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Vermicomposting as an effective approach to municipal sewage sludge management through optimization of the selected process variables

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ABSTRACT

In most developing countries, municipal sewage sludge end-use practices appear unsustainable; rather, it poses environmental concerns. This study examined the potential of vermicomposting of municipal sewage sludge and its blend with other biowaste for agricultural application. Using a response surface methodology and the Box–Behnken design in Design Expert Software (Version 10.0.7), the current study optimized the moisture content (60–90%), turning frequency (1–3 turnings/week), and substrate mixing ratios (50:50 to 80:20 wt.%) to maximize the content of nitrogen, phosphorus, and potassium. As a result, an optimal moisture content (72%), substrate mixing ratio (72.34:27.6 wt.%), and turning frequency (2 per week), producing a promising-quality vermicompost with a maximum yield of nitrogen (2.76%), phosphorus (1.80%), and potassium (1.88%) is achieved. Thus, vermicomposting can effectively turn the concerning municipal sewage sludge into useful agricultural input for its sustainable management.

Key words: coffee husks, cow dung, *Eisenia fetida*, municipal sewage sludge, vermicomposting

HIGHLIGHTS

- Optimal vermicomposting conditions were achieved through parameter optimization, including moisture content, mixing ratio, and turning frequency.
- High-quality vermicompost was harvested from municipal sewage sludge and amended with another biowaste (coffee husks and cow dung).
- The physicochemical and microbial properties of the vermicompost were analyzed for use as organic fertilizer.

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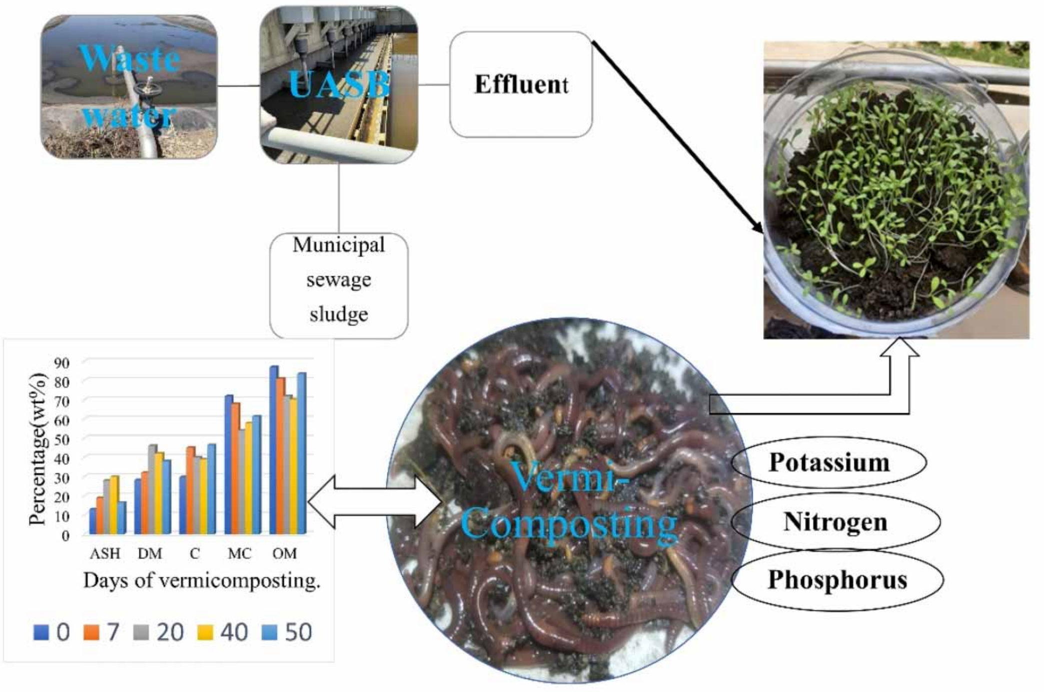
GRAPHICAL ABSTRACT



1. INTRODUCTION

Access to clean water, sanitation, and hygiene is a basic human right. However, billions still lack basic sanitation. In 2022, globally, 1.5 billion people lacked basic sanitation, with 570 million sharing improved facilities and 545 million using unimproved facilities. More than 50% of this estimate lived in sub-Saharan Africa and Central and Southern Asia (UNICEF 2023).

Significant disparities still exist in managing sewage sludge generated in most developing countries. In 2022, Africa had 779 million people without basic sanitation services and 839 million without basic hygiene services (UNICEF 2022). According to the 2022 Joint Monitoring Program for Household Sanitation report by WHO/UNICEF, Ethiopia's urban population has a sanitation service level of 45.9% for unimproved service, 28.5% for limited service, and only 17.4% for safely managed service. The only urban center in Ethiopia with a sewer connection is Addis Ababa City, the capital and administrative center. Over 60% of Ethiopia's urban areas still rely on traditional pit latrines, and 6% of the urban population practices open defecation (Ravina *et al.* 2021).

The municipal wastewater treatment sector has been greatly impacted by the continuous growth of the world's population. Annually, an average of 45 million dry tons of municipal sewage sludge is produced worldwide (Ferrentino *et al.* 2023). An increase in population density, industrialization, changes in lifestyle, and urbanization are the primary factors contributing to this increase. The composition of municipal sewage sludge varies based on the characteristics of the incoming wastewater and the treatment efficiency of the plant.

The composition of wastewater differs from that of fecal sludge due to higher concentrations of pollutants such as microplastics, plastics, hormones, and pharmaceuticals (Strande *et al.* 2014). In their 2023 study, Nikolopoulou *et al.* discovered a variety of emerging contaminants in sewage sludge from three different wastewater treatment plants in Lagos, Nigeria. Therefore, disposal methods such as incineration and landfilling, which are commonly used for sewage sludge, are not environmentally friendly (Azevedo *et al.* 2023).

Most developing countries cannot handle municipal sewage sludge generated due to technical deficiencies and limited reinforcement of environmental laws. The absence of clear legal standards for the management of sewage sludge in Ethiopia, as in many African countries, has led to severe environmental degradation and pollution. The Ethiopian Ministry of Water and Energy (MOWIE 2017) has not established specific quantitative standards for the agricultural reuse of sludge in their Urban Wastewater Management Strategy, unlike European countries (Collivignarelli *et al.* 2019).

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Economic costs of managing sludge make up to 50% of wastewater treatment plants' operational costs (Gebreeyessus & Jenicek 2016; Abdel Wahaab *et al.* 2020). The sewage sludge generated in many developing countries is often disposed of without treatment and air-dried in sludge drying beds. Sometimes, this untreated sludge is used as a soil conditioner or organic fertilizer without meeting the required standards. Sludge is commonly disposed of by dumping it in dumpsites or river bodies. This leads to the eutrophication of water bodies and the emission of offensive odors. This improper disposal of sewage sludge has led to severe environmental pollution in Addis Ababa, Ethiopia. The Akaki River and other water bodies have been contaminated with fecal matter (AAWSA 2014). The insufficient ability to manage the produced sludge poses a significant risk to both public health and the environment (Zhou *et al.* 2020).

