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PRODUCTION OF FAECAL SLUDGE-BASED COMPOST AS BIOSTIMULANT FOR CRUDE OIL-CONTAMINATED SOIL REMEDIATION

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ABSTRACT

In response to the desire to rid the environment of faecal waste and restore crude oil-contaminated soil, a process utilising dewatered faecal sludge mixed with organic kitchen waste while using sawdust as a bulking agent is harnessed to produce compost for use in the restoration of crude oil impacted soil. Co-composting is a verified method for producing organic fertilizers. Still, despite its abundance and nutrient content, faecal sludge is rarely used as compost material due to the significant concentration of pathogens. This work investigated the possibility of producing sanitised compost from dewatered faecal sludge for organic fertilizer in crude oil-polluted soil remediation. The dewatered faecal sludge and organic kitchen waste materials were co-composted in five laboratory compost reactors for 60 days. Experiments show that temperature, humidity, and pH were the determinant composting factors maintained within the allowable range during composting. The addition of a bulking agent caused the thermophilic phase to occur early. Thermophilic temperatures of the compost waste exceeded 55 °C and were controlled enough to sanitize the compost, as demonstrated by the complete inactivation of pathogens represented by the helminth eggs. The compost maturation parameters show that the composts matured within four weeks of composting. The organic carbon(C) concentration was 22.07%, the total nitrogen(N) was 1.79 ± 0.21%, the C / N ratio was 12.38, the total phosphorus(P_2O_5) was 0.31±0.01 %, and the potassium(K_2O) was 1.12±0.16 % in the compost reactors. The best compost obtained had a reduction of 3.9 Log10 for E. coli, which was only 0.1 Log10 below the WHO threshold for pathogen reduction in composts. This, in combination with the long period of temperatures >50°C, indicated that the compost was sanitized. The reactor that was not lagged or modified with a bulking agent was the least successful in reducing pathogens, with a decrease of only 1.6 Log10.

Keywords: Faecal Sludge, Compost, Wood ash, Kitchen Waste, Soil Pathogens, and Sanitization.

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1. Introduction

The level of pollution caused by petroleum-related activities and the constant and high generation and indiscriminate disposal of faecal sludge, along with other domestic pollutants, pose a serious environmental problem (Yin et al., 2016). The toxic nature of crude oil and the high organic content of faecal sludge, coupled with its ability to release hazardous substances that negatively impact global health, is a widespread problem that has resulted in the need to seek cost-effective environmental remediation techniques to reduce or eliminate these pollutants (Giwa, 2023). Inorganic fertiliser dominates the application of biostimulants for contaminated soil remediation. Fossil-based fertilisers generate greenhouse gas (GHG) emission-related environmental problems and dump excess nutrients into the water systems, causing eutrophication and air pollution [1]. Majorly, inorganic phosphate fertilisers are contaminants of much concern as they contain traces of heavy metals [2], and the continuous use of these fertilizers accumulate heavy metals in the soil, causing environmental degradation [2]. Recent publications [3] show that both nitrogen and phosphorus have exceeded supportable plant levels, and there is a need to minimize the utilisation of inorganic fertilizers to reduce eutrophication. The Food and Agricultural Organization (FAO) has recently reported that the annual global consumption of NPK fertilizer is around 180 metric tonnes [5]. However, the world demand for inorganic fertiliser is growing [4, 5]. Reducing total dependence in contaminated soil remediation on fossil-based nitrogen fertilisers as a biostimulant has encouraged research into recycling the readily available faecal sludge as a potential source of organic fertilizer [6]. However, resource recovery from faecal sludge for land use is typically conducted at an informal level without treatment considerations. Faecal sludge has the potential for resource recovery that should be formally harnessed as land-use compost products.

The high population growth results in the rapid generation of faecal waste, which has put pressure on waste disposal facilities. Moreover, because most of the world's population lacks necessary sanitation facilities, most waste, including faecal sludge, is discharged untreated into the aquifers [6, 7]. A major consequence of the indiscriminate dumping of untreated human waste is that waste pathogens directly pollute shallow groundwater, often recycled back to homes for drinking and other domestic activities without any form of treatment [8]. The World Health Declaration on Human Health listed sanitation as a fundamental human right, and a significant component of poverty eradication [6] demands proper disposal or recycling of the waste generated. Human faecal sludge/excreta are a valuable, rich source of organic matters and inorganic plant nutrients, also rich in nitrogen and have a high prospect of application as an organic amendment for contaminated soil restoration and agriculture [11, 12] but are generally under-utilized [9]. Studies have shown that digested and sanitised faecal sludge can be utilized as compost fertiliser in agriculture and soil restoration. However, pathogens in faecal sludge represent potential risks to human and animal health.

