International Journal of Recycling of Organic Waste in Agriculture (2020)9: 333-347
DOI:10.30486/IJROWA.2020.1898218.1062

ORIGINAL RESEARCH

Characteristics of co-composts produced from raw faecal sludge and organic market waste in Osun state, southwest Nigeria

Olufemi O Aluko[1, 2*], **Elizabeth O Oloruntoba**[1], **Godson R.E.E Ana**[1], **Taiwo B Hammed**[1], **Olusegun T Afolabi**[2]

Received: 08 May 2020 / Accepted: 17 August 2020 / Published online: 20 December 2020

Abstract

Purpose Faecal sludge (FS) and organic market waste (MW) have resources that could be recovered by co-composting though not fully explored under changing climatic conditions in Nigeria. This study explored the characteristics and nutrient quality of co-composts produced from pre-treated FS and MW feedstocks in Nigeria.

Method The study was exploratory and analytical in design and co-composting was purposively selected for resource-recovery. The raw faecal sludge (FS) was harvested from septic tanks of households (50%) and institutions (50%) through mechanical evacuation service trucks and dewatered using 0.1% gradient sand filter. The biodegradable MW was sorted and used for further studies. The dewatered FS (DFS) and MW were mixed in ratios 1:3, 1:5 and 1:7, respectively with DFS and MW as controls. Each of the mixes was made into 1m^3 heap and co-composted using the windrow method. The experiments were monitored for 88 days with fortnight composite sampling from each mix (13-weeks). The samples were analyzed for temperature, pH, moisture-contents, micronutrients, macronutrients and pollutants using Standard Methods.

Results At maturity, N:P:K (%) indicate good composts at 9: 5: 4, 18: 7: 19 and 3: 3: 1 in the 1: 3, 1: 5 and 1: 7 mixes, respectively, while those of controls were: 19:12:12 (DFS) and 17:14:11(MW) with no significant differences between experimental and control mixes. Also, four factors extracted (pollutants, agronomic, macronutrients and micronutrients), explained 78.2% variability.

Conclusion The matured co-compost satisfied nutrients and pollutants quality for agricultural use, recovered organic fertiliser from raw domestic and institutional faecal sludge and market waste.

Keywords Resource recovery, Co-composting, Dewatered faecal sludge, Organic market waste, Organic fertilizer, Nigeria

Abbreviations

Al	Aluminium
APHA	American public health association
CI	Clean index
C: N	Carbon: nitrogen
CLTS	Community led total sanitation
DFS	Dewatered faecal sludge
FCT	Federal capital territory
FI	Fertilising index
FS	Faecal sludge
FSC	Faecal sludge control
FSM	Faecal sludge management
K	Potassium
LGA	Local government area
MC	Moisture content
MDGs	Millennium development goals
Mg	Magnesium
MICS	Multi-indicator cluster survey
MSW	Municipal solid waste
MW	Organic market waste
OAU	Obafemi Awolowo university, Ile-Ife
OSS	On-site sanitation
OWMA	Osun state waste management agency
P	Phosphorus
PCs	Principal components
PCA	Principal component analysis
PLS	Partial least squares
PIXE	Proton Induced x-ray Emissions
S	Sulphur
SANDEC	Sanitation in developing countries of the Swiss federal institute of aquatic science and technology
SDGs	Sustainable development goals
SSA	Sub-saharan africa
SWC	Solid waste control
TCC	Total coliform count
TKN	Total kjeldahl nitrogen
TOC	Total organic carbon
UCH	University college hospital, Ibadan, Nigeria
Zn	Zinc

✉ Olufemi O. Aluko
ooaluko@gmail.com

[1] Department of Environmental Health Sciences, Faculty of Public Health, University of Ibadan, Nigeria

[2] Department of Community Health, College of Health Sciences, Obafemi Awolowo University, Nigeria

Introduction

Waste management channels waste through practically, economically and technically appropriate recovery, or disposal routes in compliance with public health standards (Suess and Huismans 1983). By convention, solid waste management is a municipal responsibility, though inadequate services dominate waste management in most local government areas (LGAs) in Nigeria. The millennium development goals (MDGs) advanced uptake in sanitation services at the household level, without considering faecal sludge management, which has been corrected through the sustainable development goal (SDG) 6.2 (McGranahan 2015).

In Nigeria, very few geographical entities, such as the federal capital territory (FCT) and the pioneer tertiary institutions, such as the Obafemi Awolowo university (OAU) and the university college hospital (UCH), Ibadan have the conventional sewerage system. Most households depended on on-site sanitation systems (OSS) (Strauss et al. 2000; Strande et al. 2014; Jenkins et al. 2015; Rao et al. 2017) and about 2.7 billion people rely on OSS globally (Rao et al. 2017; Semiyaga et al. 2017), which accumulate faecal sludge (FS). The FS fill-up rate is dependent on vaults diameter, width and depth; the number of users, the frequency of use and groundwater level (Strande et al. 2014).

The Multi-indicator cluster survey (MICS) revealed that 24.7 % of the population in Osun state have access to improved sanitation facilities (NBS/UNICEF 2017). In Nigeria, the community-led total sanitation (CLTS) is the national strategy to achieve open defecation free status, a programme that majorly focussed on excreta containment without planning for faecal sludge management (FSM) (Chuah and Ziegler 2018). Raw FS contains organic pollutants and pathogens (WHO 2010), though Otterpohl et al. (1997) and Singh et al. (2017) showed that dewatered FS (DFS) is rich in organic matter and nutrients that require sanitization before use in agriculture. Usually, FSM should be productively managed, with resources recovered through centralised and point management structures. In Nigeria, however, FSM is a challenge and its management lacks the infrastructure and political will; thereby relegated in developmental priorities and decision-making. FS is therefore discharged in dumpsites, stagnated and open water resources and on farms at the instance of some farmers. Due to the scarcity and costly chemical fertilizers, attention is placed on organic fertilisers; a fulcrum for sustainable resource recovery from FS and MW in Nigeria, hence this study.

Materials and methods

Description of the approved disposal dumpsite in the study area

The study took place at Olusosun dumpsite, Osogbo, in Osun state in Nigeria, between November 2015 and March 2016. The dumpsite was the predominant solid waste disposal facility owned, operated and managed by the Osun state waste management agency (OWMA), as at the study period. It was in use for municipal solid waste (MSW) disposal by public and private enterprises. The dumpsite is located at the outskirts of the state capital, within the boundaries of Egbedore LGA. The dumpsite was characterised by the tropical rainforest, and its temperature ranged from 19°C to 34°C and an average of 350 mm rainfall (Oyelami et al. 2013). The drainage pattern in the area is dendritic due to a clayey, weathered surface layer overlying the complex basement rock. Some streams and rivers flow northwest and discharge into river Osun (Oyelami et al. 2013). Apart from the MSW, the dumpsite receives FS emptied by vacuum emptying enterprises. There is no FS treatment facility, hence FS is discharged in the dumpsite without remediation (Plate 1a).

Pre-treatment of faecal sludge by dewatering and drying

The dewatering and thickening of FS were achieved by the low-cost sedimentation/gravity process, following the guides by Uggetti et al. (2009) and Uggetti et al. (2012). The mix of domestic and institutional faecal sludge contains water that leached out by gravity thickening before drying. The dewatering and drying trough was modelled on Koné et al. (2004) and had a volume of 4.62m^3 obtained by (5.49 meters (length) by 3.66 meters (breadth) and (0.23 metres (height) (Plate 1b). The system has a slope of 0.1% outwards, for gravitational effluent removal through the filter (fine sandy soil) media. The dewatered FS was dried at room temperature to prevent loss of nutrients by volatilization. The dewatering and dry system ensured 69% volumetric reduction from the raw FS start volume.

