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Application of ERT and VLF-EM Methods for Mapping Leachate Pollution from Agro-Processing Waste in Oghara, South-South Nigeria

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ABSTRACT
The study employed Electrical Resistivity Tomography (ERT) and Very Low Frequency Electromagnetic (VLF-EM) geophysical techniques coupled with hydrochemical analysis to identify leachate pollution from palm kernel wastes in Oghara, South-South Nigeria. The indiscriminate disposal of organic wastes generated conductive leachate solution that contaminated shallow groundwater in the study area. The ERT was carried out along five traverses, and the results revealed very low resistivity values (20.3-95 Ωm) at depths of 2-15 m. The VLF-EM data were processed using Fraser and Karous-Hjelt filters, and shallow conductive plumes (35-65 mS/m) were detected at depths of less than 15 m. The hydrochemical analysis of groundwater samples collected from up and down gradient directions (n = 10) showed an increase in total dissolved solids (1,240-3,850 mg/L), electrical conductivity (2,480-6,200 µS/cm), ammonium (4.2-18.6 mg/L), and total coliforms in the down gradient direction exceeding the NSDWQ and WHO standards for potable water. The correlation of geophysical and hydrochemical results revealed the presence of leachate plumes with high concentrations of organic acids and dissolved ions that infiltrated the shallow aquifer in the study area. The study established the extent of pollution and the risk posed to the shallow groundwater in Oghara, Nigeria, and provides baseline data for similar studies in palm oil processing industries.

INTRODUCTION

The biologically diverse and productive Niger Delta region is currently undergoing mounting environmental stresses from agricultural activities, especially agro-industries. Palm kernel processing, a critical stage of the oil palm value chain, produces large volumes of liquid and solid wastes in the form of press fibers, palm kernel shells, and fertile effluents. With poor disposal, these wastes undergo biodegradation and produce leachates with a high degree of conductivity due to the presence of organic acids, dissolved salts and ionic substances which readily percolate into the subsurface and can contaminate shallow aquifers (Gbadebo *et al*., 2021; Otti *et al*., 2014).

Oghara located in Ethiope West Local Government Area of Delta State, (South-South Nigeria), is a key centre for small and medium scale palm kernel processing. Groundwater has traditionally served as the principal source of water for domestic and agriculture purposes for the local communities. However, the extremely porous sands of the Benin Formation aquifer and heavy annual rainfall accelerate the vertical and lateral movement of leachates thereby endangering groundwater resources and public health. Although the environmental hazards associated with hydrocarbon pollution in the Niger Delta are well documented, little attention has been devoted to studies of agro-processing leachates, this remains a significant void in regional environmental studies (Airen & Osifo 2024; Anyanwu *et al*., 2023; Ohwoghere-Asuma *et al*., 2020).

Non-invasive geophysical methods are efficient means for delineating subsurface contamination without significant drilling. Electrical Resistivity Tomography (ERT) generates high resolution 2-dimensional (2D) images of the subsurface electrical resistivity structure in which regions with lower resistivity values (usually <100 Ωm) can be attributed to conductive leachate plumes and are characterized by high values of total dissolved solids (iyere *et al*., 2025; Mepaiyeda *et al*., 2025; Santos, 2006). The VLF-EM method quickly, and cost-effectively, delineates laterally extended areas of anomalous conductivity using the secondary magnetic field generated from conductive bodies. By integrating both methods, the interpretation confidence is greatly increased, reducing any ambiguity due to non-uniqueness that is inherent in single-method surveys and provides adequate characterization of the geometry, extent and migration pathway of the plume (Adeniji *et al*., 2024; Monteiro Santos *et al*., 2006).

