

## THE PHYSICO-CHEMICAL PROPERTIES OF SEWAGE SLUDGE PROCESSED FOR AGRICULTURAL USE FROM THE NYERI-KANGEMI WASTEWATER TREATMENT PLANT, NYERI COUNTY, KENYA

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### Abstract

This study was conducted to assess the physico-chemical properties and changes that occur in the composting process between raw sewage sludge inflow at the sludge tank and the composted end product in the dry beds used for agricultural application at the Nyeri-Kangemi wastewater treatment plant in Nyeri County, Kenya. Sludge samples were collected between June and October in different stages of the sludge treatment process; the sludge tank received from the primary and secondary wastewater treatment processes and the composted sludge from the dry beds. Results showed the final composted dry sludge had a pH ranging from 5.53 to 6.52. The mean values were; EC was  $3.77 \pm 0.05$  mS/cm, TOC of  $2.03 \pm 0.05$  per cent, ON of  $0.19 \pm 0.01$  per cent, TOP  $88 \pm 1.6$  mg/L, Temperature  $21.03 \pm 0.06$  °C, particle density of  $2.30 \pm 0.02$  g/cm<sup>3</sup>, Bulk density of  $0.24 \pm 0.02$  g/cm<sup>3</sup>,  $90.7 \pm 0.01$  per cent pore space, moisture content of  $11.3 \pm 0.70$  per cent, TS of  $53.40 \pm 8.82$  per cent and VS of  $29.79 \pm 9.94$  per cent. The concentrations of Fe, Ca, Mg, Mn, K, Na, Zn and Cu were  $1896.15 \pm 106.2$  mg/l,  $266.42 \pm 27.55$  mg/l,  $190.52 \pm 4.82$  mg/l,  $139.3 \pm 0.29$  mg/l,  $114.38 \pm 4.81$  mg/l,  $84.61 \pm 0.71$  mg/l,  $39.18 \pm 0.36$  mg/l and  $5.65 \pm 0.12$  mg/l respectively. This study recommends the need to do more research on how to improve and stabilise the physico-chemical parameters in the sludge treatment before agricultural use.

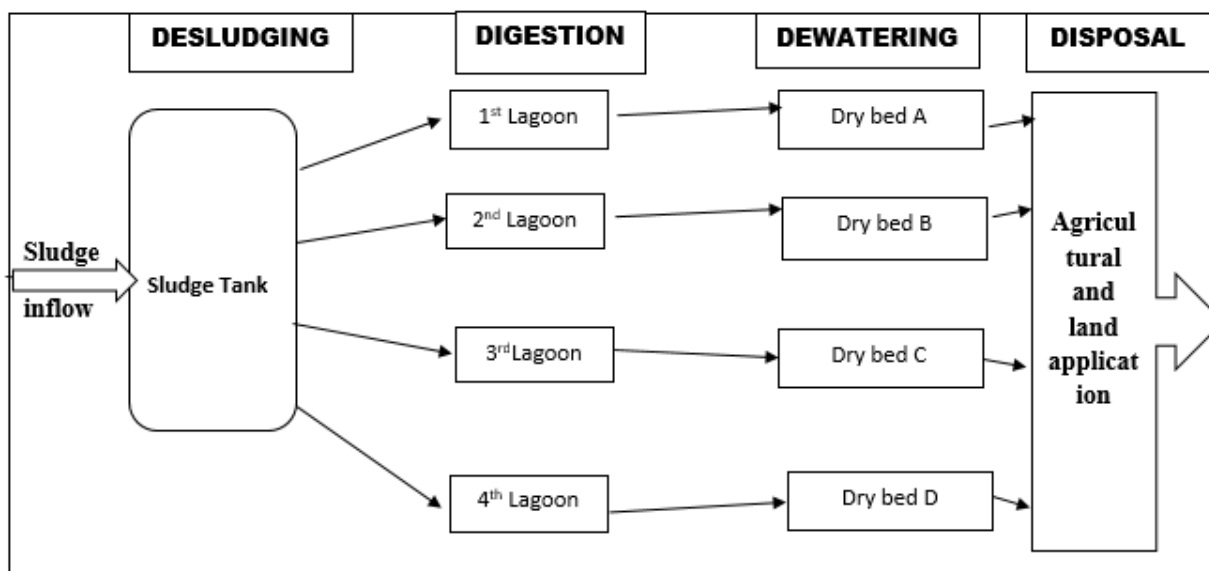
**Key terms:** Composted, particle size, sewage sludge, sludge density, total organic carbon.

