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PHYSICOCHEMICAL EVALUATION OF SLUDGE FROM A WASTEWATER TREATMENT PLANT FOR ITS POTENTIAL APPLICATION AS A NON-CHEMICAL FERTILIZER

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Abstract: *Sewage sludge disposal poses environmental concerns, yet its organic matter, macro- and micronutrients, make it potentially beneficial for enhancing soil quality and crop yield. This study focuses on developing a non-chemical fertilizer from sewage sludge sourced from a wastewater treatment plant.The sludge was modified with sawdust and plantain peels to improve nutrient balance and subsequently characterized. The evaluated properties included chemical composition, functional groups, water-holding capacity, bulk density, pH, moisture content, and organic matter. The results showed moisture content ranging from 21.8–88.3%, pH values between 6.61 and 7.20, water-holding capacity of 51.88–59.67%, bulk density of 5.8–6.1* g/cm^3*, and total organic matter content of 68.54–81.65%. Fourier Transform Infrared (FT-IR) spectroscopy confirmed the presence of alkane, alkene, alkyne, carboxylic acid, and aldehyde functional groups, indicating a complex organic matrix. Quantitative analysis revealed macronutrient contents of* P_2O_5 *(21–32%) and* K_2O *(0.470–53.1%). The identified micronutrients included ZnO (1.09–4.74%), CaO (2.79–7.57%), CuO (0.091–0.48%), MgO (0.16–2.43%), and* Fe_2O_3 *(1.14–7.36%). Heavy metal oxides were detected at trace concentrations, notably MnO (0.296–1.27%) and* TiO_2 *(0.009–1.32%). Overall, the compositional profile suggests that sewage sludge obtained from the Cross River State Water Treatment Plant is suitable for valorization as a non-chemical fertilizer.*

Key words: Sludge; Wastewater; Characterization; Modification; fertilizer

1 Introduction

Sewage sludge is known to be rich in nutrients such as nitrogen and phosphorus, organic matter, and trace elements that are beneficial for plant growth and improved crop yield. It application has been shown to significantly increase soil organic matter and macronutrient contents including nitrogen and phosphorus thereby enhancing soil fertility and reducing reliance on synthetic fertilizers (Paganini *et al.* 2024). Sewage sludge has been demonstrated to serve as a viable alternative to conventional mineral fertilizers, supplying essential nutrients and improving plant growth without adverse physiological effects, thereby potentially reducing the requirement for commercial fertilizers. Sewage sludge is also considered a suitable substitute for commercial fertilizers and the use of sewage sludge as a fertilizer decreases the requirement for commercial fertilizers (Richards *et al.,* 2018).

Sewage sludge also known as biosolids is the solid residual material produced during wastewater treatment from various sources such as domestic sewage, industrial effluent, and storm runoff. It typically contains a heterogeneous mixture of organic and inorganic matter, essential plant nutrients, trace elements, as well as potential contaminants including heavy metals and pathogenic microorganisms (Nunes *et al.* 2021). It might also contain human waste and other consumer products. Sewage sludge exists in a solid or semi-solid state. Treated sewage sludge can enrich soil with macronutrients such as phosphorus, potassium, sulfur, calcium, magnesium and micro nutrients. Integrating treated sewage sludge into organic farming practices aligns with the principles of nutrient recycling and sustainable agriculture, but its use requires overcoming several challenges associated with its safety, processing, and regulatory compliance (Balkrishna *et al.* 2025). Sewage sludge is a reliable source of nitrogen and phosphorous for plants. Nitrogen is an essential nutrient for plant growth since it is a constituent of all proteins and nucleic acids and therefore protoplasm. Normally crop yield increases with increase in the application of sewage sludge and nitrogen is often the rate limiting factor in the application of sewage sludge to agricultural lands (Stark and Clapp, 2020).

Inorganic fertilizers, especially nitrogen-based ones, often reduce soil pH and accelerate soil acidification, which can increase aluminum saturation in acidic soils; this acidifying effect is largely linked to the nitrification of ammonium in the soil. The decline in soil pH observed with frequent nitrogen fertilizer application is mainly due to the transformation of ammonium (NH_4^+) into nitrate (NO_3^-), during which hydrogen ions are released, contributing to soil acidity. In situations where sewage sludge alone may not supply the optimal nutrient balance for plant growth, it is often combined with commercial (inorganic) fertilizers to enhance overall nutrient availability, improve crop performance, and increase soil fertility more effectively than either input alone (Tkaczyk *et al.* 2020).