It is well documented that sewage sludge contains important nutrients such as nitrogen, phosphorus, and potassium for agriculture (Sakthivel & Charair 2011). Promoting nutrient recycling from organic waste such as sewage sludge provides sustainable agriculture and efficient waste management. Wastewater reuse and waste composting have been practiced for centuries (Cofie *et al.* 2016). Composting is a successful natural biological treatment technology used to recover nutrients from sewage sludge. Composting is a process that stabilizes organic matter under controlled conditions (Kosobucki *et al.* 2000). Composting using static pile and windrow methods has drawbacks such as a longer production time for mature compost, large space requirements, and labor-intensive demands. These traditional composting methods may also lead to challenges such as difficulty in controlling leaching and the prevalence of anaerobic conditions, which may result in odor emissions (Cofie *et al.* 2016). Worm and larval composting are cost-effective methods for ecologically degrading organic waste in a short period (Kosobucki *et al.* 2000).

Vermicomposting is a method that uses worms and microbes to decompose organic waste into nutrient-rich compost, which is an effective fertilizer for agriculture. Compared to other composting methods, vermicomposting is relatively faster and produces finely divided castings or humus (Ludibeth *et al.* 2012). The use of vermicomposting to treat sewage sludge has been emphasized in previous studies (Sinha *et al.* 2010; Suleiman *et al.* 2017; Boruszko 2020) as an alternative approach to sludge management.

Moisture, pH, carbon-to-nitrogen ratio, temperature, aeration, ammonia, and salt content are among the factors that affect the vermicomposting process (Ndegwa & Thompson 2000; Kaur 2020). The effects of the carbon-to-nitrogen ratio, worm stocking density, moisture content, and pH on vermicomposting have been studied by several researchers (Ndegwa & Thompson 2000; Sinha *et al.* 2010; Gurav & Pathade 2011; Kaur 2020; Dume *et al.* 2023). The effects of substrate mixing ratios in vermicomposting sewage sludge have, however, not received much attention. Uncertainty exists over the ideal combinations, what should be mixed, and in what proportions. Another aspect that has mostly been overlooked is the feedstock's ideal turning frequency. Thus, the influence of operating parameters such as turning frequency (1–3 turnings/week), mixing ratios (50:50 to 80:20 wt.%), and moisture content (60–90%) have been improved in the current study to maximize the content of nitrogen, phosphorus, and potassium to be employed in agricultural applications.

2. MATERIALS AND METHODS

2.1. Study area

Ethiopia's capital city of Addis Ababa is where the Kaliti Wastewater Treatment Plant (KWWTP) is situated (Figure 1). The wastewater treatment facility is located in Addis Ababa city's industrial area and slopes down to the Little Akaki River between latitude 8°55′11.05″N and longitude 38°45′20.46″E. Before its expansion, the wastewater collection system of the treatment plant was based on an average water consumption of 150 liters per capita per day to serve an equivalent population of 200,000 people (Ravina *et al.* 2021). Although the treatment plant's design capacity was expanded to 100,000 m^3 wastewater per day after additional extension works and commissioning in 2018, it is now operating at only 75% of its capacity due to a lack of residential connections. Transporting sludge using vacuum trucks to the treatment plant is an alternative solution for areas relying on on-site sanitation facilities.

After Nigeria, Ethiopia has the second-highest population in Africa. The city of Addis Ababa has a high population; hence, much domestic sewage is produced. Domestic sewage from various homes that are connected to the main sewerage network is treated at KWWTP. In Addis Ababa, approximately 40% of homes have a system for collecting sewage waste using vacuum trucks or piped sewer lines; the remaining 60% use on-site sanitation methods. Sewage from on-site sanitation systems, including septic tanks and pit latrines, is delivered to the treatment facility in vacuum trucks for disposal every week in the amount

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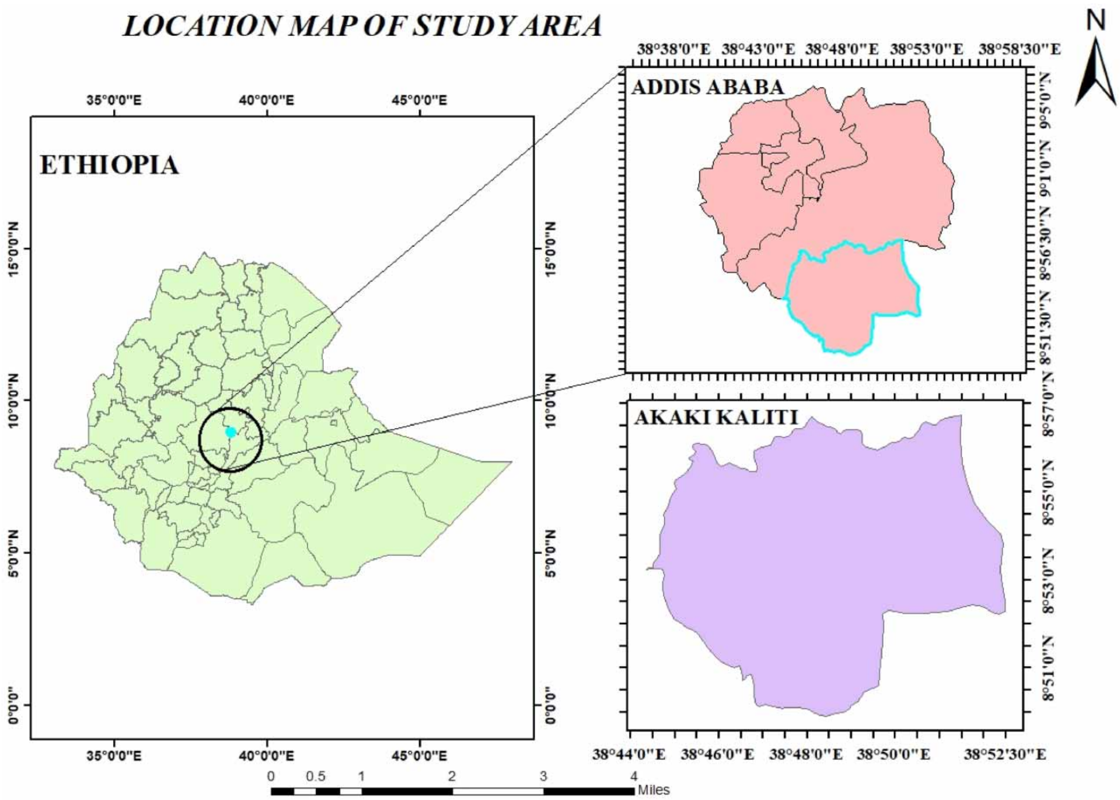

Figure 1 | Study area map of the Kaliti Wastewater Treatment Plant located in Addis Ababa, Ethiopia.

of 5,600 m^3. The treatment plant further receives waste from different institutions, such as the healthcare and hospitality sectors that the city of Addis Ababa hosts.