The underuse may be due to faecal sludge containing pathogenic microorganisms that are harmful disease harbingers and often give offensive odours or organic phytotoxic compounds [10, 6, 8]. The effect of using untreated waste has a significant implication for hygiene. Composting is a strategy to reduce pathogens and recycle organic waste into useful products that are biological, eco-friendly, and sustainable. It requires rapidly degrading organic matter under controlled conditions by microorganisms [11, 12]. It is a safe method for biologically stabilizing faecal sludge and has harnessed its usefulness by recycling the nutrient content to generate NPK-enriched composts [13]. The best mechanism to speed up the composting process is to create an ideal environment for the microorganisms to thrive in compost. Such a perfect environment involves a combination of temperature, nutrients, moisture, and excess oxygen. A triple-action model for cleaning contaminated soils, disposing of harmful organic waste, and generating income at the same time [14] is the co-composting of faecal sludge with organic waste and subsequent application to contaminated soils. Therefore, faecal sludge recycling is promoted for economic and environmental benefit as faecal sludge-based fertiliser closes the nutrient loop, nips the eutrophication problem and air pollution and creates a sustainable environment [15, 13]. Moreover, because faecal sludge and kitchen waste as co-compost material are complementary, they are typically used together. Faecal sludge is relatively high in nitrogen and ammonia, and organic kitchen waste is relatively high in organic carbon (OC) content with strong bulking capability.

To be beneficial and sought after, the compost must be fail-safe regarding its stability and maturity. The properties of finished compost depend to no small extent on the stabilisation level. Compost is mature and stable when free of pathogens, contains only minimal quantities of foreign materials and has acceptable levels of trace elements and organic contaminants [16]. To ascertain its effectiveness and longer shelf life, the compost products must be tested for quality and maturity to protect the environment and humans from any harmful substances they may contain. Compost stability is often calculated using microbial activity indices, whereas compost maturity is generally assessed by the bioassay of plants [17]. There is no single, stand-alone test to determine compost stability or maturity, but an acceptable result is achieved by adopting one of the approaches to physical, chemical, or biological tests often classified as a stability test or maturity test.

This work evaluates the efficiency of faecal sludge co-composting with organic kitchen waste to generate nutrient-rich compost to remediate contaminated soil. It encourages the science and research communities to give value and reuse waste materials rather than simply throwing them out and facing other disadvantages due to unwise use.

2. Materials and Methods

Approximately 5 m3 of faecal sludge (a combination of faeces, urine, toilet papers, flush and grey waters) were collected from septic tanks in the school hostel toilets in NDU Amassoma, Nigeria, and pumped on concrete dewatering and drying beds, essential for drying before composting. The dewatered faecal sludge was collected, sorted, and packaged for composting after 12 days in the dewatering bed. Wood ash was harvested from an Amassoma bakery. Sawdust had been sourced from a Yenagoa sawmill. At the same time, organic cooking waste was collected from the Swali market's fruit and vegetable section. The particle size of the dewatered and dried faecal material is reduced to increase the surface area to volume ratio, thereby increasing the area on which microorganisms can act, accelerating decomposition. Faecal sludge feedstock treatments included mixing with kitchen waste and ash and adding sawdust as a bulking agent. Table 2 summarises the properties of the materials. The percolate was extracted from the dewatering bed and processed until discharge onto uncultivated farmland.

2.1. Experimental setup and composting experiment

Five wood bioreactors have a volume of 20 litres, each filled with approximately 10 kg of dried faecal sludge mixed with organic cooking waste and other compost materials, as shown in Table 1. The faecal sludge-food waste mixture was treated as an accelerator and a drying agent with small amounts of wood ash. Except for Reactor 1, other reactors were insulated to reach the thermophilic temperature required for sanitising the materials. Because the composting process is aerobic, proper mixing was done weekly for aeration. The pile's moisture content was regularly monitored to keep it at 60 – 80 per cent of the water-holding capacity of the material. Also, the compost temperature was monitored and taken in the reactor at predetermined points, with an average of three readings recorded as reactor temperature, with standard deviation. The experimental process lasted under shade and at an ambient temperature in the open for nine weeks.