Plate 1a Septic sludge discharged in Olusosun dumpsite

Plate 1b The dewatered septic sludge prior to drying

Co-composting of dewatered faecal sludge and sorted market organic wastes

In collaboration with OWMA, the study collected organic solid wastes from Igbona, Owode and Olaiya markets in Osogbo metropolis. The solid waste was aggregated and sorted into organic and 'other' wastes, following the guides provided by Cofie et al. (2009, 2016), before the constitution of the various experimental, feedstock co-compost piles.

Constitution of experimental co-compost piles

Following guides provided by Cofie et al. (2009), Fernández et al. (2010) and Scoton et al. (2015), co-composting was performed at ambient climatic conditions at temperature (22°C – 38°C); humidity (40%–60 %) and C: N (20:1) mass ratio. The study constructed and utilised a 1 m^3 (1.0 m (length) × 1.0 m (width) × 1.0 m (height)) graduated mould in constituting the three co-compost and two control piles. The co-compost experimental piles comprised of dewatered FS and sorted organic market wastes in ratios 1:3, 1:5 and 1:7 by volume and composted using the aerobic windrow method (Cofie et al. 2009; Mengistu et al. 2018) (Fig. 1). The experimental mixing ratios of FS and MSW were determined by adapting the methods used by Cofie et al. (2009).

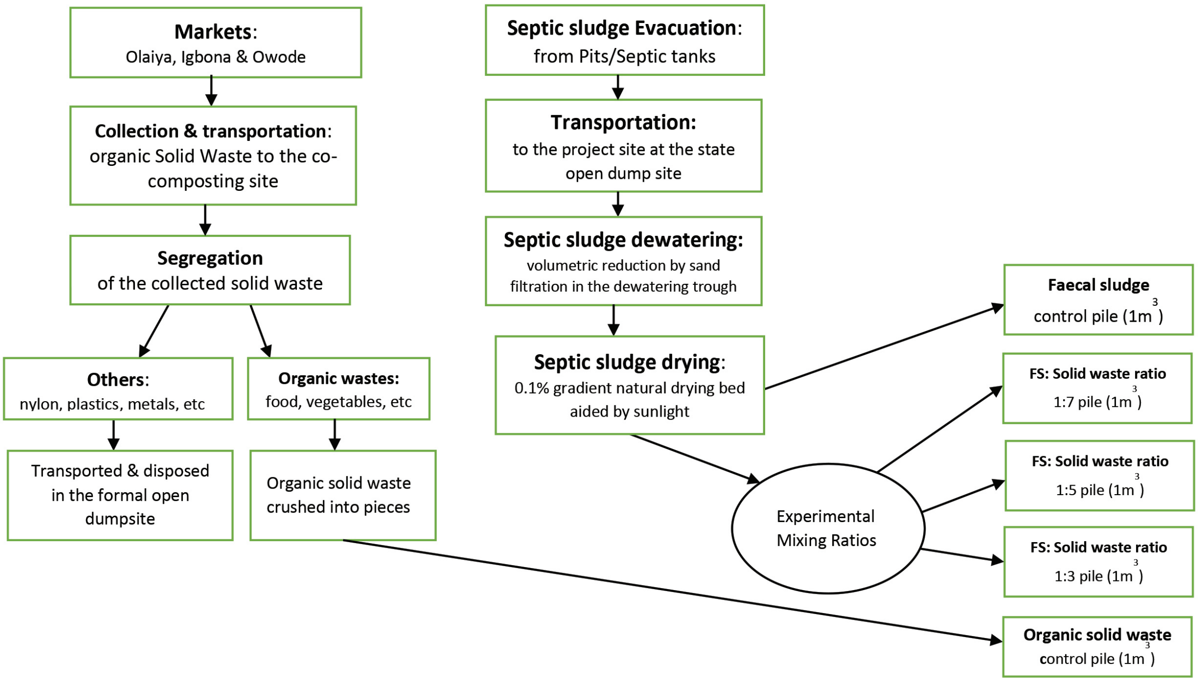

Fig. 1 Feedstock materials processing and aggregates into experimental mixes in the co-composting study

Co-composting method and turning frequency

The aerobic windrow composting method was used with the homogenized feedstock of 1 m^3 heaped to conical sizes (Mengistu et al. 2018; Nartey et al. 2017). The experimental piles were aerated by mixing, with moisture maintained at between 40% to 60% by manual water sprinkling on the constituted heaps. Also, the co-compost heaps were turned once in 3 days (Getahun et al. 2012), during the initial six weeks and decreased to once in seven days during the last weeks when the temperature plateaued at room temperature.

The co-composting experimental units and sampling methods

Following the guide by Costa et al. (2016), a composite sample, from each of the five experimental piles were obtained immediately after the constitution to establish the quality of the feedstock mixes before the co-composting process.

In the co-compost piles, temperature, pH and moisture contents were measured every day, from inception until maturity. The measurements were taken at three random sampling points, with the average presented in the study. For elemental analysis, sampling was done once at a 2-week interval, to establish the performance's trends, from inception until maturity. In this regard, two grab samples were collected after thorough mixing of the pile contents (APHA 1998) and constituted into a composite sample for each mix and transported immediately to the laboratory for further processing and analysis. The samples were oven-dried at 50°C to prevent denaturing and cooled at room temperature before analysis.

Methods of analysis for co-composts mixes

In co-compost samples, macro-elements (total organic carbon (TOC), total kjeldahl nitrogen (TKN), potassium (K), phosphorus (P) and sulphur (S); micro-elements (calcium (Ca), magnesium (Mg), iron (Fe), molybdenum (Mb), sodium (Na) and selenium); pollutant parameters (arsenic (As), lead (Pb), copper (Cu), nickel (Ni), zinc (Zn), cadmium (Cd), chromium (Cr), and the total coliform count (TCC) were analysed using standard methods (APHA/AWWA/WEF 2005). Temperature, moisture content and pH values were measured in-situ with calibrated probes, following manufacturers' instructions. Measurements were taken in three random points in co-compost heaps, at 0.1m and 0.3m depths from the highest point and stabilised before recordings. Total kjeldahl nitrogen (TKN) in each sample was analysed after digestion with sulphuric acid, following standard methods (APHA/AWWA/WEF 2005). Also, the proton induced x-ray emission (PIXE) method was used for elemental analysis of co-compost samples at the centre for energy research and development (CERD) of the Obafemi Awolowo university, Ile-Ife, according to the guide provided by Johansson and Thomas (1976) and Kwiatek et al. (1994). Also, TCC was estimated by the membrane filtration technique (Bartman and Pedley 1996) and computed according to standard methods (APHA 1998). The study data were entered and analysed using IBM-SPSS version 20 software with results presented by the summary and inferential statistics at P $\alpha < 0.05$ The relationships among the co-compost piles were shown through path weights which vary from -1 to +1 with the values closest to 1 reflecting the strongest paths while those closest to 0 reflect the weakest paths (Fan et al. 2016; Garson 2016).

Results and discussion

Changes in co-compost temperature, pH, and moisture content

The temperature of co-compost piles ranged between room temperature 23°C and 63°C, during the thermophilic, self-heating phase, and subsequently reduced to the mesophilic and room temperature range at maturity (Fig. 2a), though their moisture contents were controlled between 42.9% and 60.1%, to provide the optimum condition for natural biodegradation (Fig. 2b). Also, pH ranged between 6.6 and 7.7, and within the recommended threshold for optimum performance (Fig. 2c).