As shown in the schematic representation of the KWWTP (Figure 2), the treatment process includes a preliminary treatment unit for sewage that includes coarse and fine screening as well as the removal of grit and grease, which is followed by UASB reactors, trickling filters, secondary clarifiers, and disinfection processes that first chlorinate and then dechlorinate the supernatant. Another far-off location has a sludge drying bed connected to a UASB sludge pumping station that also accepts raw sludge that is first tested for ammonia concentration. The initial unit features baffles to reduce the speed of intake, which is additionally coarse-filtered by iron bars spaced at approximately 60 mm and is also used for incoming truck-emptied sewage. Additionally, using a 20 and 2 mm screen size installation, fine screening is carried out manually. After the screening, the influent is decreased, and the scum is eliminated using air. The sewage is then routed to approximately 20 UASB reactors, each measuring approximately 20 m^3. The UASB reactors have a three-phase separator system, where the gas is collected from the top and the sludge settles to the bottom. All anaerobic reactors operate at ambient temperature.

The biogas collected is flared in a separate unit, while the sludge goes to a sludge station where it is pumped to a drying bed engineered to protect the groundwater and the soil from contamination, as the bed also receives truck-emptied sewage; indeed, the sludge drying bed also receives sludge from the secondary clarifiers. The effluent from the UASB reactors is further aerobically degraded using media-packed trickling filters. The UASB and trickling filter systems operate with fitted recirculation systems. The effluent is further chlorinated as a disinfection treatment and is dechlorinated to keep the chlorine content of the effluent within the limit before discharging it. Chlorination and dichlorination are automatically performed using a baffling chamber to maintain contact timing.

One sludge drying bed at the KWWTP has typical dimensions of 6 m wide and 6–30 m in length, with a sand layer ranging from 230–30 mm in depth. The sludge drying beds were designed based on a sludge layer of 30 cm for UASB sludge and 40 cm for latrine sludge. The amount of sludge in the reactor is managed through the regular discharge of sludge to the

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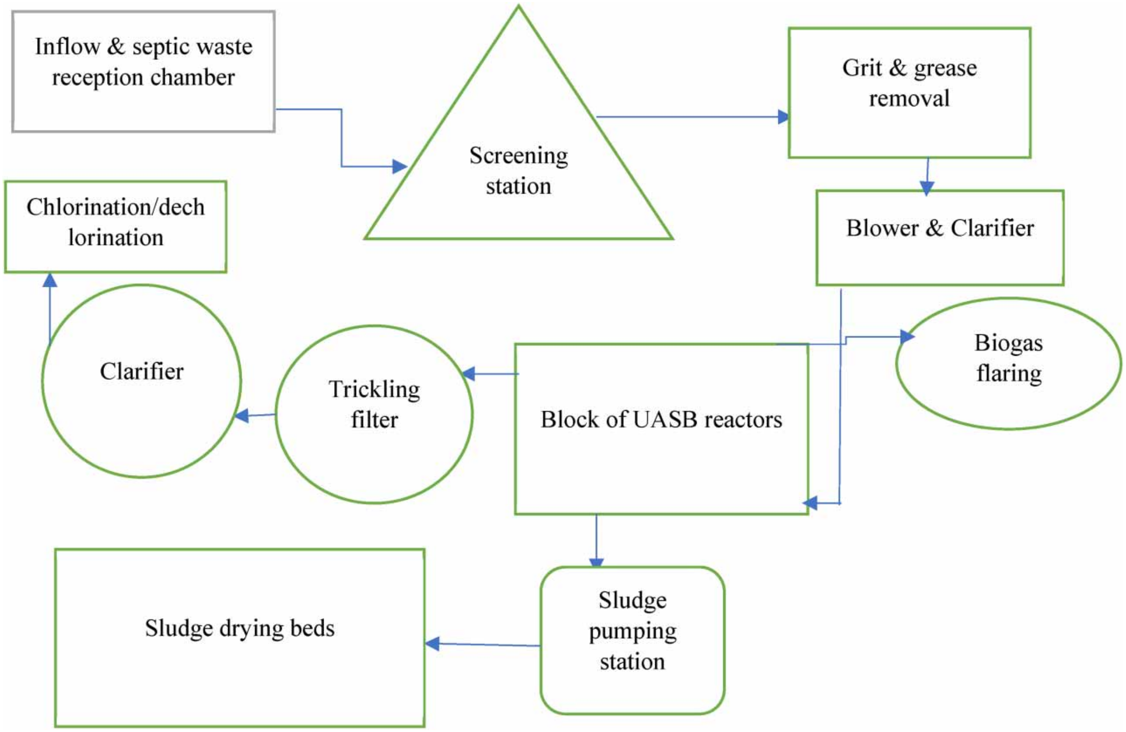

Figure 2 | Schematic representation of the Kaliti Wastewater Treatment Plant.

sludge drying beds. The sludge is discharged through valves in the storage tank; this sludge takes approximately 15 days to dry in the sludge drying beds. Sludge from on-site sanitation systems such as septic tanks that is discharged into latrine sludge drying beds takes a longer time to dry (AAWSA 2014).

2.2. Sampling

This study follows the Publicly Owned Treatment Works (POTW) Sludge Sampling and Analysis Guidance published by the United States Environmental Protection Agency (US EPA 1989). In this investigation, granular sludge from the UASB reactor and sludge from the sludge drying beds were both employed. Grab samples of dried sewage sludge were gathered at four separate positions in the sludge drying beds and blended to provide for the final vermicomposting process to provide a good representative sample of the sewage sludge. Sludge from the outflow of the UASB and the sludge drying beds was sampled to observe the difference in physical and chemical parameters. In a 3-min period, equal amounts of the sludge were collected to obtain a fair representative sample. The sampled sludge was kept below 4 °C in an ice box and was transported to the laboratory for further analysis.

2.3. Raw materials

Coffee husks totaling 20 kg were bought from the Ethiopian city of Hawassa, and 10 kg of pre-composed cow manure was employed as an amendment material. Due to the high toxicity level and variability of sewage sludge, pre-composted cow dung was chosen in the study to favor the activity of microbial organisms and earthworms during the vermicomposting process. According to Gurav & Pathade (2011), the ideal particle size for coffee husks was reduced to 1–2 mm by first grinding them. As the primary organic waste degraders in the investigation, *Eisenia fetida* earthworms were used. This collection of worms came from the Ethiopian Agricultural Research Ambo Plant Protection Research Center. This species of earthworm is used in most vermicomposting studies (Degefe *et al.* 2012; Ludibeth *et al.* 2012).

2.4. Experimental setup and description

After obtaining the required raw materials, a pilot-scale vermicomposting experiment was set up. The experiment was carried out in a greenhouse at Addis Ababa University's School of Natural and Computational Sciences, which has an average

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ambient temperature of 30 °C. The experimental setup included plastic containers with a 10-liter capacity. Due to their ease of construction and maintenance, plastic bins were used as vermin reactors. For drainage and aeration, the bottom sides and top of the plastic containers were perforated. This study utilized a total of 20 plastic runs or bins. Figure 3 presents a general, concise, schematic description of a composting process.