Table 1: Co-compost Experimental Design

S/No	Reactor Number	Compost Design
1	Reactor 1(Control)	Fecal Sludge + Sawdust (Ratio = 1:1)
2	Reactor 2	Fecal Sludge + Kitchen waste + Sawdust + Ash (Ratio = 1:2:2:0.2)
3	Reactor 3	Fecal Sludge + Kitchen waste + Sawdust (Ratio = 1:2:2)
4	Reactor 4	Fecal Sludge + Kitchen waste + Sawdust (Ratio = 1:4:4)
5	Reactor 5	Fecal Sludge + Kitchen waste + Sawdust (Ratio = 1:1:1)

Figure 1: Composting reactor setup

2.2. Compost sampling and Physico-chemical analysis

Representative samples were taken randomly from various points in the reactor every seven days to evaluate the physicochemical changes in the compost. Following the Pisa et al. (2013) technique, the samples were sun-dried, pulverised, homogenised and sieved with a 2 mm sieve [18] The moisture content was determined as weight loss by drying a representative compost mass sample in an oven at 105 °C to a constant weight [19] to determine the moisture and the dry matter contents of the composting mass. Each compost's surface and centre temperature were tracked with a digital temperature probe every two days.

The pH was measured with a pH meter, and electrical conductivity (EC) was measured using the APHA model [20]. Chemical analysis was undertaken to determine the nitrogen, potassium, and phosphorus present in the compost. The C: N ratio was calculated using Organic Carbon and Total Nitrogen as individual values.

2.3. Compost maturity and stability determination

With no single criteria for assessing the maturity and stability of composts due to their diverse origin, we used monitoring of C/N ration and EC for maturity and pH change for stability by observing their overall trend as described by a monotonic function. A pH range of 6.9 - 8.3 indicates that compost has achieved stability, and effort must be made to lower the pH if it exceeds these values. The sample's pH and electrical conductivity (EC) were measured using a pH meter and a conductivity meter when the sample was dissolved in deionised water, allowed to equilibrate for 30 minutes, and subsequently filtered. Total organic carbon (TOC) and moisture contents defined by Walkley and Black [21] were determined, while total N was calculated using the Kjeldahl method.

2.4. Statistical analysis

Analysis of variance (ANOVA) with replication was performed on all data using the statistical package Microsoft Excel version 2013. The statistical analysis was conducted to compare the variation (factors) in each composting reactor and its effect on compost stability, maturity and pathogen removal, compared with the limits set by the WHO and the US EPA to gage if the parameters displayed by the composts exceeded those limits set. The standard deviation of the mean values was determined for each reactor treatment, and the result was an average of 3 replicate results.

3. Results and Discussion

Observation shows that total N was high (3.4 ± 0.2) in DFS and (3.1%) in sawdust by characterising the compost feedstock. The C: N ratios for DFS, Sawdust and kitchen wastes were 43.5, 25.1 and 11.1. In the Dewatered Faecal Sludge, total coliform populations ranged from 2.0 x 10^3 to 3.0 x 10^5 MPN g^{-1}, while E. Coli concentrations were around 4.0 x 103 CFU g^{-1}. The average population of helminth eggs was 1/10 g. Table 2 shows the characteristics of the different composting materials before the co-composting phase.

Table 2: Composition of macro elements in the compost raw materials

S/ No	Parameter	Dewatered Faecal Sludge	Kitchen waste	Saw Dust
1	Total Organic	32.1 ± 0.3	45.5 ±1.70	52.9 ±

	Carbon (g/kg)		)	0.91
2	Total N (g/kg)	3.4 ± 0.2	3.28± 0.04	0.59 ±0.04
3	C: N Ratio	9.2 ± 0.4	13.9 ± 0.35	89.8 ±4.56
4	Total Phosphorus (P)	1.6 ± 0.1	0.57 ± 0.30	0.05± 0.01
5	K-Total	0.9 ± 0.2	2.3± 0.32	0.43± 0.11
6	pH	7.3 ± 0.1	5.67 ± 0.4	7.06 ± 0.12
7	Faecal coliforms MPN/g	$2.1 \times 10^3 \pm 0.2 \times 10^3$ MPN g^{-1}		

3.1. Physicochemical Parameters Analysis of Compost

There was a significant variation in total nitrogen during the composting process (P= 0.001); it was insignificant at P > 0.05. As of the 30th day of sampling for Reactors 2, 4 and 5, the resulting composts met the major stability/maturity indices. Conversely, on the 14th-day Reactor, 3 reached the critical limit for the index parameters. A significant difference in efficiency in pathogens was noted in the reactors (P = 0.001). Reactor 3 was the most effective in reducing pathogens that met the WHO standard.