Sludge has been observed to improve the physico-chemical and biological properties of soils which in turn facilitates better growth of plants (Aggelides and Londra 2020). Sludge increases the humus content of the soil, the porosity, field capacity and wilting point all increase as a result of application of sewage sludge (Delibacak *et al.,* 2019). Organic matter which forms over half of the mass of sewage sludge also improves the physical condition of soils (Khaleel *et al.,* 2021). The application of sewage sludge can reduce soil bulk density, increase porosity, improve water-holding capacity and infiltration rate, while enhancing soil organic matter content and nutrient levels, thereby improving soil physical and chemical properties. However, long-term or excessive application may lead to the accumulation of heavy metals and nitrate in soil, increasing the risks of groundwater pollution and adverse impacts on human health. Additionally, there are controversies in existing studies regarding the effect of sewage sludge application on soil aggregate stability. Therefore, prior to the land application of sewage sludge, a comprehensive assessment of sludge characteristics, soil types and crop species is necessary to balance its resource utilization and environmental safety (Hu and Shan, 2025).

With the continuous growth of the global population, wastewater treatment facilities are increasingly challenged by the management of large volumes of sewage sludge generated in urban areas. Improper disposal of solid wastes such as sewage sludge and other biowastes poses serious threats to environmental quality, leading to problems including groundwater contamination and soil degradation. However, sewage sludge has considerable potential as a fertilizer and, when properly treated and managed, can be recycled as a valuable resource for sustainable soil fertility improvement. This research is aimed at evaluating the physiochemical characterization of sewage sludge from wastewater treatment plants for its potential application as a non-chemical fertilizer. The choice for modifying the sludge using plantain peels and saw dust is that plantain peels are rich in essential nutrients such as potassium, phosphorus, calcium, and organic carbon, which complement the nutrient profile of sewage sludge while sawdust increases carbon content and porosity, improving aeration and microbial activity during composting.This blending creates a more balanced fertilizer suitable for plant growth, promoting circular economy and reducing environmental pollution.

2.0 Materials and methods

2.1 Sample Collection and Preparation/Pre-treatment

The sewage sludge sample was collected from Cross River State Water Treatment Plant (CRSWBL) in a plastic bag. The sludge sample was dried on a flat wooden board during the summer season for five (5) days to reduce the moisture content and smell. Sun-drying markedly reduces moisture content, improving sludge stability and increasing the relative concentration of dry matter constituents. The dried sample was ground with a mortar and pestle, sieved to <75 µm, and stored in plastic containers at room temperature for characterization and modification.

2.2 Sewage sludge modification

The wastewater sludge was modified with varying proportions of sawdust and plantain peels to improve nutrient balance and enhance composting efficiency and stabilization. 40g of each prepared blend (except sample A) comprising wastewater sludge, sawdust, and plantain peels, mixed in the proportions presented in Table 1, were dissolved in 20 mL of deionized water and stirred continuously to achieve homogeneity. The mixtures were allowed to stand for 72 h, after which they were sun-dried to remove excess moisture. The dried samples were subsequently ground and sieved to obtain a uniform particle size for further analysis.

Table 1: Composition of modified and unmodified samples

	Modifying material (%)		
Sample	Sludge	Plantain peels	Sawdust
A	100	–	–
B	60	20	20
C	70	10	20
D	70	20	10

2.3 Characterization of modified and unmodified samples

The chemical composition and functional groups of the modified and unmodified sludge were characterized using XRF and FTIR, respectively. Additional parameters determined included pH, moisture content, water-holding capacity, and total organic matter.

2.3.1 pH of modified and unmodified samples

The pH was measured using a digital pH meter. For each sample, 0.5 g was weighed into a beaker and 40 mL of deionized water was added. The suspension was stirred with a glass rod, and the pH was recorded after 30 minutes using the pH meter.

2.3.2 Moisture content

Moisture content determination involved placing 2 g of each sample into a pre-weighed, dry crucible, followed by oven drying at 105 °C for 3 hours until a constant weight was attained. The crucible was then cooled in a desiccator and weighed, and the moisture content was calculated from the resulting weight loss using Eq. 1.

$$\%\ \text{Moisture} = \frac{w_1 - w_2}{w_1} X 100 \qquad 1$$

Where; w_1= sample weight before drying and w_2 = weight of the sample after drying.