2.5. Experimental design

The vermicomposting experiment was carried out according to a protocol that was previously reported (Biruntha *et al.* 2020) for a maximum of 50 days. According to respective proportions, each treatment unit contained the sewage sludge substrate, amendment materials (cow dung and coffee husks), and earthworms. The control tests, which were also kept to examine how earthworms affected the conversion of substrates, did not include any earthworms in the substrate mixture.

The three potential parameters of moisture content (60–90%), turning frequency (1–3 turnings/week), and mixing ratios of sewage sludge to amendments (50:50 to 80:20 wt.%) were varied from a range of values to optimize the vermicomposting process parameters to generate high-quality vermicompost. This was done using the Box–Behnken Design and Response Surface Methodology of Design Expert Software, Version 10.0.7. A randomized design was used for the experimental construction. The experiment was designed, and the runs were randomly distributed using Design Expert software version 10.0.7. In this experiment, three factors with three levels each were taken into account. The levels of the selected factors in this study are presented in Table 1.

A Box–Behnken under-response surface methodology was used for the experimental design. Each numerical factor has three levels (−1, 0, +1) in a Box–Behnken architecture. This design was selected because it uses fewer samples, which saves time, and because it is more effective and simpler to set up and interpret than other designs. In either a general factorial design or a regular multilevel categorical design, an experiment with three factors at three levels and two duplicates would have 54 experimental runs. The sample size for the identical experiment would be smaller in the Box–Behnken design.

For simulating a response surface, the Box–Behnken design required 17 runs. Three of the 20 plastic bins or runs used in the experiment were kept empty of earthworms to assess how quickly sewage sludge organically deteriorates or decomposes without the help of the worms. Table 2 contains information about the experimental runs with input parameters. The experiment's randomization was crucial to its successful conclusion, which prevented the conditions in one run from affecting those in the preceding runs. To calculate the experimental error and guarantee that statistical analyses such as ANOVA were conducted, five center points were employed in the design.

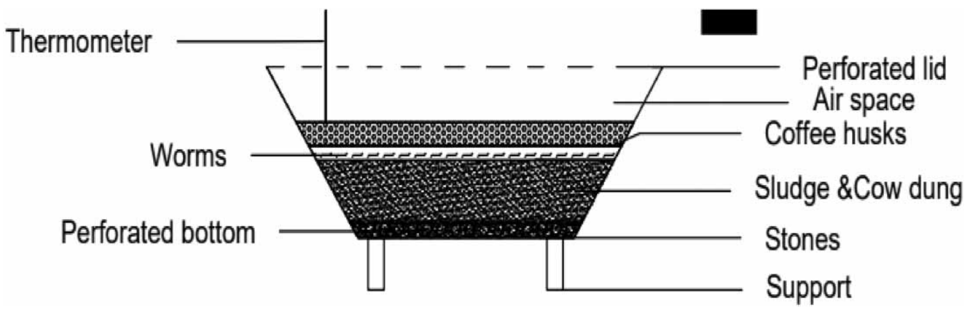

Figure 3 | General sketch of a vermicompost bin.

Table 1 | Level and code of variables for optimization of process parameters using a response surface methodology

Factors	Unit	Coded symbol	Level 1	Level 2	Level 3
Moisture content	(%)	A	60	75	90
Mixing ratios	w/w	B	50:50	70:30	80:20
Turning frequency	Turnings/week	C	1	2	3

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Table 2 | Box–Behnken design and combination of process variables

Run order	A: Moisture content	B: Mixing ratios	C: Turning frequency
1	60	50	2
2	60	65	1
3	75	80	1
4	60	80	2
5	60	65	3
6	75	65	2
7	75	50	1
8	90	65	1
9	90	50	2
10	75	65	2
11	75	65	2
12	75	65	2
13	75	50	3
14	90	65	3
15	75	65	2
16	75	80	3
17	90	80	2

2.6. Laboratory procedures

To evaluate the possible chemical and physical changes that may have taken place during the biological process, samples of the compost were examined during the vermicomposting period using established methods (Table 3). Temperature readings were obtained twice a week, and the results of the weekly average were taken into account. The pH, moisture content, electrical conductivity (EC), ash, and organic matter concentrations were among the other factors that were examined during the vermicomposting process. Nitrogen, phosphorus, and potassium, the three most crucial nutrients required in agricultural practices, were the key parameters that were examined after 50 days of vermicomposting. The analysis of heavy metals and micronutrients was conducted using flame atomic absorption spectrometry at the Ethiopian Construction Design and Supervision Works Corporation Laboratory.

Table 3 | Test parameters analyzed in the study and their respective standard methods

Parameters	Standard test method	Reference
pH	Potentiometric – Standard method 940D soil and waste	Mc Lean (1982)
Electrical conductivity	Conductivity cell potentiometric-conductivity meter of model 145	Mc Lean (1982)
Moisture content	Thermogravimetric method	Lazcano *et al.* (2008)
Ash content	Remains after ignition at 550 °C	Lazcano *et al.* (2008)
Total nitrogen	Kjeldahl method	Bremner & Mulvaney (1982)
Phosphorus	Olsen method	Sertsu & Bekele (2000)
Potassium	Flame photometer method	Page *et al.* (1982)
Heavy metal analysis	Atomic absorption spectrophotometer (Flame AAS)	Chapman & Pratt (1961)
Total and fecal coliforms, *E. coli*	Standard methods for the examination of water and wastewater	APHA (2005)
Helminth eggs count	Standard methods for the recovery of helminth ova in wastewater and sludge	Moodley *et al.* (2008)

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3. RESULTS AND DISCUSSION

3.1. Characterization of the sludge sample

The physicochemical and biological characterization results presented in this study are based on samples taken at a certain time during the sampling period and not on samples that are representative of the sludge produced throughout the year; however, they provide a general overview. The characterization of sewage sludge is necessary for the efficient end-use of sewage sludge. The results for selected physical, chemical, and biological characteristics of granular sludge from the UASB reactors are presented in Table 4.

The characteristics of sewage sludge vary significantly between two wastewater treatment facilities, and its composition depends on the nature of the treated sludge and treatment technology (Kominko *et al.* 2017; Rorat *et al.* 2018). This statement is in harmony with the findings of a study that was carried out in Poland to determine the physical and chemical properties of sewage sludge sampled from two municipal WWTPs. The authors observed a significant difference between the composition of nutrients and metals from one treatment plant to the other (Kiper *et al.* 2019). The variability in the composition of sewage sludge may also be attributed to the different materials used for anal cleaning, climatic factors, and the source area of the influent.

