is evident, that this study will fill significant research gaps, in addition to gaining useful insights into co-composting. Additionally, the scope of this study will complement other studies and improve understanding of co-composting of organic waste, chicken manure, and faecal sludge.

Materials and methods

Study area

This research was performed at the Ga West Municipality in Greater Accra region of Ghana, with focus on the town Ajden Kotoku, home to the Accra Compost and Recycling Plant (ACARP), one of the country's biggest recycling plants. It is an integrated waste processing and recycling company established to receive, sort, process and recycle solid and liquid waste to produce organic compost for agronomic purposes in Ghana and the sub region. The facility has a capacity of 600 metric tonnes per day. The municipality was mainly chosen because of the dynamics of growing population, the ongoing urbanisation, industrialisation, and commercialisation. The Ga West Municipality is located within the geographical boundaries of latitude 50°48' North and 5°39 North and longitude 0°12 West and 0°22 West. It is bounded by Ga East and Accra Metropolitan Assembly to the East, Akuapem South to the North and Ga South to the South and West [38] with coverage areas including Ablekuma South, Ablekuma North, Ablekuma, Ayawaso, Ayawaso East, Ayawaso West, Okaikoi North, Okaikoi South, Accra Central, Adenta Municipal, Ga South, Ga West, Ga Central, Ga East, Osu Clottey, Madina.

The study area has a tropical monsoonal climate with rainfall mainly associated with mesoscale convective systems and controlled by advection of moisture from the Gulf of Guinea [8]. The seasonal rainfall pattern in the area is bi-modal with a major wet season from March to July [74, 90] during which feedstock used for this research were collected. However, due to natural occurrences, rainfall pattern was erratic and the temperature at the time of feedstock collection was 25 °C.

Ratio modelling and compost production

Different mixing ratios of MOW, CM and FS were applied to obtain an initial C/N ratio between 20:1 and 50:1 necessary to initiate the co-composting process. C/N ratios were modelled using the equation [5]:

$$C/N\text{ratio} = \frac{\sum weight\ of\ carbon\ in\ all\ subtrate(\%)}{\sum weight\ of\ nitrogen\ in\ all\ subtrate(\%)}$$

Municipal solid waste was collected and segregated into organic and inorganic waste. The organic waste was then shredded by heavy duty commercial shredder machine with a capacity to shred about 600 tonnes of waste per day. After shredding, particles size obtained was less than 2 inches. The shredded organic waste was then mixed with chicken manure and pre-treated faecal sludge at the following mixing ratios: MOW-CM (1:1, 2:1, 1:2); MOW-FS (1:1, 3:1); and MOW-CM-FS (1:1:1, 2:1:1, 1:2:1) after which they were heaped into piles on the composting field. Compost piles stood at an average height of 21 inches and width of 23 inches with an average weight of about 9.30 kg. The control pile was made up of only MOW. Compost piles were monitored for thirteen (13) weeks. The piles underwent aerobic composting, during which physicochemical analysis were carried out alongside periodic watering and turning. After the composting period, compost quality and stability tests were carried out. The compost production process is shown in Fig. 1.

Physicochemical and microbial properties of co-compost

Laboratory analysis of key physicochemical and microbiology parameters were carried out on the piles to monitor and manage the composting process as well as test their properties. Further tests were conducted to determine the quality and performance of the compost product. The parameters included pH, temperature, moisture content, organic matter,

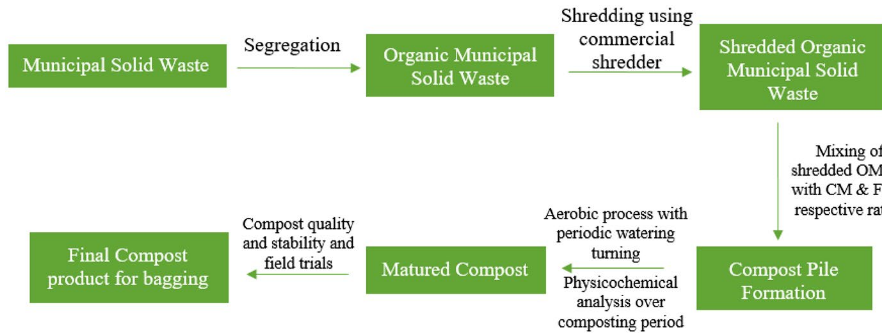


Fig. 1 Compost production process

organic carbon, and C/N ratio, nitrogen, phosphorus, and potassium, zinc, copper, cadmium, lead, and nickel, total coliforms, *E. coli,* and *Salmonella spp*. Compost quality parameters included germination index, respiration rate, and self-heating. A summary of methods and equations used are presented in Table 1.

Data analysis

Statistical analyses were computed using SPSS version 25.0. Analysis of variance (ANOVA) and descriptive statistics were applied to data sets to determine means and standard deviations. Significant differences between variables were determined at 95% confidence level. Principal component analysis (PCA) was applied to the composting results using R software version 4.1.2 to evaluate the differentiation of compost groups according to their physicochemical properties.

Results and discussions

Physicochemical characteristics of pristine feedstock

pH for pristine municipal organic waste (MOW), chicken manure (CM), and faecal sludge (FS) was found to be 7.8 ± 0.007, 8.22 ± 0.240, and 7.93 ± 0.198, respectively. Chicken manure recorded the highest pH as it has a tendency towards alkalinity due to the presence of NH_3 and basic cations such as K^+ [28, 75]. MOW, CM, and FS recorded moisture content of 13.5 ± 0.71%, 16.1 ± 0.283% and 91.45 ± 0.212% respectively. Faecal sludge contains urine which increases its moisture content [33]. The presence of sawdust which is hydrophilic contributes to lower moisture in chicken manure. Organic matter and carbon content were in the order CM > FS > MOW. The high organic matter content for CM could be attributed to the presence of sawdust in the manure. Sawdust, which is rich in carbon was visibly present. It is used as bedding to collect chicken droppings. Mandal and Bhanja [71] highlight the carbonaceous nature of sawdust and its ability to increase organic matter. Nitrogen content for FS, CM, and MOW was in the order 0.99 > 0.74 > 0.53. High nitrogen levels have been associated with uric acid and undigested proteins present in chicken manure and faecal sludge [71]. The mixing ratios of compost piles are presented in Table 2. Table 3 summarizes the composition of the feedstock.

Compost piles, mixing ratios and pile characteristics

Figure 2 shows the correlation of compost piles. Mixing ratios for each pile were modelled to obtain an initial C/N ratio between 20:1 and 50:1 necessary to initiate the co-composting process [71]. An optimal decomposition efficacy was attained by altering the C/N ratios. A high initial C/N ratio slows down the initial process and requires a longer time than usual, whereas a low initial C/N ratio causes the emission of high NH_3 [43, 71, 123]. The physicochemical properties of mixed piles are presented in Table 4. From the ratio modelling, it was observed, that there was a strong positive correlation between the properties of piles 5 and 8. Although the physical properties of piles 5 and 8 were highly correlated, practically they did not yield similar compost quality. This may be due to other experimental factors such as fluctuations in temperature and moisture content. Similar observations were made for piles 2 and 3. Therefore, it can be inferred that statistically, the physicochemical properties of piles 5 and 8 as well as 2 and 3 have minimum variations. Thus, based on feedstock availability and cost, the target physicochemical properties of the feedstock could be achieved with either mixing ratio.

Physicochemical characteristics of compost piles

Temperature

Temperature affects composting processes [110]. The temperature profile of the piles followed the typical temperature profile of mesophilic-thermophilic-mesophilic [111] as shown in Fig. 3.

Table 1 Summary of methods and equations

Parameter	Method	Formula	Variables	Description	Source
Moisture content	Oven drying method (105 °C for 24 h)	Moisture content (%) = $100 \times \frac{(W1-W2)}{W1}$	W1—wet weight (g) W2—dry weight (g)	A sample of known weight was oven dried at (105 °C) for 24 h, cooled and reweighed	[96]
Organic matter	Ignition loss	Organic matter (%) = $100 \times \frac{DM}{TVS}$	Total volatile solids (TVS) = Dry weight – Calcined weight Dried matter (DM) = W2–W1	After initial oven drying at 105 ºC, the samples are ignited in a muffle furnace for 2 h at 360 ºC. The percent weight loss during the ignition step is reported as dried matter/total volatile solids	[39]
Organic carbon	Indirect determination, using Van Bemmelen factor of 1.724;	Organic carbon (%) = $100 \times \frac{\%OM}{1.72}$	OM—Organic matter	Organic carbon content is derived as an indirect determination of organic matter using an approximate correction factor called the "Van Bemmelen factor" of 1.724. The calculation of organic carbon assumes that organic matter contains 58 percent organic carbon	[47]
Nitrogen	Kjeldahl method	Total nitrogen (%) = $100 \times \frac{14\times(B-T)\times N\times V}{W\times Aliquot\times 1000}$	B—volume of standard HCl used in blank titration T—volume of standard HCl used in sample titration W—weight of sample in milligram. N—normality of standard HCl V—Volume (100)	1.0 g of compost sample is treated with concentrated Sulphuric acid, H_2SO_4 and Hydrogen peroxide, H_2O_2. The sample is then distilled and titrated against 0.01N HCl	[129]
C/N ratio	Carbon to nitrogen ratio	C/N ratio = $\frac{\%OC}{\%TN}$	OC—Organic carbon TN—Total nitrogen	C:N is the ratio of carbon to nitrogen. For instance, a C:N ratio of 10:1 means there are ten units of carbon (C) for each unit of nitrogen (N) in the soil	[5]
Phosphorus	Atomic absorption spectrometric (AAS) method	Phosphorus content (g) in 100 g sample (%) = $100\times\frac{C\times df}{1000000}$	C—concentration of P (µg/ml) as read from the standard curve df—dilution factor	Compost sample was dissolved in standard solution of KCl (with stock solutions of 5.0, 10.0, 15.0 and 20.0 ml) and mixed acid (HNO_3, H_2SO_4 and $HClO_4$ in the ratio 9:4:1). The mixture was then heated till it turned colourless. After which it was allowed to cool. Samples were then atomized, and concentrations determined using the AAS	[34]
Potassium	Atomic absorption spectrometric (AAS) method	Potassium content (g) in 100 g sample (%K) = $100 \times \frac{C\times df}{1000000}$	C—concentration of K (µg/ml) as read from the standard curve df—dilution factor		

Table 1 (continued)

Parameter	Method	Formula	Variables	Description	Source
Heavy metals	Atomic absorption spectrometric (AAS) method	Heavy metal concentration $\left({}^{mg}/_{kg}\right) = \frac{Concentration\left({}^{mg}/_{L}\right)\times V}{W}$	V—final volume of solution W—initial weight of compost sample measured	1.0 g of compost sample was dissolved in 4.0 ml of concentrated Sulphuric acid, H_2SO_4. The mixture was then heated and allowed to cool. 10 drops of Hydrogen peroxide, H_2O_2 were added and reheated till the mixture changed colour from black to dark brown to light brown to colourless. Heavy metal was detected using flame atomic absorption spectrophotometer with air-acetylene flame and hollow cathode lamps (HCl) as light sources. Final concentrations of the metals in the compost samples were calculated	[76]
Compost quality	Phytotoxicity bioassay (Germination index—maximum percentage germination, also termed as germination capacity)	$GI(50\%\text{extract}) = (\frac{N}{A_G} \times \frac{L}{A_L}) \times 100$ $GI(100\%\text{extract}) = (\frac{N}{A_G} \times \frac{L}{A_L}) \times 100$ $\text{Final/Overall GI} = \frac{50\%GI\times 100\%GI}{2}$	N—number of germinated seeds A_G—average number of germinated seeds in the control L—radical length of germinated seeds A_L—average radicle length of germinated seeds	100.0 ml of distilled water was added to 50.0 g of each compost sample. 100% and 50% extract were derived from the mixture. All petri dishes were filled with cotton wool (serving as a bed) and 10 tomatoes seeds. The seeds in the petri dishes labelled 100% were watered with the 100% extract of their respective compost samples and the same applied to the 50% extract, petri dishes labelled control had their seeds watered with distilled water. The petri dishes were covered to retain the moisture and stored in an incubator with a temperature of about 27 °C for about 4–5 days. On the 5^{th} day the seeds that had germinated were counted and their radicle lengths were measured. Germination Index was calculated using the stated formula	[79, 114]