2.3.3 Bulk density

The true density was determined using Archimedes' principle. A 1.0 g dried sample, wrapped in polyethylene film, was immersed in water, and the water level before and after immersion was recorded. The density was calculated as the ratio of the dried sample mass to the volume of water displaced

2.3.4 Total organic matter of samples

This was determined by igniting the oven dried samples at a temperature of 350 °C. The total of organic matter was determined from Eq. 2,

$$W_1 = W_2 - W_3 \qquad 2$$

Where; W_1= Total weight of organic matter, W_2 = weight of oven dried sample and W_3 = weight of ignited sample

2.3.5 Water holding capacity of samples

Holding capacity was evaluated by placing 2 g of each sample on filter paper in a measuring cylinder, adding 20 mL of deionized water, and then collecting the filtrate to measure its volume and calculate its mass using Eq. 3

$$\%\ \text{water holding capacity} = \frac{\text{mass of water}}{\text{Total mass of saturated fertilizer}} \text{ X } 100\% \qquad 3$$

2.3.6 FTIR of samples

The functional groups present in the modified and unmodified sludge samples were determined using a Fourier Transform Infrared (FT-IR) spectrometer (Varian 660 MidIR Dual MCT/DTGS Bundle with ATR). Sample tablets were prepared by mixing each sample with potassium bromide at a ratio of 1:100 (sample:KBr). Spectra were recorded over the frequency range of 4000–500 cm^{-1} with a detector resolution of 4 cm^{-1} and 200 scans per sample. The resulting FT-IR refractograms, showing the relationship between wave number and absorption, were tabulated.

2.3.7 X-ray fluorescence of samples

The chemical composition of the modified and unmodified samples was determined using energy-dispersive X-ray fluorescence (XRF; model ARL9900, Thermo Scientific, USA). The instrument operates by measuring the propagation of X-rays from the tube through the optical path to the detector. Powdered samples were placed in a waxed, gold-plated sample holder and secured on both sides with adhesive tape. The energy dispersive patterns were obtained with the help of a computer attached to the instrument and each compound recorded in percentage.

Samples were oven-dried at 105 °C to constant weight, ground to a fine powder, and sieved (<75 µm). The powders were prepared as pressed pellets using a suitable binder (or fused with lithium borate flux to form glass beads). XRF analysis was conducted using calibrated standards, and results were reported as oxide compositions in wt.% normalized to 100%.

3.0 Results and discussion

3.1 Physical Composition of modified and unmodified non-chemical fertilizer

The physical properties of the samples are shown in Table 2. Sample A had the highest moisture content (58.1%), followed by C (41.8%), D (38.3%), and B (31.5%). The high moisture levels likely reflect the elevated water content of the original sludge

Sample C exhibited the highest pH (7.4), indicating it is slightly basic, while Sample A had the lowest pH (6.6), reflecting a more acidic nature. This suggests that the sludge is generally acidic, and the addition of modifying agents increases the pH, as observed in Samples B, C, and D. The relatively low pH of Sample A may result from the high organic nitrogen content in the sludge, which can decompose into amino acids and release hydrogen ions, contributing to acidity. Overall, the pH values of all samples (6.6–7.4) fall within the acceptable range for agricultural application (Sial *et al*., 2016)

Water holding capacity is an important parameter for assessing the suitability of sludge for agricultural use. As shown in Table 2, the water-holding capacity of the samples ranged from 51.88% to 59.44%, with Sample C having the highest and Sample D the lowest. The lower retention of Sample D suggests it contains larger pores, which is significant for soil–water–plant interactions and the maintenance of soil structure. Soil organic matter also plays a central role in nutrient storage and turnover, supports a diverse soil biota, and reduces soil vulnerability to erosion through its influence on soil structure, nutrient cycling, and ecosystem functions. An increase in soil organic matter generally reduces soil bulk density, enhances soil aggregate stability, increases water holding capacity, and improves water infiltration in a wide range of soil types. Soil organic matter improves soil physical properties; organic matter increases porosity and water retention while lowering soil compaction. The application of organic materials increases soil water retention, especially in soil having lower surface tension (Jock and Ilechukwu,. 2023).