In this study, as seen in Table 4, the mean pH value of the liquid sewage sludge was found to be 6.8 ± 0.03. This finding is consistent with the typical chemical composition and properties of digested sludge presented by other researchers (Fytili & Zabaniotou 2008). Slightly acidic to neutral pH values were observed in the sewage sludge samples in this study. Such a pH value obtained is in the range of good anaerobic conditions; however, the presence of volatile acids in the anaerobic digestion process makes the pH in the lower range of optimal conditions. Other scholars attribute such findings to the presence of calcium and magnesium ions in the sludge samples (Romanos *et al.* 2019). Determining the sludge pH value is an important parameter because in cases where the value is low, it would gradually affect the pH of the soil, which can later affect nutrient uptake by plants. The pH value of the liquid sludge in this study was close to neutral, which is the safe and optimum value for its use in agriculture.

The moisture content (Table 4) was 96%, indicating that it is almost entirely liquid. Liquids are heavy and, in most cases, difficult to transport and handle. For this reason, dewatering of the sludge is usually employed. The method of dewatering liquid sludge determines the overall moisture variation between the liquid and dry sludge samples. Sewage sludge with a high moisture content cannot be used for the composting process. Excess moisture creates anaerobic conditions, and aeration is an important factor that affects the composting process (Gurav & Pathade 2011).

Table 4 | Selected physicochemical and biological characteristics of granular sludge from the UASB reactors

Parameters	Quantity/Unit (Mean ± SD)
pH	6.80 ± 0.03
Electrical conductivity (mS/cm)	2.05 ± 0.03
Total dissolved solids (mg/L)	995 ± 35
Moisture content (MC) (%)	96 ± 1
Total solid (%)	4 ± 1
Heavy metals	
Cadmium	Below detection limit
Lead (mg/L)	0.010 ± 0.001
Chromium (mg/L)	0.910 ± 0.001
Zinc (mg/L)	21.69 ± 0.70
Copper (mg/L)	2.55 ± 0.24
Bacteriological parameters	
Total coliforms (CFU/ml)	5.24×10^6
E. coli (CFU/ml)	2.38×10^6

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Analysis of the five metals was carried out to determine the health and environmental hazards of municipal sewage sludge. These heavy metals included Cd, Pb, Cr, Zn, and Cu, which are among the heavy metals of primary concern in the environment based on their high levels of toxicity (Águila-Juárez *et al.* 2011; Agoro *et al.* 2020).

The heavy metals analyzed in this study are among the principal elements restricting the use of sludge for agricultural purposes. Research has indicated that the concentrations of heavy metals in sewage sludge vary depending on the origin of the sludge (Fytili & Zabaniotou 2008). In a study carried out in South Africa to assess the distribution of five heavy metals (Cd, Pb, Cu, Zn, and Fe) in wastewater and sewage sludge from three wastewater treatment facilities, the authors found that the concentrations of the metals varied from one treatment facility to the other, ranging from below detection to being detected but below hazardous levels in all study locations (Agoro *et al.* 2020).

In this study, the results presented (Table 4) revealed that the concentration of Cd in the sludge samples was below the detection limit, while Zn exhibited the highest concentration. According to WHO (2006) regulatory standards, the elements Cd and Pb were below permissible levels, while Cr and Cu were slightly above hazardous levels by >0.86 and >0.55 mg/L, respectively. The trace element Zn exhibited the highest concentration and exceeded regulatory permissible limits by >6.69 mg/L. The KWWTP treats only municipal or domestic waste; hence, the high concentration of the trace element Zn may have been attributed to the illegal discharge of wastewater into the main sewerage network by some industries. Some scholars attribute the presence of heavy metals to corrosion within the sewerage network, especially when the plant has lived for some time and no proper operation and maintenance works are in place (Zhang *et al.* 2017).

Samples of dry sludge were also obtained from the sludge drying beds of the KWWTP and characterized for their composition. The results of the selected physical, chemical, and biological characteristics are presented in Table 5.

There was an increase in EC values (Table 4) in the dry sludge samples compared with the liquid sludge samples (Table 5). This increase may have been attributed to the increase in TDS in the sludge drying beds since the wastewater treatment plant employs conventional sand drying beds to dewater its sludge. The recorded EC values were below the maximum tolerable limits for plants of 4.0 mS/cm (Belmeskine *et al.* 2020). High EC values in a sample are an indication of salinity. Earthworms are sensitive to a high concentration of salts. However, the species of earthworms (*E. fetida*) used in this study can survive and adapt to extreme environmental and saline conditions (Bhat *et al.* 2018).

To successfully use sludge as an organic fertilizer, the organic matter content of the sludge is an important parameter. In municipal sewage sludge, the organic matter content is usually higher than 50% of dry matter (Kominko *et al.* 2017). Organic matter application in the form of sewage sludge increases soil aggregate formation and improves water infiltration (Usman *et al.* 2012). The mean values of volatile solids of dry sludge samples obtained from the characterization study were 86.99% (Table 5), which reveals that the sewage sludge is rich in organic matter content. Other studies indicate typical volatile solids values for digested sludge to be in the ranges of 30–60% of total solids (Fytili & Zabaniotou 2008).

Table 5 | Physicochemical and biological characteristics of the sludge samples obtained from the sludge drying beds

Parameters	Quantity/Unit (Mean ± SD)
pH	7.42 ± 0.06
Electrical conductivity (EC) (mS/cm)	3.56 ± 0.02
Moisture content (%)	71.78 ± 0.03
Total solids (TS) (%)	28.22 ± 0.03
Ash content (%)	13.01 ± 0.02
Volatile solids (%)	86.99 ± 0.02
Total dissolved solid (TDS) (mg/L)	1005 ± 1
Carbon content (%)	29.78 ± 0.01
Total nitrogen (wt.%)	0.94
Carbon-to-nitrogen ratio	31.7
Total coliforms (CFU/ml)	4.34×10^6
Total fecal coliforms (CFU/ml)	1.66×10^6
Helminth eggs (per gram)	70 ± 2

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The value of the carbon-to-nitrogen ratio of the sludge was 31.7 (Table 5). For the faster decomposition of organic waste, many authors suggest a carbon-to-nitrogen requirement of 20:1 to 30:1 parts of carbon-to-nitrogen (Ndegwa & Thompson 2000). The ash results (Table 5) revealed that sewage sludge is rich in biomass with appreciable mineral or inorganic content; hence, resource recovery can also potentially be explored in other streams, such as cement in the construction industry.

Microorganisms such as fecal coliforms, *Escherichia coli*, bacteria, and helminth eggs represent a risk to human health. The origin of pathogens in sewage sludge is human feces and animals whose excrement is disposed into the sewerage network (Cárdenas-Talero *et al.* 2022). The presence of these pathogens is usually high in low- and middle-income countries (Rocha *et al.* 2016). The results obtained from the microbial analysis of the municipal sewage sludge samples (Tables 4 and 5) indicated that the microbial biological community was very high beyond recommended microbiological quality guidelines (WHO 2006). Hence, the use of untreated municipal sewage sludge and wastewater in agricultural practices may present a great health hazard to field workers and crop consumers, who may be at great risk of suffering from helminthic infections and bacterial infections such as typhoid and cholera. It was, therefore, important to treat this sludge before reuse.