Table 1 (continued)

Parameter	Method	Formula	Variables	Description	Source
Compost stability	Dewar self-heating test	$CO_2C(mg) = (HCL_b - HCL_S) \times 12$ Organic carbon(g) = weight of sample $\times \%moisture \times \%carbon$	HCl_b—volume of HCl used in titration of blank HCl_S—volume of HCl used in titration of sample	Compost sample was placed in a Dewar vessel, and the temperature measured frequently. A peak in temperature was recorded and used to evaluate the composts' maturity	[39, 40]
	Respiration test	mg CO_2•C/g organic carbon/day $= \frac{massCO2•C(mg/day)}{OrganicCarbon(g)}$	CO_2•C—mass of CO_2-carbon generated (mg)	A volume of 20.0 ml of 1 M NaOH solution in a beaker was placed at the centre of glass jars containing 50.0 g compost sample from each pile. The jars were airtight. The setups were kept at a constant room temperature between 26–30 °C. The 1 M NaOH solution was taken out, and 3 drops of phenolphthalein indicator was added and then titrated against 1 M HCl. The process was repeated for 4 consecutive days. The CO_2 absorbed was then calculated	
Pathogens	Microbial analysis using agar			Composts were dispersed in agar medium to ensure that individual microbial cells, spores, or mycelial fragments have reasonable opportunity, when exposed to suitable conditions, to develop into discrete and macroscopically visible colonies	[14, 29]

Table 2 Summary of compost piles and mixing ratios

Compost piles	Mixing ratio		
	municipal organic waste	Chicken manure	Faecal sludge
Pile 1 (Organic municipal solid waste)	1	0	0
Pile 2 (Organic municipal solid waste: Chicken manure)	1	1	0
Pile 3 (Organic municipal solid waste: Chicken manure)	2	1	0
Pile 4 (Organic municipal solid waste: Chicken manure)	1	2	0
Pile 5 (Organic municipal solid waste: Faecal sludge)	1	0	1
Pile 6 (Organic municipal solid waste: Faecal sludge)	3	0	1
Pile 7 (Organic municipal solid waste: Chicken manure: Faecal sludge)	1	1	1
Pile 8 (Organic municipal solid waste: Chicken manure: Faecal sludge)	2	1	1
Pile 9 (Organic municipal solid waste: Chicken manure: Faecal sludge)	1	2	1

Table 3 Characteristics parameters of feedstock

Parameters	Initial feedstock		
	Municipal organic waste	Chicken manure	Faecal sludge
pH	7.80 ± 0.01	8.22 ± 0.24	7.93 ± 0.20
MC (%)	13.15 ± 0.07	16.10 ± 0.28	91.45 ± 0.21
OM (%)	26.42 ± 3.81	70.74 ± 0.01	59.03 ± 2.67
OC (%)	15.36 ± 2.21	41.13 ± 0.01	34.32 ± 1.55
N (%)	0.53 ± 0.02	0.74 ± 0.04	0.99 ± 0.12
C/N ratio	28.87 ± 0.05	55.43 ± 0.75	34.53 ± 0.63

The mesophilic phase of composting was observed in the first week. All piles except for pile 5 recorded temperatures greater than the ambient of 30 °C. The minimum observed was 29.85 °C for Pile 5 and a maximum of 31.90 °C for Pile 4. In weeks 2 and 3, the thermophilic phase was observed with a minimum of 37.15 °C in Pile 1 and a maximum of 49.17 °C in Pile 4. A steady fluctuation was observed between weeks 4 and 10. In week 13, a steady temperature of 28 °C which lesser than the ambient temperature of 30 °C was recorded at the curing stage of composting. It can be inferred that mechanical mixing and watering improve temperature distribution in compost piles [4]. Furthermore, the temperature variation in the piles compared to the control could be associated with the bulking agents [51]. Bulking agents like chicken manure and faecal sludge contribute to better aeration for microbial respiration [7, 128]. This enhances exothermic microbial activities and increases temperatures [49]. All piles except piles 2 (47.12 °C), 3 (46.35 °C) and 4 (49.17 °C) did not meet the optimal thermophilic temperatures due to pile sizes. Small compost piles are known to dissipate heat rapidly [105]. The variations for temperature for each pile were statistically significant at $p < 0.05$. Compost maturity was obtained at 91 days and was found to be within optimal composting maturity days of 90 to 270 days [103].

Moisture content

Moisture content plays a key role in composting [124]. The moisture content levels of feedstocks are presented in Table 3. The experimental results for moisture content were in the order Pile 4 > 7 > 8 > 9 > 3 > 5 > 6 > 2 > 1 as shown in Fig. 4. The variations in moisture content are attributed to thermophilic temperatures and vigorous microbial activity [49].

The observed moisture content for piles 5, 6, 7, 8, and 9, was due to the faecal sludge feedstock. During composting,

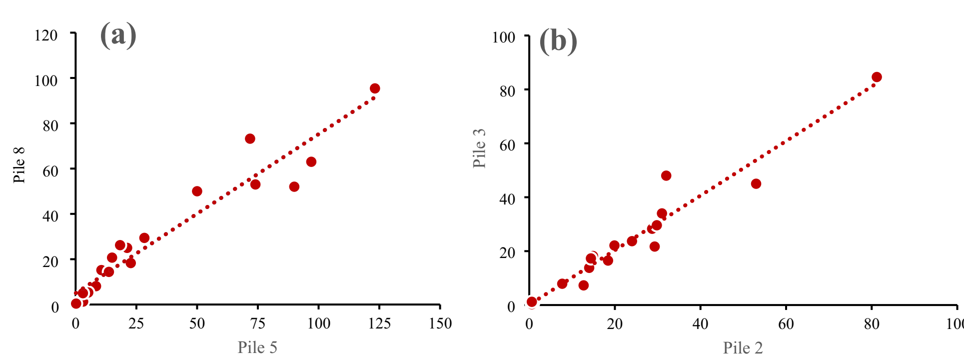


Fig. 2 Correlation of compost **a** piles 5 and 8 **b** piles 2 and 3

Table 4 Physicochemical properties of mixed piles

Parameters	pH		Temp (°C)		Moisture content (MC %)		Organic matter (OM %)		Organic carbon (OC %)		Total nitrogen (TN %)		C/N ratio	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Pile 1	8.09±0.71	7.67±0.29	30.29±0.30	28.70±0.10	17.50±1.88	15.80±0.20	19.33±0.46	19.75±0.05	11.24±0.27	11.49±0.02	0.39±0.02	0.64±0.03	28.87±0.08	17.84±0.05
Pile 2	7.74±0.72	7.71±0.17	30.81±0.21	28.70±0.10	12.58±1.81	19.85±2.71	25.14±1.89	23.99±2.15	14.62±1.10	13.95±1.25	0.33±0.01	0.93±0.06	44.34±2.05	14.94±0.02
Pile 3	7.79±0.62	7.92±0.01	30.63±0.46	28.33±0.15	11.12±0.45	22.13±2.06	24.98±2.31	23.72±0.39	14.52±1.34	13.79±0.23	0.37±0.02	0.76±0.03	39.78±1.55	18.24±0.04
Pile 4	7.19±0.14	7.84±0.01	31.90±0.11	28.50±0.10	12.17±0.32	28.05±1.45	26.91±1.16	26.68±0.81	15.65±0.67	15.51±0.47	0.32±0.01	0.81±0.09	48.42±2.25	19.10±0.025
Pile 5	7.52±0.18	8.44±0.02	29.85±0.06	28.50±0.10	32.52±2.37	21.18±1.18	21.67±0.55	18.29±1.20	12.60±0.33	10.64±0.70	0.39±0.012	0.71±0.11	32.56±0.45	14.99±0.02
Pile 6	7.31±0.30	8.22±0.07	30.59±0.07	28.57±0.25	29.90±0.95	20.70±0.20	23.51±0.16	20.05±0.07	13.67±0.08	11.66±0.04	0.44±0.02	0.62±0.03	31.04±0.60	18.93±0.04
Pile 7	7.27±0.20	8.11±0.02	30.65±0.50	28.73±0.06	24.52±0.20	27.05±2.05	30.26±0.96	25.05±0.09	17.60±0.56	14.56±0.06	0.44±0.012	0.67±0.03	40.04±2.17	21.66±0.06
Pile 8	7.23±0.30	8.09±0.01	30.87±0.15	28.67±0.06	24.12±1.12	24.92±1.40	28.39±2.46	26.23±0.18	16.51±1.44	15.25±0.11	0.44±0.03	0.74±0.04	37.92±1.18	20.68±0.11
Pile 9	7.21±0.04	7.87±0.01	31.38±0.12	28.43±0.21	20.97±0.27	22.30±1.77	36.39±1.44	28.10±0.77	21.16±0.84	16.34±0.45	0.48±0.015	0.70±0.03	43.83±2.09	23.34±0.56

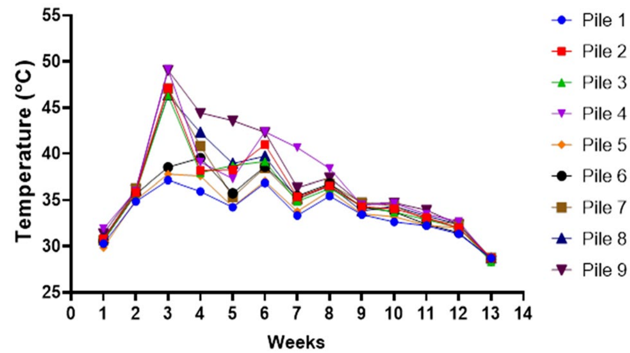


Fig. 3 Temperature variations of compost piles

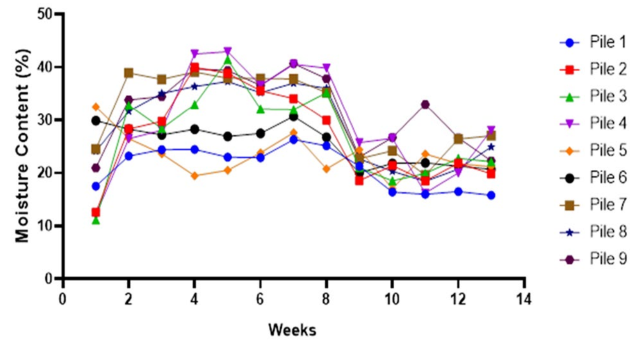


Fig. 4 Moisture content of compost piles

moisture serves as a medium for chemical reaction, nutrient transport, microbial mobility, and activity [102] responsible for breaking organic matter into humus [18, 77]. However, decomposition is inhibited by excess moisture. High levels of moisture create anaerobic conditions, which do not complement aerobic composting [55]. Initial lower moisture content values observed are associated with sawdust contained in the chicken manure used. Sawdust is hydrophilic and has high carbon content. Both properties contribute to lower moisture contents. In terms of absolute values, the moisture content of the piles at day 1 of composting ranged from 11.12 to 32.52%. The rise in moisture content in week 4 and 6 is associated with the drop in temperature and rainfall [93, 130]. The final moisture content ranged from 15.80% to 28.05%. The overall variation in moisture content throughout the composting period was influenced by the inconsistent rise and fall of temperatures and watering.