The characteristics of the feedstock co-compost materials (Table 1) showed that temperature was ambient (28.3°C and 29.0°C) and moisture contents were optimal (49.0% to 61.0%). The pH ranged from 6.6 to 6.9, the TKN averaged 1.77% (sorted MW) and 2.82% (dewatered FS) and the C: N ratio varied from 22.3 to 24.9. Also, potassium, phosphorus and calcium respectively ranged from 1.6% to 2.3%, 1.4% to 1.8% and 1.2% to 1.7%. Also, total coliform count (TCC/100ml) ranged from 136×10^7 to 449×10^7.

In agreement with Costa et al. (2016), the temperature was self-moderating and determines co-composts quality at maturity. Except for the FSC pile, the temperature of experimental co-compost piles reached thermophilic phase within 72 hours, in agreement with Karanja et al. (2005) and Jeong et al. (2017). Temperature progression from mesophilic to thermophilic range in experimental piles indicated the presence of a high degree of biodegradable constituents, microbial activity and their self-insulating capacity (Sundberg et al. 2004). The temperature range agrees with studies by Scoton et al. (2016) and Cheng et al. (2017). At temperatures above 55°C, pathogenic microorganisms are decimated in composts in agreement with Cofie et al. (2016) and Nartey et al. (2017) while Niwagaba et al. (2009) showed that high compost temperatures decimate pathogens, but inadequate to achieve total sanitisation irrespective of the co-composting method used.

The pH range of composts was in congruence with previous studies where a progression in pH was reported during co-composting of diverse substrates (Mengistu et al. 2018; Al-Muyeed et al. 2017). The turning frequency in co-compost piles was consistent with those in previous studies, driven by temperature changes in the sanitisation of matured compost (Koné et al. 2004;

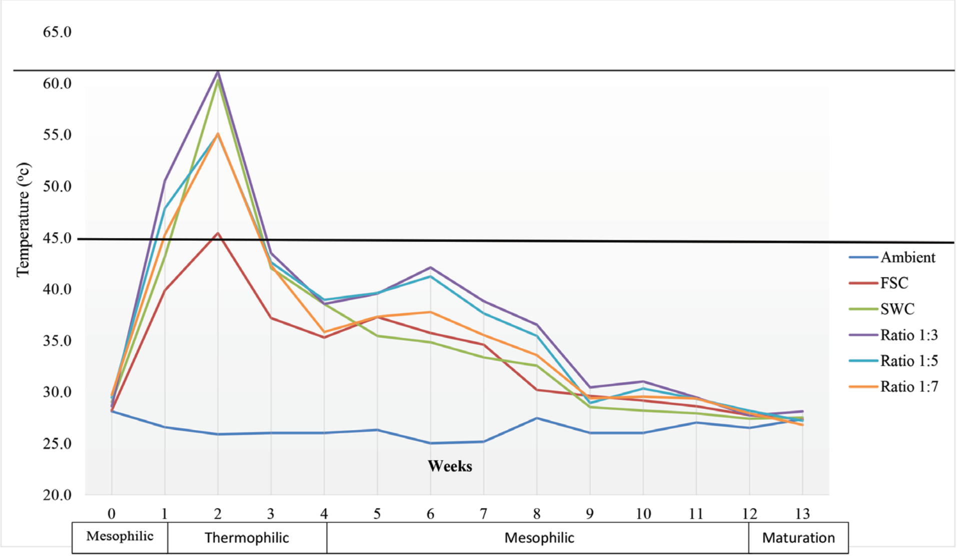

Fig. 2a Temperature changes during the co-composting period

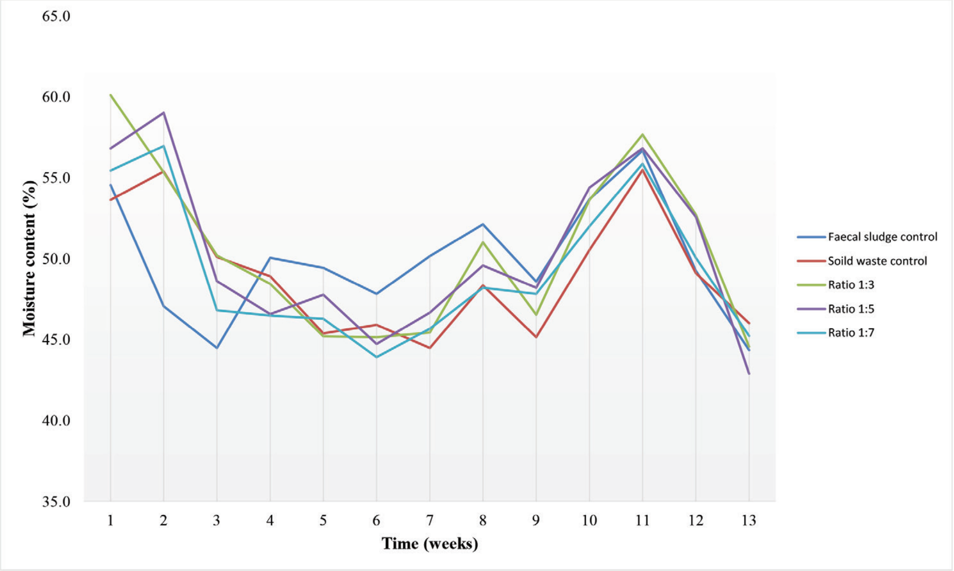

Fig. 2b Moisture content changes during the co-composting period

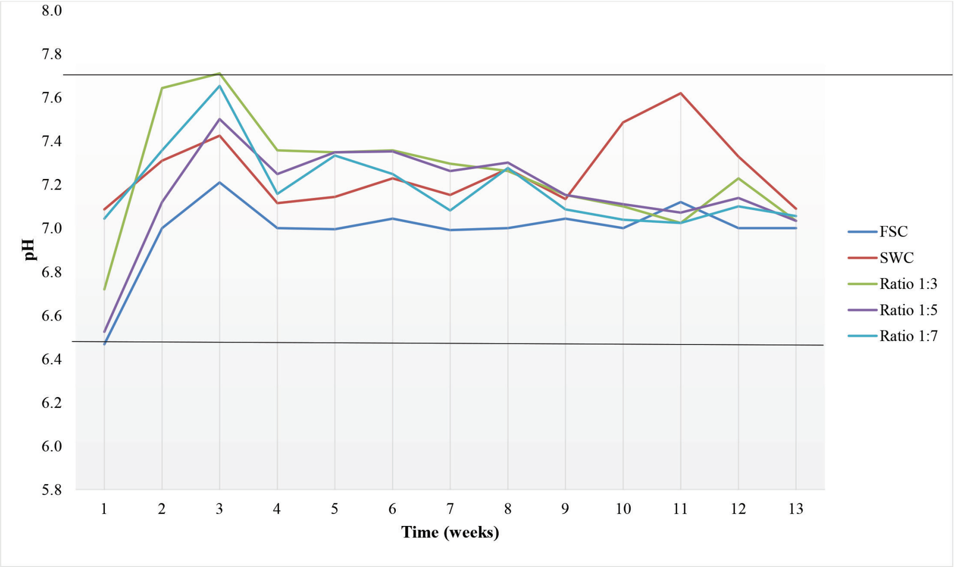

Fig. 2c pH changes during the co-composting period

Table 1 Physical, chemical and microbiological characteristics of co-compost feedstocks