3.2. The vermicomposting process

3.2.1. Physiochemical changes during vermicomposting

The degradation of organic waste and the interaction of earthworms and microorganisms bring about significant physical–chemical changes in the compost (Amouei *et al.* 2017). There was a general increase in the pH up to the 20th day of composting (Table 6). The variation in the pH value may have been caused by the alkalinization of the biowaste from the release of ammonia gas during the degradation of the organic waste (Uçaroğlu & Alkan 2016). Toward the 50th day of vermicomposting, the pH value of the compost dropped to neutral, indicating the stability and maturity of the compost since hummus has a pH buffering capacity. The results of the variation in pH during the vermicomposting period are in agreement with other studies (Uçaroğlu & Alkan 2016). Concerning EC, there was a decreasing trend throughout the vermicomposting period. A decrease in EC values may be due to the stabilization of final mixtures and the decrease in ions after forming complex hummus.

3.2.2. Compost maturity

The vermicompost obtained from municipal sewage sludge amended with cow dung and coffee husks developed a dark black fine color with finely divided and homogenized crushed crumbs, an indication of mature castings. This was observed toward the latter part of the vermicomposting period, in the 5th to 6th weeks of vermicomposting. There was a change in the physical appearance of the compost, as shown in Figure 4(a) and 4(c). Harvesting the vermicompost involved manually separating the earthworms from the biowaste, as shown in Figure 4(b) and 4(d). This was made easier by exposing the biowaste that had the earthworm to natural light, as the earthworms would tend to settle toward the bottom of the biowaste as they prefer dark places.

3.3. Characterization of the vermicompost product

The physicochemical and biological characteristics of the vermicompost obtained from the optimum operating conditions are presented in Table 7.

Qualitative analysis of the vermicompost indicated that the degradation of the municipal sewage sludge by the *E. fetida* earthworms was successful, as there was no bad odor. The composite vermicompost obtained from most experimental runs had a dark fine color and smelled like that soil. A carbon-to-nitrogen ratio of 16:1 was recorded, which is an indication

Table 6 | Physical–chemical changes during the vermicomposting process of sewage sludge

Parameters	0 days	7th day	20th day	40th day	50th day
pH	7.42 ± 0.06	7.57 ± 0.12	8.68 ± 0.18	8.00 ± 0.12	7.34 ± 0.05
EC (mS/cm)	3.56 ± 0.02	3.15 ± 0.03	2.76 ± 0.12	2.17 ± 0.03	1.4 ± 2.2
MC (%)	71.78 ± 0.03	68 ± 2	54 ± 4	58 ± 2	61.4 ± 0.1
TDS (mg/L)	1005 ± 1	1580 ± 2	1380 ± 2	1080 ± 2	496 ± 17
TS (%)	28.22 ± 0.03	32.1 ± 2.1	46 ± 4	42.1 ± 2	38.6 ± 0.1

Mean value and SD of the three replicates.

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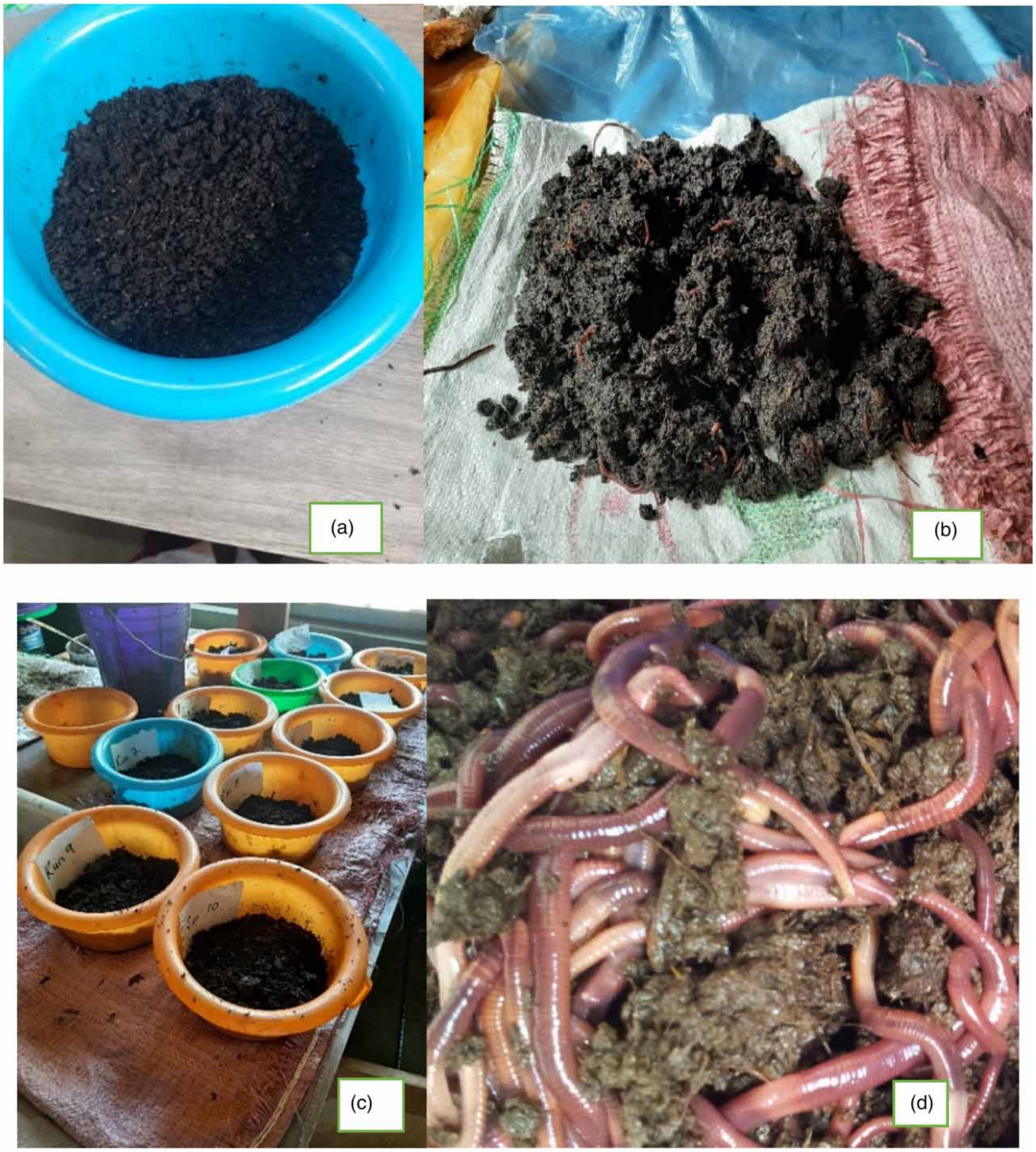

Figure 4 | Harvesting of the vermicompost: pictures (a) and (b) show the organic waste. (c) Experimental bins were laid out during the harvesting of the vermicompost. (d) *Eisenia fetida* earthworms feeding on the substrate.

of an advanced degree of stabilization of the organic matter and reflects a satisfactory degree of maturity according to guidelines for assessing compost quality (Ozores-Hampton 2017). The composite vermicompost obtained in this study contained 2.84% nitrogen, 1.22% available phosphorus, and 1.57% potassium (NPK) as the three major important elements. Vermicompost fertilizer characteristics and nutrients vary with earthworm feed type. Typical nutrient analysis of the vermicompost showed a carbon-to-nitrogen ratio of 12–15, nitrogen range of 1.5–2.5%, potassium range of 1.25–2.25, and phosphorus range of 1–2%, following the established guidelines (Chaoui 2010).