It is important to note, however, that low resistivity anomalies are not exclusively indicative of leachate contamination. Clay horizons, saline groundwater, lateritic deposits, and seasonal variations in soil moisture could also generate similar anomalies (Mepaiyeda et al., 2025; Santos, 2006). Without hydrochemical and microbiological verifications petrophysical data from geophysical surveys are ambiguous and subject to misinterpretation. The identification of low-resistivity anomalies as palm kernel leachate in this study is based upon: (i) spatial coincidence with VLF-EM anomalies; (ii) association with waste disposal points; (iii) relatively shallow depth distribution indicative of recent surface disposal; (iv) local hydrogeology of the Benin Formation sands; and (v) hydrochemical verification by up- and down-gradient groundwater monitoring. At the same time the lack of borehole lithological data is acknowledged as an important limitation of this study.

In order to map the leachate plume and study the vulnerability of aquifer in Oghara, this study utilized ERT (Electrical Resistivity Tomography) and VLF-EM (Very Low Frequency - Electromagnetic) methods.

Study Area

The study was carried out in Oghara which is the administrative headquarters of Ethiope West Local Government Area (LGA), Delta State, South-South Nigeria. Oghara is situated on the western periphery of the Niger Delta Basin approximately between latitudes 5°56'N - 5°59'N and longitudes 5°39'E - 5°42'E, as a portion of Ethiope West LGA which covers a total area of 536 km². According to National Population Commission (2006), the population of Oghara is approximately more than 200,000, and this population continues to rise steadily due to agro-industrialization.

The climate in Oghara is tropical monsoon (Kppen Am) which features a long-wet season, lasting from March to November, and a short dry season, annual rainfall in the area is 2,000–3,000 mm; with July recording the highest rainfall. Typical daily temperatures in the area range between 24°C and 32°C; relative humidity is generally between 60 and 90%. These climatic conditions promote the decomposition of organic wastes and increase the generation and infiltration rate of leachate (Igben & Eregare, 2022).

Geologically, the area is underlain by the Benin Formation (Oligocene - Recent). The Benin Formation, predominantly characterized by thick, loose to semi-consolidated sands, with intermittent layers of clay and lignite is the dominant aquifer of the Niger Delta. The shallow aquifer, composed of coarse to medium-grained sands, is a major source of groundwater for drinking and irrigation in Oghara, and the high permeability of the sands combined with high precipitation renders the shallow aquifer highly susceptible to contamination (Egbai and Emuoibonuvie, 2020; Airen & Osifo 2023).

Oghara is well known as an area with relatively small and medium scale palm kernel processing, which generates large quantities of organic wastes (husks, press fibers and effluents) on site. These wastes are dumped adjacent to the processing plant and this generates conductive leachate that is high in organic acids and dissolved ions.

These dumping sites, most times are near settlement areas and shallow hand-dug wells or boreholes, thus a great potential for groundwater pollution exists.

The suitable climatic condition, abundance of agro-processing, and a receptive hydrogeological regime due to Benin formation make Oghara an appropriate place to investigate the infiltration of leachate plumes with combined ERI and VLF-EM geophysical techniques (Oseji *et al*., 2020).

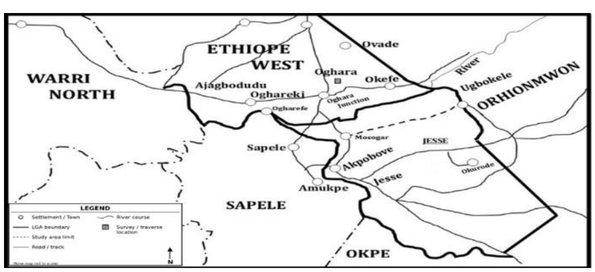

Figure 1: Map of Ethiope West Showing the Study Area

MATERIALS AND METHOD

Very Low Frequency Electromagnetic (VLF-EM) technique

VLF-EM data were collected utilizing naturally occurring radio waves (15-30 kHz) with a portable VLF receiver. At each station, both the real (in-phase) and imaginary (quadrature) components of the secondary magnetic field were recorded.

The obtained raw data was filtered using the Fraser filter to obtain positive peaks at points of zero-crossings for ease of identifying conductive features. The filter is defined as:

$$F_n = (M_{n+2} + M_{n+3}) - (M_n + M_{n+1}) \quad (1)$$

where F_n is the filtered value and M_n is the measured value at station n (Fraser, 1969).