Parameters	Unit	Dewatered faecal sludge	Sorted market solid waste
Temperature	°C	28.3	29.0
Moisture content	Percent	61	49
pH		6.6	6.9
Total kjeldahl nitrogen	Percent	2.82	1.77
Total organic carbon	Percent	63.0	44.0
Organic matter	Percent	15.6	15.3
C: N ratio		22.3	24.9
Potassium (K)	Percent	1.564	2.262
Phosphorus (P)	Percent	1.812	1.395
Sulphur (S)	Percent	1.471	1.273
Calcium (Ca)	Percent	1.655	1.244
Magnesium (Mg)	Percent	0.634	0.427
Iron (Fe)	Percent	0.135	0.105
Sodium (Na)	Percent	0.151	0.136
Copper (Cu)	Percent	0.007	0.002
Zinc (Zn)	Percent	0.493	0.065
Aluminium (Al)	Percent	0.472	0.201
Silicon (Si)	Percent	2.596	4.744
Chloride (Cl)	Percent	0.236	1.056
Manganese (Mn)	Percent	0.204	0.011
Total coliform count	TCC/100ml	136 x 10^7	449 x 10^7

Parkinson et al. 2004; Cofie et al. 2009; Nartey et al. 2017). Though temperature and pH were self-regulataing during the composting process, the moisture contents were regulated at between 40% and 65%, from inception to maturity to prevent moisture from being a process limiting variable.

Characteristics of co-composts at various composting stages

The initial co-compost heaps were weakly acidic while those of matured composts transited from neutral, to weakly basic. The moisture contents of the co-compost at the initial, thermophilic and mesophilic phases ranged from 48-64%, except when matured and below 40%. Also, the proportion of TKN varied marginally from the initial co-compost heaps to matured co-composts, in contrast to a reduction in their organic carbon contents from initial heaps (63%) to matured co-compost samples (14.3%). The C: N ratio reduced from start-up values (24.9%-18.9%) to (10.1%-9.5%) in matured co-composts (Table 2).

The total coliform reduction in matured co-compost mixes revealed higher reductions in FSC, SWC and a marginal reduction in ratio 1:7 mix, in contrast to a 46% increase in the coliform count of 1:5 mix. In co-composts, elevated temperatures eliminate pathogens, which may recolonise at mesophilic and room temperature at maturity (Gold et al. 2016) due to available nutrients, hence the situation in the current study.

The recycling of MW is largely dependent on demand for sanitised composts (Vergara and Tchobanoglous 2012) whose quality is dependent on the feedstock properties, such as C: N ratio, pH and organic matter (Kaboré et al. 2010; Anwar et al. 2015); microbiota (Galitskaya et al. 2017), and process control conditions (Kaboré et al. 2010; Anwar et al. 2015). The C: N ratio, macro-nutrients and micro-nutrients of feed-

Table 2 Characteristics of co-compost heaps at various treatment stages during the co-composting process

Parameters (Unit)	(Feedstock stage (room temperature					Thermophilic stage (≥45 °C)					Mesophilic stage (≤ 44 °C)					Matured Stage (room temperature)				
	FSC	SWC	Ratio 1: 3	Ratio 1: 5	Ratio 1: 7	FSC	SWC	Ratio 1: 3	Ratio 1: 5	Ratio 1: 7	FSC	SWC	Ratio 1: 3	Ratio 1: 5	Ratio 1: 7	FSC	SWC	Ratio 1: 3	Ratio 1: 5	Ratio 1: 7
Temp (ºC)	28.30	29.00	28.60	29.40	29.70	38.60	48.30	51.60	47.60	49.50	33.45	32.80	34.13	34.13	33.23	26.80	27.20	27.10	27.30	27.20
pH	6.60	6.90	6.80	7.00	7.10	7.00	7.50	7.60	7.50	7.50	7.08	7.25	7.35	7.30	7.28	7.20	7.30	7.20	7.10	7.30
MC (%)	61.00	49.00	66.00	64.00	64.00	51.00	52.50	48.00	52.50	50.00	51.00	49.25	48.50	48.75	48.25	35.00	33.00	34.00	32.00	35.00
TKN (%)	2.82	1.77	1.85	1.98	2.45	2.00	1.50	1.30	1.80	1.40	1.52	1.82	1.60	1.45	1.49	1.87	1.68	1.75	1.82	1.47
TOC (%)	63.00	44.00	33.00	45.00	49.00	39.40	37.00	21.50	25.40	27.00	22.23	20.30	17.75	17.58	15.80	18.01	16.90	16.90	17.30	14.30
C: N (%)	22.34	24.86	18.86	22.73	20.00	19.70	24.70	16.50	14.10	19.30	15.20	11.20	11.63	13.03	11.35	9.60	10.10	9.70	9.50	9.70
K (%)	1.56	2.26	1.38	2.62	1.65	1.09	1.52	1.46	2.03	1.75	0.49	1.83	1.81	1.10	1.23	1.15	1.11	0.78	1.89	0.48
P (%)	1.81	1.40	1.53	1.31	1.75	1.20	1.19	1.19	1.07	0.71	1.51	0.73	1.21	1.12	1.08	1.24	1.38	1.00	0.70	1.46
S (%)	1.47	1.27	1.13	0.84	1.49	0.89	0.93	0.98	1.43	0.50	1.32	0.48	0.77	0.76	0.63	0.63	0.76	0.62	0.35	1.23
Ca (%)	1.66	1.24	1.59	1.54	1.79	1.36	1.61	1.61	1.45	1.52	1.51	1.28	1.65	1.38	1.43	1.55	1.57	1.28	1.42	1.51
Mg (%)	0.63	0.43	0.60	0.67	0.71	0.56	0.71	0.57	0.65	0.56	0.54	0.56	0.58	0.46	0.49	0.42	0.79	0.38	0.58	0.55
Fe (%)	0.14	0.11	0.15	0.11	0.13	0.81	0.97	0.72	0.70	0.84	0.80	1.04	0.88	0.83	0.83	0.55	1.56	0.63	0.87	0.77
Na (%)	0.15	0.14	0.16	0.15	0.20	0.15	0.23	0.23	0.16	0.18	0.16	0.17	0.21	0.14	0.11	0.09	0.22	0.10	0.14	0.12
Cu (%)	0.01	0.00	0.00	0.01	nd	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.01
Zn (%)	0.49	0.06	0.34	0.28	0.39	0.02	0.03	0.07	0.15	0.01	0.11	0.02	0.09	0.17	0.15	0.00	0.02	0.01	0.07	0.06
Cr (%)	Nd	0.03	0.02	0.01	0.01	Nd	0.01	0.01	0.01	0.01	nd	0.01	0.01	0.02	0.01	nd	0.01	0.01	0.01	0.01
Mn (%)	0.20	0.01	0.02	0.01	0.02	0.03	0.03	0.02	0.02	0.02	0.03	0.02	0.03	0.02	0.02	0.03	0.02	0.03	0.02	0.02
FI	4.40	4.40	4.60	4.40	4.40	4.60	4.80	4.60	4.80	4.60	4.40	4.80	4.50	4.50	4.50	4.70	4.50	4.60	4.70	4.10
CI	4.50	4.00	4.10	4.30	4.30	4.40	4.70	4.30	4.30	4.60	4.50	4.50	4.50	4.10	4.10	5.00	5.00	5.00	5.00	5.00
TCC value	$132*10^7$	$499*10^7$	$12*10^7$	$15*10^7$	$36*10^7$	$78*10^7$	$81.5*10^7$	$98.5*10^7$	$135*10^7$	$57*10^7$	$57*10^7$	$83*10^7$	$46.3*10^7$	$92.5*10^7$	$140.3*10^7$	91.7*	97.8*	0.0	46.0^+	8.5*

B: Temp= temperature; MC= moisture content; FI= fertilising index; CI= clean index; TCC=total coliform count (TCC/100ml); *= reduction (%); += increase (%); Nd= not detectable stock materials were optimal and consistent with those Fernández et al. (2010), Lohri et al. (2017) and Nartey et al. (2017), though had a high coliform counts that exceeded the threshold limit of <1000 CFU/g for compost (IRC 2015). Hence, the feedstock materials if used without sanitising can result in soil and farm produce contamination (Nartey et al. 2017).