The initial characterization study of sludge samples met a contaminant grade 2 standard (EPA Victoria 2004) because contaminant levels were excessive. However, after treating the sludge using an ecologically friendly approach for 50 days, a contaminant grade 1 was achieved. Contaminant grade 1 is the highest quality biosolid with relatively low contaminant

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Table 7 | Physicochemical and biological experimental values for the vermicompost produced from optimum operating conditions after 50 days of maturation

Parameters (unit)	Research findings (Mean ± SD)
pH	7.34 ± 0.05
EC (mS/cm)	1.4 ± 2.2
Moisture content (%)	61.4 ± 0.1
Carbon-to-nitrogen ratio	16.1
Organic carbon (%)	17.11 ± 0.54
Ash content	16.5 ± 0.5
Nitrogen (%)	2.84 ± 0.07
Phosphorus (%)	1.22 ± 0.03
Potassium (%)	1.57 ± 0.04
Copper (mg/kg)	10.6 ± 1.6
Zinc (mg/kg)	260.1 ± 1.4
Manganese (mg/kg)	241.4 ± 1.2
Iron (mg/kg)	415.7 ± 1.6
E. coli	Not detected

levels. Contaminant grade 1 limits are also applicable for receiving soil contaminant limits (EPA Victoria 2004). These limits have been set up to ensure that the application of biosolids does not cause chemical contamination of receiving soils and are established based on the most conservative endpoint from human health, environment, and food safety.

Selected metals analyzed from the composite vermicompost were within the acceptable limit except for zinc (FAO/WHO 2011). There was also a reduction in pathogen levels in the vermicompost compared to the initial sewage sludge samples. This may have been attributed to the dilution of sewage sludge with other amendments, such as cow dung and coffee husks, which reduced the toxicity levels. Earthworm and bacteria degradation mechanisms may also have led to the reduction of pathogens in the vermicompost as they release antibacterial coelomic fluid (Sinha *et al.* 2010). The significant reduction in pathogens in the vermicompost enables it to be called a Class A biosolid. Class A biosolid products can be used on home lawns and gardens, parks and golf courses, and other places where public contact is likely.

3.4. Optimization of the vermicompost with the response surface method

The optimization of key process parameters coded as A – moisture content, B – mixing ratios, and C – turning frequency for the production of good quality compost from municipal sewage sludge was demonstrated using a response surface methodology under a Box–Behnken design of Design Expert version 10.0.7. Response surface methodology was employed to estimate the effect of the three process variables on the quantity of nitrogen, phosphorus, and potassium in the vermicompost. As seen from the perturbation plots (Figure 5(a)–5(c)), all process parameters had a significant effect ($p < 0.05$) on the response variables (NPK).

3.4.1. Effect of process parameters on nitrogen, phosphorus, and potassium

An increase in the mixing ratio of the sewage sludge directly increased the quantity of nitrogen, phosphorus, and potassium in the vermicompost (Figure 5(a)–5(c)). These effects can be attributed to the fact that municipal sewage sludge is rich in nitrogen, phosphorus, and potassium, so increasing its proportion in the mixing ratio substrates positively increased the nutrient status of the vermicompost. Due to the dense nature of sewage sludge, prior studies suggest that earthworms cannot survive in treatments with a sewage sludge mixing ratio greater than 95%. Treatments having a mixing ratio of sewage sludge < 80% exhibit the highest survival and better reproduction of the earthworm (Ludibeth *et al.* 2012).

Increasing the moisture content of the feedstock, on the other hand, increased the quantity of nitrogen, phosphorus, and potassium nutrients only up to an optimal value (Figure 5(a)–5(c)). A further increase in moisture content resulted in a decrease in three (NPK) macronutrients. This is because excess moisture in the bins creates anaerobic conditions that destroy

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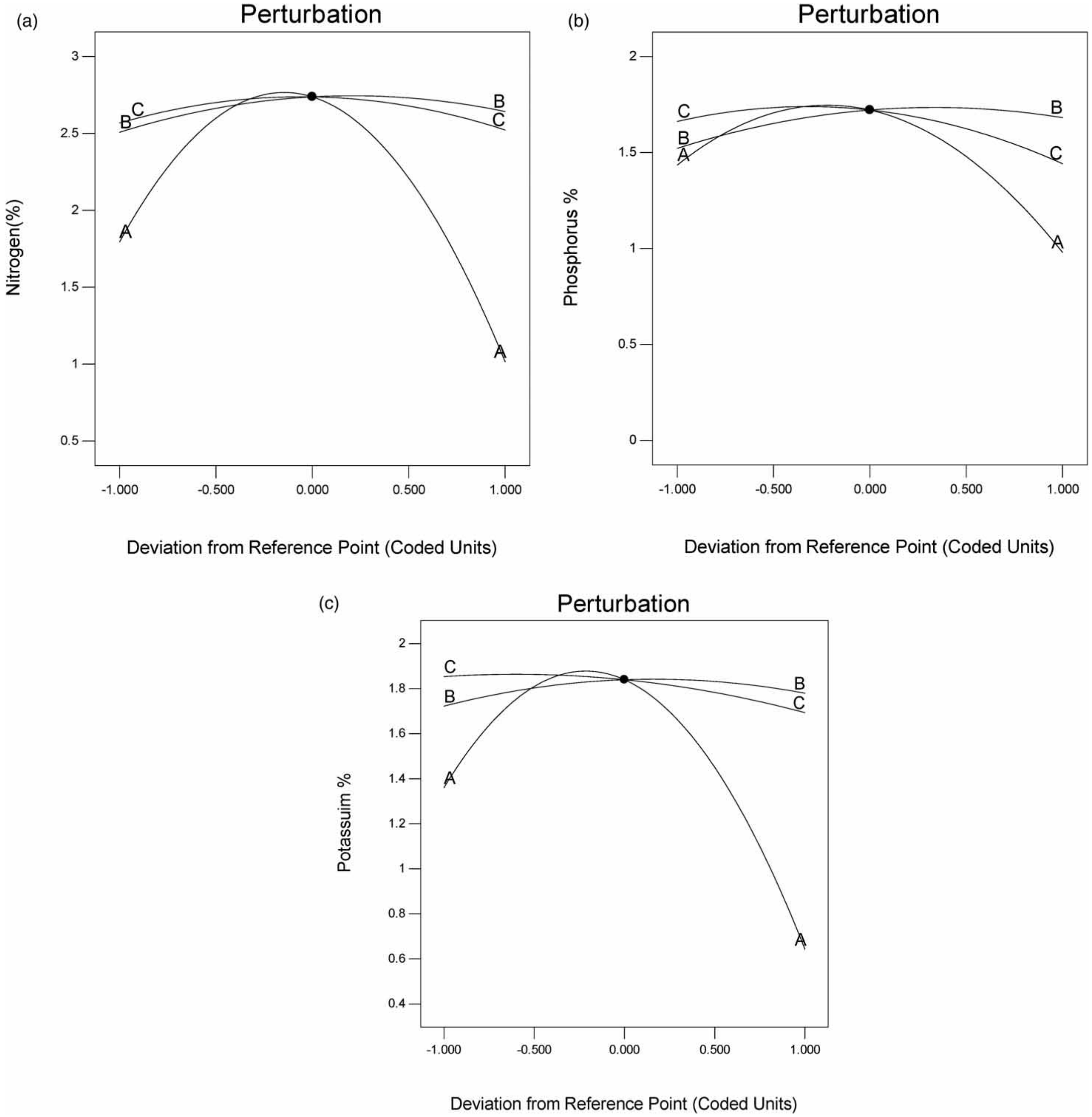