Qualitative interpretation of the data was achieved with the use of Karous-Hjelt filtering technique which provides the pseudo-section of relative current density. A positive correlation for high current density values on the filtered data corresponds to conductive bodies corresponding to leachate plumes (Karous & Hjelt, 1983).

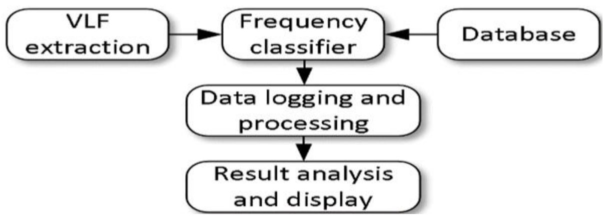

Figure 2: Workflow of Very Low Frequency (VLF) Survey

Electrical Resistivity Tomography (ERT)

A 2-D ERT was conducted using a PASI resistivity meter. The Wenner array arrangement was chosen because of its good signal strength and suitable nature for studying environmental contamination. The geometric factor for equal electrode spacing a is given by

$$K = 2\pi a \quad (2)$$

Apparent resistivity ρ_a is given by

$$\rho_a = K \cdot \frac{V}{I} = 2\pi a \cdot \frac{V}{I} \quad (3)$$

where V is the measured potential difference and I is the injected current (Loke, 2000). The results of the survey were inverted using the software RES2DINV. Low resistivity zones (< 97 Ωm) were inferred as the leachate-contaminated zones due to increased ionic content of water from palm kernel processing waste.

Data Quality Control and Survey Limitations

Various quality control measures were carried out during ERT acquisition including daily checks of electrode contact resistances and selective reciprocity measurements. Comprehensive reciprocity measurements, systematic contact resistance reporting, and detailed noise/error modeling were limited during this survey and should be considered as survey limitations. Topographic variations along the traverses were moderate and not corrected for during inversion, which may cause minor artifacts in the depth-direction but have little effect on the lateral extent of structures.

This study does not involve systematic groundwater water level measurements, assessment of hydraulic gradients or borehole lithology. Therefore, the identification of lateral variations in the extent of plumes and separation of lithology and contamination effects are based on relationships observed in the geophysical data, patterns in the location of waste dumps, and coincident hydrochemical measurements.

Hydrochemical Sampling and Analysis

To confirm suspected contamination sources and provide quantitative information on groundwater quality, ten (10) groundwater samples were taken from hand dug wells and boreholes both within and around the site during July 2025. Of these, 5 samples were taken up-gradient and 5 samples were taken within the plumes indicated by the geophysical surveys. With respect to the five (5) traverses, sampling was done within 12-38 m from the nearest wells.

The following in-situ measurements were made using a Hanna HI 98129 multiparameter probe pH, Electrical Conductivity (EC), and Temperature. The samples were taken using rinsed polyethylene bottles and stored in a cooler at 4 °C until analysis in the laboratory which was completed within six (6) hours of collection. Standard methods (APHA. 2017) were used to analyze Total Dissolved Solids (TDS) by gravimetry, Chloride (Cl^-) by Argentometry, Nitrate (NO_3^-) by UV Spectrophotometry, Sulfate (SO_4^{2-}) by Turbidimetry, Ammonium (NH_4^+) by Nesslerization, and Trace Metals (Fe, Mn, Pb, Cr) by Atomic Absorption Spectrophotometry. Standard procedures were used to determine total coliform and Escherichia coli by the Most Probable Number (MPN) method.

The results were compared to the Nigerian Standard for Drinking Water Quality (NSDWQ) (SON. 2007) and the World Health Organization (WHO) Guidelines for Drinking-water Quality (WHO. 2011) to interpret the results in relation to potability.

