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Physicochemical, Elemental, Morphological, and Microbiological Properties of WUPA Sewage Sludge: Implications for Potential Soil Remediation

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ABSTRACT
Sustainable management of sewage sludge is a persistent environmental challenge, particularly in rapidly developing areas. This study explores the physicochemical, mineralogical, and microbiological properties of raw sewage sludge from the WUPA Wastewater Treatment Plant, Abuja, Nigeria, to establish the quality of the raw sludge prior to conditioning and to evaluate its suitability for use in soil remediation. Analytical techniques employed comprise Energy Dispersive X-ray Fluorescence (EDXRF) for elemental composition SiO_2 has concentration of 67.50wt% as the highest and SeO_2 with lowest concentration of 0.00040wt%, Scanning Electron Microscopy (SEM) for morphological analysis result show that carbon (79.00 wt.%, 84.55 atomic%) and oxygen (18.14 wt.%), Fourier Transform Infrared Spectroscopy (FTIR) for functional group identification indicate 3698 to 3265cm^{-1} assigned to O–H stretching of alcohol and hydroxyl compounds, the band at 1543cm^{-1} is associated with aliphatic nitro compounds, of medium intensity. The analyzed wastewater sludge had a pH of 6.96 which falls within the optimal range of 6.5-7.0 for plant nutrient availability, indicating it is suitable for agricultural application without pH correction, low salinity, and high organic matter content. Heavy metals such as zinc and copper were within permissible limits of 2.00Mg/l & 0.5Mg/l for liquid sludge. SEM micrographs revealed a heterogeneous, porous structure conducive to soil aeration, while FTIR spectra revealed typical absorption bands of humus substances, including hydroxyl, amide, carboxyl, and aliphatic groups consistent with the presence of humus, which plays an important role in nutrient retention, soil aggregation, and organic matter stability. Microbiological analysis identified potential pathogens, underscoring the need for adequate stabilization before land application. The results suggest that, WUPA sewage sludge shows potential for use following appropriate stabilization/treatment and further safety evaluation as a valuable soil amendment for the remediation of agricultural soil.

Keywords: Sewage Sludge, WUPA, Soil Remediation, Heavy Metals, Microbiology

INTRODUCTION

Effective wastewater treatment is crucial for protecting public health, preserving the natural environment, supporting economic growth and development, and ultimately enhancing the quality of life. Sewage sludge (SS) is the residue that accumulates in sewage treatment plants. It can be described as the solid, semisolid, or sediment residue material that is generated as a by-product of wastewater treatment processes. This residue is generally categorized as primary and secondary sludge. Primary sludge is generated from screening, sedimentation, and further preliminary processes, whereas secondary sludge is the biological waste material collected from biological treatment processes. Some treatment plants also receive faecal sludge from domestic on-site wastewater treatment systems. Often, the sludge is collected jointly for further processing and management (Archis & Jerry, 2025).

Handling and managing sewage sludge are crucial elements in the system design, planning, and running of every wastewater treatment plant. The two primary objectives of conditioning sludge before disposal are to reduce its quantity and to stabilize the bio-based materials. Stabilized sludge has an inoffensive odour and is safe to handle, while a reduced sludge quantity lowers operational and storage costs (Archis & Jerry, 2025; Lamastra et al, 2018).

Sewage sludge is a semisolid residual material obtained from the gravitational settling of suspended solids during wastewater treatment. Managing large amounts of sludge accounts for a substantial share of total operational costs, and for this reason sustainable reuse strategies that balance environmental and economic considerations are essential. The primary methods for disposing of sludge include incineration, municipal solid waste landfilling, and soil application. Sewage sludge is a complex mixture of organic and inorganic materials, including particulate matter, microorganisms, and chemicals. Proper handling of sewage sludge is essential to prevent environmental pollution, protect public health, and ensure compliance with regulatory requirements. The treatment of sewage sludge involves various physical, chemical, and biological processes to reduce its volume, stabilize its composition, and eliminate pathogens (EPA, 2020).

Sewage treatment plants generate significant amounts of sludge, which poses environmental and health concerns if not managed properly. The treatment, conditioning, and disposal or reuse of sewage sludge are vital considerations in the design and operation of wastewater treatment plants. Sludge

conditioning is a critical step in sludge management, as it improves dewaterability and stability of the sludge, making it easier to handle and dispose of (Archis & Jerry, 2025; Qrenawi & Rabah, 2021).

Owing to rapid urbanization and a growing national economy, an increase in urban water consumption and sewage discharge has been observed. This uptrend was correlated with a rise in the production of excess sludge, a by-product of the biochemical treatment process in wastewater treatment facilities. Available statistics indicated that the average annual dry sludge production in the US, European Union, and China amounted to 7.2 million, 10 million, and 39 million tons, respectively (Cecconet et al., 2022). Owing to its high-water content, which typically ranges from 95% to 99%, the excess sludge is characterized by a large volume. Furthermore, this sludge contains bacteria, pathogens, heavy metals, among other substances. These constituents render the sludge unstable, odorous, and prone to deterioration. Compounding this issue is the high risk of secondary pollution, making subsequent disposal a costly and challenging process that poses a potential threat to the environment. Therefore, it is imperative to develop effective sludge treatment methods to address this essential challenge (Zhuo et al, 2024).

Sewage sludge management remains a global environmental challenge. In Nigeria, increasing urbanization has intensified sludge generation, necessitating innovative reuse strategies. Soil remediation using sludge offers dual benefits: waste valorization and restoration of degraded soils. However, comprehensive characterization is essential to balance benefits against risks of heavy metal contamination and pathogen introduction.

Sludge is a significant environmental concern globally, with millions of tons generated annually (Anyakora et al, 2022). Effective sludge management is therefore critical, underscoring the need for sustainable and efficient treatment solutions (Bingdi et al, 2021).