Inadequate moisture content in compost piles during composting leads to low biological activities and hence, poor decomposition. The optimum moisture content of 50% to 60% was not achieved. The size of compost piles and inconsistent watering are known factors that contribute to lower moisture content [69]. However, the variations for moisture content for each pile were statistically significant at $p < 0.05$.

pH

The pH of feedstocks is presented in Table 3. pH of the piles was observed to generally decline between weeks 1 and 9. During the aerobic phase of composting, biological activities produce organic acids [27], contributing to lower pH. pH is an essential parameter that should be maintained during the composting period. pH levels usually influence metabolic activities, nutrient availability to microorganisms, and heavy metal solubility. Hence, a neutral pH level is recommended for the optimal composting process. Experimental data revealed fluctuations in pH for week 2. The alkaline nature of chicken manure and faecal sludge contribute to pH fluctuations in compost [116]. It was observed that there was a drastic pH decrease in week 6 and 9 of composting, where the pH of decomposition was 6.74 and 6.96 for week 6 and 7.17 and 7.35 for week 9. The decrease in the pH values is attributed to the biological activities of the aerobic decomposition, where the hydrogen atom (acid) was produced [50]. From weeks 10 through 13, pH values increased and stabilized between 7.7 and 8.5 potentially due to the reduced production of organic acids associated with lowered biological activities. The final pH of the piles in week 13 ranged from 7.7 to 8.4. All compost piles were within the optimum pH value range of 5.5 to 9.0 [49, 98] and statistically significant at $p < 0.05$. The pH variation during the composting period is illustrated in Fig. 5.

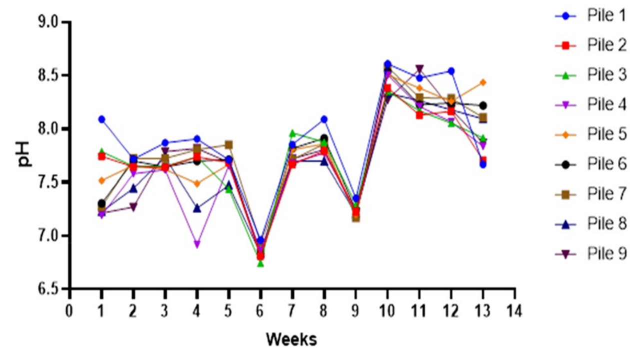


Fig. 5 pH variation of compost piles

Organic matter and organic carbon

Organic matter and carbon content levels are as shown in Fig. 6 and presented in Table 3. Minimum and maximum percentages of organic matter at the early phase of composting were 19.33 and 36.39% for piles 1 and 9, respectively. At the end of the composting period, the organic matter content of pile 1 and pile 9 was found to be 19.75 and 28.10%, respectively. Organic carbon content showed a similar trend with the initial minimum organic carbon content being 11.49% in pile 1 and the initial maximum being 21.15% recorded in pile 9. At the end of the composting period, the organic carbon content of pile 1 and pile 9 reduced to 11.24 and 16.34%, respectively. Pile 1 recorded the least organic matter variations because of the absence of chicken manure. At curing, the organic carbon content ranged from 10.64 to 16.34%, with pile 5 and pile 9 having minimum and maximum values, respectively. Turning of compost piles might have altered the aeration of the compost mass and accelerated the degradation process to enhance the loss of carbon as carbon dioxide. The results were similar to the findings of Guo et al. [35] who demonstrated higher losses of carbon content due to higher aeration rates as a result of turning. Similarly, high microbial activities, the decomposition of biodegradable substrates under ambient conditions, and the conversion of elemental carbon to carbon dioxide contribute to a decline in organic matter content [11, 97, 111]. Organic matter in matured compost piles was within the expected range of 15 to 45% [115] and statistically significant at $p < 0.05$.

The observed increases in organic matter and organic carbon content during the composting process are associated with the inactivity of microbial activities influenced by pH, moisture, and temperature variations. Additionally, piles with chicken manure (piles 2, 3, 4, 7, 8, and 9) had relatively higher OM content. Chicken manure improves organic matter in composts and soils [3]. The presence of carbonaceous sawdust in the chicken potentially improved the piles' organic carbon and organic matter content [71].

Nitrogen, phosphorus and potassium

Nitrogen content of feedstocks is presented in Table 3. The initial nitrogen content ranged from a minimum of 0.32% recorded in pile 4 and a maximum of 0.48% recorded in pile 9. At the end of the week 13 composting period, the nitrogen content of pile 4 and pile 9 increased to 0.81 and 0.70%, respectively. The overall final nitrogen content of the compost piles ranged from 0.62 to 0.93%, with pile 6 and pile 2 having the minimum and maximum values, respectively. The results of Nitrogen levels are shown in Fig. 7. All blends except pile 1 had high nitrogen content at maturity due to chicken manure and faecal sludge, which are nitrogen-rich materials [40]. Nitrogen (N) level in compost increases with time, and matured compost is expected to have total nitrogen content between 0.7% and 1% [111]. The breakdown of large amounts of organic carbon increases the release of nitrogen [67]. Nitrogen-fixing bacteria, loss of dry mass with regards to carbon dioxide, and water loss by evaporation due to the heat changes during organic matter oxidation also influenced the increase in nitrogen [54].

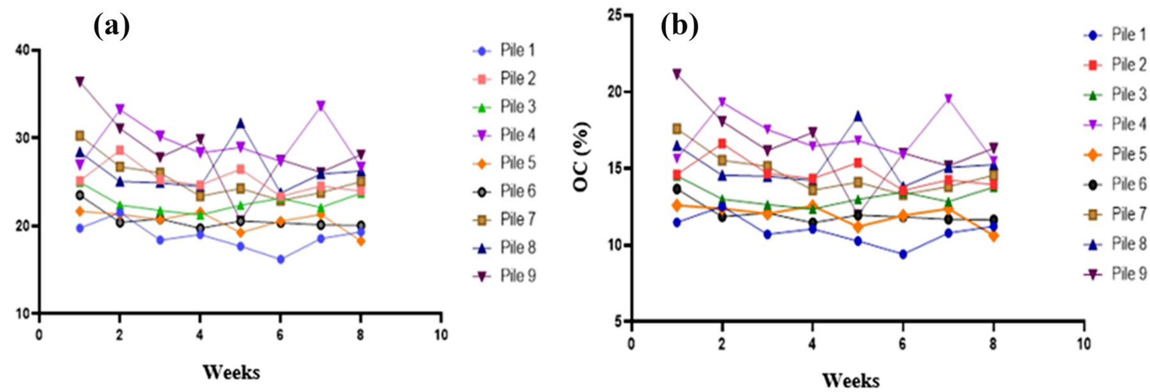


Fig. 6 **a** % OM and **b** % OC content of compost piles

Phosphorus is a vital nutrient in plant growth. It is approximately about 20% of the nitrogen content [109]. Ideal phosphorus levels in compost range from 0.0003 to 0.0025% [61]. Minimum and maximum phosphorus content were 0.7% recorded in piles 6 and 3.1% recorded in pile 5, respectively, which were higher than the ranges predicted by Jamaludin [61]. Low phosphorus contents are influenced by microbial activities [54]. However, high phosphorus levels can be associated with the presence of phosphorus in organic waste and excretion from chicken manure [113]. The experimental results for phosphorus were in the order Pile 4 > 2 > 9 > 7 > 3 > 8 > 1 > 5 > 6 represented in Fig. 8

Potassium plays an important role in amino acids and protein synthesis and controls water movement. Unlike nitrogen and phosphorus, potassium found in compost is readily available for plant uptake. Low levels of potassium are associated with extreme leaching of potassium salts [78]. The ideal potassium levels in compost range from 0.014 to 0.07% [61]. The use of fibrous materials with high absorptive capacity, good structural integrity, and porosity for composting results in high potassium levels. High levels of potassium affect plants' uptake of other critical nutrients [18]. At week 13, the minimum and maximum potassium content were 0.04% recorded in pile 6 and 0.68% recorded in pile 4 respectively. Experimental result for potassium is presented in Fig. 9. It was observed that all piles with chicken manure, piles 2, 3, 4, 7, 8, and 9 recorded relatively higher potassium content than piles without chicken manure, piles 1, 5, and 6. Pile 4, which has a higher mixing ratio of chicken manure recorded the highest potassium content. This establishes the fact that the presence of potassium in chicken manure contributed to this observation. However, higher values of potassium have been reported by Nutongkaew et al. [84].

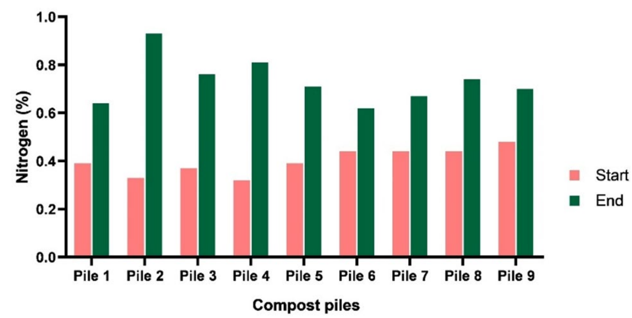


Fig. 7 Initial and final N (%) in compost piles

Carbon to nitrogen ratio (C/N ratio)

C/N ratio is one of the crucial parameters used in tracking composting progress and the maturity of compost [18]. It balances nutrients in compost, representing the quantity of available carbon relative to nitrogen which is very important for plant growth [49]. C/N ratio is expected to reduce by the end of the composting period [6]. A similar trend was observed during the composting process. The initial C/N of feedstocks is presented in Table 3. C/N ratios at the early phase of composting ranged from a minimum of 29:1 in pile 1 to a maximum of 48:1 in pile 4. High levels of carbon content found in chicken manure and nitrogen losses via ammonia release contributed to the C/N ratios in the initial composting phase. At week 13, the minimum and maximum C/N ratios were 15:1 and 23:1 recorded in pile 2, 5 and pile 9, respectively. Similarly, Adebayo et al. [2] reported C/N ratios of ˂ 25. It was further observed that at week 13, all compost piles were within the ideal C/N ratio value of 35:1 [98]. The variations for C/N ratio for each pile was statistically significant at $p < 0.05$. C/N ratios are represented in Fig. 10.

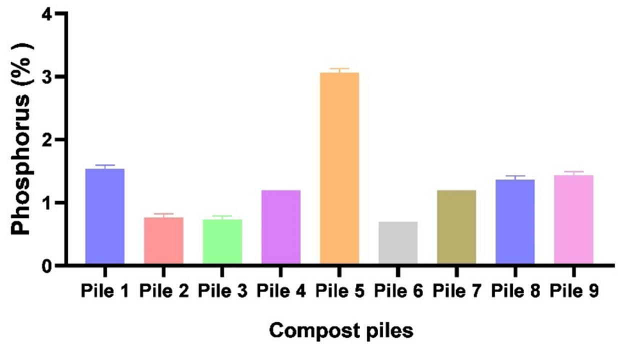


Fig. 8 Final P (%) in compost piles

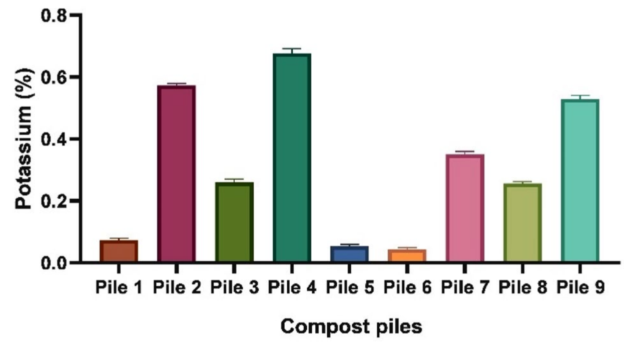


Fig. 9 Final K (%) in compost piles

Heavy metals

Nickel acts as a toxic heavy metal and an essential microelement for plants. Sources of Ni in compost piles includes organic waste from areas with anthropogenic activities, such as mining, smelting and the application of bulk agents, e.g., faecal sludge or animal manure. Commonly, Ni results in numerous phytotoxic effects, such as, limited shoot and root growth, reduced leaf area, chlorosis, and necrosis. However, low concentrations of Ni have positive effects on seed germination, growth of shoots, and roots, fruit yield and quality. Ni in moderate levels also promotes the synthesis of chlorophyll, protein, and carbohydrates in plant tissues [59]. Ni values recorded at the end of the composting process ranged from 4.8 to 19.2 mg/kg in the order of pile 6 > 3 > 9 > 2 > 4 > 7 > 8 > 5 > 1. Similarly, Ni values of 10.5 to 16.6 mg/kg has been reported [104]. The presence of electronic waste in municipal solid waste is a source of Ni in compost through leaching [57].