3.1.1. Variation of pH during Composting

Figure 1 shows the pH variation with time during composting progress in the composting reactors. A low pH at the start of composting is expected as the degradation of organic substances leads to the formation of organic acid. The prevailing aerobic conditions, made possible by constant mixing of the composting mass, allow oxygen circulation, leading to increased acid production, subsequently consumed to form ammonia by the compost bacteria. Acid consumption and ammonia formation increase pH, making the process a major controlling factor. The composting mass pH values serve as a measure of the maturity of the compost. A non-significant variation at pH > 0.001 was observed using ANOVA to check the reactors' pH variation. A final reading of the pH taken on the ninth week showed that the pH in the reactors was all basic, showing that the compost was mature. This result is consistent with similar findings from Said et al. and Bazrafshan et al. [22, 23].

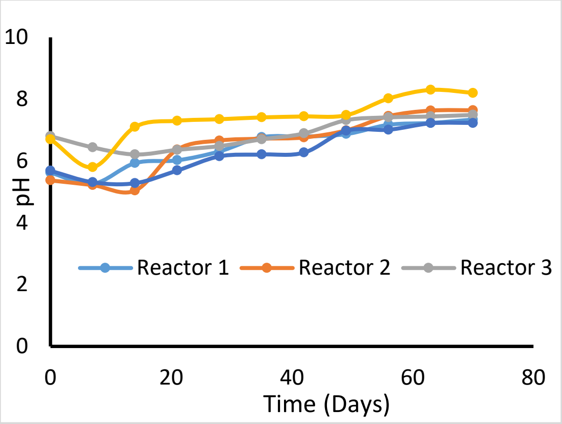

Figure 1: Evolution of pH during composting

3.1.2. Temperature

During the active and cure stages of the composting process, the reactors' temperature profile indicated a process supporting active microbial degradation, as shown in Figure 2. Successions of early rising and falling of temperature were observed in all the reactors. The repeated rise and fall was followed by a gradual decrease in temperature, with time to reach the temperature in the atmosphere. Reactor 4 rose above the ambient to a maximum sanitising temperature of 62.3°C compared to Control Reactor 1, which only exceeded a maximum temperature of 42.2°C. Reactors 2 and 3, on the other hand, achieved a sanitising temperature above 54oC because of the lower ratio than Reactor 4. The sanitising temperatures were amply sustained for more than a week to remove the latent pathogens in the compost material. Other researchers [6] who composted source-separated faeces using Styrofoam as insulators reached 10°C-15°C above the ambient temperature. The temperature profile significantly impacts the pathogens' thermal inactivation rate, depending on the temperature and exposure length [10, 6].

Reactor 5 and the control reactor (Reactor 1) did not produce sanitisation temperature according to WHO's suggested temperature requirements. Perhaps the most likely reason for the control reactor is that it was neither insulated nor treated with the bulking agent. There was no retention of generated heat, and the oxygen needed for correct aerobic composting was unavailable. The cooling and maturation period in all the reactors occurred after about three weeks of composting, indicating that maturation and stabilisation of the organic matter have been reached. We may not necessarily conclude that the compost is stable and matured using the temperature profile alone but with other parameters to elucidate the maturity and stability of the compost.

The compost products of reactors 1 and 5 may not be used as fertilisers or soil conditioners as they do not meet the WHO's standards for compost products.