RESULTS AND DISCUSSION

Results

VLF Results

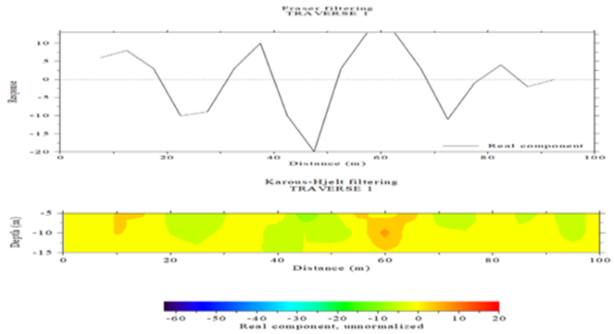

Figure 3: 2-D Conductivity Section Along Traverse 1

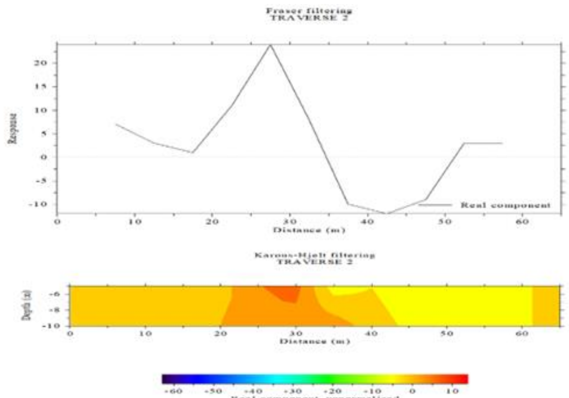

Figure 4: 2-D Conductivity Section along Traverse 2

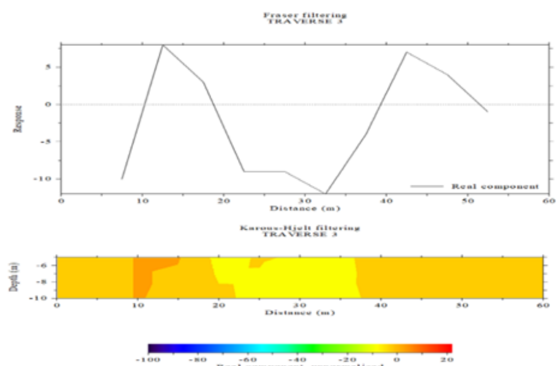

Figure 5: 2-D Conductivity Section along Traverse 3

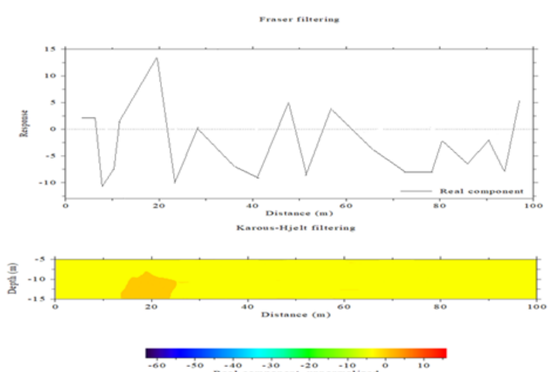

Figure 6: 2-D Conductivity Section along Traverse 4

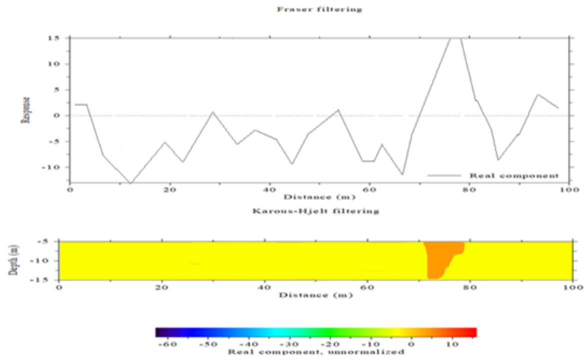

Figure 7: 2-D Conductivity Section along Traverse 5

ERT Result

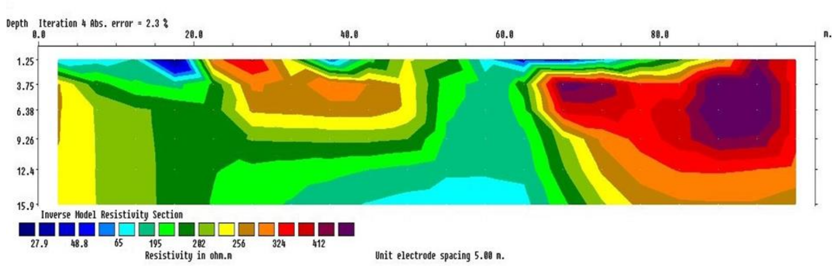

Figure 8: 2-D Resistivity Section along Traverse 1

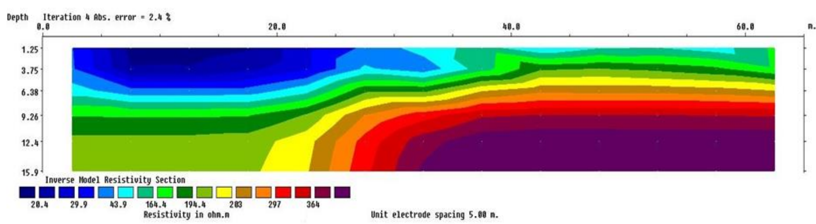