Macronutrients and micronutrients quality at thermophilic and matured co-compost stages

The co-compost mixes recorded a loss in macronutrients, such as organic carbon, nitrogen, P, K and S at thermophilic and matured stages, corresponding to progressive mineralisation of organic carbon of 15.9% and 71.4% respectively for SWC and FSC at maturity. The co-compost ratio 1:5 had the lowest nitrogen loss (9.1%) at the thermophilic stage while at maturity, the co-compost ratio 1:7 had the highest nitrogen loss (40.0%). However, there were increases in K of co-compost ratios 1:3 and 1:7 at the thermophilic stage of bioconversion, while ratio 1:7 had the highest K loss (70.6%) at maturity (Table 3).

Table 3 Macronutrients loss in the thermophilic and matured stages in co-composts

Compost Heaps	Total organic carbon (TOC)		Total Kjeldahl Nitrogen (TKN)		Phosphorus (P)		Potassium (K)		Sulphur (S)	
	T (%)	M (%)	T (%)	M (%)	T (%)	M (%)	T (%)	M (%)	T (%)	M (%)
FSC	37.5	71.4	29.1	33.7	33.9	31.9	30.4	26.7	39.5	57.4
SWC	15.9	61.6	15.3	5.1	14.4	1.0	33.0	50.7	27.3	40.5
Ratio 1:3	34.8	48.8	29.7	5.4	22.1	34.6	-5.5	43.8	13.9	45.1
Ratio 1:5	43.6	61.6	9.1	8.1	18.2	46.2	22.4	27.9	-70.0	58.8
Ratio 1:7	44.9	70.8	42.9	40.0	59.4	16.5	-6.0	70.6	66.7	17.4

Key: FSC= faecal sludge control; SWC= solid waste control; T=co-compost heaps at thermophilic stage; M= Co-compost heaps at matured stage

The progressive decreases in TOC contents were in agreement with those reported by previous studies (Mengistu et al. 2018; Cofie et al. 2009; Anwar et al. 2015; Al-Muyeed et al. 2017; Krishnan et al. 2017; Singh et al. 2017). The rate of carbon mineralisation was highest during the thermophilic stage, in consonance with Anwar et al. (2015), though TOC loss (15.9-44.9%) was lower when compared with those of Tiquia et al. (2002), where the TOC ranged from 50% to 63% in aerobic windrows.

The progressive loss in nitrogen during the thermophilic co-composting was similar to those reported by Mengistu et al. (2018), perhaps due to the formation and volatilization of ammonia during the active composting phases. In contrast, the co-compost piles at mesophilic and matured stages had a higher proportion of nitrogen, though lower than those of the initial piles. The progressive increase in nitrogen may be due to the concentration effect that resulted from biodegradation of organic carbon compounds resulting in the weight-volume loss which might show relatively as an increase in the approximate nitrogen base (Dias et al. 2010). Rather than agreeing with Mengistu et al. (2018) that nitrogen losses occurred at a higher rate than organic matter mineralisation during the thermophilic stage, a possibility by Wang et al. (2016) is fixing atmospheric nitrogen by Nitrosomonas in the co-composts under aerobic conditions during the later stages of composting. However, suggested that Nitrosomonas are inhibited at temperatures > 40^{o}C and only activated during the later mesophilic Morisaki et al. (1989) and maturation stages.

In composting, the C: N ratio portends compost maturity and its reduction is caused largely by microbial mineralisation of organic carbon. A gradual reduction in the C: N ratio in all experimental heaps was consistent with the works of Gao et al. (2010) and Costa et al. (2016). The matured compost had C: N ratio below 15; this is in line with studies by Bernal et al. (2009), Al-Muyeed et al. (2017) and Mengistu et al. (2018), though in contrast to the C: N ratio of 25.8 by Adewumi et al. (2005) with poultry manure and municipal solid waste as feedstocks.

The N: P: K values of 1.820%, 0.703% and 1.886% were equivalent to about 18.2kg/m^3 of nitrogen, 7.03 kg/m^3 of Phosphorus as phosphate, and 18.86 kg/m^3 of potassium as the primary macronutrients of the ratio 1:5 dewatered FS: MSW co-compost mix. The compost properties improved soil properties by increasing its aeration and water holding capacity, according to Mandal et al. (2014) and Anwar et al. (2015). Similarly, the phosphorus value in the matured co-composts was lower than the threshold for organic compost in Nigeria. In contrast, potassium value exceeded the national special programme on food security guideline range of 1.5-3.0%, and 1.0-1.5%, respectively.

Also, the highest potassium value in FS (0.78%) before thermal treatment by Osibote et al. (2016) was lower than those used in this study but at par when compared with those contained in the matured co-composts. This suggests that the FS has lower, initial potassium and phosphorus values when compared to those of other countries such as Ghana, perhaps due to diet and soil conditions, among others. Moreover, the micronutrient in the matured composts was permissible and should support plant growth in trace quantities (Anwar et al. 2015). The macronutrients and micronutrients quality of the study co-composts were within the guidelines' values provided by IWMI and SANDEC (2002). However, one of the challenges in compost regulation is the divergent threshold values for parameters and varied from country to country where developed. This should, however, be standardized globally, to allow comparison within, and between countries. The compost quality was in harmony with the quality control indices obtained by Vinod and Ravindernath (2015) in India, was within the permissible limits prescribed by the fertiliser control order (India).

Multivariate exploratory analysis of co-compost variables

In the multivariate relationships among co-composts parameters, the eigenvalues extracted four factors and fifteen components that explained 78.2% of its variability (Table 4).

Table 4 Initial eigenvalues and total variance explained by the PCA model

Components	Eigenvalue (total)	Percent (%) of variance	Cumulative %
1	3.974	**26.494**	26.494
2	3.300	**22.002**	48.496
3	2.845	**18.968**	67.464
4	1.604	**10.696**	78.159
5	0.842	5.615	83.774
6	0.663	4.418	88.192
7	0.436	2.905	91.097
8	0.354	2.362	93.459
9	0.323	2.154	95.613
10	0.205	1.368	96.981
11	0.151	1.006	97.988
12	0.115	0.769	98.757
13	0.079	0.524	99.281
14	0.061	0.406	99.687
15	0.047	0.313	100.000

PCA = Principal component analysis

67.5% of the variance could be explained respectively by principal component (PC1) (26.5%), PC2 (22.0%), PC3 (19.0%) and PC4 (10.7%). Chromium is one of the composite index parameters for clean index (Vinod and Ravindernath 2015) and previous studies identified it in garden and kitchen waste, however, with progressive mineralisation from the feedstock, to matured co-compost piles (Hanc et al. 2012). The abundance of chromium in kitchen and garden waste has been demonstrated by previous studies (Déportes et al. 1995; Stefanakis et al. 2011; Hanc et al. 2012). The variables that defined PC 1 were TKN, chromium, silicon, fertilising index and clean index. This factor groups the properties associated with compost maturity based on their fertilising and pollutant indices, apart from nitrogen which is a process limiting variable. All the parameters were positively correlated, except chromium and silicon. In PC 2, Al, Zn and TOC defined the agronomic character of co-composts, showed a positive correlation and the variables progressively decreased as the compost matures. PC 3 was defined by the macronutrients' variables; Mg: K ratio, K, P and S. In Factor 3, only P was negatively correlated. PC 4 was essentially micronutrients with only Cu negatively correlated (Table 5).