Sewage sludge possesses characteristics that are crucial for soil remediation, including high organic matter content, which boosts fertility and humus development (Magdalene, 2024); a balanced nutrient composition (N, P, K) that supports plant growth but requires careful management to avoid eutrophication (Alonso et al, 2024); and the presence of heavy metals, including cadmium (Cd), lead (Pb), mercury (Hg), chromium (Cr), copper (Cu), nickel (Ni), and zinc (Zn), which pose significant barriers to its safe reuse. Inadequately treated sewage sludge, when repeatedly applied to agricultural soils, can lead to the accumulation of heavy metals, posing hazards to long-term soil fertility, crop yield, and overall ecological health (Rahim et al, 2024). Effective remediation similarly relies on decreasing pathogen load, often attained through the potential benefits of encouraging the advance of native microalgae in sewage sludge for its stabilization in a closed system under carbon (IV) oxide release and non-addition of oxygen. This brings about a decrease in volatile solids and pathogen bacteria (*E. coli*, fecal coliforms, and *Salmonella*), as well as evaluating microalgae biomass generation. Moreover, the effect of the process on the extracellular polymeric substance (EPS) profile, settleability, and filterability properties of sludge is correspondingly investigated (Ben et al, 2024), while the mineralogical fraction offers binding spots for contaminants and stabilizes soil structure. Recent studies have established sludge valorization in diverse contexts, and critical evaluations stress sustainability and techno-economic possibility nonetheless note gaps in pathogen control and regulatory harmonization (Yaacoubi et al, 2026). Notwithstanding these advances, there remains a deficiency of unified studies combining physicochemical, mineralogical, and microbiological characterization in a single framework, insufficient attention on biosafety and pathogen reduction, and inadequate evaluation of environmental effects. Furthermore, there is deficient information or data on WUPA sewage sludge with implications aimed at potential soil remediation. The present study addresses these gaps by providing a holistic characterization of WUPA sewage sludge thus presenting a comprehensive framework for evaluating its suitability in soil remediation**.**

This study characterized the physicochemical, elemental, morphological and microbiological properties of sewage sludge generated at the WUPA Wastewater Treatment Plant, Abuja, to evaluate its potential and limitations for soil-remediation applications.

MATERIALS AND METHODS

The WUPA Sewage Treatment Plant is situated close to the Idu Industrial District, Abuja, Federal Capital Territory. Abuja is positioned near the geographical midpoint of Nigeria. The plant is near the WUPA River, at approximately latitude 9.029201°N and longitude 7.382141°E. It covers an area of 297,900 m^2 and is designed to serve a population equivalent (PE) of 700,000, with an average dry weather flow capacity of 5,500 m^3/hr, or 132,000 m^3/day. Below is the map of location of study.

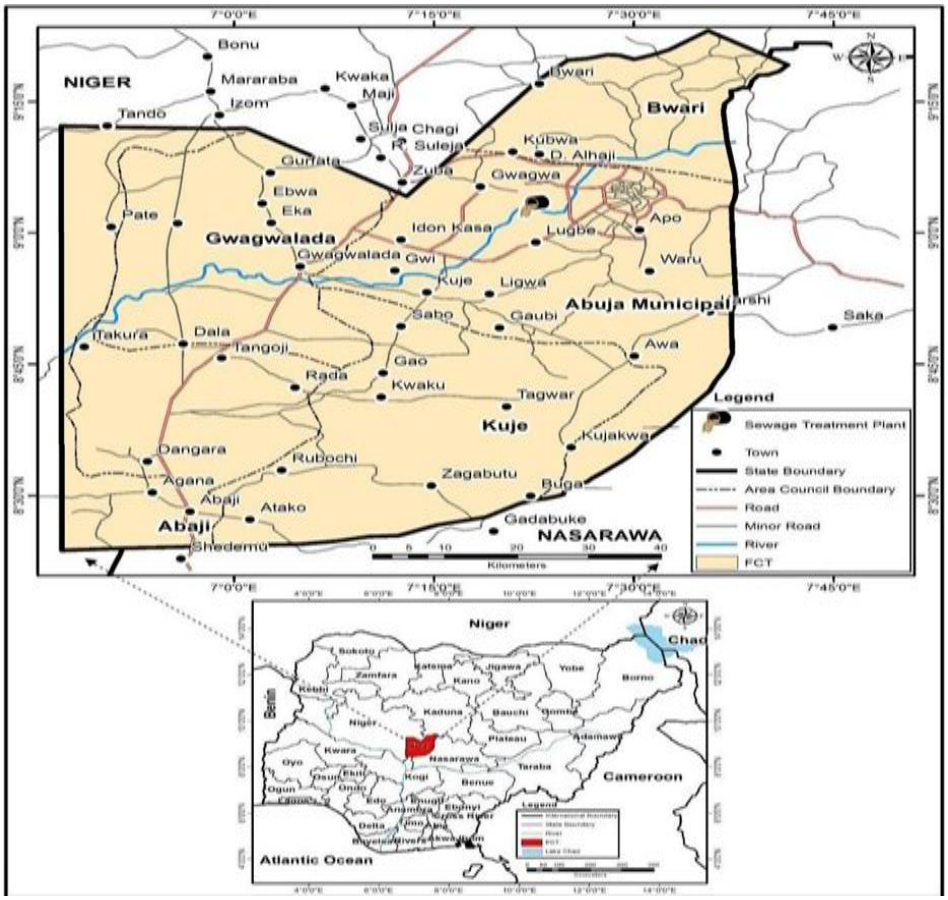


Figure 1: Map of Abuja showing the location of Wupa Basin Sewage Treatment Plant (WBSTP) Abuja

It is also designed to treat sewage from phases I, II, III, and IV of Abuja city. The plant was built to address rising concerns over sewage disposal as Abuja developed into an international metropolitan area.

Table 1: Various Parameters of WUPA Sewage Treatment Plant (Abuja WWTP, 2003)

S/N	Parameters	Quantity/Unit
1	Average dry weather flow	132,000 m3/day
2	Average hourly flow	5,500 m3/day
3	Peak flow	9,000 m3/day
4	BOD Load	4.2 ton/day
5	COD Load	8.4 ton/day

The WUPA sewage treatment plant is the largest of its type in sub-Saharan Africa. It is noted for its state-of-the-art, computerized components, placing the plant on a par with modern treatment plants worldwide

Despite its scale, there is limited peer-reviewed data on the comprehensive characterization of its sludge for agricultural soil remediation purposes.