Bulk density measures the mass of dry sludge per unit volume, including the pore spaces. Bulk density influences pore size distribution, which also affects the soil's ability to hold and supply water to plants.The bulk densities of Samples A, B, C, and D were 5.8, 6.4, 6.7, and 6.1 g/cm^3, respectively. Sludge with lower bulk density generally has greater pore space, promoting better aeration, water movement, and access to nutrients for plant roots, whereas high bulk density reduces pore volume and restricts these processes(Kumar, 2025).

Total organic content refers to the proportion of organic compounds such as carbohydrates, proteins, fats, and humic substances present in sludge. It is usually expressed as a percentage of the total dry weight. Organic matter supplies essential nutrients (N, P, K, micronutrients) to crops and acts as a slow release fertilizer. The total organic content ranges between 68.54 and 81.65%. The total organic matters slightly decreases with the modification of the sludge in the order A>B>C>D. Raw sewage sludge typically contains 60–80% organic solids (volatile solids) of total solids, depending on the source and treatment processes (Veluchamy and Kalamdhad, 2017). High organic content increases soil's water-holding capacity, helping crops during dry periods.

Table 2: Physical properties of modified and unmodified samples

Sample	Moistu conten (%)	pH	Water holding capacity water/g (sample)	Bulk density (g/cm^3)	Total organic matter (
Sample	58.1	6.61	54.45	5.8	81.65
Sample	21.8	7.2	59.44	6.4	77.74
Sample	41.8	7.4	55.67	6.7	69.69
Sample	38.3	6.9	51.88	6.1	68.54

3.2 FT-IR of the modified and unmodified sludge samples

Fourier Transform Infrared (FTIR) spectroscopy was employed to identify the functional groups present in the sewage sludge samples, both unmodified and modified with plantain peels and sawdust. The spectra provided insight into the chemical composition and potential nutrient availability of the samples for use as a non-chemical fertilizer. The FTIR spectra revealed absorption bands in the wavenumber range of 4000–400 cm⁻¹, indicating the presence of various organic and inorganic functional groups.The FT-IR spectra of the samples are presented in Figures 1–4, while the corresponding functional groups are summarized in Table 4.