Figure 9: 2-D Resistivity Section along Traverse 2

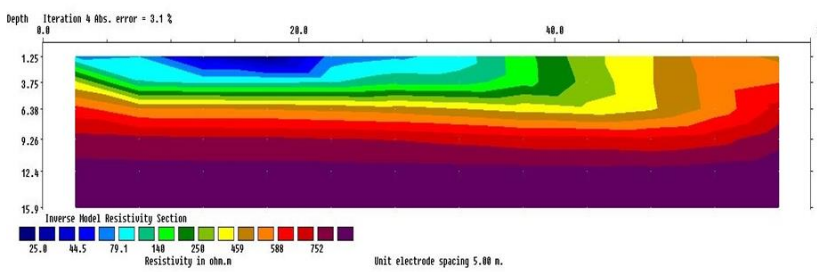

Figure 10: 2-D Resistivity Section along Traverse 3

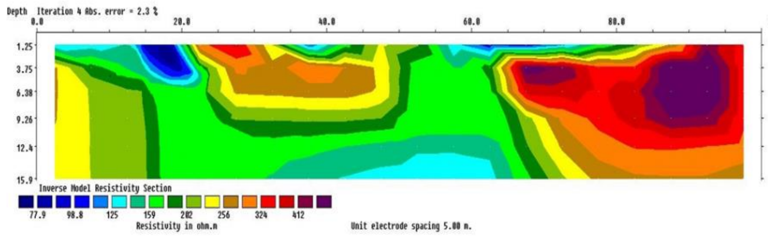

Figure 11: 2-D Resistivity Section along Traverse 4

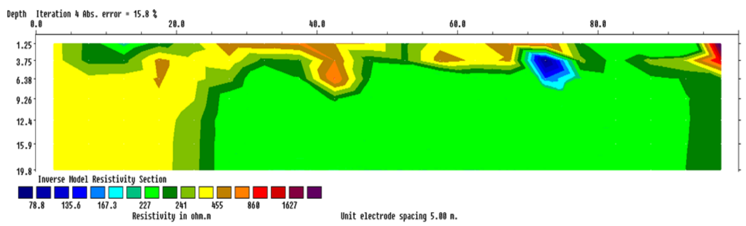

Figure 12: 2-D Resistivity Section along Traverse 5

Correlation of EM – VLF and 2D Resistivity Results

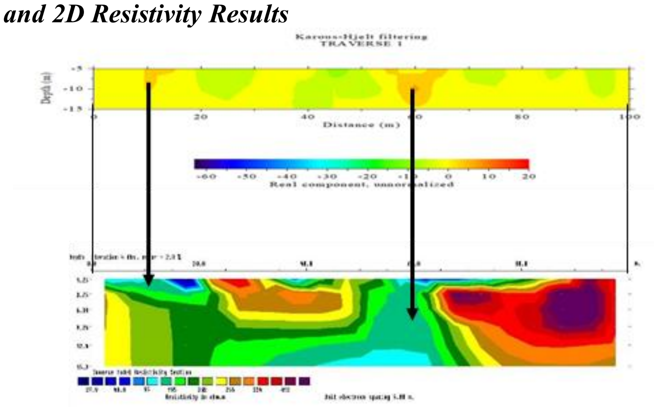

Figure 13: Correlation of VLF Conductivity & ERT Methods along Traverse 1

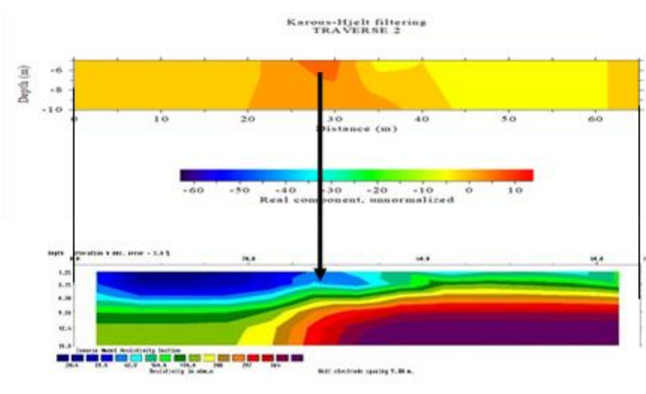

Figure 14: Correlation of VLF Conductivity & ERT Methods along Traverse 2

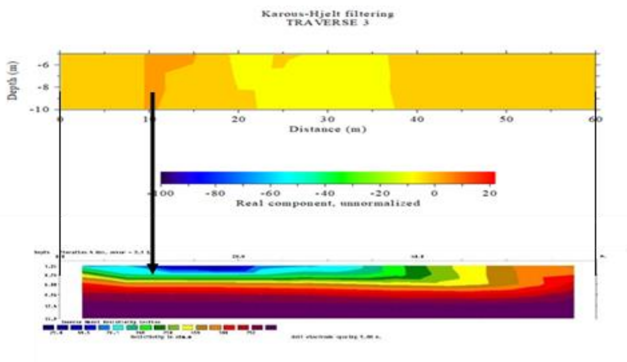