Zinc is an essential element of life [91]. The origin of Zinc in compost piles is associated with municipal organic waste and faecal sludge used during composting. Sources of Zn include industrial activities, such as mining, coal and waste combustion, steel processing, sewage sludge, use of galvanized materials, car emissions, car washes, metallurgy, and painting. Zn in low volumes contributes to the stimulation of the soil microbiome [108]. Although Zn has low levels of toxicity, its high bio-transfer potential can create high concentrations that could exceed the recommended amounts in plants, cattle, and humans [68] as well as interrupt soil homeostasis [108]. Thus, specific approaches should be employed to control the Zn content of organic waste [68]. Zinc levels ranged from 7.3 to 17.3 mg/kg in the order of pile 4 > 8 > 5 > 2 > 6 > 7 > 9 > 1 > 3. Higher Zn values between 274.35 to 665.12 mg/kg has been reported in other studies [19, 26]. Leaching of Zn from spent household batteries and electronic scraps found in MOW is facilitated at a favourable pH [95]. This contributes to Zn levels in composts. The variation in the values of Zn reported as compared to other studies can be associated with the origin of the pristine feedstocks.

Cadmium is a highly carcinogenic metal [62]. Cd primarily enters and accumulates in the human body through the food chain [17]. Cd occurrence in compost piles is a result of the organic waste used. Sources of Cd-rich MOW include areas predominate with smelting activities, industrial emissions, and vehicular emissions [92]. Cadmium disturbs crop growth by altering ultra-structures and reducing chlorophyll biosynthesis and gas exchange characteristics [117]. Cd causes oxidative burst in plants by producing reactive oxidative species (ROS) and casing electrolyte leakage through membrane burst [16]. It also weakens the defence system of plants which causes the reduction of enzymatic and non-enzymatic antioxidants [1]. High levels of Cd have toxic effects on soil organisms and can easily transfer into vegetative cover and ultimately the food chain [66]. Recorded values of Cd ranged between 12.9 mg/kg and 73.2 mg/kg in the order of pile 8 > 7 > 5 > 4 > 2 > 6 > 3 > 1 > 9. Other studies obtained lower Cd levels ranging from 1.43 to 3.33 mg/kg [26] and 6.30 mg/kg [44]. Bioleaching of Cd in municipal waste into organic fractions can be associated with the presence of sulphur and iron reducing bacteria [58].

Copper is widely spread through anthropogenic activities such as smelting and the application of bulk agents, e.g., faecal sludge or animal manure. Cu in the right quantity has a high affinity for binding to organic matter [87]. Copper deficiencies decrease the growth and chlorosis of leaves [81] Whereas, excessive amounts of copper contaminate the soil and limit the growth of plants by causing an adverse effect on yield and quality [121]. Cu levels ranged from 3.0 to 69.7 mg/kg in the trend pile 3 > 4 > 2 > 9 > 1 > 8 > 7 > 6 > 5. Other studies have found Cu levels between 48.07 and 111.99 mg/kg [26] and 21.92 mg/kg [19]. The presence of dissolved organic carbon in MSW facilitates leaching of Cu into organic feedstock through organic ligand exchange.

Lead is a non-essential element [52]. Pb is a toxic heavy metal that is widely distributed contaminant in the environment [53]. High levels of Pb are associated with organic

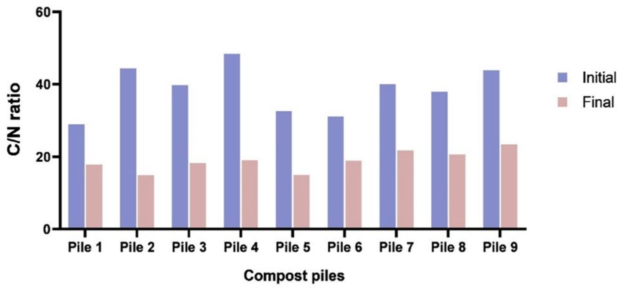


Fig. 10 C/N ratio of compost piles

wastes derived from Pb-contaminated sites such as smelting and mining sites [60]. High levels of Pb contaminate the soil and affect livestock and public health through the food chain [107]. Nevertheless, low values of Pb can be reduced through composting processes [52]. According to Manga et al. [73], Pb values ranged from 38.3 to 44.6 mg/kg. Similarly, Pb values recorded were between 18.3 mg/kg and 42.7 mg/kg in the order of pile 1 > 4 > 6 > 2 > 7 > 9 > 5 > 3 > 8. At favourable pH, Pb leaching from municipal waste is enhanced [106].

The heavy metal concentrations present in the piles (Fig. 11) except Cd were within the Compost Quality Standards & Guidelines [21] and Canadian Compost Quality standards [24].

Microbial quality

The mineralization and immobilization of nutrients can be influenced by microbial diversity and activity, consequently affecting the process of composting [127]. The results in this study were consistent with the previous reports [12, 25, 122]. Experimental data (Fig. 12) showed high levels of pathogens, especially total coliforms and *E. coli,* in piles 4, 5, 6, 7, 8 and 9 compared to piles 1, 2 and 3. The high volumes of chicken manure and faecal sludge present in piles could be associated with high levels of coliforms [72, 78, 104]. Total viable count ranged from 6×10^5 CFU/ml recorded in pile 2 to 519×10^5 CFU/ml recorded in pile 6. Total coliforms ranged from 27×10^5 CFU/ml as observed in pile 1 to 158×10^5 CFU/ml in pile 6. *E. coli* ranged from 12×10^5 CFU/ml in pile 1 to 207×10^5 CFU/ml recorded in pile 6. *Salmonella sp* ranged from 10×10^5 CFU/ml in pile 9 to 74×10^5 CFU/ml in pile 5. Pathogens found in composts originate from the feedstock used [82]. High levels pathogens in compost products can be harmful [13, 32]. As the composting process progresses, it is expected that there will be a decrease in pathogen levels due to high temperatures (thermophilic phase). However, the experimental results showed otherwise. This could be due to small compost pile sizes. Smaller piles dissipate heat and do not maintain steady temperatures, required to kill pathogens and sterilize the compost end-product [30].

Compost quality and stability

Germination index (Phytotoxicity Bioassay)

Germination index evaluated compost maturity and phytotoxicity. The acceptable GI value for compost products that make the compost phytotoxin-free is 80% [10, 111]. The GI values recorded were in the order Pile 5 > 7 > 1 > 6 > 8 > 3 > 9 > 2 > 4. Seed sensitivity has been associated with variations in the germination rate [111]. Compost piles recorded GI values greater than 80% as observed in Fig. 13 This implies that all composts piles could be safely used for agricultural purposes without any phytotoxic effects. The variations for GI for each pile were statistically significant at $p < 0.05$.

Carbon dioxide respiration

A carbon dioxide respiration test value of ≤ 5 mg CO_2•C/g organic carbon/day indicates compost stability [114]. Compost respiration in the compost piles ranged from a minimum of 0.2 mg CO_2•C/g organic carbon/day recorded to a maximum of 1.2 mg CO_2•C/g organic carbon/day in the order pile 3 > 2 > 7 > 8 > 9 > 6 > 4 > 5 > 1. Brewer and Sullivan [20] and Wong and Fang [120] reported similar respiration values of up to 5 mg CO_2•C/g organic carbon/day. Sadaka et al. [99] recorded values between 3.64 to 10.77 mg CO_2•C/g organic carbon/day. A successful composting process was realised under acceptable conditions. It was observed that over the 13 weeks of composting, compost products were stable and had no biological activities present, hence making the compost suitable for agriculture purposes. The variations for carbon dioxide for each pile were statistically significant at $p < 0.05$. Compost respiration is presented in Fig. 14

Self-heating test

The acceptable temperature for the self-heating test is an ambient temperature which implies the absence of microbial activities and compost stability [89]. Mahapatra et al. [70] reported temperatures between 10 and 46 °C whereas Wilson and Dalmat [119], recorded temperature of 25 °C for self-heating test. The experimental data observed in Fig. 15 showed that compost piles were approximately equal to the ambient temperature of 30 °C. This suggests that at curing, compost piles were stable at the end of the composting process and can successfully be used for agriculture purposes. The self-heat values recorded could

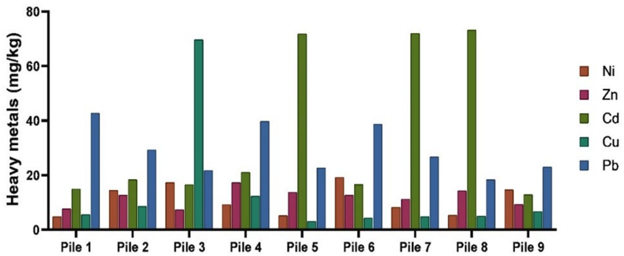


Fig. 11 Heavy metal content in compost piles

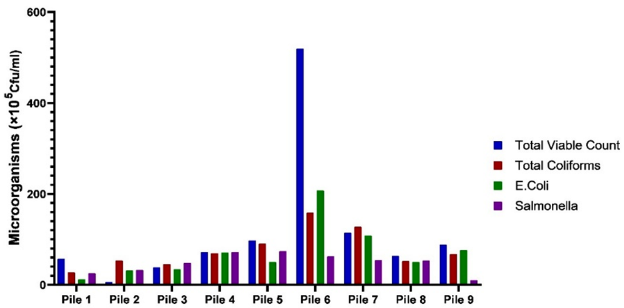


Fig. 12 Microorganism loads in compost piles

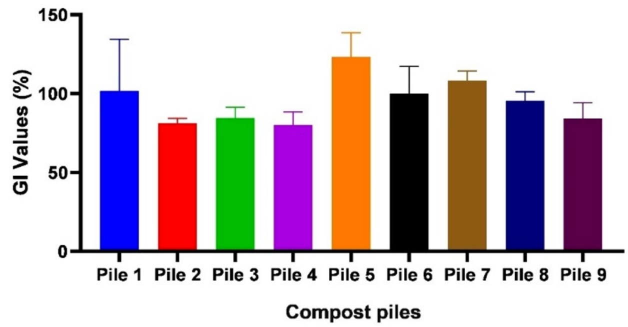


Fig. 13 Germination index of compost piles

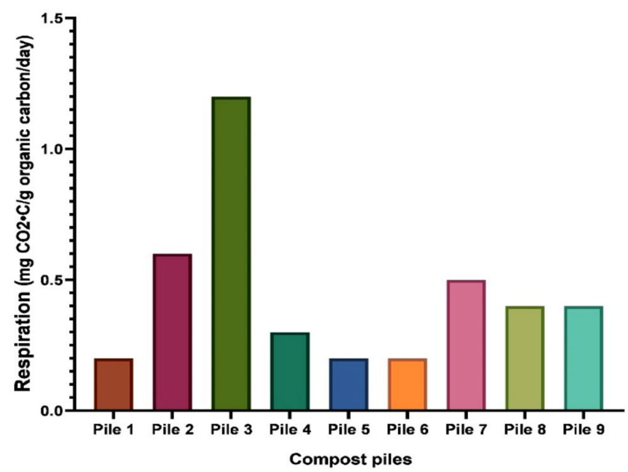


Fig. 14 Respiration rates of compost pilesFig. 16

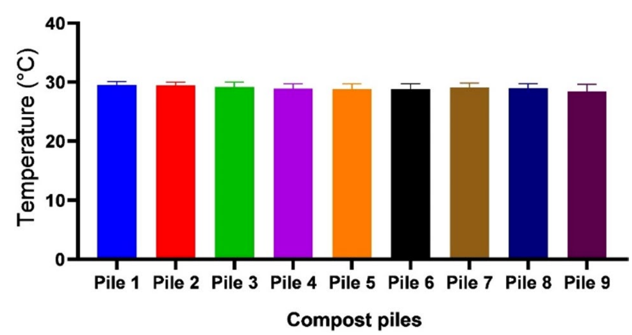


Fig. 15 Self-heating of compost piles

be associated with the fact that at optimum moisture content, biological activities are enhanced to give composts the elevated temperature required [69]. The variations for self-heating for each pile were statistically significant at $p < 0.05$.