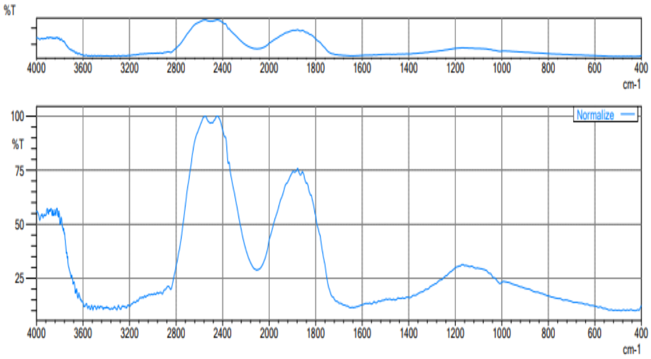

Figure 1: FT-IR Spectrum for sample A

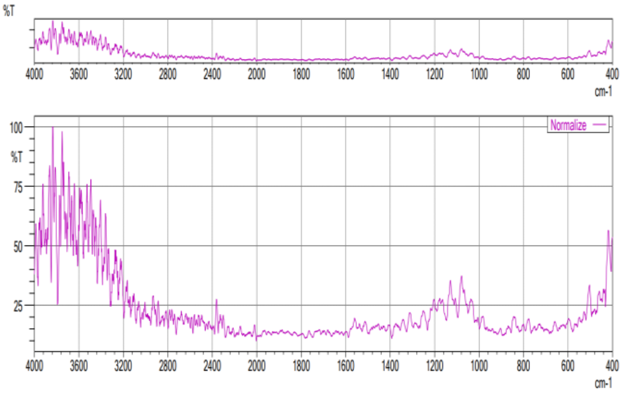

Figure 2: Spectrum for sample B

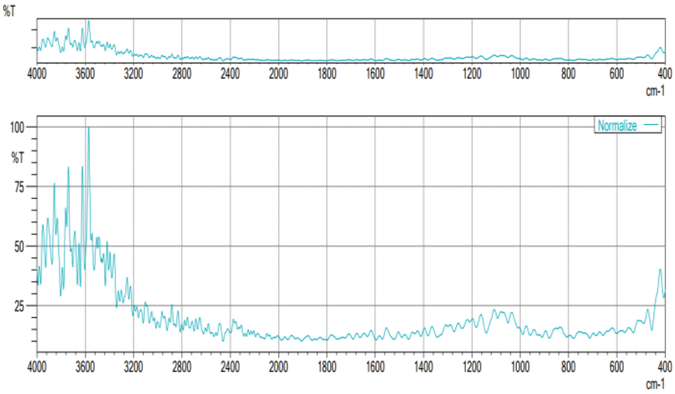

Figure 3: FT-IR Spectrum for sample C

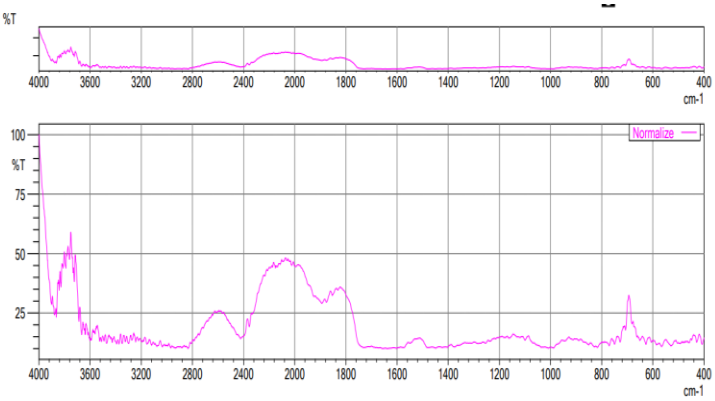

Figure 4: FT-IR Spectrum for sample D

O–H and N–H Stretching within the region of 3600 cm^{-1} to 3400 cm^{-1} were observed in sample A. The broad peaks in this region suggest the presence of hydroxyl and amine groups, which are indicative of moisture content, proteins, and other nitrogenous compounds in the sludge. The C–H Stretching at 2890 cm⁻¹ corresponds to aliphatic C–H stretching vibrations from organic matter. The presence of these groups suggests that the sludge retains significant organic content, which is crucial for slow-release nutrient availability in soils (Parolo *et al*. 2017)

Table 3: Vibrational Frequencies and Assignments of Samples

Sample	Broad band (cm^{-1})	Functional Group
A	3600	O–H
	3400	N–H
	2890	C–H
	2631	C–C
B	3767	O–H
	3421	N-H
	3040	C–H
	2386	C–C
	2135	COO^-
	1584	C=O
C	3817	O–H
	3590	N-H
	2942	C–H
	1796	C=O
	1421	$C\text{-}H_2$
D	3780	O–H
	2915	C–H
	2415	C–C
	1887	C=O
	1336	O–H
		C–O

The peaks in the regions of 2135 and 1584 cm^{-1} in sambple B represent carbonyl and carboxylate groups from proteins, amino acids, and organic acids. The modified samples show increased peak intensity, suggesting that the addition of plantain peels and sawdust enhances organic functionalization and this can improve the bioavailability of nutrients when applied as a fertilizer (Sukamto and Rahmat, 2023).

The band in sample C at 1796 cm^{-1} is attributed to C=O stretching of carbonyl groups (esters/anhydrides) in lignocellulosic materials (Kostryukov *et al.* 2023), while the peak around 1421 cm^{-1} corresponds to symmetric stretching of carboxylate ($-COO^-$) groups and/or CH_2 bending vibrations (Gulec *et al.* 2024), indicating the involvement of oxygen-containing functional groups in adsorption processes.

The band observed at 1336 cm^{-1} in sample D (Table 4) may be attributed to O–H bending and C–O stretching vibrations of phenolic groups, characteristic of lignin structures present in the plantain peel and sawdust. Contributions from C–N stretching of amine groups in the sludge matrix may also be present (Pandey, 1999).

The FTIR analysis confirms that modification with plantain peels and sawdust increases the density and diversity of functional groups in sewage sludge. Enhanced hydroxyl, carboxyl, and polysaccharide groups improve water retention, nutrient availability, and microbial activity, all of which are essential properties for a non-chemical fertilizer (Rahman *et al.* 2020). Generally, the spectra (Figures 1–4) and functional group assignments (Table 4) together demonstrate that the modification process successfully enriches the sludge, making it suitable for agricultural applications as a slow-release, environmentally friendly fertilizer. However, when plantain peels and sawdust were added, resulted in some original sludge peaks appear weaker or disappear, they were masked or diluted, not gone chemically. Because these materials are rich in cellulose, hemicellulose, and lignin. Their peaks (especially broad O–H and C–O bands) can overlap with or dominate the sludge peaks (Li *et. al.* 2026). Similarly,sawdust has a porous, fibrous structure. Therefore organic compounds from sludge can adsorb onto cellulose/lignin surfaces. This changes the local chemical environment of those functional groups and will lead to FTIR peaks may decrease in intensity or shift because the bonds are now in a different environment (Narkesabad *et. al.*, 2023).