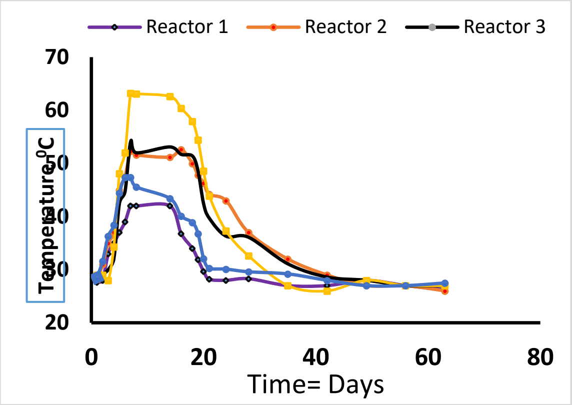

Figure 2: Evolution of temperature during composting

3.1.3. C: N ratio

The ratio of carbon to nitrogen (C: N ratio), although not a test within itself, is critical for assessing composting system quality performance and progress. The C/N ratio can be used with other maturity indicators to assess the degree of decomposition of organic material. So, compost maturity and stability are a C: N ratio function. The carbon-to-nitrogen ratio represents the degree of organic matter degradation leading to compost stability. The C / N ratio is often used as the compost maturity index.

This can be seen from the plot of the C/N ratio against time, and observation reveals that the C: N ratio decreased during the composting process in all reactors due to carbon loss and an increase in nitrogen content per unit material. The carbon-to-nitrogen ratio of 15-30:1 is important for the aerobic metabolism of microbes. Figure 3 shows that the C: N ratios at the start of the composting process were high in all the reactors. Generally, the C / N ratio measures the degree of decomposition of organic waste and usually reduces the carbon-nitrogen ratio during composting, regardless of the composting process. Perfect C / N ratios range from 12 to 25 [23].

Rector 2, 3, and 4 C / N ratios were lower than the recommended ratio by the WHO for the application of compost on land, which is between 13 and 22. The low C: N value indicates that the compost has matured but may not necessarily mean that the compost is sanitised. For Rector 5 (C/N = 19.2) and Rector 1, the control reactor (C/N = 23.0), although within the ratio set by the WHO, showed a decrease in degradation rate, implying low substrate mineralisation. This is a consequence of nitrogen deficiency in the composting mix. In all the composting reactors except the control, the C: N ratio fulfilled the WHO requirements for maturity.

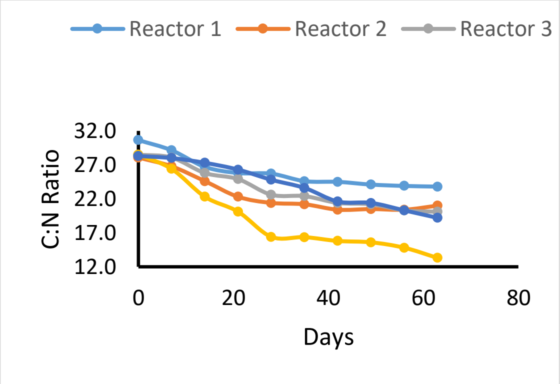

Figure 3: The change of C/N during the tests

3.1.4. Total faecal coliforms (E-coli)

Indicator faecal coliform microorganisms are determined using a standard method of bacteriological testing (27).

The results of plate reading on pathogen population heterogeneity in reactors are shown in Table 3. All the composts met the sanitisation criteria in WHO 2006 [24]. In compost materials, faecal coliform was substantially reduced to meet the allowable WHO limit (< 1000 CFU / g). This decrease was observed in all reactors except Reactor 1. The reduction confirms the composting model and feedstock combination's effectiveness in sanitising faecal sludge for compost production. A temperature above the pathogen threshold temperature should remove the pathogen. The composting mix achieved and retained this sanitizing temperature (500C – 550C) for more than a week, except for the control reactor, without any bulking adjustment and lagging. This temperature range created the sanitising temperature for the thermophilic removal of faecal coliform from the compost. Other researchers, including Faecam et al. and Vinneras et al. [14, 29], drew a similar conclusion and felt that if the temperature is kept above 50 - 55 ° C for at least a week, the pathogen inactivation time will be shorter. The most sanitized compost was Reactor 4, which was also the fastest-sanitation compost.