Further, the paths of co-compost variables from quality, micronutrients and pollutants present a negative coefficient (0.015 and 0.012). Macronutrients and process control indices had a coefficient of positive values (0.951 and 0.062), indicating negative and positive effects on co-compost quality, respectively. The endogenous variables explained 97.7% of the co-composts' variance; contributed by macronutrients, micronutrients, process control and pollutant indices. The model has an increasing indirect path in micronutrients, pollutants, process control and macronutrients. The partial least scores (PLS) of paths analysis showed that macronutrients, as a block has the highest correlation (0.951), while others showed weak correlation values (Fig. 3).

The multivariate data analysis classified parameters into factors, according to the guide provided by Soares et al. (2017). The variables that defined the predominant factor were TKN, Chromium, Silicon, Fertilising index and clean index, apart from Nitrogen which is a macronutrient required for plant growth (Brinton 2000; Mandal et al. 2014). PC 2 defined the agronomic characteristics of the matured co-compost, and the parameters progressively decreased by mineralisation during the composting process. PC 3 denotes essential macronutrients Mg: K ratio, K, P and S with the only P being negatively correlated while PC 4 loaded micronutrients with the only Cu negatively correlated. The macronutrients and process control indices had a positive effect on co-compost quality, while the micronutrients and pollutants indices exhibited a negative effect on the co-compost quality.

Table 5 Principal component loadings of the co-compost data

Component score coefficient matrix				
Parameters	**Principal components (PCs)**			
	PC 1	**PC 2**	**PC 3**	**PC 4**
Total Kjedhal nitrogen	**0.267**	0.198	-0.189	-0.029
Clean Index	**0.245**	-0.012	-0.058	-0.088
Chromium (Cr)	**-0.234**	-0.040	-0.058	0.026
Fertilising index	**0.214**	0.007	-0.120	0.131
Silicon (Si)	**-0.169**	0.126	-0.111	-0.094
Aluminium (Al)	-0.035	**0.288**	-0.041	-0.073
Zinc (Zn)	-0.041	**0.281**	-0.019	-0.087
Total organic carbon	0.100	**0.235**	-0.052	0.038
Mg: K ratio	-0.041	-0.083	**0.350**	0.094
Potassium (K)	0.063	0.060	**-0.262**	0.133
Phosphorus (P)	-0.044	0.155	**0.255**	0.068
Sulphur (S)	0.022	0.141	**0.227**	0.108
Sodium (Na)	-0.107	-0.121	0.112	**0.432**
Magnesium (Mg)	0.036	0.023	0.076	**0.373**
Cupper (Cu)	0.175	-0.006	0.066	**-0.195**

Extraction method: Principal component analysis.
Rotation method: Varimax with Kaiser normalization.
Component Scores.

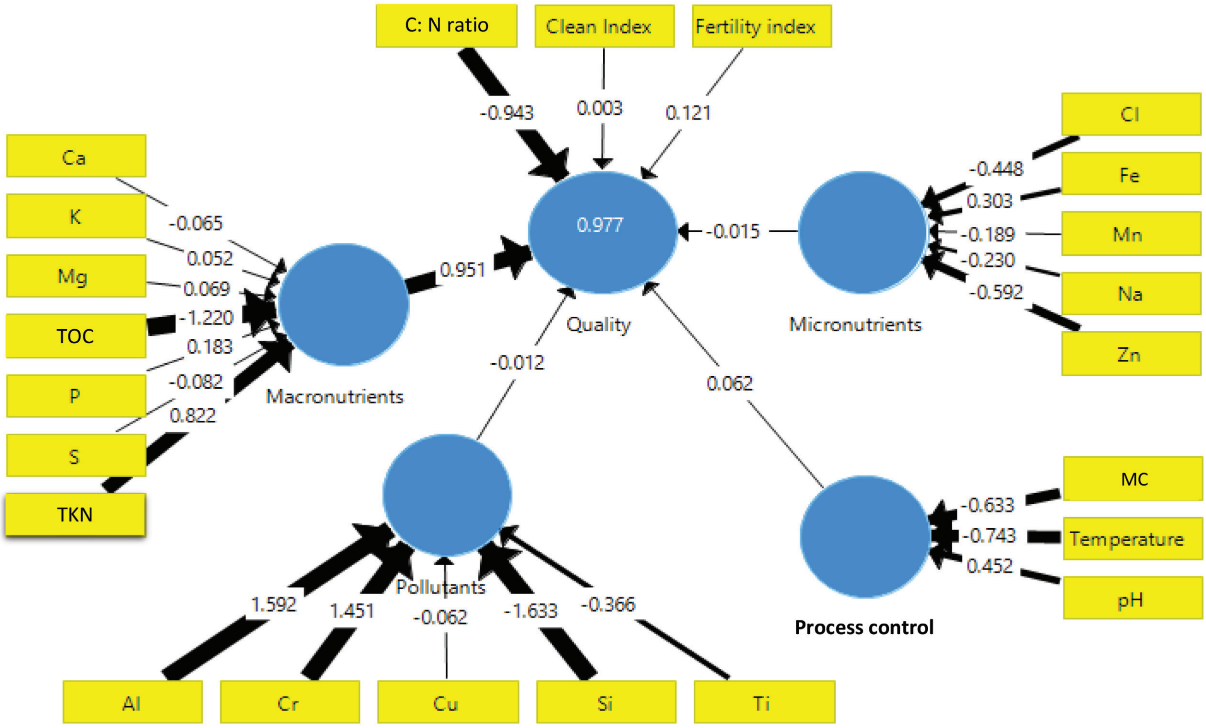

Fig. 3 Path analysis of variables in the five co-compost piles

Conclusion

The study revealed mixed, but similar results in the co-composting study using ratios 1:3, 1:5 and 1:7 mixes. The co-compost feedstock materials and matured compost blends had high coliform counts beyond the threshold limit of <1000 CFU/g for matured compost. The matured co-compost blends satisfied the macronutrients', micronutrients' and acceptable pollutants' quality, suitable for all agricultural demands in soil conditioning and fertilising procedures. Therefore, the study showed that the co-composting of dewatered faecal sludge with the organic market waste is a potential resource recovery strategy, which should be optimised, to arrest the perennial discharge of raw faecal sludge into the environment.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgements The authors acknowledge the moral support of the ministry of environment and the waste management agency in Osun state, Nigeria; in particular, sanitarian Wale Ogungbe (director, environmental sanitation, ministry of environment), Alh. Ganiyu Oyeladun (general manager, OWMA), Mr Henry Olufemi Ogunbamiwo (director, environmental health and sanitation, OWMA) and sanitarian Surulere Fatai Oyewole, who guided and advised on administrative and technical convenience in the cause of the research. The authors appreciate the management of the centre for energy research and development of the Obafemi Awolowo university for undertaking the elemental analysis using proton induced x-ray emissions technology at a discounted price for all study samples. We are also appreciative of the staff of the Soil Science laboratory in the Obafemi Awolowo university, for support in the analysis of total carbon and TKN.

Compliance with ethical standards

Conflict of interest The authors declare that there are no conflicts of interest associated with this study.