## 1.0 INTRODUCTION

The physico-chemical and biological characteristics of sewage sludge depend on the wastewater's origin (Kominko et al., 2018). Usually, sewage of domestic origin (such as municipal wastewater) is rich in organic matter (OM); nutrients such as nitrogen, phosphorous, and calcium. The organic matter and mineral components may improve soil physicochemical properties such as porosity, density, and water retention properties (Camargo et al., 2016). Sludge can be the accumulated solids, semi-solids, or slurry residue produced as an end-product of wastewater treatment processes (Zhen et al., 2017). Sludge may be composed and mixed with other organic matter for use in agriculture to increase production and as a conditioner to improve soil properties (Laura et al., 2020). The Nyeri-Kangemi wastewater treatment plant is one of the well-managed treatment plants in Kenya and is very effective in the wastewater treatment process (Kariunga et al., 2018). The plant has treatment processes designed with trickling filters, sedimentation tanks, anaerobic lagoons, and maturation ponds.

## 2.0 LITERATURE REVIEW

The sludge treatment process (fig.1) consists of the desludging chamber. This tank separates the sludge and the liquid components through hydraulic pressure allowing the sludge to dislodge every 3 hours. The raw sludge from the different desludging chambers in the wastewater treatment process is then pumped into the sludge tank, where sludge is allowed to settle before it is pumped to the sludge lagoons.



**Figure 1: Sludge Treatment Process at Nyeri-Kangemi Wastewater Treatment Plant**

The sludge lagoons are simply digestion tanks where anaerobic digestion takes place for a period of three to four months. Vegetation and scum are allowed to accumulate over time as part of the biological treatment process of sludge and later on are removed. The treated sludge then flows through underground pipes that distribute it into the drying beds by gravity. The dry beds are fitted with concrete slabs with spacing between them that allow the water from the dewatering process to infiltrate the water recycling pipes underground. The sludge is then allowed to dry for a month during the wet season and fourteen days during the dry season before being sold to farmers for agricultural application at five (5)

USD per tonne. The plant produces between 75 and 250 tonnes of composted sludge per month. The sludge sold leads to a gross profit of around 332 USD to 1107 USD per month (NYEWASCO, 2007).

Studies of the physicochemical characteristics of sewage sludge are seldom in Kenya. Yet, choosing the appropriate sewage sludge disposal method depends on precise region-based data on the physicochemical properties that are usually unavailable in literature (Gudda et al., 2017). No publications or documentation exist on the physico-chemical properties of sewage sludge at this sewage treatment plant. However, this study was carried out to determine the physicochemical properties of sludge processed for agricultural and landfill applications at the Nyeri-Kangemi wastewater treatment plant.

### 3.0 METHODS

The study site for this research was Nyeri-Kangemi wastewater treatment plant. Sludge samples were collected in triplicates from the raw sludge tank and the dry beds containing composted dried sludge. The sludge treatment process has one sludge tank, four sludge digestion lagoons, and sixteen dry beds. The samples from the sludge tank and dry beds used the zigzag method, whereby samples were taken randomly following the zigzag pattern in the sampling area. 2.5L of the raw sludge was collected from the six points on the zigzag pattern and mixed in a separate bucket to obtain three composites of 5L each. The samples in the dry beds were collected from the three dry beds with fully composted sludge ready for disposal. The samples were collected from each dry bed in the zigzag pattern and mixed in a separate bucket to make one composite sample. The collected samples were transported to Egerton University soil science laboratory, where it was air-dried for 45 to 60 days using solar radiation. The dried samples were crushed and mixed together to ensure homogeneity of the sludge before being sieved through a 2 mm steel sieve, mixed again, kept in plastic bags and stored at 4°C for further processing. The means of the physico-chemical parameters were analysed using the Shapiro-Wilk normality test, and all data which passed the normality test were subjected to a two-sample t-test. Those that failed the normality test were subjected to two samples Mann-Whitney U tests. This was done to compare and find out if there was a significant difference between lagoon 1 and lagoon 2. The significance level was set at  $\alpha=0.05$ . This was analysed using R vegan, statistical analysis software. The data for Total solids (TS), sludge bulk density, particle density, pH, electrical conductivity (EC), and total organic phosphorus (TOP) passed the Shapiro-Wilk normality test and were subjected to a t-test. On the other hand, the data for volatile solids (VS), temperature, total organic carbon (TOC), total organic nitrogen (ON), porosity, sludge moisture content, sludge texture, Calcium (Ca), Sodium (Na), Potassium (K), Magnesium (Mg), Manganese (Mn), Zinc (Zn), Iron (Fe) and Copper (Cu) failed the normality test and was subjected to non-parametric Mann-Whitney U test (Table 1).