Figure 15: Correlation of VLF Conductivity & ERT Methods along Traverse 3

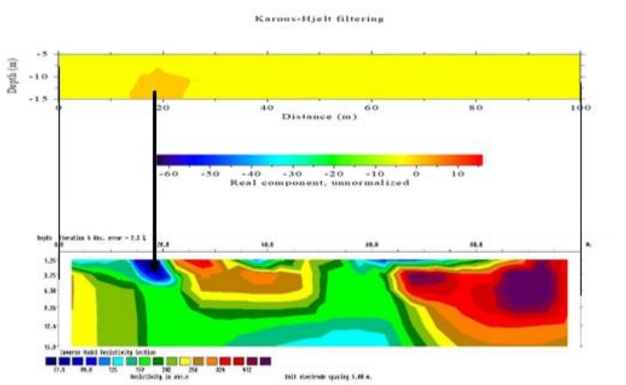

Figure 16: Correlation of VLF Conductivity & ERT Methods Along Traverse 4

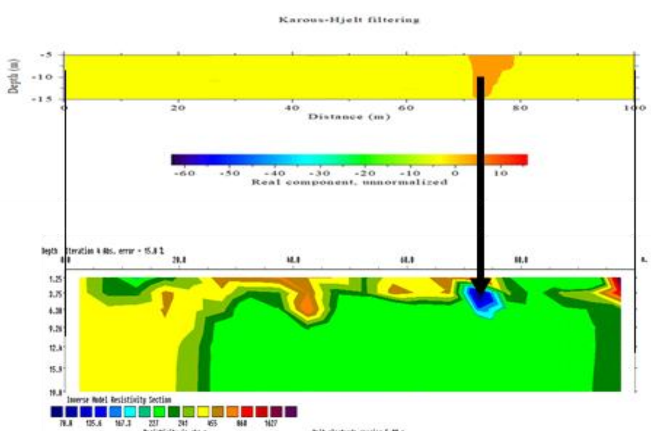

Figure 17: Correlation of VLF Conductivity & ERT Methods Along Traverse 5

Hydrochemical Characterization

The hydrochemical results (Table 1) indicate that groundwater samples collected from down-gradient (plume) locations have significantly higher electrical conductivity (EC), total dissolved solids (TDS), ammonium (NH_4^+), iron (Fe), manganese (Mn), and total coliform bacteria compared to those from up-gradient (background) and both exceed the NSDWQ and WHO standards.