Figure 5 | Perturbation plots showing the effect of all factors on nitrogen (N), phosphorus (P), and potassium (K): (a) N; (b) P; (c) K. Factor: A – Moisture content (75%); B – Mixing ratio (65 wt.%); C – Turning frequency (2 per week).

much of the goodness of the vermicompost. Above 90% moisture content of the feedstock, the pore spaces are displaced by excess moisture, creating anaerobic conditions and less oxygen transport; as a result, the microbes in the compost consume oxygen in the moisture, which affects the activity of the earthworms (Gurav & Pathade 2011).

Increasing the turning frequency affected the quantity of nitrogen until optimal points were reached, as shown in Figure 5(a). This is because the frequent turning of the compost results in ammonia loss and subsequent low values of nitrogen. Therefore, as seen from the interactive effects of process factors, there exists a strong relationship between the process parameters and responses. Hence, optimization of the study was essential to produce good quality vermicompost.

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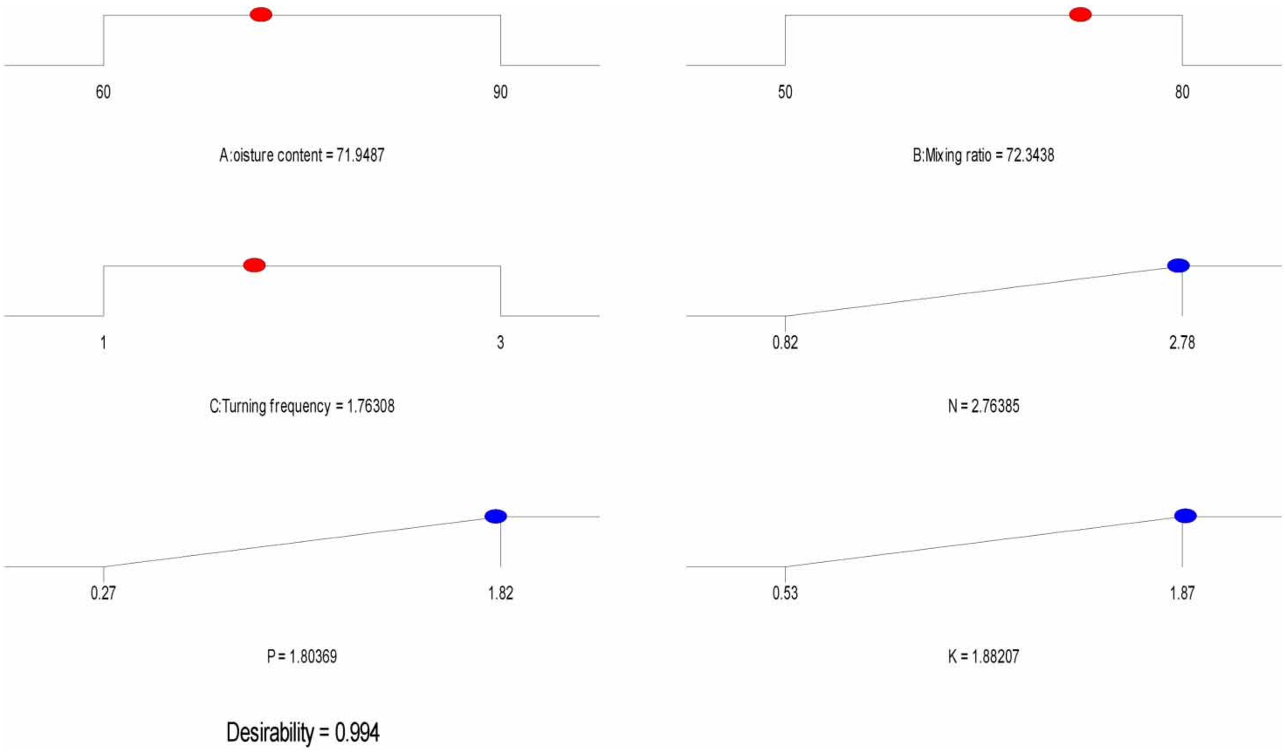

Figure 6 | Ramp plot of the optimization solution for the responses.

3.4.2. Process optimization of the vermicomposting process

As seen in the ramp plot in Figure 6, the ideal conditions for obtaining the maximum yield of nitrogen, phosphorus, and potassium from the vermicomposting operating conditions were a moisture content of 72%, a mixing ratio of up to 72.34 wt.%, and a turning frequency of 2 per week. These conditions would result in maximum nitrogen of 2.76%, phosphorus of 1.80%, and potassium of 1.88%.

4. CONCLUSIONS

The results of the present study indicated that vermicomposting is among the most natural and effective options for recycling organic wastes, including municipal sewage sludge. The sludge characterization study revealed that proper end-use and disposal options are necessary to minimize public health and environmental concerns. On the other hand, the organic matter and proximate analysis of the sewage sludge indicated the potential for exploring resource recovery for agricultural applications. Indeed, vermicomposting can be considered in the sustainable management of municipal sewage sludge and its blend with other biomasses, especially under optimized conditions. In fact, the management of municipal sewage sludge using the vermicomposting technique may have limitations, especially if huge volumes of wastewater are treated per day. However, this technique is viable to most developing countries that cannot afford the enormous costs of other sludge treatment or stabilization alternatives. Hence, future research on vermicomposting should focus on large-scale trials and conduct a techno-economic assessment to better understand whether this simple ecological approach to managing sewage sludge could be feasible at full-scale conditions or not. Future research should also concentrate on determining the representativeness of the sludge produced year-round for effective end-use and disposal options as there is little information on the characterization of municipal sewage sludge in developing countries. The findings of this study are based on samples taken at a specific time during the sampling period.

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AUTHOR CONTRIBUTIONS

All authors contributed to the study's conception and design.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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