References

Adewumi IK, Ogedengbe MO, Adepetu JA, Aina PO (2005) Aerobic composting of municipal solid wastes and poultry manure. J appl sci res 1:292–297

Al-Muyeed A, Oko-williams A, Islam K, Ali L, Nath SK, Sanyal PR (2017) Co-composting of faecal sludge with solid waste to improve faecal sludge management practice in Sakhipur municipality. In: Local action with international cooperation to improve and sustain water, sanitation and hygiene services. Loughborough, pp 1–7

Anwar Z, Irshad M, Fareed I, Saleem A (2015) Characterization and recycling of organic waste after co-composting - A review. J Agric Sci 7:68. https://doi.org/10.5539/jas.v7n4p68

APHA (1998) Standard methods for examination of water and wastewater, 19th edition. American public health association, Washington DC

APHA/AWWA/WEF (2005) Standard methods for the examination of water and wastewater, 21st edn. American public health association, American water works association, and water and environment federation, Washington DC

Bartram J, Pedley S (1996) Chapter 10 - Microbiological analyses. In: Bartram J, Ballance R (eds) Water quality monitoring - A practical guide to the design and implementation of freshwater quality studies and monitoring programmes. UNEP/WHO. 27pp. Available at: https://www.researchgate.net/publication/253953121_Water_quality_monitoring_a_practical_guide_to_the_design_and_implementation_of_freshwater_quality_studies_and_monitoring_programmes

Bernal MPP, Alburquerque JAA, Moral R (2009) Composting of animal manures and chemical criteria for compost maturity assessment: A review. Bioresour technol 100:5444–5453. https://doi.org/10.1016/j.biortech.2008.11.027

Brinton W (2000) Compost quality standards and guidelines. New York, NY, United States

Cheng X, Wang J, Chen B, Wang Y, Liu J, Liu L (2017) Effectiveness of phosphate removal during anaerobic digestion of waste activated sludge by dosing iron (III). J Environ Manage 193:32–39. https://doi.org/10.1016/j.jenvman.2017.02.009

Chuah CJ, Ziegler AD (2018) Temporal variability of faecal contamination from on-site sanitation systems in the groundwater of northern Thailand. Environ Manage 61:939–953. https://doi.org/10.1007/s00267-018-1016-7

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

Cofie O, Nikiema J, Impraim R, Adamtey N, Paul J, Koné D (2016) Co-composting of solid waste and fecal sludge for nutrient and organic matter recovery. Resource recovery and reuse series 3. International water management institute (IWMI). CGIAR research program on water, land and ecosystems (WLE)

Costa MSSDM, Carneiro LJ, Costa LADM, Pereira DC, Lorin HEF (2016) Composting time reduction of agricultural wastes. Eng Agrícola 36:1206–1217. https://doi.org/10.1590/1809-4430-eng.agric.v36n6p1206-1217/2016

Déportes I, Benoit-Guyod JL, Zmirou D (1995) Hazard to man and the environment posed by the use of urban waste compost: A review. Sci. Total Environ 172:197–222. https://doi.org/10.1016/0048-9697(95)04808-1

Dias BO, Silva CA, Higashikawa FS, Roig A, Sánchez-Monedero MA (2010) Use of biochar as bulking agent for the composting of poultry manure: Effect on organic matter degradation and humification. Bioresour Technol 101:1239–1246. https://doi.org/10.1016/j.biortech.2009.09.024

Fan Y, Chen J, Shirkey G, John R, Wu SR, Park H, Shao C (2016) Applications of structural equation modeling (SEM) in ecological studies: An updated review. Ecol Process 5:19. https://doi.org/10.1186/s13717-016-0063-3

Fernández FJ, Sánchez-Arias V, Rodríguez L, Villaseñor J (2010) Feasibility of composting combinations of sewage sludge, olive mill waste and winery waste in a rotary drum reactor. Waste Manag 30:1948–1956. https://doi.org/10.1016/j.wasman.2010.04.007

Galitskaya P, Biktasheva L, Saveliev A, Grigoryeva T, Boulygina E, Selivanovskaya S (2017) Fungal and bacterial successions in the process of co-composting of organic wastes as revealed by 454 pyrosequencing. PLoS One 12:1–20

Gao M, Li B, Yu A, Liang F, Yang L, Sun Y (2010) The effect of aeration rate on forced-aeration composting of chicken manure and sawdust. Bioresour Technol 101:1899–1903. https://doi.org/10.1016/j.biortech.2009.10.027

Garson GD (2016) Partial least squares: Regression and structural equation models: 2016 edition. Statistical associates blue book series 10. Statistical associates publishing. 265pp

Getahun T, Nigusie A, Entele T, Gerven TV, Bruggen BVD (2012) Effect of turning frequencies on composting biodegradable municipal solid waste quality. Resour Conserv Recycl 65:79–84. https://doi.org/10.1016/j.resconrec.2012.05.007

Gold M, Dayer P, Faye MCAS, Clair G, Seck A, Niang S, Morgenroth E, Strande L (2016) Locally produced natural conditioners for dewatering of faecal sludge. Environ Technol 37:2802–2814. https://doi.org/10.1080/09593330.2016.1165293

Hanc A, Szakova J, Svehla P (2012) Effect of composting on the mobility of arsenic, chromium and nickel contained in kitchen and garden waste. Bioresour Technol 126:444–452. https://doi.org/10.1016/j.biortech.2011.11.053

IRC (2015) Value at the end of the sanitation value chain. Available at: https://www.researchgate.net/profile/Soumya_Balasubramanya/publication/299429922_VeSV-Value_at_the_end_of_Sanitation_Value_Chain/links/5890077f45851573233e8650/VeSV-Value-at-the-end-of-Sanitation-Value-Chain.pdf

IWMI (International water management institute) and SANDEC (Sanitation in Developing Countries) (2002) Co-composting of faecal sludge and solid waste: Preliminary recommendations on design and operation of co-composting plants based on the Kumasi pilot investigation. 91pp. Available at: https://sswm.info/sites/default/files/reference_attachments/IWMI%20SANDEC%202002%20CoComposting%20of%20Faecal%20Sludge%20and%20Solid%20Waste.pdf

Jenkins MW, Cumming O, Cairncross S (2015) Pit latrine emptying behavior and demand for sanitation services in Dar Es Salaam, Tanzania. Int J environ res public health 12:2588–2611. https://doi.org/10.3390/ijerph120302588

Jeong K-H, Kim JK, Ravindran B, Lee DJ, Wong JWC, Selvam A, Karthikeyan OP, Kwag JH (2017) Evaluation of pilot-scale in-vessel composting for Hanwoo manure management. Bioresour Technol 245:201–206. https://doi.org/10.1016/j.biortech.2017.08.127

Johansson SAE, Thomas B (1976) Analytical application of particle-induced X-ray emission. Nucl Instruments Methods 37:473–516

Kaboré TWT, Houot S, Hien E, Zombré P, Hien V, Masse D (2010) Effect of the raw materials and mixing ratio of composted wastes on the dynamic of organic matter stabilization and nitrogen availability in composts of Sub-Saharan Africa. Bioresour Technol 101:1002–1013. https://doi.org/10.1016/j.biortech.2009.08.101

Karanja N, Kwach H, Njenga M (2015) Low-cost composting training manual based on the UN-HABITAT / URBAN HARVEST-CIP Community based waste management initiatives. 37pp. Available at: https://www.researchgate.net/publication/319187370_LOW_COST_COMPOSTING_TRAINING_MANUAL

Kone D, Gallizzi K, Drescher S, et al (2004) Efficiency of Helminth eggs removal in dewatered faecal sludge by co-composting. In: People-centred approaches to water and environmental sanitation: Proceedings of the 30th WEDC conference. pp 34–38