Table 1 Hydrochemical Parameters of Groundwater Samples from Oghara Study Area

Parameter	Up-gradient Range (n=5)	Down-gradient Range (n=5)	NSDWQ Limit	WHO Limit	Exceedance Down-gradient
pH	6.2 – 6.8	4.8 – 5.6	6.5 – 8.5	6.5 – 8.5	Acidic
EC (μS/cm)	420 – 780	**2,480 – 6,200**	1,000	1,500	Yes
TDS (mg/L)	210 – 390	**1,240 – 3,850**	500	1,000	Yes
Cl^- (mg/L)	18 – 35	85 – 210	250	250	No
NO_3^- (mg/L)	2.1 – 8.4	28 – 62	45	50	Partial
SO_4^{2-} (mg/L)	12 – 28	45 – 118	100	250	Partial
NH_4^+ (mg/L)	0.05 – 0.18	**4.2 – 18.6**	0.2	0.5	Yes
Fe (mg/L)	0.08 – 0.22	**1.8 – 4.5**	0.3	0.3	Yes
Mn (mg/L)	0.02 – 0.08	**0.4 – 1.2**	0.2	0.1	Yes
Pb (mg/L)	<0.01	<0.01 – 0.03	0.01	0.01	Trace
Total Coliform (MPN/100 mL)	2 – 12	**2,400 – 8,100**	0	0	Yes
E. coli (MPN/100 mL)	0	**450 – 1,800**	0	0	Yes

The down-gradient wells, which are located within the geophysically defined plumes and close to the waste disposal sites, had EC values that were 3.2 – 14.8 times higher than the NSDWQ, TDS values were 2.5 – 7.7 times higher than the NSDWQ, and NH_4^+ levels that were 21 – 93 times higher than the NSDWQ. The total coliform and *E. coli* bacteria levels were also significantly higher, indicating groundwater pollution. Thus, the conductive anomalies identified by the geophysical methods are a manifestation of chemical and microbiological groundwater pollution.

Discussion

Very Low Frequency Electromagnetic (VLF-EM)

The VLF-EM survey and filtered with Fraser and Karous-Hjelt filtered images showed shallow conductive anomalies associated with the contamination from leachates generated from palm kernel agro-processing waste at Oghara in the South-South region of Nigeria. These anomalies observed from both filter modes which agree strongly suggest increase in conductivity at depths below the surface due to ionic content of waste from processing of palm kernel and effluent discharge.

On traverse 1 a prominent conductor anomaly around 60m in the near surface layer (~0 – 15m) was identified using both filters. A good correlation between the spike on the Fraser filter and the cluster of current density on Karous-Hjelt pseudo-section suggests that the conductor is real. This represents an encroaching contamination source as a result of accumulation of solid palm kernel processing waste and resultant release of dissolved ions that decrease resistivity at shallower levels.

A clear conductive anomaly at a very shallow level (~0 – 10 m) between 25m and 35m on traverse 2 is clearly defined on Fraser filter a prominent positive spike, and a thin conductive body at a very shallow depth of approximately 0 – 10m on Karous-Hjelt pseudo-section. The consistent results from the two filtering modes also indicate presence of conductor. This is likely related to a stream of chemical-rich effluent from palm kernel processing.

Moderate conductive anomaly existed at ~10 – 15m and 37 – 60m for traverse 3 both at shallow depth (~0 - 10m). The strong anomalies recorded by the filters suggests that the contamination here is directly related to dissolved organic material, oil and salt from palm kernel waste. Since these are occurring at a shallow depth, the first impact of the waste on topsoil can be expected and migration to deeper layer can occur if not treated.