### 4.0 RESULTS AND DISCUSSION

This section describes the data for the physico-chemical parameters obtained from sludge tank samples and the dry bed samples. The values were compared with standards described in the Environmental Management and Co-ordination Act (2012) on permissible limits of sludge into the environment. Statistical test results for the data are presented in Table 1.

**Table 1: Statistical Analyses for the Physico-chemical Parameters Comparing the Raw and the Dry Beds Sludge**

No	Parameters	Shapiro-Wilk normality	Mann-Whitney U test	T-test
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	<b>test</b>	<b>(p=0.05)</b>	<b>(P=0.05)</b>	
1	Bulk density	passed	N/A	0.004615*
2	total carbon	failed	0.0722	N/A
3	EC	passed	N/A	0.0002**
4	MOISTURE	passed	N/A	1
5	particle density	passed	N/A	0.6164
6	PH	passed	N/A	0.000222
7	POROSITY	failed	0.0722	N/A
8	Temperature	failed	0.07652	0.9997
9	Total Nitrogen	failed	0.184	N/A
10	Texture	failed	0.6193	N/A
11	Total phosphorous	passed	N/A	0.9653
12	Total solids	passed	N/A	0.05197*
13	Volatile solids	failed	0.1	N/A
14	Calcium	failed	0.33333	N/A
15	Copper	failed	0.7366	N/A
16	Iron	failed	0.9997	N/A
17	potassium	failed	0.9506	N/A
18	magnesium	failed	0.2593	N/A
19	sodium	failed	0.2343	N/A
20	phosphorous	failed	0.1678	N/A
21	zinc	failed	0.0733	N/A
22	manganese	failed	0.0986	N/A

**Table 2: Physical Properties of Sludge Samples from Sludge Well and Dried Sludge Samples in Dry Beds at the Nyeri-Kangemi Wastewater Treatment Plant.**

SITES	Temperature (°C)	bulk density (g/cm <sup>3</sup> )	Particle density (g/cm <sup>3</sup> )	Porosity (%)	Total solids (%)	Volatile solids (%)	Moisture (%)
Sludge Tank	23.13 ± 0.15	0.14 ± 0.03	2.33 ± 0.15	94.4 ± 0.01	12.66 ± 0.48	11.22 ± 0.09	77 ± 1.00
Dry Bed	21.03 ± 0.06	0.24 ± 0.02	2.30 ± 0.02	90.7 ± 0.01	53.40 ± 8.82	29.79 ± 9.94	11.3 ± 0.70

Table 2 summarises the selected physical properties of both raw sludge in the sludge tank/well and the by-product, which is dried sludge found in the dry bed. The raw sludge had a significantly higher temperature ( $P = 0.9997$ ) of  $23.13 \pm 0.15$  °C compared to the dried sludge at  $21.03 \pm 0.06$  °C. The bulk density increased through the treatment process from  $0.14 \pm 0.03$  g/cm<sup>3</sup> in the raw sewage to  $0.24 \pm 0.02$  g/cm<sup>3</sup>. There was no significant difference ( $P=0.0046$ ) in the bulk density in the two sites. The particle density slightly decreased ( $P=0.6164$ ) from  $2.33 \pm 0.15$  g/cm<sup>3</sup> to  $2.30 \pm 0.02$  g/cm<sup>3</sup> in the dried one. The raw sludge had a total pore space of  $94.4 \pm 0.01$  per cent and significantly decreased to  $90.7 \pm 0.01$  per cent in the dry beds ( $P=0.0722$ ); nevertheless, the moisture content in the raw sludge was  $77 \pm 1.00$  per cent. The Total solids and the volatiles solids increased from  $12.66 \pm 0.48$  per cent to  $53.40 \pm 8.82$  per cent and  $11.22 \pm 0.09$  per cent to  $29.79 \pm 9.94$  per cent, respectively. The Mann-Whitney test showed that the volatile solids were significantly different in the raw sludge compared to the dry composted sludge as shown in table 1.