Figure 2: Gravity Thickener and Bioreactor at WUPA Treatment Plant

Sample Collection

Composite sludge samples were collected from the dewatering stage of the WUPA Wastewater Treatment Plant over two weeks to account for temporal variability. Approximately 5 kg of sludge was collected per sampling event, homogenized, and stored in sterile polyethylene containers. Samples were transported on ice to the laboratory and stored at 4 °C before analysis, with all analyses completed within 48 hours to minimize compositional changes. The analysis done with the liquid sludge was physicochemical analysis and microbiological analysis. The sampling method used was composite sampling, where multiple samples were collected from different points in the reactor and combined to create a representative sample. The sampling equipment was prepared by cleaning the sampler (2m long equipment that has a cup-like material at the tip/edge).

The sludge was removed and air-dried at the plant for 12 days, as summarized below:

Table 2: Sample Collection Date and Average Parameters

S/N	Date	Average daytime temp. (°C)	Average daytime wind speed(m/s)	Pressure (mmHg)	Humidity (%)
1	08|10|25	+28	2.2	703	85.0
2	09|10|25	+29	2.2	703	85.0
3	10|10|25	+27	3.2	719	79.0
4	11|10|25	+28	2.2	718	79.8
5	12|10|25	+26	2.6	718	79.0
6	13|10|25	+27	2.6	718	78.0
7	14|10|25	+27	2.5	719	78.0
8	15|10|25	+28	2.8	719	75.5
9	16|10|25	+28	2.25	718	74.5
10	17|10|25	+28	2.5	718	73.0
11	18|10|25	+29	2.45	719	69.0
12	19|10|25	+29	2.25	719	69.0
	Average	28°	2.5	716	77%



Figure 3: Dried Sludge from WUPA Wastewater Treatment Plant

Some analysis like ED-XRF, FTIR, SEM-EDS, AAS and microbial analysis were carried out with the dried sludge.

Analytical Procedure

Energy Dispersive X-Ray Fluorescence (ED-XRF) Analysis

In this study, the chemical compositions of wastewater sludge were obtained using Thermo Fisher Scientific Energy Dispersive X-ray Fluorescence (EDXRF) Analyzer. Analysis was done using the standard method with 80% Accuracy as compared with method having less standard of 50% Accuracy. The standard method is totally dependent on calibration curve of each element. The standard methods were formed by standard Reference material obtained from International atomic Energy IAEA or National Institute of Standard and Technology. All provide certificate of Analysis e.g. Montana soil SRM 2710, IAEA Soil 7 for Geological Sample, IAEA – 155 provide for biological Sample while the less Standard ones were calibrated from factory. The instrument has three mediums of operation

i. Helium gas for liquid sample
ii. Vacuum Pump for light Elements.
iii. Air for heavy Element and light element excluding Sodium which can only be gotten in vacuum.

The dried sewage sludge sample was first ground to a fine powder with the aid of mortar and pistol. 2g of the sample was weighed and then poured into a sample holder and covered with cotton wool to prevent it from spraying.

The bottom of the sample holder is made of polypropylene which is a thermoplastic. The sample holders containing the samples were run in a vacuum or air for 10 minutes to form pellets before inserting them into the XRF Spectrometer for elemental analysis. The method was calibrated using geological or biological calibration. The analysis can be done either elemental or oxides form.

Fourier Transform Infra-red (FT-IR) spectroscopy

A Fourier Transform Infrared Spectrophotometer (FT-IR) is an analytical instrument used to measure the absorption or transmission of infrared radiation by a sample. The model used was Agilent Cary 630ZnSE Engine FTIR and Ragaku mini flex XRD. The FT-IR technique is based on the principle that different chemical bonds in a molecule absorb infrared

radiation at specific frequencies, and by measuring the absorption or transmission of this radiation, it is possible to identify the types of chemical bonds present in the sample.
Here are the basic steps involved in operating the FT-IR spectrophotometer:

i. Sample preparation: The sample was prepared by placing it on a sample holder or directly on the instrument's sample stage.
ii. Background measurement: A background measurement was taken by measuring the infrared radiation passing through a sample holder. This measurement was used to correct any infrared radiation absorbed or scattered by the sample holder or the instrument itself.
iii. Spectral acquisition: The instrument emitted a beam of infrared radiation that passed through the sample and was detected by a detector. The instrument scanned a range of frequencies, typically in the mid-infrared region (4000-400 cm^-1), and recorded the amount of radiation absorbed or transmitted by the sample at each frequency. This process produced a spectrum that represents the unique absorption pattern of the sample.
iv. Data analysis: The acquired spectrum was analyzed using software that can identify the characteristic peaks and patterns in the spectrum. These peaks correspond to the different types of chemical bonds present in the sample, and by comparing the spectrum to a database of known spectra, it was possible to identify the sample's chemical composition.
v. Interpretation of results: The identified chemical groups and functional groups were used to determine the type of compound present in the sample, its purity, and its structural properties, ecological or biological calibration. The analysis can be done either elemental or oxides form.

Scanning Electron Microscope Procedure

The scanning electron microscopy (SEM) was performed to examine the physical structure change of sewage sludge using SEM model Phenom ProX, by phenom World Einhoven, The Netherlands. Sample was placed on double adhesive which was on a sample stub, sputter coated by quorum technologies model Q150R, with 5nm of gold. Thereafter it was taken to the chamber of SEM machine where it was viewed via NaVCaM for focusing and little adjustment. It was then transferred to SEM mode, focus and brightness contrasting were automatically adjusted, afterward the morphology of specific magnification was stored in a USB stick.

Determination of Heavy Metal

Conventional aqua regia digestion was performed in 250cm3 glass conical flask covered with watch glass. A well-mixed air-dried sludge sample of 3g was digested in 20cm3 of aqua regia (3:1 of HCl and HNO3 respectively) on a hotplate for 3hrs at 110oC. After evaporation to near dryness, the sample was diluted with 20cm3 of 2% (v/v with H2O) nitric acid and transferred into a 100cm3 volumetric flask after filtering through Whatman no. 42 filter paper and diluted to 100cm3 with deionized water [158] The filtrates were separately analyzed using Thermo Scientific Atomic Absorption Spectrophotometer (AAS) Spectrophotometer (ICE 3000 AA 02134104V1.30)

Bacteriological Examination for Liquid Sludge

Bacteriological analysis was carried out through the following processes for liquid sludge

Sample preparation

1g of the sludge was weighed and diluted with 100ml of prepared enrichment broth (peptone water) the mixture was incubated for 24hrs.