Table 3: Variation of the pathogen population in the reactors

Faecal coliform				
Reactor	Initial FC MPN/ g,	Final FC MPN/ g,	**% Reduction**	**sanitized**
Reactor 1	$21x10^3$	7214	63.78	No
Reactor 2	$21x10^3$	1443	92.77	Yes
Reactor 3	$21x10^3$	1387	93.03	Yes
Reactor 4	$21x10^3$	856	98.0%	Yes
Reactor 5	$21x10^3$	2157	89.20	Yes

3.2. Quality stability and nutrient content of the produced composts

Considering Figures 4, 5, and Table 4, the consistency and stability of the produced composts were assessed. Considering the EPA requirements, compost should not be heated to above 20^0C above ambient temperatures. The assumption is that compost must have an index value of V or IV for maturity. The outcome of the self-heating test shows that the composts reheated while standing at temperatures between 00C and 200C above the ambient temperatures, meeting the maturity index criterion for finished and curing stage composts. The result shows that Reactors 3 and 4 had very low self-heating capacity, indicating maturity, while reactors 1 and 5 were still at the co-composting stage with an index of 3.

It is accessing the compost maturity and stability using the pH tests and the decreasing trend in the carbon-nitrogen ratio (C: N) to show that at the beginning (Figure 4), pH values in all reactors exhibited a standard pattern that temporarily fell due to accumulation of organic acids at the thermophilic level. This is because of the high fermentation rate of organic matter in the composting mix. At the thermophilic peak in reactor 3, the pH began to increase and reached a maximum of 9.02 and 7.9 in reactor 5. The rise was due to the release of ammonia in the proteolytic process [25]. At the cooling and maturation stage, the pH decreases to a neutral value. Although the pH value is not an appropriate parameter for evaluating compost maturity since a monotonous feature cannot reflect its overall trend [25]. While some scholars claim that the C: N ratio is not inherently a maturity guarantee, the ratio does produce reliable results. The decreasing trend in all reactors' C / N ratio correlated well with the reactor temperature during composting.

Table 4:

Reactor	**Description of treatment**	**Final pH**	**K**	**P**	**C**	**N**	**C/N Ratio**	**Level of maturity**
1	FS/SD/		5	11	110	16	6.87	
2	FS/SD/KW (1:1 :1)		7	14	87	11	7.91	
3	FS/SD/KW (1:2: 2)		5	11	110	16		
4	FS/NPK/KW		16	17	110	30		
5	FS/SD/KW (1:4:4)		13	23	210	21		

FS = Faecal Sludge, SD = Sawdust, KW = Kitchen waste

3.3. Conclusion

There were noticeable differences in the composting reactors. In converting faecal sludge to quality compost, several control measures must be implemented, and it is crucial to implement and carry out these checks. Results show that faecal sludge mixed with kitchen waste and bulking agents when composted under Nigerian tropical weather conditions will potentially provide safe compost for use as organic fertiliser for farming and contaminated soil remediation. During composting, the smell of ammonia was insignificant (a clear sign that the process was aerobic) and indicated that nitrogen was retained to boost the compost's fertiliser value. The implication is that the pH change in the compost was not likely high enough to affect the pathogens and ammonia emissions. The composting of faecal sludge mixed with organic kitchen waste and sawdust as a bulking agent hastened the waste's biodegradation process and led to stable compost production. The parameters of compost maturity indicate that faecal sludge co-composted with kitchen waste matured within three weeks of composting. The co-composting product test results after 60 days show that organic carbon (C) concentration was an average of 22.07 ± 5.26 per cent, total nitrogen (N) of 1.79 ± 0.21 per cent, while the C/N ratio was an average of 12.38, total phosphorus (P) = 0.31±0.01 per cent and potassium (K) 1.12±0.16 per cent, respectively. With such parameters, the compost generated is well suited for use in the remediation of contaminated soil, having met the WHO requirement for compost application on contaminated land. Eliminating pathogens from the composts was a critical consideration, and the composting method effectively kept pathogens below the threshold. When using a combination of kitchen waste and sawdust as a bulking agent, the sanitation of faecal sludge was quite adequate. This manuscript's contribution is to recycle human faecal sludge. In addition to recycling human faecal sludge, the results can also deeply eliminate the growth of helminth eggs that harm humans and soil fertility. This study has broadened our knowledge of faecal sludge treatment technologies, and it is recommended that the co-composting of organic waste involving faecal sludge be adopted to pursue a sustainable environment. By adopting the composting process, organic cooking waste and dewatered faecal sludge can be converted into a value-added compost fertilizer that allows the recycling of organic matter and nutrients from plants. Finally, this work encourages the scientific and research community to give value and reuse faecal sludge and other organic waste materials rather than simply throwing them out due to imprudent choice with attendant drawbacks.

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