3.3 Chemical composition of samples

The chemical compositions of the samples are summarized in Table 4. XRF analysis revealed the presence of P_2O_5 (1.02–22.34%) and K_2O (6.59–37.82%) in the samples. The lowest concentration of K_2O was observed in Sample C, while the highest concentration was recorded in Sample D. Similarly, Sample C exhibited the lowest P_2O_5 content (1.02%), whereas Sample B showed the highest concentration (22.34%). Potassium enhances disease resistance and improves plant tolerance to drought, salinity, and cold, while phosphorus promotes flowering, seed development, and fruiting (Ortel *et al.,* 2024).

Moderate amounts of micronutrients, including ZnO (1.09–4.74%), CaO (2.79–7.57%), CuO (0.091–0.48%), MgO (0.16–2.43%), and Fe_2O_3 (1.14–7.36%), were also detected in the samples (Table 4). These elements are essential for healthy plant growth and development. Heavy metal oxides such as MnO (0.296–1.27%), TiO_2 (0.009–1.32%), and NiO (0.01–8.00%) were present in trace amounts; however, high concentrations of these metals can adversely affect crop growth (Jock *et al.*, 2022). A high chlorine content (16.26%) was detected in the sludge, which is attributed to the addition of chlorine as a disinfectant during water treatment.

Sample A (100% sludge) do not contain this element because Rhodium is not a common constituent of wastewater sludge. In many wastewater treatment plants, the baseline concentration of rhodium is effectively zero or below detection limits. Analytical limits and matrix effects can easily lead to “not detected” results as may be the case in sample D.

Table 4: XRF analysis of samples

Elements	Samples (wt.%)			
	A	B	C	D
SiO_2	2.6597	4.971	2.531	2.844
V_2O_5	0.229	0.246	0.017	0.023
Cr_2O_3	0.049	0.084	0.043	0.02
MnO	-	1.272	0.341	0.296
Fe_2O_3	7.3629	5.035	2.482	1.141
CO_3O_4	0.084	0.131	0.033	2.009
NiO	0.01	7.026	5.002	8.006
CuO	0.091	0.325	0.362	0.479
Nb_2O_3	0.028	0.024	0.068	0.023
P_2O_5	12.18	22.341	1.015	20.575
SO_3	5.437	6.132	0.553	3.029
CaO	-	2.793	6.2613	7.571
MgO	0.321	1.683	2.433	0.1602
K_2O	12.652	10.218	6.589	37.818
Al_2O_3	1.215	2.722	1.575	1.157
Ta_2O_5	0.024	0.067	-	0.055
TiO_2	-	0.659	0.0091	1.324
ZnO	-	4.736	1.093	2.031
Cl	16.265	11	7.929	6.048
ZrO_2	0.207	0.2	0.017	0.005
Ru_2O	-	0.84	2.783	-
Na_2O	8.004	18.34	27.96	27.413
Rh_2O_3	-	15.137	37.238	-

3.4 Comparison of nutrient content of sewage sludge with conventional fertilizers

The comparison of nutrients contents of different sewage sludge with conventional and standard fertilizer is presented in Table 5. For standard fertilizer contents, these are approximate typical value, exact values vary by formulation. The P_2O_5 content of 10–20% in a standard fertilizer (Table 5) is common in NPK blends like 10:10:10. The nutrient content observed in the present study was higher than that reported in previous studies. This difference may be attributed to the source of the sewage sludge and the modifying agents used in this work.