Total Coliform Test

i. MacConkey agar was prepared according to the manufacturer's guidance
ii. 1ml of prepared sample was pipetted into the petri-dish in a sterile environment (on a laminar flow bench)
iii. The sterilized cooled molten agar was poured into a petri-dish containing 1 ml of sample'
iv. The petri dish was rotated gently clock wisely and anti-clock wisely.
v. It was allowed to solidify and then inverted
vi. It was labeled accordingly
vii. It was Incubated at 370C for 24 hours
viii. After 24 Hours the pinkish red colonies were counted
ix. Coliform appeared pinkish red/rose – red on MacConkey agar after incubation.

Fungi Test

i. SDA agar was prepared according to the manufacturer's guidance
ii. 1ml of prepared sample was pippetted into the petri-dish in a sterile environment (on a laminar flow bench)
iii. The sterilized cooled molten agar was poured into a petri-dish containing 1 ml of sample
iv. The petri dish was rotated gently clock wisely and anti-clock wisely.
v. It was allowed to solidify and then inverted
vi. It was labeled accordingly
vii. It was incubated at 350C for between 24 to 72 hours
viii. After the incubation period elapsed, the white colonies were counted

NOTE: Fungus colonies appear whitish on SDA agar after incubation.

Total Bacteria Test

i. Nutrient agar was prepared according to the manufacturer's guidance
ii. 1ml of prepared sample was pippetted into the petri-dish in a sterile environment (on a laminar flow bench)
iii. The sterilized, cooled molten agar was poured into a petri-dish containing 1 ml of sample'
iv. The petri dish was rotated gently clock wisely and anti-clock wisely.
v. It was allowed to solidify and then inverted
vi. It was labeled accordingly
vii. It was incubated at 370C for 24 to 48 hours

After the incubation Hours the colonies were counted

Procedure for Bacteriological Examination of Dried Sludge

Media was prepared according to the manufacturers' instruction (PCA) and (EMB) Agar
For bacteria TC count; PCA was used.
For fungi CFU, PCA+ Chloramphenicol was used (To inhibit growth of bacteria)
For E. coli & Coliforms, EMB Agar was used.

i. Sample was ground using pestle and mortar
ii. Three sterile test tubes were used: A, B, C, were placed appropriately on the test tube rack and labelled properly.
iii. 1g of powdered sample was weighed using weighing balance. It was then placed in a sterile distilled water and covered with a sterile foil paper (sample A served as a stock solution) this was done for sample B and C.

iv. The stock solution A was mixed by placing the thumb and turning it upside down for 2-4 times for proper mixing. It was also carried out on sample B and C respectively.
v. Using a micro pipette, sample A was serially diluted by removing 1ml from the stock solution A to the test tube (1) and mixed properly.
vi. 1ml was removed from test tube (1) and added to test tube (2) They were mixed. Well.
vii. 1ml from test tube (2) was added to test tube 3 and mixed properly. (1ml was removed and discarded which serve as the dilution factor.)

Pour Plaiting Techniques

100ml from sample a test tube (3) was removed and dispensed in a sterile petri dish. It was poured plated with plate count agar, mixed for even distributed and allowed to solidify. It was inverted and incubated at 370C for 18 – 24 hours for Bacteria and 22-250C for 72 hours for Fungi. The result was observed and the colonies counted using a colony counting machine

RESULTS AND DISCUSSION

Energy Dispersive X-Ray Fluorescence (XRF) of Samples

The elemental and oxide composition of WUPA wastewater treatment plant sludge was determined, and the results are presented in Table 3.

Table 3: Energy Dispersive X-Ray Fluorescence Concentration of WUPA Wastewater Treatment Sludge

Oxide	Element	WUPA Wastewater oxide Concentration (Wt.%) ± SD	Oxide	Element	WUPA Wastewater oxide Concentration (Wt. %) ± SD
CuO	Cu	0.01043	Fe_2O_3	Fe	8.328
ZnO	Zn	0.12447	Co_3O_4	Co	0.6000
Ga_2O_3	Ga	0.00300	NiO	Ni	0.02000
Ta_2O_5	Ta	0.00878	TiO_2	Ti	0.5546
WO_3	W	0.06000	V_2O_5	V	0.2032
-	Au	0.05158	Cr_2O_3	Cr	0.0121
PdO	Pd	0.132	MnO	Mn	0.4568
Ag_2O	Ag	0.00165	La_2O_3	La	0.00700
SnO_2	SnO_2	0.0211	CeO_2	Ce	0.200
-	I	0.000483	-	Cl	0.0119
Cs_2O	Cs	0.080	K_2O	K	0.5626
BaO	Ba	0.158	CaO	Ca	2.270
MgO	Mg	0.50	As_2O3	As	0.00715
Al_2O_3	Al	3.44	SeO_2	Se	0.00040
SiO_2	Si	67.50		Br	0.0297
P_2O_5	P	0.956	Rb_2O	Rb	0.0744
SO_3	S	0.2158	SrO	Sr	0.2734
CdO	Cd	0.00279	Y_2O_3	Y	0.536
PbO	Pb	0.0317	ZrO_2	Zr	0.3710
Bi_2O_3	Bi	0.00469	Nb_2O_5	Nb	0.0279
ThO_2	Th	0.00085	MoO_3	Mo	0.0600
U_3O_8	U	0.04328			

Table 3 shows the elemental and oxide concentrations of WUPA sludge. It was observed that SiO_2 has the highest oxide concentration, Fe has the highest elemental concentration in the sludge with the weight of 5.8wt%. It was also observed that very thin layer of SiO_2 was measured. It further shows that short wavelength was emitted in the sample analyzed which indicated the electron bombardment excitation was adopted. Also, the table shows that Selenium (Se) and Selenium dioxide (SeO_2) have the lowest concentration. It further shows that the sludge will be applicable for agricultural use to avoid soil contamination of soils and food chains. The results show an agreement with the finding of (Priyanka, 2022).