Krishnan Y, Bong CPC, Azman NF, Zakaria Z, Othman NA, Abdullah N, Ho CS, Lee CT, Hansen SB, Hara H (2017) Co-composting of palm empty fruit bunch and palm oil mill effluent: Microbial diversity and potential mitigation of greenhouse gas emission. J Clean Prod 146:94–100. https://doi.org/10.1016/j.jclepro.2016.08.118

Kwiatek WM, Dutkiewicz EM, Glebowa L, Marczewska E, Sowa M (1994) Sample preparation procedure for PIXE, PIGE and RBS techniques applied for biological studies in Henryk Niewodniczanski Institute of Nuclear Physics. 76–77

Lohri CR, Diener S, Zabaleta I, Mertenat A, Zurbrügg C (2017) Treatment technologies for urban solid biowaste to create value products: A review with focus on low- and middle-income settings. Rev Environ Sci Biotechnol 16:81–130. https://doi.org/10.1007/s11157-017-9422-5

Mandal P, Chaturvedi MK, Bassin JK, Vaidya AN, Gupta RK (2014) Qualitative assessment of municipal solid waste compost by indexing method. Int J Recycl Org Waste Agric 3:133–139. https://doi.org/10.1007/s40093-014-0075-x

McGranahan G (2015) Realizing the right to sanitation in deprived urban communities: Meeting the challenges of collective action, coproduction, affordability, and housing tenure. World Dev 68:242–253. https://doi.org/10.1016/j.worlddev.2014.12.008

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 6:5. https://doi.org/10.1186/s40068-017-0079-4

Morisaki N, Phae CG, Nakasaki K, Shoda M, Kobuta H (1989) Nitrogen transformation during thermophilic composting. J Ferment Bioeng 67:57–61

Nartey EG, Amoah P, Ofosu-Budu GK, Muspratt A, Pradhan Sk (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

NBS/UNICEF (2017) Multiple indicator cluster survey 2016-17. National Bureau of Statistics and United Nations Children's Fund. Accessed at: https://www.unicef.org/nigeria/NG_publications_mics_201617.pdf

Niwagaba C, Nalubega M, Vinnerås B, Sundberg C, Jönsson H (2009) Bench-scale composting of source-separated human faeces for sanitation. Waste Manag 29:585–589. https://doi.org/http://dx.doi.org/10.1016/j.wasman.2008.06.022

Osibote BA, Osibote IA, Bolaji OM, Ana GREE (2016) Effect of thermal treatment on microbial load of faecal sludge from some faecal sludge collection sites in Oyo state, south western, Nigeria. Jordan J Biol Sci 9:243–248

Otterpohl R, Grottker M, Lange J (1997) Sustainable water and waste management in urban areas. Otterpohl Wasserkonzepte, Kanalstraße 52, D-23552 Lübeck, Germany

Oyelami AC, Aladejana JA, Agbede OO (2013) Assessment of the impact of open waste dumpsites on groundwater quality: A case study of the Onibu-Eja dumpsite, Southwestern Nigeria. Procedia Earth Planet Sci 7:648–651. https://doi.org/10.1016/j.proeps.2013.03.168

Parkinson R, Gibbs P, Burchett S, Misselbrook T (2004) Effect of turning regime and seasonal weather conditions on nitrogen and phosphorus losses during aerobic composting of cattle manure. Bioresour Technol 91:171–178. https://doi.org/10.1016/S0960-8524(03)00174-3

Rao K., Otoo M, Drechsel P, Hanjra M. (2017) Resource recovery and reuse as an incentive for a more viable sanitation service chain. Water Altern 10:493–512

Scoton EJ, Battistelle RAG, Bezerra BS, Bezerra BS, Renófio A, Akutsu J (2015) Parameters evaluation of the co-composting of sewage sludge and grass clippings using the respirometric method. Int J Environ Waste Manag 16:262. https://doi.org/10.1504/IJEWM.2015.073034

Scoton EJ, Battistelle RAG, Bezerra BS, Akutsu J (2016) A sewage sludge co-composting process using respirometric monitoring method in hermetic rotary reactor. J Clean Prod 121:169–175. https://doi.org/10.1016/j.jclepro.2015.04.081

Semiyaga S, Okure MAE, Niwagaba CB, Nyenje PM, Kansiime F (2017) Dewaterability of faecal sludge and its implications on faecal sludge management in urban slums. Int J Environ Sci Technol 14:151–164. https://doi.org/10.1007/s13762-016-1134-9

Singh S, Mohan R., Rathi S, Raju NJ (2017) Technology options for faecal sludge management in developing countries: Benefits and revenue from reuse. Environ Technol Innov 7:203–218. https://doi.org/10.1016/j.eti.2017.02.004

Soares MAR, Quina MJ, Reis MS, Quinta-Ferreira R (2017) Assessment of co-composting process with high load of an inorganic industrial waste. Waste Manag 59:80–89. https://doi.org/10.1016/j.wasman.2016.09.044

Stefanakis AI, Komilis DP, Tsihrintzis VA (2011) Stability and maturity of thickened wastewater sludge treated in pilot-scale sludge treatment wetlands. Water Res 45:6441–6452. https://doi.org/10.1016/j.watres.2011.09.036

Strande L, Ronteltap M, Brdjanovic D (2014) Faecal sludge management: systems approach for implementation and operation. p 403

Strauss M, Heinss U, Montangero A (2000) On-site sanitation: When the pits are full--planning for resource protection in faecal sludge management. Schriftenr Ver Wasser Boden Lufthyg 105:353–360. https://doi.org/105 353-360

Suess M.J Huismans J (1983) Management of hazardous wastes: Policy guidelines and code of practice. UNEP/WHO

Sundberg C, Smårs S, Jönsson H (2004) Low pH as an inhibiting factor in the transition from mesophilic to thermophilic phase in composting. Bioresour Technol 95:145–150

Tiquia SM, Wan JHC, Tam NFY (2002) Dynamics of yard trimmings composting as determined by dehydrogenase activity, ATP content, arginine ammonification, and nitrification potential. Process Biochem 37:1057– 1065

Uggetti E, Llorens E, Pedescoll A, Ferrer I, Castellnou R, García J (2009) Sludge dewatering and stabilization in drying reed beds: Characterization of three full-scale systems in Catalonia, Spain. Bioresour Technol 100:3882–3890. https://doi.org/10.1016/j.biortech.2009.03.047

Uggetti E, Argilaga A, Ferrer I, García J (2012) Dewatering model for optimal operation of sludge treatment wetlands. Water Res 46:335–344. https://doi.org/10.1016/j.watres.2011.10.040

Vergara SE, Tchobanoglous G (2012) Municipal solid waste and the environment: A global perspective. Annual Review of Environment and Resources 37(1): 277–309. https://doi.org/10.1146/annurev-environ-050511-122532

Vinod B, Ravindernath A (2015) Compost quality assessment of greater hyderabad municipal corporation (GHMC), India. Int J Eng Res Appl 5:1–9

Wang P, Zhang H, Zuo J, Zhao D, Zou X, Zhu Z, Jeelani N, Leng X, An S (2016) A hardy plant facilitates nitrogen removal via microbial communities in subsurface flow constructed wetlands in winter. Scientific reports 6(1). School of life science, Institute of wetland ecology, Nanjing University, Nanjing, China: Nature Publishing Group: 33600. https://doi:10.1038/srep33600

World Health Organization (WHO) (2010) Third edition of the WHO guidelines for the Safe use of wastewater, excreta and greywater in agriculture and aquaculture. 12pp