**Table 3: Selected Chemical Characteristics of Raw Sludge Samples**

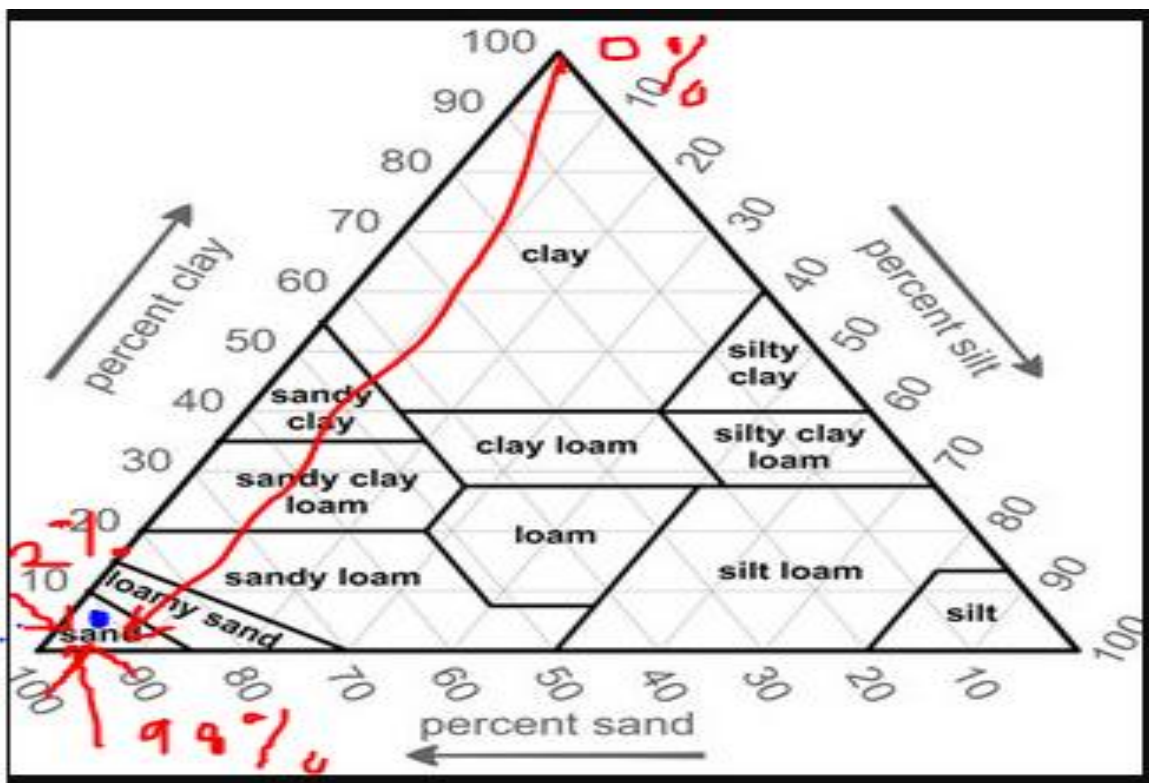
PARAMETERS	PH	EC (mS/cm)	Total Carbon (%)	Total Organic Matter (%)	Total Nitrogen (%)	Total phosphorus (mg/l)
Sludge Tank	5.53 - 5.72	4.03 ± 0.05	2.47 ± 0.05	4.27 ± 0.05	0.20 ± 0.01	91.67 ± 1.25
Dry Bed	6.52 - 6.79	3.77 ± 0.05	2.03 ± 0.05	3.42 ± 0.05	0.19 ± 0.01	88 ± 1.63