Table 5: Nutrient content of various sewage sludge with conventional fertilizer

Nutrient	Sewage sludge (%)	Conventional fertilizer (%)	Reference
Nitrogen (N)	1.5 - 4.0	10 - 30	EPA (2021)
Phosphorus (P)	0.5 - 2.0	5 - 15	Cardenas-Talero *et al.* (2022)
Potassium (K)	0.5 - 2.5	5- 10	Orner *et al.* (2022)
Calcium (Ca)	1.0 - 5.0	1 - 5	Ghosh *et al.* (2024)
Iron (Fe)	0.1- 0.5	0.05 - 0.5	Kumar *et al.* (2017)
Zinc (Zn)	0.02- 0.1	0.01 - 0.1	Cárdenas-Talero *et al.* (2022)
Copper (Cu)	0.01- 0.05	0.01 - 0.1	Zhang *et al.* (2016)
Manganese (Mn)	0.01 - 0.1	0.01- 0.05	Orner *et al.* (2022)
P_2O_5	1.02-22.3	10–20*	Present study
K_2O	6.6-37.8	10–20*	
ZnO	1.09–4.74	0.5–2*	
CaO	2.79–7.57	10–25*	
Fe_2O_3	1.14–7.36	5–15*	

*Standard fertilizer contents

Conclusion

A physicochemical evaluation was conducted on wastewater treatment plant sludge modified with sawdust and banana peels. The resulting modified products contain essential macronutrients and micronutrients required for plant growth and development. The pH, water-holding capacity, and total organic content fall within acceptable limits. FTIR analysis revealed a diverse range of functional groups in the sewage sludge. Based on these characteristics, the modified products show strong potential for use as effective non-chemical fertilizers.

Conflict of interests

The authors hereby declare and confirm that there are no competing interests associated with the publication of this paper.

REFERENCES

Aggelides, S. M. and Londra, P. A. (2020). Effects of Compost Produced from Town Wastes and Sewage Sludge on the Physical Properties of a Loamy and a Clay Soil. *Journal of Bioresource Technology*, 71(24): 253-259.

Balkrishna,A,. ,Kaushik, P., Singh , S., Agrahar,P., Kumar,B., Kumar, P., and Arya, V.P. (2025). Potential use of sewage sludge as fertilizer in organic farming, *Cleaner Waste Systems,* 10:1-15

Cardenas-Talero, L.J., Silva-Leal, J.A., Perez Vidal, .A. and.Torres-Lozada, P. (2022). The influence of municipal wastewater treatment technologies on the biological stabilization of sewage sludge: a systematic review, *Sustainability,* 14 (10):5910-5920

Delibacak, A., Okur, E.A. and Ogun, R. (2019). Influence of treated Sewage Sludge Applications on Temporal Variations of Plant Nutrients and Heavy Metals in a Typical Xerofluvent Soil. *Journal of Nutrient Cycle Agroecosystem*, 83(42): 249–257.

EPA, (2021). Nutrient Content of Sewage Sludge and Fertilizers. Environmental Protection Agency Reports

Ghosh, S., Ahmed, R., & Patel, M. (2024). Modification of wastewater treatment sludge with agricultural waste for soil amendment: Physicochemical and spectroscopic evaluation. *Journal of Organic Waste Valorization*, *12*(3), 145–158.

Gülec, F., Williams, O., Samson, A., Kostas,T.E., Stevens, A.L.,and Lester,E.(2024) Exploring the utilisation of natural biosorbents for effective methylene blue removal. *Applied Sciences,* 14 (1:1-24

Hu, Y. and Shan, Y. (2025). Effects of sewage sludge on soil physical, chemical, and biological properties: A review. *Frontiers in Sustainable Development,* 5(11):25-30

Khaleel, R., K. Reddy, K. R. and Overcash, M. R. (2021). Changes in Soil Physical Properties due to Organic Waste Applications: A Review. *Journal of Environmental Quality,* 10(3) 133-41.

Kostryukov, S. G., Matyakubov, H. B.,Masterova, Y. Y., Kozlov, A. S., Pryanichnikova, M. K., Pynenkov, A. A. and Khluchin,N. A. (2023). Determination of Lignin, Cellulose, and Hemicellulose in Plant Materials by FTIR Spectroscopy *Journal of Analytical Chemistry,* 78 (6):.718–727.