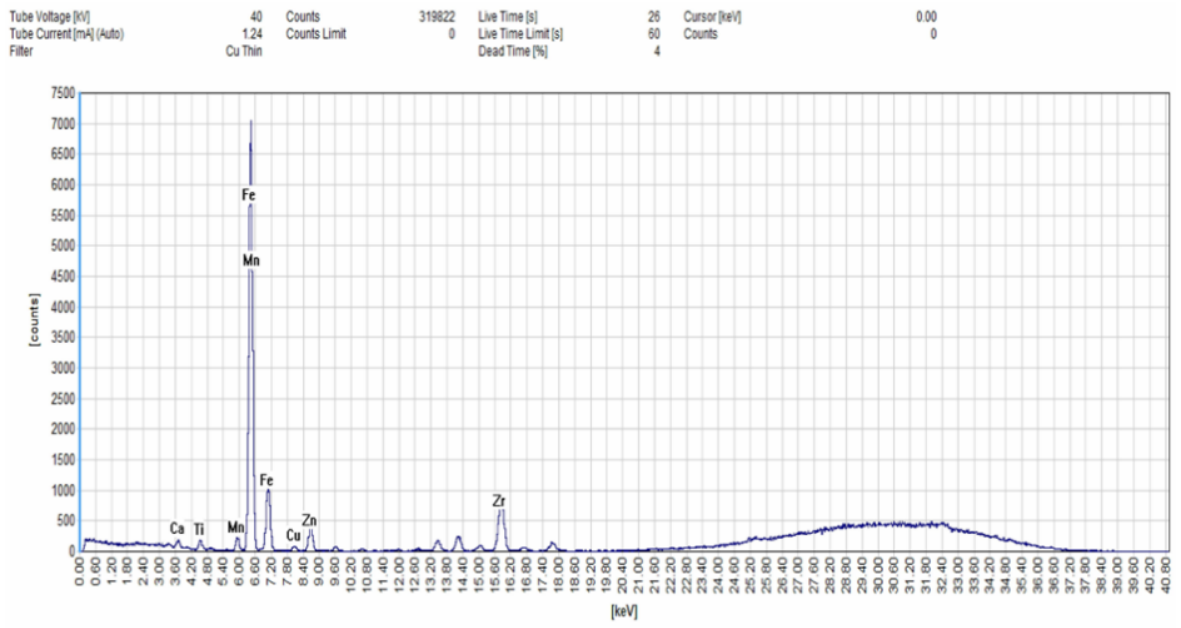


Figure 4: ED-XRF plot interpretation of WUPA Wastewater Sludge

WUPA sludge was in the form of small spherical dark brown powder. Fig. 4 represents the XRF pattern of the sewage sludge. It shows a high amount of SiO_2 (67.50wt %), ferric oxide Fe_2O_3 (8.33wt %) and CaO (2.70wt %). Small amounts (<1%) of the following oxide P_2O_5, K_2O, SO_3, TiO_2, MgO, MnO, Cl, ZnO, BaO, ZrO_2, CO_3O_4, CUO, SrO, Cr_2O_3 I, Y_2O_3, NiO, Br and Nb_2O_5 were also identified. The peaks were generated using X-ray fluorescence analysis. The concentration (wt%) of each compound along with their element are summarized in Table 4, which shows that the WUPA sludge sample consists of high amount of SiO_2. These results are in agreement with literature (Priyanka, 2022; Beckhoff, 2006).

Fourier Transform Infrared Spectroscopy (FT-IR)

Table 4: FT-IR of WUPA treatment plant sludge

Peak No.	Wavenumber (cm^{-1})	Intensity	Assigned Vibration	Functional Group
1	790.20	79.25	C-H out-of-plane bending	Aromatic ring (substituted benzene) or alkene =C-H bending
2	909.47	62.22	=C-H out-of-plane bending	Vinyl group (terminal alkene, CH_2=CH-) or alkene
3	998.93	50.44	=C-H wagging/out-of-plane deformation	Trans-alkene or terminal alkene
4	1416.39	92.39	CH_2 bending (scissoring) / COO^- symmetric stretch	Aliphatic hydrocarbons or carboxylate-containing compounds
5	1543.12	91.35	N-H bending coupled with C-N stretching (Amide II band) or aromatic C=C stretching	Amide-containing compounds (proteins, polyamides) or aromatic systems

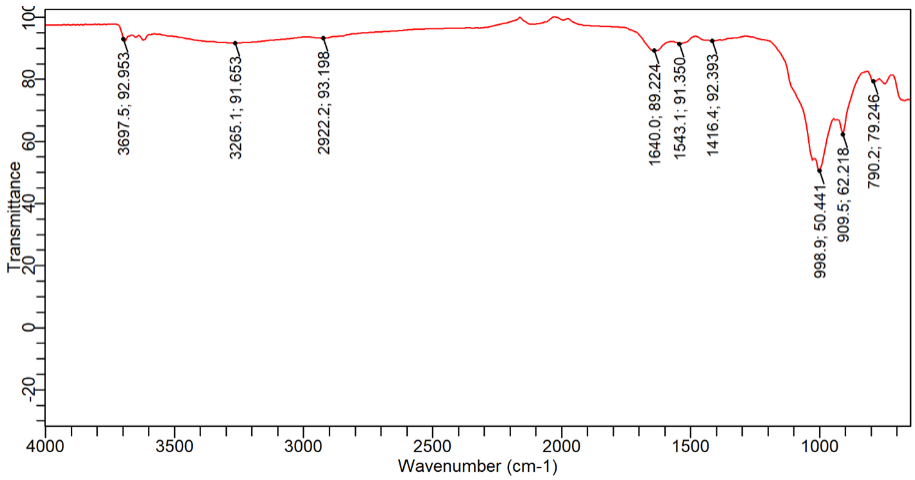


Figure 5: FT-IR Spectrum of WUPA treatment plant sludge

FT-IR plot interpretation of WUPA Treatment plant sludge

The FTIR spectrum of WUPA sludge (Fig. 5) shows several vibrational stretching and bending absorption peaks, with their corresponding functional groups as follows: Peak at 790 cm^{-1}

Typically assigned to aromatic C-H out-of-plane bending vibrations. With reference range from 675-900 cm^{-1}. Peak at 909 cm^{-1} is the characteristic of terminal alkene (=CH_2) C-H out-of-plane deformation. Often observed in vinyl-containing compounds with reference range: 900-990 cm^{-1}.