Table 3 shows that the pH ranged from 5.53 to 6.52 from sludge digester tanks to dry sludge beds. The electrical conductivity recorded was  $4.03 \pm 0.05$  mS/cm in the raw sludge and dropped slightly to  $3.77 \pm 0.05$  mS/cm. The total organic carbon significantly decreased from  $2.47 \pm 0.05$  per cent to  $2.03 \pm 0.05$  per cent, while the total organic matter was  $4.27 \pm 0.05$  per cent in the sludge tank and  $3.42 \pm 0.05$  per cent in the dried sludge. The total organic nitrogen was significantly low at  $0.20 \pm 0.01$  per cent in the sludge tank and  $0.19 \pm 0.01$  per cent in the dry bed. The total organic phosphorus was  $91.67 \pm 1.25$  mg/l in the well and  $88 \pm 1.63$  mg/l in the dry beds. All these parameters recorded a significant difference between raw and dry sludge except for electrical conductivity and pH.

**Table 4: The Raw and Dried Sludge Texture in the Sludge Tank and Dry Bed Samples**

SAMPLE	Texture (g/L)	Temp (°C)	Sand (%)	Clay (%)	Silt (%)	Textual Class
SLUDGE WELL	$1.33 \pm 0.47?$	20	98	2	0	Sandy
DRYBED	$1.67 \pm 0.47$	20	98	2	0	Sandy

The raw sludge texture was  $1.33 \pm 0.47$  g/l at a 20 °C hygrometer reading with 98 per cent sand, 2 per cent clay, and 0 per cent silt. A comparison from the textural triangle diagram shows that the raw sludge is in the sandy soil textural class. The soil textural classification was also sandy, with a hygrometer reading of  $1.67 \pm 0.47$  g/L at 20°C as shown in table 2 above.



**Figure 4: The Textual Triangle Diagram for the Classification of Sludge.**

**Table 5: Metal Concentrations of Raw Sludge Samples from Sludge Well and Dried Sludge Samples in Dry Beds at the Nyeri-Kangemi Wastewater Treatment Plant**

Metals	P (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	Fe (mg/L)	Cu (mg/L)	Zn (mg/L)	Mn (mg/L)
Sludge Tank	10 ± 1.25	21.96 ± 0.04	48.59 ± 0.62	16.58 ± 0.06	21.96 ± 0.04	1.645 ± 0.28	0.035 ± 0.03	0.04 ± 0.01	0.475 ± 0.09
Dry Beds	800 ± 38.85	114.38 ± 4.81	266.42 ± 27.55	190.52 ± 4.82	84.61 ± 0.71	1896.175 ± 106.20	5.645 ± 0.12	39.175 ± 0.36	139.3 ± 0.29

Table 5 sums up the metal concentrations in both the sludge tank sample and the dry beds. Calcium recorded the highest concentration of  $48.59 \pm 0.62$  mg/l in the sludge tank, followed by Potassium and Sodium at  $21.96 \pm 0.04$  mg/l and  $21.96 \pm 0.04$  mg/l, respectively. Copper and Zinc had the lowest concentrations of  $0.04 \pm 0.03$  mg/l and  $0.04 \pm 0.01$  mg/l. In the dry bed samples, the metals iron, copper, zinc and manganese increased significantly, with the highest concentration recorded in iron at  $1896.18 \pm 106.20$  mg/l, while the lowest concentration recorded was copper with a concentration of  $5.65 \pm 0.12$  mg/l. All the above-selected metals recorded a significant difference in the raw sludge compared to the dry beds.

**Table 6: Standards for Sludge Discharge into the Environment the Environmental Management and Co-Ordination Act (2012)**

Parameters	PH	Suspended solids (mg/L)	Temp °C	Zn (mg/l)	Fe (mg/l)	Cu (mg/l)	Total P (mg/l)	Total N (%)	Mn (mg/l)
Permissible limits	6.5-8.5	100	30	200	1	80	2	2-5	10

Table 6 presents some of the standards for sludge discharge into the environment according to the Kenyan law under the Environmental Management Co-ordination-Act 2012 revised edition.