Kumar, V., Chopra, A.K.and Kumar, A. (2017). A review on sewage sludge (biosolids) a resource for sustainable agriculture, *Arch. Agric. Environ. Sci.*, 2 (4): 340-347

Kumar, N. (2025). Effect of Zero Tillage Practice on Physical Properties of Soil: A Review. *International Journal of Environmental Sciences*, 11(22):5394-5403

Li,J., Chen, D.,, Fang, Z., H, X., Chen, X., Xu, J., Wang, Y., Sheng Su, S., Hu, S. and Xiang, J.(2026). Rapid prediction of cellulose, hemicellulose, and lignin content in biomass using FTIR based on transfer learning, Journal of Cleaner Production, 543 (8):1-15

Jock, A.A. and Ilechukwu, S.T. (2023). Formulation and Characterization of Organic Fertilizer from Animal Waste. *Nigerian Journal of Engineering.* 30(3): 75-80

Jock, A. A., Shinggu, P.C., Ahuchaogu, I.F., Shuwa, M.S. and Agba, P.A. (2022). Removal of chromium (III) metal ions from fertilizer wastewater using kaolin clay. *Journal of Pure and Applied Sciences,* 1-9

Narkesabad, S.Z., Rafiee, R. and Jalilnejad, E. (2023). Experimental study on evaluation and optimization of heavy metals adsorption on a novel amidoximated silane functionalized *Luffa cylindrica,* Scientific Reports, 13:1-16

Nunes, N., Ragonezi, C., Gouveia, S.S.C. and Carvalho, A.A.P.M. (2021). Review of Sewage Sludge as a Soil Amendment in Relation to Current International Guidelines: A Heavy Metal Perspective, *Sustainability* 2021, *13*(4), 2317

Orner, L., Smith, J., & Ahmed, R. (2022). A comparative study of potassium in sewage sludge and conventional fertilizers. *Agricultural Science Journal*, 1-10

Ortel, C. C., Roberts, T. L. and Rupe, J. C. (2024). A review of the interaction between potassium nutrition and plant disease control, *Agrosyst Geosci Environ.* 1-11

Paganini, E. A. L., Silva, R. B., Roder, L. R., Guerrini, I. A., Capra, G. F., Grilli, E., &

Ganga, A. (2024). A systematic review and meta-analysis of the sustainable impact of sewage sludge application on soil organic matter and nutrient content. *Sustainability*, 16(22), 9865. 1-20

Pandey, K. K. (1999). A study of chemical structure of soft and hardwood and wood polymers by FTIR spectroscopy. *Journal of Applied Polymer Science*, 71(12), 1969–1975.

Parolo, E.M., Savini, M. and Loewy, M.R. (2017). Characterization of soil organic matter by FT-IR spectroscopy and its relationship with chlorpyrifos sorption, *Journal of Environmental Management,* 1-10

Veluchamy C. and Kalamdhad, S.A. (2017). Influence of pretreatment techniques on anaerobic digestion of pulp and paper mill sludge: A review, *Bioresources Technology,* 245: 1206- 1219

Rahman, G. K. M., Rahman, M.,Alam, S.M. and Kamal, Z.M. (2020). Biochar and Organic Amendments for Sustainable Soil Carbon and Soil Health, In book: Carbon and Nitrogen Cycling in Soil, 45-85

Richards, B. K., Steenhuis, T. S., Pevverly, J. H. and Mc Bride, M. B. (2018). Metal Mobility at an Old, Heavily Loaded Sludge Application Site. *Journal of Environmental Pollution*, (89)365-377.

Sial, R.A., Chaudhary, M.F., Abbas, S.T., Latif, M.I. and Khan, A.G. (2016) Quality of Effluents from Hattar Industrial Estate. *Journal of Zhejiang University* SCIENCE B, 7: 974-980.

Stark, S. A. and Clapp, C. E. (2020). Residual Nitrogen Availability from Soils Treated with Sewage Sludge in a Field Experiment. *Journal of Environmental Quality*, 9(2):505-12.

Sukamto, S. and Rahmat, A. (2023). Evaluation of FTIR, Macro and Micronutrients of Compost from Black Soldier Fly Residual in Context of Its Use as Fertilizer. *ASEAN Journal of Science and Engineering, 3*(1): 21-30

Tkaczyk, P., Płóciniak, M.A., Skowrońska, M., Bednarek, W., Kuśmierz, S. and Zawierucha, E. (2020). The Mineral Fertilizer-Dependent Chemical Parameters of Soil Acidification under Field Conditions, *Sustainability*, *12* (17), 7165; 1-11

Zhang,Y., Xu, Z. and. Liu, X. (2016). Sewage sludge as an alternative fertilizer: a global perspective, *Waste Manag,* 11-5

.