Peak at 999 cm^{-1} is associated with trans-alkene C-H wagging or terminal vinyl group deformation, with reference range from 960-1000 cm^{-1}. Peak at 1416 cm^{-1} indicate CH_2 bending vibration in aliphatic chains with reference range from 1400-1450 cm^{-1}.

Peak at 1543 cm^{-1} show Strong peak in the region of the Amide II band (N-H bending + C-N stretching). It also overlaps with aromatic ring C=C stretching vibrations with reference range:

Amide II: 1510-1580 cm^{-1} and aromatic C=C: 1500-1600 cm^{-1}

The observed peaks collectively suggest the possible presence of aromatic ring(s) (790 and 1543 cm^{-1}) alkene/vinyl groups (909 and 999 cm^{-1}) and aliphatic CH_2 groups (1416 cm^{-1}) these results are consistent with the findings of (Nandiyanto, 2019).

Scanning Electron Microscope results for WUPA Sewage Sludge

The selected area in Fig. 6 served as the region for SEM-EDX analysis of the WUPA sludge sample. The results are presented in Table 5 and Figure 7.

Table 5: Results of Scanning Electron Microscope - Energy Dispersive Spectroscopy for WUPA treatment plant Sludge

ELEMENT	WEIGHT (%)	MINIMUM DETECTION LIMIT	ATOMIC (%)
C K	79.00	0.07	84.55
O	18.14	0.15	14.58
F	0.21	0.17	0.14
AI	0.19	0.04	0.09
Si	0.35	0.04	0.16
Fe	2.12	0.10	0.49

Table 5 shows the elemental composition of WUPA sewage sludge obtained via SEM-EDS analysis. The sludge is dominated by carbon (79.00 wt%, 84.55 atomic %) and oxygen (18.14 wt. %), confirming its high organic content, with minor contributions from Fe, Si, Al, and F.

The suffix "K" in the SEM–EDX results denotes detection through the K-shell X-ray emission lines of the respective elements. In energy-dispersive spectroscopy, the electron beam excites atoms in the sludge sample, ejecting electrons from the innermost (K-shell) orbital.

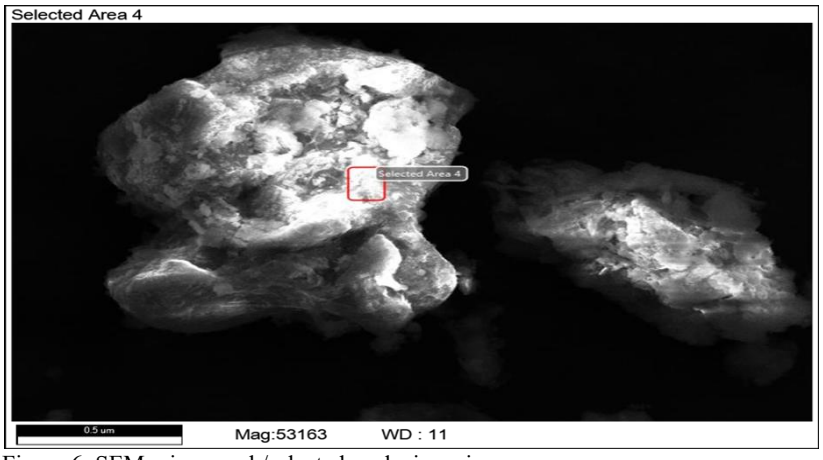


Figure 6: SEM micrograph/selected analysis region

The morphological characteristics of WUPA sewage sludge were examined using Scanning Electron Microscopy (SEM), as presented in Figure 6. The micrograph reveals a highly irregular, rough, and agglomerated surface morphology, typical of dewatered biological sludge. The structure appears as amorphous flocs with heterogeneous particle size and no defined crystalline shape, characteristic of organic-rich sludge containing extracellular polymeric substances and microbial biomass.

The micrographs also revealed a porous aggregated nature of structure conducive to soil aeration and suggest strong inter-particle bonding. The presence of iron (2.12 wt% Fe) likely contributes to coagulation and binding of the organic matrix, as iron salts are commonly used as coagulants in wastewater treatment, leading to the formation of the larger, irregular aggregates seen in the selected area.

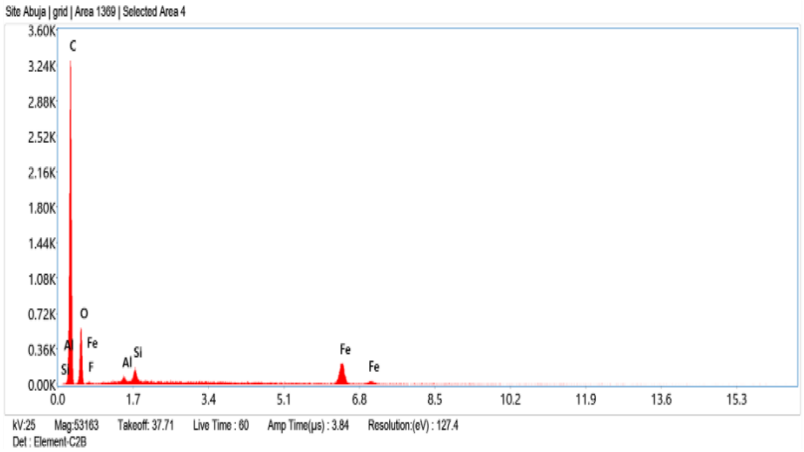


Figure 7: Corresponding EDS Spectrum

Heavy Metal Result of WUPA Sewage Sludge

Atomic Absorption Spectrophotometry was used to determine heavy metal concentrations, expressed in mg/kg, as shown in Tables 6 and 7 for dried and liquid sludge, respectively.