### Physical Properties of Raw Sludge Samples from Sludge at the Nyeri-Kangemi Wastewater Treatment Plant

The raw sewage contained a significantly higher temperature ( $23.13 \pm 0.15^\circ\text{C}$ ) compared to the dried product sludge used as fertiliser ( $21.03 \pm 0.06^\circ\text{C}$ ). The relatively higher temperatures of the liquid raw sludge received at the sludge tank may be due to exothermic digestion processes in the digestion tanks where microorganisms present actively metabolise the available organic matter, releasing heat in the process (Sweeten, 2008). Dubey et al. (2021) report that sorption of some emerging contaminants (EC) such as 17- $\alpha$ ethinylestradiol (EE2) in activated sewage sludge is an exothermic process through both physisorption and chemisorption. This suggests that the sorption mechanism of substrates and ECs in the liquid raw sludge may be the reason for the higher temperatures of the liquid sludge. Nevertheless, the temperature was within the standard limit for sludge discharge and agricultural use.

The particle density recorded in the sludge tank and in the dry bed was about ten (10) times more than the bulk density recorded in the raw sewage (figure 2). The lower bulk density values could be attributed to water vapour, void volume and some gases that significantly lower the density in the sludge tank (EI-

Nahhal et al., 2014). Kelly (2005) recorded similar values when investigating the specific gravity of solids in digested sludge material, where the bulk density ranged between  $1.55 \text{ g/cm}^3$  and  $1.72 \text{ g/cm}^3$ . The density of the investigated sludge suggested that the samples contained very high fractions of solid materials, and the mechanical analysis of sludge texture suggested the solid materials were mainly sand (Figure 2).

The sandy nature indicates a high porosity of the sludge. This is similar to values reported by Ruan and Liu (2013), who found a high porosity (78%) in the structure of activated sludge. They attributed this to the fact that sludge may be comprised of different layers with different sizes, spaces, and pores that enabled a higher void volume.

The moisture content in the dry bed was low due to the loss of water through the dewatering processes of evaporation into the atmosphere and infiltration through the space between the concrete slabs on the floor of the dry beds. These results are similar to those of Al-Malack et al. (2008) in their investigation of the physico-chemical characteristics of municipal sludge produced in three major cities in the eastern province of Saudi Arabia. They found that the initial moisture content of sludge for the wastewater treatment plants was in the range of 95 - 97 per cent and 13 - 45 per cent for the dried sludge samples.

The Total solids (TS) and the volatiles solids (VS) significantly increased in the sludge tank and the dry bed, respectively ( $12.66 \pm 0.48\%$  to  $53.40 \pm 8.82\%$  and  $11.22 \pm 0.09\%$  to  $29.79 \pm 9.94\%$ ). This increase in the values of TS and VS after dewatering agrees with a study by Douglas et al. (2021), where there was a significant increase of TS of sludge samples from pit latrine during the dry season. In addition, al-Malack et al. (2008) also recorded an increase in the VS from 51, 51 and 53 per cent to 65, 62 and 66 per cent at the sludge tank, lagoons and dry beds respectively. This can be attributed to infiltration evaporation, weathering effects and biodegradation activities that help in the dewatering processes and therefore increase the concentration of the remaining solids in sludge (Doglas et al., 2021).

## **The Chemical Properties of Raw Sludge from Sludge well and Dried Sludge in Dry Beds**

The pH of both the raw and dried sludge shifted towards neutrality, which was within the range of 5.5 to 9.5 recommended for agricultural land application (Badza et al., 2020). This change in pH may be attributed to evaporation and weathering effects in the dry beds, which increase the ion concentration in the sludge (Sweeten, 2008). The relatively low pH value in the sludge tank can be attributed to nitrate formation, leading to hydrogen ions being released during the nitrification process (Cáceres et al., 2018). Nevertheless, it is vital noting that even though the nitrate component was not analysed in this study, generally, the nitrification process causes the oxidation of ammonia to nitrates, which lowers the pH of the raw sludge in the sludge tank (Bozym & Siemiatkowski, 2018).