Multivariate statistics

Analysis of variance

Two-way ANOVA without replication was performed at $\alpha = 0.05$ to determine the level of significance of the variations in each pile and between piles (piles 1 to 9) under physical and quality variables of moisture content, organic matter, organic carbon, C/N ratio, germination and respiration tests, and self-heating. For the variations within each pile, $p > 0.05$ indicating that the observations within the variables of each pile were not statistically significant. However, the variations of compost quality between the piles were statistically significant with $p < 0.05$. This implies that the ratio modelling contributed uniquely to the final compost quality.

Principal component analysis

Principal component analysis (PCA) was applied to evaluate how physicochemical properties contribute to compost quality. Data were standardized to minimize the effect of covariation. The number of principal components was determined using the explained variance table, scree plot and eigen vectors. Kaizer normalization was adopted for higher communalities. Eigen values greater or equal to 0.3 were used in interpreting the components. Three principal components explained a total of 71.5% of the variations in the compost quality. PC1 explained 33.3%, PC2 23.9% and

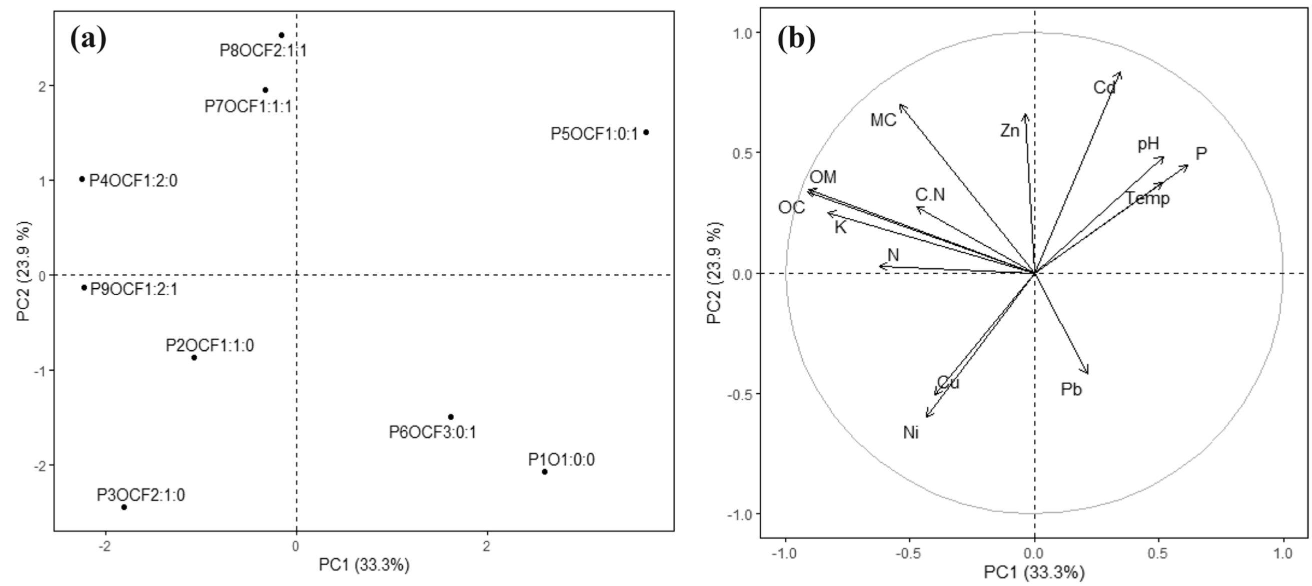


Fig. 16 Component score plot for **a** final compost piles **b** physicochemical property loadings

PC3 14.3%. PC1 was negatively correlated by the variables OM, OC, and K. PC2 was also positively correlated by the variables MC, Cd and Zn and negatively correlated by the variable Ni. PC3 was positively correlated by pH and Cu and negatively correlated by Zn and Pb. From the loadings plot, it can be inferred that piles 4, 5, 7 and 8 had relatively higher nutritional properties than piles 1, 2, 3, 6, 9. Pile 1 and 3 particularly had very low nutritional properties, and this may be associated with the absence of faecal sludge in pile 3, and the absence of both chicken manure and faecal sludge in pile 1. Although chicken manure was absent in pile 5, optimum pH, temperature and a high level of phosphorus contributed positively to the highest germination index observed. The PCA results also highlighted the higher maturity of pile 5 in comparison to the other piles. The relatively high maturity was influenced by optimum pH and temperature, higher levels of P and Cd and lower MC, OM, OC, C/N ratio, N, K, Ni, Cu and Zn. The two-dimensional plot of the component scores and loadings is presented in Fig. 16 and the eigen vectors in Table 5.

Conclusion

Organic waste, chicken manure and faecal sludge feedstock were successfully co-composted for higher compost performance using ratio modelling, as shown in Table 6. Micronutrients such as Ni, Zn, Cd, Cu, Pb, P and K were within acceptable European Union (EU) standards except for Cd. The contribution of moisture content, organic matter, organic carbon, C/N ratio, germination index, respiration rates, and self-heating to compost quality was found to be statistically significant at $p < 0.05$. Variations in final compost quality were significant at $p < 0.05$. Germination index was found to be 80.1 to 108.3% within the acceptable maturity range. Germination index obtained also indicated that the final composts were phytotoxin free. Respiration rate ranged from 0.2 to 1.2 mg CO_2•C/g organic carbon/day, within the acceptable range of compost stability. Self-heat was at an ambient temperature of 30 °C as required. Compost quality, maturity and stability tests indicated that all compost piles were suitable for use.

Table 5 Extracted eigen vectors

Parameter	Coefficient of eigen vectors		
	PC1	PC2	PC3
pH	0.24	0.26	0.40
Temperature (°C)	0.24	0.20	−0.40
Moisture content (% MC)	−0.25	0.38	0.07
Organic matter (% OM)	−0.42	0.19	0.00
Organic carbon (% OC)	−0.42	0.18	0.00
C/N ratio	−0.22	0.15	0.20
Nitrogen (% N)	−0.29	0.02	−0.14
Phosphorus (% P)	0.29	0.24	0.11
Potassium (% K)	−0.38	0.14	−0.27
Nickel (mg/kg)	−0.20	−0.33	0.16
Cadmium (mg/kg)	0.16	0.46	0.19
Copper (mg/kg)	−0.19	−0.28	0.37
Zinc (mg/kg)	−0.02	0.36	−0.30
Lead (mg/kg)	0.10	0.23	−0.49

Table 6 Summary of parameters analysed for compost piles

Parameters	Pile 1	Pile 2	Pile 3	Pile 4	Pile 5	Pile 6	Pile 7	Pile 8	Pile 9
pH	7.67 ± 0.29	7.71 ± 0.17	7.92 ± 0.01	7.84 ± 0.01	8.44 ± 0.02	8.22 ± 0.07	8.11 ± 0.02	8.09 ± 0.01	7.87 ± 0.01
Temperature (°C)	28.70 ± 0.10	28.70 ± 0.10	28.33 ± 0.15	28.50 ± 0.10	28.50 ± 0.10	28.57 ± 0.25	28.73 ± 0.06	28.67 ± 0.06	28.43 ± 0.21
Moisture Content (%MC)	15.80 ± 0.20	19.85 ± 2.71	22.13 ± 2.06	28.05 ± 1.45	21.18 ± 1.18	20.70 ± 0.20	27.05 ± 2.05	24.92 ± 1.40	22.30 ± 1.77
Organic Matter (%OM)	19.75 ± 0.05	23.99 ± 2.15	23.72 ± 0.39	26.68 ± 0.81	18.29 ± 1.20	20.05 ± 0.07	25.05 ± 0.09	26.23 ± 0.18	28.10 ± 0.77
Organic Carbon (% OC)	11.49 ± 0.02	13.95 ± 1.25	13.79 ± 0.23	15.51 ± 0.47	10.64 ± 0.70	11.66 ± 0.04	14.56 ± 0.06	15.25 ± 0.11	16.34 ± 0.45
C/N Ratio	17.84 ± 0.05	14.94 ± 0.02	18.24 ± 0.04	19.10 ± 0.025	14.99 ± 0.02	18.93 ± 0.04	21.66 ± 0.06	20.68 ± 0.11	23.34 ± 0.56
Nitrogen (%N)	0.64 ± 0.03	0.93 ± 0.06	0.76 ± 0.03	0.81 ± 0.09	0.71 ± 0.11	0.62 ± 0.03	0.67 ± 0.03	0.74 ± 0.04	0.70 ± 0.03
Phosphorus (%P)	1.53 ± 0.06	0.77 ± 0.06	0.73 ± 0.06	1.20 ± 0.00	3.07 ± 0.06	0.70 ± 0.00	1.20 ± 0.00	1.37 ± 0.06	1.43 ± 0.06
Potassium (%K)	0.07 ± 0.01	0.57 ± 0.01	0.26 ± 0.01	0.68 ± 0.02	0.05 ± 0.01	0.04 ± 0.01	0.35 ± 0.01	0.26 ± 0.01	0.53 ± 0.01
Nickel (mg/kg)	4.80 ± 0.10	14.43 ± 0.31	17.27 ± 0.15	9.17 ± 0.31	5.20 ± 0.10	19.20 ± 0.30	8.30 ± 0.00	5.30 ± 0.10	14.67 ± 0.15
Cadmium (mg/kg)	14.90 ± 0.20	18.40 ± 0.52	16.50 ± 0.30	20.97 ± 0.21	71.80 ± 0.30	16.63 ± 0.15	72.00 ± 1.00	73.23 ± 0.57	12.93 ± 0.32
Copper (mg/kg)	5.60 ± 0.53	8.63 ± 0.55	69.67 ± 1.53	12.33 ± 1.53	3.00 ± 1.00	4.33 ± 1.53	4.83 ± 1.04	5.00 ± 1.00	6.67 ± 1.53
Zinc (mg/kg)	7.67 ± 1.53	12.67 ± 1.53	7.30 ± 1.13	17.33 ± 2.08	13.67 ± 2.52	12.67 ± 1.53	11.17 ± 0.76	14.33 ± 1.53	9.33 ± 1.53
Lead (mg/kg)	42.67 ± 0.58	29.33 ± 0.58	21.67 ± 0.58	39.67 ± 1.16	22.67 ± 1.16	38.67 ± 0.58	26.67 ± 1.53	18.33 ± 0.58	23.00 ± 1.00
Total Viable Count (× 10^5 CFU/ml)	57.0	6.0	38.0	72.0	97.0	519.0	114.0	63.0	88.0
Total Coliform (× 10^5 CFU/ml)	27.0	53.0	45.0	69.0	90.0	158.0	127.0	52.0	67.0
E.Coli (× 10^5 CFU/ml)	12.0	31.0	34.0	71.0	50.0	207.0	108.0	50.0	76.0
Salmonella (× 10^5 CFU/ml)	25.0	32.0	48.0	72.0	74.0	62.0	54.0	53.0	10.0
Germination Test (%)	101.80 ± 32.67	81.19 ± 3.06	84.56 ± 6.87	80.09 ± 8.27	123.20 ± 15.43	99.81 ± 17.51	108.30 ± 6.19	95.38 ± 5.85	84.18 ± 9.98
Respiration Test (mg CO2•C/g organic carbon/day)	0.2	0.6	1.2	0.3	0.2	0.2	0.5	0.4	0.4
Self-Heating Test (°C)	29.50 ± 0.58	29.45 ± 0.53	29.15 ± 0.87	28.88 ± 0.85	28.83 ± 0.89	28.83 ± 0.89	29.08 ± 0.78	29.03 ± 0.74	28.45 ± 1.17