Table 6: Range Of Heavy Metals in Dried WUPA Wastewater Sludge

Parameters	Concentrations (Mg/Kg) ± Sd	Epa Standard Ceiling Concentration (Mg/Kg) (Epa 2020)
Zinc	369.3	421
Copper	201.52	300
Lead	29.93	164
Cadmium	0.38	3
Nickel	26.20	70
Arsenic	0.25	20

Table 7: Range of Heavy Metals in Liquid WUPA Wastewater Sludge

Parameters	Concentration (Mg/L) ± SD	EPA Standard Ceiling Concentration (Mg/L) (Epa 2020)
Zinc	0.37	2.00
Copper	0.47	0.5
Lead	0.34	Not specified
Cadmium	0.04	0.05
Nickel	0.17	Not specified
Arsenic	0.02	Not specified

Table 6 and 7 shows the concentration of six toxic metals (Zn, Cu, Pb, Cd, Ni and As) under study. Higher content of Zinc, Copper, lead and Nickel was observed in the liquid sludge. The resulting immobilization of these elements is probably caused by the alkaline reaction of sewage sludge. At high pH, the solubility of the metal compounds decreases and the cations are less prone to leaching from the waste. On the other hand, the concentrations of Cadmium and Arsenic as determined in the stabilized sludge were lower. The reason may be the partial leaching of metals from the strongly alkaline sludge. Differences in metal mobility (and thus their bio-accumulation) may result from several factors related to the complex chemical composition of sewage sludge and the pH of either fresh or stabilized sludge. These results when compared to standard (EPA Standards for the use or disposal of sewage sludge, 2020) and findings by (Tytla et al, 2016; Anna et al, 2019). Show similarity. This indicates that the heavy metals obtained are within acceptable standard specification /limit for use of the sewage sludge for soil remediation.

Physicochemical and Bacteriological Parameters Results

Tables 8 and 9 represent the Moisture contents, solid concentration, Physicochemical and Bacteriological characteristic of WUPA sewage sludge

Physicochemical Analysis: pH, electrical conductivity, organic matter, and heavy metal concentrations were measured using standard protocols

Table 8: Physicochemical Characteristics of WUPA Sewage Treatment Plant Sludge

Parameters	Unit	Sludge ± SD
Temperature	^{0}C	26.9
TDS	mg/L	276.5
Turbidity	NTU	255
Electric Conductivity	µSCm^{-1}	561
Moisture Content	%	94.6
Solid Concentration	%	5.4
Ph	-	6.96

Organic matter	%	68.0
Organic carbon	%	39.4
Colour	PtCo	79
BOD_5	mg/L	5050
COD	mg/L	9750

Table 9: Microbial Characteristics of WUPA Sewage Treatment Plant Sludge (Liquid)

S/N	Parameter	Units	Before Reactor	Reactor	After Reactor
1	Bacteria	MPN/mL	2×10^6	1×10^6	1×10^4
2	Fungi	MPN/mL	4×10^1	1×10^2	1×10^1
3	Coliforms	MPN/mL	1.1×10^3	1×10^4	1×10^3

Table 10: Microbial Characteristics of Dried WUPA Sewage Treatment Plant Sludge

Parameters	Unit	Dried sludge
Bacteria	CFU/100mL 10^{-2}	128
Fungi	CFU/100mL 10^{-2}	99
Total Coliforms	CFU/100mL 10^{-2}	24

Table 8 shows that the pH value (6.96) is within the neutral range. The optimum pH range for healthy soil that supports plant growth is generally 6.5–7.5 according to the Food and Agriculture Organization (FAO), while the World Health Organization (WHO) tolerance limit is 6.5–8.0. The electrical conductivity of 561 µS cm^{-1} found in this work is within the WHO acceptable limit of below 1250 µS cm^{-1} (Bot et al, 2005).

Table 11: Pathogen Indicator Orgamism Density Limits for Class A and B Biosolids (Ojo et al, 2023)

Classification	Fecal Coliforms
Class A	<1,000MPN/g Total solid
Class B	<2,000,000MPN/g Total Solid or <2,000,000CFU/g Total Solid

Conversion from CFU/100 mL to CFU/g total solids (TS)
Total coliform value is= 2.4×10^2
= 0.24CFU/100ML
Total solids (TS) = 5.4%,
5.4%=5.4 g TS per 100 mL
Convert to CFU/g TS: $\frac{\text{CFU/100 mL}}{\text{GTS/100 mL}} = \frac{\text{0.24 CFU/100 mL}}{\text{5.4 g TS/100 mL}}$
=0.0444CFU/gTS

Therefore, the dried sludge meets the Class A microbial standard based on the available coliform data. The total coliform concentration of the dried WUPA sewage treatment plant sludge was 0.24 CFU/100mL. Using a total solids content of 5.4%, the equivalent concentration was calculated as 0.044 CFU/g total solids. This value is substantially below the Class A biosolids limit of 1,000 CFU (or MPN) per gram total solids. Consequently, the sludge is classified as Class A biosolids with respect to microbial quality.
Therefore, the study demonstrates potential suitability for soil-amendment/remediation applications. Nevertheless, there are some limitations discovered in the study, particularly absence of long-term metal-leaching data, incomplete pathogen characterization, possible organic micropollutants, and uncertainty regarding repeated sludge application for soil amendment/remediation utilization.

CONCLUSION

WUPA sewage sludge displays promising properties for soil remediation, combining nutrient enrichment (N, P, K, Ca, Mg), organic matter replenishment, and mineral supplementation, all of which can improve soil aeration, water-holding capacity, and fertility. It also exhibits microbial bioremediation potential. A pre-treatment strategy, such as conditioning, is essential to optimize its safe use in agriculture.
The physicochemical and compositional characteristics of WUPA sewage sludge show potential value as a soil amendment, but microbial contamination and other safety considerations necessitate adequate stabilization/conditioning and further testing before agricultural application. Physicochemical analyses revealed a sludge matrix dominated by organic matter, with high carbon and oxygen content, which is further supported by the mineralogical evaluation.
The synergy between organic matter, mineral constituents, and microbial activity positions WUPA sludge as a multifunctional amendment, capable of restoring agricultural soils, improving fertility, and stabilizing contaminants when properly stabilized and conditioned. However, there is need for field validation, pathogen reduction, contaminant-leaching studies and long-term environmental-risk evaluation for effective soil-amendment/remediation application.
Collectively, the findings reveal that WUPA sewage sludge is not merely a waste product but a valuable resource for sustainable soil remediation within a circular economy framework. Its application, when appropriately stabilized and monitored for heavy metals and pathogens, can convert environmental liabilities into assets, contributing to agricultural productivity, ecological recovery, and improved environmental quality. Acknowledge the need for field validation, pathogen reduction, contaminant-leaching studies and long-term environmental-risk evaluation.