Sludge from both the sludge tank and the dry beds had high electrical conductivity (EC), indicating high concentrations of organic and inorganic ions in the sludge and, therefore, high salinity (Suanon et al., 2016). This high EC, therefore, indicates that the sludge is not ideal for application to all agricultural crops. In other studies, it was established that EC values of 2.5 - 3.0 mS/cm are harmful to fruit crops (Khadra et al., 2019), and EC values of 4.5 - 5 mS/cm are harmful to stem crops as they lower their germination rates and causes plant withering (Suanon et al., 2016). The total organic carbon exhibited high values, which could be attributed to the fact that the total organic matter was significantly low ( $4.27 \pm 0.05\%$  in the sludge well and  $3.42 \pm 0.05\%$  in the dried sludge). Sewage sludge is considered a rich source of organic matter and is therefore considered a good soil conditioner (Badza et al., 2020). Nevertheless, this is mostly true for

sludge with an organic matter content of above 50 per cent. The organic matter content of the investigated sludge was less than 5 per cent, indicating that it is not very good for use as a soil ameliorant (Badza et al., 2020).

According to Srinivasarao et al. (2015), the phosphorous level in the sludge between 0 - 20 mg/l is considered a phosphorus deficiency; 20 – 80 mg/l phosphorus is sufficient, and above 80 mg/l is a high phosphorus level. The sludge from Kangemi WWTP exhibited very high levels of total organic phosphorus ( $91.67 \pm 1.25$  mg/l in the sludge well and  $88 \pm 1.63$  mg/l in the dry bed). On the other hand, the total organic nitrogen level was significantly low and showed very little variation between the sludge tank and the dry bed. These low values of total organic nitrogen may be due to the degradation of organic components in the anaerobic digestion process (Singh et al., 2017). These results are similar to those of Badza et al., 2020 who investigated the characteristics of sludges of anaerobic and aerobic digesters and found 1.4 per cent and 4.1 per cent total organic nitrogen, respectively, which suggested that the sludge was well nitrified.

### Plant Essential Metal Concentrations of the Sludge Samples

The concentration of these essential metals in the sludge tank followed the following order from the highest to the lowest;  $Ca > Na > K > Mg > Fe > Mn > Zn > Cu$ , while in the dry bed samples, it was;  $Fe > Ca > Mg > Mn > K > Na > Zn > Cu$  which is similar to results reported by Jodral-Segado et al., (2006). The high calcium concentration in the sludge was attributed to lower pH levels in the sludge. Sodium, Potassium, Magnesium and Iron recorded in the dry sludge samples are readily available in sludge as exchangeable ions, and therefore the lower acidity recorded in this study means only a few hydrogen ions are available, allowing more of the metal ions to occupy the remaining exchange sites in sludge (Segado et al., 2006; Chimdi et al., 2012 ). The low concentrations of Zn and Cu recorded in both the sludge tank and the dry beds samples may be due to high levels of carbonates in the sludge (Santos et al., 2010). There were high levels of metal concentration in the dry bed samples compared to the sludge tank samples. Barraoui et al. (2021) recorded a similar trend and explained that this was possibly due to the anaerobic digestion process between the two sites leading to more than 10-fold increases in the concentration. Shrivastava et al. (1998) and Ajeej et al. (2015) reported similar increases in the metal concentrations in the dry sludge. Iron, manganese and total phosphorous in the dry sludge exceeded the standard limits set for discharge into the environment.

## 5.0 CONCLUSIONS AND RECOMMENDATIONS

**Conclusions:** This study investigated the sludge from the inlet, the concentration point in the sludge tank and at the end of the process in the dry bed where sludge is collected for agricultural application. This was to determine the physico-chemical characteristics of the sludge processed at the Nyeri wastewater and treatment plant in Kangemi, Nyeri County. The investigation showed that the sewage sludge produced is slightly acidic and has high salinity making it unsuitable for agricultural application in some crops. In addition, the organic matter was relatively low, and therefore the sludge is not a good soil ameliorant. On the other hand, the sludge contained a high fraction of solid materials and, therefore, a high porosity which makes it good for irrigated agricultural land due to its high water holding capacity. Furthermore, the metal concentrations significantly increased in the dry bed sludge. Generally, the land application of the sludge from the Kangemi WWTP may lead to secondary pollution of iron, manganese and phosphorus elements in the environment and, therefore, negative impact on the receiving water bodies and their associated organisms.

**Recommendations:** Based on this study's findings, there is a need to do more research on how to improve and stabilise the physico-chemical parameters in the sludge treatment before agricultural use. In addition, more research should be done to investigate the suitability of the sludge as a substrate for different agricultural crops grown in the region around Nyeri County.

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