Although all piles were within acceptable standards, three piles (3) emerged as the optimum compost products in the order of compost quality Pile 9 > Pile 8 > Pile 7. This was based on their performance during final compost analysis and field trials. The substrate ratios applied through ratio modelling, suggest the feasibility of large-scale production and safe use of co-compost from organic waste, chicken manure and faecal sludge. The results encourage the recycling of pile 9 (Organic municipal solid waste (1) Chicken manure (2) Faecal sludge (1)), pile 8 (Organic municipal solid waste (2) Chicken manure (1) Faecal sludge (1)) and pile 7 (Organic municipal solid waste (1) Chicken manure (1) Faecal sludge (1)) into economical compost products that will serve as sustainable solution of waste management as well as a stepping stone towards a circular economy. At the end of the study, it was recommended that further studies should explore varying the moisture content to achieve the optimum range.

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Data availability Data available on request from the authors.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Abbas T, Rizwan M, Ali S, Adrees M, Mahmood A, Zia-ur-Rehman M, Ibrahim M, Arshad M, Qayyum MF (2018) Biochar application increased the growth and yield and reduced cadmium in drought stressed wheat grown in an aged contaminated soil. Ecotoxicol Environ Saf 148:825–833. https://doi.org/10.1016/j.ecoenv.2017.11.063
2. Adebayo OS, Kabbashi NA, Alam MZ, Mirghani MS (2015) Recycling of organic wastes using locally isolated lignocellulolytic strains and sustainable technology. J Mater Cycles Waste Manag 17:769–780. https://doi.org/10.1007/s10163-014-0309-z
3. Adeyemo AJ, Akingbola OO, Ojeniyi SO (2019) Effects of poultry manure on soil infiltration, organic matter contents and maize performance on two contrasting degraded alfisols in southwestern Nigeria. Int J Recycl Org Waste Agric 8:73–80. https://doi.org/10.1007/s40093-019-0273-7
4. Ahn HK, Mulbry W, White JW, Kondrad SL (2011) Pile mixing increases greenhouse gas emissions during composting of dairy manure. Bioresour Technol 102:2904–2909. https://doi.org/10.1016/J.BIORTECH.2010.10.142
5. Akratos CS, Tekerlekopoulou AG, Vasiliadou IA, Vayenas DV (2017) Cocomposting of olive mill waste for the production of soil amendments. Elsevier Inc., Amsterdam, Netherlands, pp 161–182
6. Al-Bataina BB, Young TM, Ranieri E (2016) Effects of compost age on the release of nutrients. Int Soil Water Conserv Res 4:230–236. https://doi.org/10.1016/j.iswcr.2016.07.003
7. Alburquerque JA, Gonzálvez J, García D, Cegarra J (2006) Effects of bulking agent on the composting of "alperujo", the solid by-product of the two-phase centrifugation method for olive oil extraction. Process Biochem 41:127–132. https://doi.org/10.1016/J.PROCBIO.2005.06.006
8. Amekudzi LK, Yamba EI, Preko K, Asare EO, Aryee J, Baidu M, Codjoe SNA (2015) Variabilities in rainfall onset, cessation and length of rainy season for the various agro-ecological zones of Ghana. Climate 3:416–434. https://doi.org/10.3390/cli3020416
9. Andersen MS (2007) An introductory note on the environmental economics of the circular economy. Sustain Sci 2:133–140. https://doi.org/10.1007/S11625-006-0013-6
10. Ansari M, Zafar U, Ejaz U, Sohail M, Pirzada A, Aman A (2021) Comparison of composting of chemically pretreated and fermented sugarcane bagasse for zero-waste biorefinery. J Mater Cycles Waste Manag 23:911–921. https://doi.org/10.1007/s10163-021-01176-w
11. Appiah-Effah E, Nyarko KB, Awuah E, Antwi EO (2018) Rotary drum composter as a low cost method for the removal of Ascaris lumbricoides and Trichuris Trichiura in faecal sludge compost. Water Pract Technol 13:237–246. https://doi.org/10.2166/wpt.2018.018
12. Awasthi SK, Liu T, Awasthi MK, Zhang Z (2020) Evaluation of biochar amendment on heavy metal resistant bacteria abundance in biosolids compost. Bioresour Technol 306:123114. https://doi.org/10.1016/j.biortech.2020.123114
13. Ayilara MS, Olanrewaju OS, Babalola OO, Odeyemi O (2020) Waste management through composting: challenges and potentials. Sustain 12:1–23. https://doi.org/10.3390/su12114456
14. Baird RB, Eaton AD, Clesceri LS (2012) Standard methods for the examination of water and wastewater. American Public Health Association, American Water Works Association, Water Environment Federation
15. Barrios-Hernández ML, Buenaño-Vargas C, García H, Brdjanovic D, van Loosdrecht MCM, Hooijmans CM (2020) Effect of the co-treatment of synthetic faecal sludge and wastewater in an aerobic granular sludge system. Sci Total Environ 741:140480. https://doi.org/10.1016/J.SCITOTENV.2020.140480
16. Bashir A, Rizwan M, Ali S, Adrees M, Rehmanur MZ, Qayyum MF (2020) Effect of composted organic amendments and zinc oxide nanoparticles on growth and cadmium accumulation by wheat; a life cycle study. Environ Sci Pollut Res 27:23926–23936. https://doi.org/10.1007/s11356-020-08739-8
17. Beccaloni E, Vanni F, Beccaloni M, Carere M (2013) Concentrations of arsenic, cadmium, lead and zinc in homegrown vegetables and fruits: estimated intake by population in an industrialized area of Sardinia, Italy. Microchem J 107:190–195. https://doi.org/10.1016/j.microc.2012.06.012
18. Bharti VS, Dotaniya ML, Shukla SP, Yadav VK (2017) Managing soil fertility through microbes: prospects, challenges and future strategies. Agro-Environmental Sustainability. Springer, Cham., pp 81–111
19. Biosci IJ, Azeem M, Chaudhry AN, Faheem M, Imran M, Riaz A, Satti A (2014) Nutrients release pattern during co-composting of poultry litter and different sources of fast food wastes Department of soil science and soil water conservation. Pir Mehr Ali Shah Arid Agriculture 6655:105–115
20. Brewer LJ, Sullivan DM (2003) Maturity and stability evaluation of composted yard trimmings. Compost Sci Util 11:96–112. https://doi.org/10.1080/1065657X.2003.10702117
21. Brinton WF, Gardner G (2000) Compost quality standards & guidelines compost standards & guidelines. Woods End Res Lab 1–42.
22. Bryndum S, Muschler R, Nigussie A, Magid J, de Neergaard A (2017) Reduced turning frequency and delayed poultry manure addition reduces N loss from sugarcane compost. Waste Manag 65:169–177. https://doi.org/10.1016/J.WASMAN.2017.04.001
23. Bujoczek G, Oleszkiewicz J, Sparling R, Cenkowski S (2000) High solid anaerobic digestion of chicken manure. J Agric Eng Res 76:51–60. https://doi.org/10.1006/JAER.2000.0529
24. Canadian Council of Ministers of the Environment (CCME) (2005) Guidelines for compost quality
25. Chen Y, Xu Y, Qu F, Hou F, Chen H, Li X (2020) Effects of different loading rates and types of biochar on passivations of Cu and Zn via swine manure composting. J Arid Land 12:1056–1070. https://doi.org/10.1007/s40333-020-0026-5
26. Chen Z, Li Y, Peng Y, Ye C, Zhang S (2021) Effects of antibiotics on hydrolase activity and structure of microbial community during aerobic co-composting of food waste with sewage sludge. Bioresour Technol 321:124506. https://doi.org/10.1016/j.biortech.2020.124506
27. Cheung HNB, Huang GH, Yu H (2010) Microbial-growth inhibition during composting of food waste: effects of organic acids. Bioresour Technol 101:5925–5934. https://doi.org/10.1016/j.biortech.2010.02.062
28. Chuenchart W, Logan M, Leelayouthayotin C, Visvanathan C (2020) Enhancement of food waste thermophilic anaerobic digestion through synergistic effect with chicken manure.