REFERENCES

Abuja Waste Water Treatment Plant (2003), "Description of the operation of the control system,"JN.985-4427 October 2003-PN.4907, SCC Nig Ltd.

Alonso, J.M., Abreu, A.H.M., Andreoli, C.V. *et al.* "Chemical characteristics and valuation of sewage sludge from four different wastewater treatment plants". *Environ Monit Assess* **196**, 34 (2024). https://doi.org/10.1007/s10661-023-12211-8

Archis A, Jerry A.N. (2025) "Sludge treatment and disposal in wastewater treatment" (2025) Britannica encyclopedia/websource. 21st June 2025. https://www.britannica.com. Accessed 14th July 2025

Anyakora N.V, Ajinomoh C.S., Ahmed. A.S.,Mohammed-Dabo, J.A. Ejeh S.P, Abba H., Okoro J. (2022) "Modelling of sludge drying parameters in a Paved Drying Bed" International journal of Engineering and Computer science. ISSN:2319-7242. https://doi.org/10.18535/ijecs/v11i03.

Anna T, Kinga W. and Wojciech M. (2019), 'Wolf Digestion Procedure and Determination of Heavy Metals in Sewage Sludge an Analytical Problem' Sustainability 2019, 11, 1753; https://doi.org/10.3390/su11061753

Beckhoff B. Kanngießer, N. Langhoff R. Wedell H. Wolff (2006), Handbook of Practical X-Ray Fluorescence Analysis' ISBN-13 978-3-540-28603-5 Springer Berlin Heidelberg New York.

Bingdi C., Tao Z., Weijun H., Dongsheng W. (2021) "Enhanced Technology Based for

sewage sludge deep watering: A review." Water Research Volume 89, Februuary, 2021,116650. https://doi.org/10.1016/j.watres2020.116650

Ben H., H., Debuigne, A., Kleinjan, H., Toye, D., & Léonard, A. (2024). "Enhancing Sewage Sludge Stabilization, Pathogen Removal, and Biomass Production through Indigenous Microalgae Promoting Growth: A Sustainable Approach for Sewage Sludge Treatment" *Recycling*, *9*(5), 97. https://doi.org/10.3390/recycling9050097

Bot A., and Benites J. (2005) "The Importance of Soil Organic Matter" Food and Agriculture Organization of the United Nations Rome FAO Publications, Available: www.fao.org [26th Oct.2025].

El Yaacoubi, C., Bensaddik, M., Bensitel, N., Azar, F.-Z., Dimane, F., El Hammoudani, Y., & El Kasmi, A. (2026). "Sustainable Wastewater Sludge Valorization: A Critical Review of Life Cycle Assessment and Techno-Economic Studies." *Resources*, *15*(8), 99. https://doi.org/10.3390/resources15080099

EPA (2020); 'Environmental Regulations and Technology, Control of Pathogens and Vector Attraction in Sewage Sludge. United States Environmental Protection Agency.

Lamastra L., Suciu N.A., & Trevian M. (2018) "Sewage sludge for sustainable agriculture: contaminants, contents and potential use as fertilizer. Chemical and Biological Technologies in agriculture 5, Article number 10 (2018). https://doi.org/10.1186/s40538-018-0122-3

Magdalene M. (2024), "Properties of organic matter in compost based on sewage sludge." Journal of ecological engineering, 25(7),70-81 https://doi.org/10.12911/22998993/187964 ISSN 2299-8993

Nandiyanto, A.B.D.,Dani A.B., Ragadhitta R.& Oktiani R. (2019). "How to Read and Interpret FTIR Spectroscope of Organic Material" Indonesian journal of Science and Technology Vol 4, DOI: http://dx.doi.org/10.17509/ijost.v4i1.15806 | p- ISSN 2528-1410 e- ISSN 2527-8045.

Ojo O. Ogwueleka T.C, Evuti A.M. (2023)" Study on the application of bio solids from WUPA Sewage Treatment Plant in soil remediation" University Abuja, Faculty of Engineering.

Priyanka S., Vibha M., Dwivedi M. K. and Tiwari M. K. (2022) 'Elemental Investigation of Sewage Sludge Samples Using Synchrotron Radiation Based Xrf Spectrometry' Dickensian Journal volume 22.

Qrenawi, L.I. and Rabah, F.K.J. (2021) "Sludge management in water treatment plants: literature review." International. Journal of Environment and Waste Management, Vol. 27, No 1, pp.93-Ana27 (1):93. https://doi.org/10.1504/IJEWM.2021.111909.

Rahim M, Lise A, Hatice Y, A. Evren T, Bariş Ç. (2024), "Sustainable heavy metal removal from sewage sludge: A review of bioleaching and other emerging technologies", Science of The Total Environment, Volume 955,2024,177020, ISSN 0048-9697,

Standards for the use or disposal of sewage sludge (2025) Title 40-Protection of Environment. Chapter 1-Environmental Protection Agency. Subchapter 0-Sewage Sludge. Up- to- date as of 9/16/2025.

Tytła, M.; Widziewicz, K.; Zielewicz, E. (2016) "Heavy metals and their chemical specification in sewage sludge at different stages of processing". *Environ. Technol. 37*, 899–908.

Cecconet & Capodaglio A, G, (2022).:" Sewage Sludge Biorefinery for Circular Economy" Sustainability 2022,14(22),14841; https://doi.org/10.3390/SUI42214841 MDPI Resources.

Zhuo L, Fang L, Lingzhi He, Siqi W, Yi Wu, Zhuqi C (2024) "Physical conditioning methods for sludge deep dewatering" A critical review. Journal of Environmental Management, volume 360, June 2024,121207. https://doi.org/10.1016/j.jenvman.2024.121207

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