Biomass Bioenerg 136:105541. https://doi.org/10.1016/J.BIOMBIOE.2020.105541
29. Clark FE (2016) Agar-plate method for total microbial count. Methods Soil Anal Part 2 Chem Microbiol Prop. https://doi.org/10.2134/agronmonogr9.2.c48
30. Cooperband LR (2000) Composting: art and science of organic waste conversion to a valuable soil resource. Lab Med 31:283–289. https://doi.org/10.1309/w286-lqf1-r2m2-1wnt
31. Danso GK, Otoo M, Ekere W, Ddungu S, Madurangi G (2017) Market feasibility of faecal sludge and municipal solid waste-based compost as measured by farmers' willingness-to-pay for product attributes: evidence from Kampala Uganda. Res 6(3):31. https://doi.org/10.3390/resources6030031
32. Dumontet S, Dinel H, Baloda SB (1999) Pathogen reduction in sewage sludge by composting and other biological treatments: a review. Biol Agric Hortic 16:409–430. https://doi.org/10.1080/01448765.1999.9755243
33. Fakkaew K, Koottatep T, Pussayanavin T, Polprasert C (2015) Hydrochar production by hydrothermal carbonization of faecal sludge. J Water Sanit Hygiene Devel. https://doi.org/10.2166/washdev.2015.017
34. Ferreira RB, Oliveira SR, Franzini VP, Virgilio A, Raposo JL, Neto JAG (2011) Evaluation of lines of phosphorus and potassium by high-resolution continuum source flame atomic absorption spectrometry for liquid fertilizer analysis. At Spectrosc 32:56–61. https://doi.org/10.46770/as.2011.02.002
35. Gao M, Liang F, Yu A, Li B, Yang L (2010) Evaluation of stability and maturity during forced-aeration composting of chicken manure and sawdust at different C/N ratios. Chemosphere 78:614–619. https://doi.org/10.1016/j.chemosphere.2009.10.056
36. Gbenatey E, Philip N, Godfred A, Muspratt A (2017) Effects of co-composting of faecal sludge and agricultural wastes on tomato transplant and growth. Int J Recycl Org Waste Agric 6:23–36. https://doi.org/10.1007/s40093-016-0149-z
37. Geissdoerfer M, Savaget P, Bocken NMP, Hultink EJ (2017) The circular economy—a new sustainability paradigm? J Clean Prod 143:757–768. https://doi.org/10.1016/J.JCLEPRO.2016.12.048
38. Ghana Statistical Service (2021) Ghana 2021 Population And Housing Census
39. Grandgirard J, Poinsot D, Krespi L, Nénon JP, Cortesero AM (2002) Costs of secondary parasitism in the facultative hyperparasitoid Pachycrepoideus dubius: does host size matter? Entomol Exp Appl 103:239–248
40. Grant CC, Peel MJS, Zambatis N, Van Ryssen JBJ (2000) Nitrogen and phosphorus concentration in faeces: an indicator of range quality as a practical adjunct to existing range evaluation methods. Afr J Range Forage Sci 17:81–92. https://doi.org/10.2989/10220110009485743
41. Grau F, Drechsel N, Haering V, Trautz D, Sisira WJ, Weerakkody K, Marschner B, Mudiyanselage Priyanga D, Dissanayake S, Sinnathamby V (2017) Impact of fecal sludge and municipal solid waste co-compost on crop growth of raphanus sativus L. and capsicum anuum L. under stress conditions. Resouces. 6:26. https://doi.org/10.3390/resources6030026
42. Guerra-Rodríguez E, Vázquez M, Díaz-Raviña M (2000) Co-composting of barley wastes and solid poultry manure. Bioresour Technol 75:223–225. https://doi.org/10.1016/S0960-8524(00)00069-9
43. Guo R, Li G, Jiang T, Schuchardt F, Chen T, Zhao Y, Shen Y (2012) Effect of aeration rate, C/N ratio and moisture content on the stability and maturity of compost. Bioresour Technol 112:171–178. https://doi.org/10.1016/J.BIORTECH.2012.02.099
44. Guzman MALG, Udtojan MAA, Del Castillo MF, Espiritu EQ, Estiva JAN, Unson JRS, Dumo JRE, Espinas JRE (2020) Efficiency of combined co-composting, vermicomposting, and drying in the treatment of cadmium, mercury, helminths, and coliforms in sludge from wastewater facilities for potential agricultural applications. Philipp J Sci 149:179–188
45. Hachicha S, Sellami F, Cegarra J, Hachicha R, Drira N, Medhioub K, Ammar E (2009) Biological activity during co-composting of sludge issued from the OMW evaporation ponds with poultry manure—Physico-chemical characterization of the processed organic matter. J Hazard Mater 162:402–409. https://doi.org/10.1016/J.JHAZMAT.2008.05.053
46. Hartley W, Dickinson NM, Riby P, Leese E, Morton J, Lepp NW (2010) Arsenic mobility and speciation in a contaminated urban soil are affected by different methods of green waste compost application. Environ Pollut 158:3560–3570. https://doi.org/10.1016/j.envpol.2010.08.015
47. Heaton L, Fullen MA, Bhattacharyya R (2016) Critical analysis of the van Bemmelen conversion factor used to convert soil organic matter data to soil organic carbon data: comparative analyses in a UK loamy sand soil. Espaço Aberto 6:35–44. https://doi.org/10.36403/espacoaberto.2016.5244
48. Heinonen-Tanski H, Singh S, Ibrahim MA, Pawar S, Brdjanovic D (2022) Public perceptions of reuse of faecal sludge co-compost in Bhubaneswar. India. https://doi.org/10.3390/su14084489
49. Hemidat S, Jaar M, Nassour A, Nelles M (2018) Monitoring of composting process parameters: a case study in Jordan. Waste Biomass Valoriz 9:2257–2274. https://doi.org/10.1007/s12649-018-0197-x
50. Hemidat SM, Nelles M (2018) Monitoring of composting process parameters : a case study in Jordan. Waste Biomass Valoriz. https://doi.org/10.1007/s12649-018-0197-x
51. Himanen M, Hänninen K (2011) Composting of bio-waste, aerobic and anaerobic sludges - Effect of feedstock on the process and quality of compost. Bioresour Technol 102:2842–2852. https://doi.org/10.1016/j.biortech.2010.10.059
52. Huang C, Zeng G, Huang D, Lai C, Xu P, Zhang C, Cheng M, Wan J, Hu L, Zhang Y (2017) Effect of Phanerochaete chrysosporium inoculation on bacterial community and metal stabilization in lead-contaminated agricultural waste composting. Bioresour Technol 243:294–303. https://doi.org/10.1016/j.biortech.2017.06.124
53. Huang DL, Zeng GM, Feng CL, Hu S, Jiang XY, Tang L, Su FF, Zhang Y, Zeng W, Liu HL (2008) Degradation of lead-contaminated lignocellulosic waste by Phanerochaete chrysosporium and the reduction of lead toxicity. Environ Sci Technol 42:4946–4951. https://doi.org/10.1021/es800072c
54. Huang GF, Wong JWC, Wu QT, Nagar BB (2004) Effect of C/N on composting of pig manure with sawdust. Waste Manag 24:805–813. https://doi.org/10.1016/j.wasman.2004.03.011
55. Huang W, Hall SJ (2017) Elevated moisture stimulates carbon loss from mineral soils by releasing protected organic matter. Nat Commun 8(1):1774. https://doi.org/10.1038/s41467-017-01998-z
56. Hwang HY, Kim SH, Kim MS, Park SJ, Lee CH (2020) Co-composting of chicken manure with organic wastes: characterization of gases emissions and compost quality. Appl Biol Chem 63:1. https://doi.org/10.1186/s13765-019-0483-8
57. Ishchenko V (2019) Journal of Environmental Science and Health. Part A Toxic/Hazardous Sub Environ Eng Heavy Metals Municip Waste Content Leach Ability Waste Fract Vitalii Ishchenko Heavy Metals Municip Waste Content. https://doi.org/10.1080/10934529.2019.1655369
58. Ishigaki T, Nakanishi A, Tateda M, Ike M, Fujita M (2005) Bioleaching of metal from municipal waste incineration fly ash using a mixed culture of sulfur-oxidizing and iron-oxidizing bacteria. Chemosphere 60:1087–1094. https://doi.org/10.1016/J.CHEMOSPHERE.2004.12.060
59. Jakubus M, Graczyk M (2020) Availability of nickel in soil evaluated by various chemical extractants and plant accumulation.

Agronomy 10(11):1805. https://doi.org/10.3390/agronomy10111805
60. Jalali M, Khanlari ZV (2008) Environmental contamination of Zn, Cd, Ni, Cu, and Pb from industrial areas in Hamadan Province, western Iran. Environ Geol 55:1537–1543. https://doi.org/10.1007/s00254-007-1103-1
61. Jamaludin SN, Abdul Kadir A, Azhari NW (2017) Study on NPK performance in food waste composting by using agricultural fermentation. MATEC Web Conf. 103:05015. https://doi.org/10.1051/matecconf/201710305015
62. Khan A, Khan S, Khan MA, Qamar Z, Waqas M (2015) The uptake and bioaccumulation of heavy metals by food plants, their effects on plants nutrients, and associated health risk: a review. Environ Sci Pollut Res 22:13772–13799. https://doi.org/10.1007/s11356-015-4881-0
63. Kuffoura R, Awuah E, Sarpong D, Anyemedu FOK, Koné D (2013) Effects of different solid loading rates of faecal sludge on the dewatering performance of unplanted filter bed. Civ Environ Res. 3:39–49
64. Latifah O, Ahmed OH, Susilawati K, Majid NM (2015) Compost maturity and nitrogen availability by co-composting of paddy husk and chicken manure amended with clinoptilolite zeolite. Waste Manag Res 33:322–331. https://doi.org/10.1177/0734242X15576771
65. Li J, Yu K (2011) A study on legislative and policy tools for promoting the circular economic model for waste management in China. J Mater Cycles Waste Manag 13:103–112. https://doi.org/10.1007/s10163-011-0010-4
66. Li Y, Ning F, Cong W, Zhang M, Tang Y (2016) Investigating pellet charring and temperature in ultrasonic vibration-assisted pelleting of wheat straw for cellulosic biofuel manufacturing. Renew Energy 92:312–320. https://doi.org/10.1016/j.renene.2016.02.006
67. Liu D, Zhang R, Wu H, Xu D, Tang Z, Yu G, Xu Z, Shen Q (2011) Changes in biochemical and microbiological parameters during the period of rapid composting of dairy manure with rice chaff. Bioresour Technol 102:9040–9049. https://doi.org/10.1016/j.biortech.2011.07.052
68. Lopes C, Herva M, Franco-Uría A, Roca E (2011) Inventory of heavy metal content in organic waste applied as fertilizer in agriculture: evaluating the risk of transfer into the food chain. Environ Sci Pollut Res 18:918–939. https://doi.org/10.1007/s11356-011-0444-1
69. Luangwilai T, Sidhu HS, Nelson MI (2018) One-dimensional spatial model for self-heating in compost piles: investigating effects of moisture and air flow. Food Bioprod Process 108:18–26. https://doi.org/10.1016/j.fbp.2017.12.001
70. Mahapatra S, Ali MH, Samal K (2022) Assessment of compost maturity-stability indices and recent development of composting bin. Energy Nexus. 6:100062. https://doi.org/10.1016/j.nexus.2022.100062
71. Mandal AB, Bhanja SK (2017) Nitrogen use efficiency in poultry husbandry—Indian perspective. Indian Nitrogen Assess. https://doi.org/10.1016/B978-0-12-811836-8.00017-3
72. Manga M, Camargo-Valero MA, Anthonj C, Evans BE (2021) Fate of faecal pathogen indicators during faecal sludge composting with different bulking agents in tropical climate. Int J Hyg Environ Health. https://doi.org/10.1016/j.ijheh.2020.113670
73. Manga M, Camargo-Valero MA, Evans BE (2022) Recycling of faecal sludge: nitrogen, carbon and organic matter transformation during co-composting of faecal sludge with different bulking agents. Ready Sub Int J Environ Res Public Heal. 19(17):10592
74. Manzanas R, Amekudzi LK, Preko K, Herrera S, Gutiérrez JM (2014) Precipitation variability and trends in Ghana: an intercomparison of observational and reanalysis products. Clim Change 124:805–819. https://doi.org/10.1007/s10584-014-1100-9
75. Materechera SA, Mkhabela TS (2002) The effectiveness of lime, chicken manure and leaf litter ash in ameliorating acidity in a soil previously under black wattle (Acacia mearnsii) plantation. Bioresour Technol 85:9–16. https://doi.org/10.1016/S0960-8524(02)00065-2
76. Maurya A (2018) Analysis of heavy metal in soil through atomic absorption spectroscopy for forensic consideration. Int J Res Appl Sci Eng Technol 6:1188–1192. https://doi.org/10.22214/ijraset.2018.6173
77. McLaurin WJ, Wade GL (2012) Composting And Mulching; A Guide To Managing Organic Landscape Refuse. The University of Georgia Cooperative Extension 816:6–7.
78. Mengistu T, Gebrekidan H, Kibret K, Woldetsadik K, Shimelis B, Yadav H (2018) Comparative effectiveness of different composting methods on the stabilization, maturation and sanitization of municipal organic solid wastes and dried faecal sludge mixtures. Environ Syst Res. 6:1–6. https://doi.org/10.1186/s40068-017-0079-4
79. Michailides M, Christou G, Akratos CS, Tekerlekopoulou AG, Vayenas DV (2011) Composting of olive leaves and pomace from a three-phase olive mill plant. Int Biodeterior Biodegrad 65:560–564. https://doi.org/10.1016/j.ibiod.2011.02.007
80. Miezah K, Obiri-Danso K, Kádár Z, Fei-Baffoe B, Mensah MY (2015) Municipal solid waste characterization and quantification as a measure towards effective waste management in Ghana. Waste Manag 46:15–27. https://doi.org/10.1016/j.wasman.2015.09.009
81. Miyazawa M, Giminez SMN, Yabe MJS, Oliveira EL, Kamogawa MY (2002) Absorption and toxicity of copper and zinc in bean plants cultivated in soil treated with chicken manure. Water Air Soil Pollut 138:211–222. https://doi.org/10.1023/A:1015555116292
82. Noble R, Roberts SJ (2004) Eradication of plant pathogens and nematodes during composting: a review. Plant Pathol 53:548–568. https://doi.org/10.1111/j.0032-0862.2004.01059.x
83. Núñez F, Pérez M, Leon-Fernández LF, García-Morales JL, Fernández-Morales FJ (2022) Effect of the mixing ratio on the composting of OFMSW digestate: assessment of compost quality. J Mater Cycles Waste Manag 24:1818–1831. https://doi.org/10.1007/s10163-022-01438-1
84. Nutongkaew T, Duangsuwan W, Prasertsan S, Prasertsan P (2014) Physicochemical and biochemical changes during composting of different mixing ratios of biogas sludge with palm oil mill wastes and biogas effluent. J Mater Cycles Waste Manag 16:131–140. https://doi.org/10.1007/s10163-013-0165-2
85. Ofori-Boateng C, Lee KT, Mensah M (2013) The prospects of electricity generation from municipal solid waste (MSW) in Ghana: a better waste management option. Fuel Process Technol 110:94–102. https://doi.org/10.1016/J.FUPROC.2012.11.008
86. Omari RA, Aung HP, Hou M, Yokoyama T, Onwona-Agyeman S, Oikawa Y, Fujii Y, Bellingrath-Kimura SD (2016) Influence of different plant materials in combination with chicken manure on soil carbon and nitrogen contents and vegetable yield. Pedosphere 26:510–521. https://doi.org/10.1016/S1002-0160(15)60061-3
87. Oorts K (2012) Copper. Heavy Met Soils 22:1–161. https://doi.org/10.1007/978-94-007-4470-7_13
88. Oteng-Ababio M (2016) Rethinking waste as a resource : insights from a low-income community in Accra. Ghana. https://doi.org/10.1186/2195-2701-1-10
89. Oviedo-Ocaña ER, Torres-Lozada P, Marmolejo-Rebellon LF, Hoyos LV, Gonzales S, Barrena R, Komilis D, Sanchez A (2015) Stability and maturity of biowaste composts derived by small

municipalities: correlation among physical, chemical and biological indices. Waste Manag 44:63–71. https://doi.org/10.1016/j.wasman.2015.07.034
90. Owusu K, Waylen PR (2013) The changing rainy season climatology of mid-Ghana. Theor Appl Climatol 112:419–430. https://doi.org/10.1007/s00704-012-0736-5
91. Pace MG, Miller BE, Farrell-Poe KL (1995) The Composting Process. Utah State University Cooperative Extension, pp 1–2.
92. Bo PL, Ma J, Liang WX, Hou H (2016) Heavy metals in soils from a typical county in Shanxi Province, China: levels, sources and spatial distribution. Chemosphere 148:248–254. https://doi.org/10.1016/j.chemosphere.2015.12.049
93. Pandey C, Shukla S (2006) Effects of composted yard waste on water movement in sandy soil. Compost Sci Util 14:252–259. https://doi.org/10.1080/1065657X.2006.10702293
94. Powlson D, Smith P, De NM (2011) Soil organic matter. Eur J Soil Sci 62:1
95. Quina MJ, Bordado JCM, Quinta-Ferreira RM (2009) The influence of pH on the leaching behaviour of inorganic components from municipal solid waste APC residues. Waste Manag 29:2483–2493. https://doi.org/10.1016/J.WASMAN.2009.05.012
96. Reeb JE, Milota MR, Western Dry Kiln Association (1999) Moisture content by the oven-dry method for industrial testing. Wood Sci Eng 66–74
97. Richa Gupta MB (2013) Implementation of bulking agents in composting: a review. J Bioremed Biodegrad. https://doi.org/10.4172/2155-6199.1000205
98. Rynk R (1992) On-farm composting handbook. Monogr Soc Res Child Dev 77:132. https://doi.org/10.1111/j.1540-5834.2012.00684.x
99. Sadaka SS, Richard TL, Loecke TD, Liebman M (2006) Determination of compost respiration rates using pressure sensors. Compost Sci Util 14:124–131. https://doi.org/10.1080/1065657X.2006.10702273
100. Sagoe G, Safo F, Amofa-sarkodie ES, Appiah-effah E, Ekumah E, Kwaw E, Sefa K (2019) Heliyon GIS-aided optimisation of faecal sludge management in developing countries: the case of the greater Accra metropolitan area. Ghana. Heliyon. 5:e02505. https://doi.org/10.1016/j.heliyon.2019.e02505
101. Shapovalov Y, Zhadan S, Bochmann G, Salyuk A, Nykyforov V (2020) Dry anaerobic digestion of chicken manure: a review. Appl Sci 10(21):7825. https://doi.org/10.3390/app10217825
102. Sharma D, Yadav KD, Kumar S (2018) Role of sawdust and cow dung on compost maturity during rotary drum composting of flower waste. Bioresour Technol 264:285–289. https://doi.org/10.1016/j.biortech.2018.05.091
103. Shimizu N, Karyadi JNW, Harano M, Iwabuchi K, Kimura T (2018) Cattle manure composting in a packed-bed reactor with forced aeration strategy. Eng Agric Environ Food 11:65–73. https://doi.org/10.1016/j.eaef.2018.01.002
104. Silva ME, Lemos LT, Cunha-Queda CA, Nunes OC (2009) Co-composting of poultry manure with low quantities of carbon-rich materials. Waste Manag Res 27:119–128. https://doi.org/10.1177/0734242X08096693
105. Smith SR, Jasim S (2009) Small-scale home composting of biodegradable household waste: overview of key results from a 3 year research programme in West London. Waste Manag Res 27:941–950. https://doi.org/10.1177/0734242X09103828
106. Spalvins E, Dubey B, Townsend T (2008) Impact of electronic waste disposal on lead concentrations in landfill leachate. Environ Sci Technol 42:7452–7458. https://doi.org/10.1021/es8009277
107. Stouraiti C, Xenidis A, Paspaliaris I (2002) Contaminated Soils By the Application of Lignite. Water Air Soil Pollut 137:247–265
108. Strachel R, Wyszkowska J, Baćmaga M (2017) The role of compost in stabilizing the microbiological and biochemical properties of zinc-stressed soil. Water Air Soil Pollut 228:1–5. https://doi.org/10.1007/s11270-017-3539-6
109. Sweeten JM, Auvermann BW (1988) Composting manure and sludge. Texas Agrilcul Ext Serv L. 2289:1–7. https://doi.org/10.1038/sj.ejcn.1600320
110. Tang JC, Shibata A, Zhou Q, Katayama A (2007) Effect of temperature on reaction rate and microbial community in composting of cattle manure with rice straw. J Biosci Bioeng 104:321–328. https://doi.org/10.1263/jbb.104.321
111. Tibu C, Annang TY, Solomon N, Tawiah DY (2019) Effect of the composting process on physicochemical properties and concentration of heavy metals in market waste with additive materials in the Ga West Municipality, Ghana. Int J Recycl Org Waste Agric 8:393–403. https://doi.org/10.1007/s40093-019-0266-6
112. Tognetti C, Mazzarino MJ, Laos F (2007) Improving the quality of municipal organic waste compost. Bioresour Technol 98:1067–1076. https://doi.org/10.1016/j.biortech.2006.04.025
113. Toor GS, Hunger S, Peak JD, Sims JT, Sparks DL (2006) Advances in the characterization of phosphorus in organic wastes: environmental and agronomic applications. Adv Agron 89:1–72. https://doi.org/10.1016/S0065-2113(05)89001-7
114. Trautmann, Nancy M, Krasny ME (1998) Composting in the classroom: Scientific inquiry for high school students. In: Composting in the classroom: Scientific inquiry for high school students. Kendall/Hunt Publishing Company, pp 71–82
115. Tremier A (2012) Home-made composts quality: Methods of assessment and results (Doctoral dissertation, irstea)
116. Wan L, Wang X, Cong C, Li J, Xu Y, Li X, Hou F, Wu Y, Wang L (2020) Effect of inoculating microorganisms in chicken manure composting with maize straw. Bioresour Technol 301:122730. https://doi.org/10.1016/J.BIORTECH.2019.122730
117. Wang S, Wang F, Gao S (2015) Foliar application with nano-silicon alleviates Cd toxicity in rice seedlings. Environ Sci Pollut Res 22:2837–2845. https://doi.org/10.1007/s11356-014-3525-0
118. Wei Y, Li J, Shi D, Liu G, Zhao Y, Shimaoka T (2017) Environmental challenges impeding the composting of biodegradable municipal solid waste: a critical review. Resour Conserv Recycl 122:51–65. https://doi.org/10.1016/j.resconrec.2017.01.024
119. Willson GB, Dalmat D (1986) Measuring compost stability. Biocycle 27:34–37
120. Wong JWC, Fang M (2000) Effects of lime addition on sewage sludge composting process. Water Res 34:3691–3698. https://doi.org/10.1016/S0043-1354(00)00116-0
121. Wyszkowski M (2019) Soil contamination with copper and its effect on selected soil properties after applying neutralizing substances. Polish J Environ Stud 28:2465–2471. https://doi.org/10.15244/pjoes/90357
122. Xu N, Tan G, Wang H, Gai X (2016) Effect of biochar additions to soil on nitrogen leaching, microbial biomass and bacterial community structure. Eur J Soil Biol 74:1–8. https://doi.org/10.1016/j.ejsobi.2016.02.004
123. Xu Z, Li G, Huda N, Zhang B, Wang M, Luo W (2020) Effects of moisture and carbon/nitrogen ratio on gaseous emissions and maturity during direct composting of cornstalks used for filtration of anaerobically digested manure centrate. Bioresour Technol 298:122503. https://doi.org/10.1016/J.BIORTECH.2019.122503
124. Yee L, Tin C, Phun C, Bong C, Shiun J (2020) A review on the impacts of compost on soil nitrogen dynamics. Chem Eng Trans 63(349):354. https://doi.org/10.3303/CET1863059

125. Yousefi J, Younesi H, Ghasempoury SM (2013) Co-composting of municipal solid waste with sawdust: improving compost quality. Clean: Soil, Air, Water 41:185–194. https://doi.org/10.1002/clen.201100315
126. Yuan J, Zhang D, Li Y, Chadwick D, Li G, Li Y, Du L (2017) Effects of adding bulking agents on biostabilization and drying of municipal solid waste. Waste Manag 62:52–60. https://doi.org/10.1016/J.WASMAN.2017.02.027
127. Zhang L, Dong H, Zhu Y, Zhang J, Zeng G, Yuan Y, Cheng Y, Li L, Fang W (2019) Evolutions of different microbial populations and the relationships with matrix properties during agricultural waste composting with amendment of iron (hydr)oxide nanoparticles. Bioresour Technol 289:121697. https://doi.org/10.1016/j.biortech.2019.121697
128. Zhao L, Gu WM, He PJ, Shao LM (2011) Biodegradation potential of bulking agents used in sludge bio-drying and their contribution to bio-generated heat. Water Res 45:2322–2330. https://doi.org/10.1016/J.WATRES.2011.01.014
129. Zhou H, Zhao Y, Yang H, Zhu L, Cai B, Luo S, Cao J, Wei Z (2018) Transformation of organic nitrogen fractions with different molecular weights during different organic wastes composting. Bioresour Technol 262:221–228. https://doi.org/10.1016/j.biortech.2018.04.088
130. Zhu-Barker X, Bailey SK, Paw UKT, Burger M, Horwath WR (2017) Greenhouse gas emissions from green waste composting windrow. Waste Manag 59:70–79. https://doi.org/10.1016/j.wasman.2016.10.004

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