The fourth traverse gave a clear conductive anomaly > 20m at shallow depth (~0 – 10m) indicated by sharp Fraser spike and conductive body in Karous-Hjelt pseudo-section. The existence is well explained as infiltration of leachate pore fluid due to unarranged disposal and long period discharge of palm kernel waste and effluent in the open.

A shallow (~0 – 15m) well-defined conductive anomaly occurred centered at 72 – 79m on the 5th traverse. The high values at the Fraser filter correspond to the shallow conductive anomaly delineated in Karous-Hjelt profile and confirm it as conductive plume. This anomaly is well expected at that depth owing to distinct geophysical contrast created by the high salts and organic matter content of palm kernel processing effluents. Though some faint anomalies are also observed along the traverse, the anomaly at 72 – 79m stands out both in intensity and vertical extent.

Electrical Resistivity Tomography (ERT)

The result of 2D ERT indicates that waste from the agro processing industry are actually polluting the study area Oghara. From Traverse 1, two anomalies of a conductive nature are indicated. The first is between the lateral positions 0m-20m while the second anomaly is between the lateral position 55m-68m and extends vertically between 3m and 15m with low resistivity values of between 30Ωm and 72Ωm, this is lower than that of the surrounding rock formation and represents zone with massive contamination and thus saturated with conductive ionic fluid originating from leachates of palm kernel waste. This lateral and vertical extensions imply continued seepage of waste into the subsurface with potential to infiltrate into deeper aquifer.

In the Traverse 2, there is a strong anomaly of a conductive nature between the lateral distance of 0m and 40m down to 7.0m vertical depth, with low resistivity values between 20.3Ωm and 58.3Ωm. The anomaly of such contrast with the rock implies infiltration of conductive fluids, characteristic of seepage of waste from the palm kernel processing. For traverse 3, the anomaly was observed between the horizontal distance of 0m and 34.2m with a vertical distance to 4.5m, with low resistivity between 39.2Ωm and 76.7Ωm. The shallow depth indicates recent or active disposal on the surface with consequent infiltration of palm kernel waste into the superficial layer.

In traverse 4, the 2-D ERT showed a well-defined conductive zone from 14.9-22 m along the horizontal direction. The anomalous body penetrates from surface to a depth of 5.2 m vertically and shows resistivity values from 77.9 to 95 Ωm. This pattern indicates the active movement of contaminants vertically through infiltration and that localized but concentrated soil contamination resulted from the disposing of waste material. For traverse 5, a sharp conductive anomaly occurred from 69.2-75.4 m laterally. The anomaly occurred between the depths of 3.3 to 7.5 m vertically and with resistivity values ranging from 79 to 95Ωm. These values may indicate that the groundwater in this part is highly conductive and saturated with moist and ionic contaminants which reflects contamination of ground water in this portion of the area due to the mobility of leachates from palm kernel agro-processing activities.

Correlation and Interpretation of ERT and VLF-EM Data

In the investigation of the traverses across the sites, excellent correlation between the VLF-EM conductive anomalies and the ERT low resistivity zones were recorded along the traverses (figure 13 to 17) indicating infiltration of leachate from the palm kernel waste. The ERT identified two zones of contamination along Traverse 1 from 0-20m lateral distance and 55-68m lateral distance that ranges from 2-3m and 15m depth respectively with resistivity value between 30-72 Ωm which correspond with the recorded conductive anomaly from +5 to +10 from the Fraser and Karous-Hjelt filtered section respectively. This agreement suggests high accumulation of electrically conductive ionic fluids.

On traverse 2, the VLF-EM data shows a noticeable conductor zone from 25-32 m on the Karous-Hjelt filtered image which coincides with the ERT section with very low resistivity zone from 0-35 m at a depth from 0- 7 m and resistivity 20.3-58 Ωm. Both the features of high conductivity and very low resistivity suggest saturation by leachates. On traverse 3, the Karous-Hjelt filtered VLF-EM image shows conductor between 10-12m from the profile and at low resistivity zone with resistivity 39.2-76.7 Ωm in the ERT profile extending up to 10 m and a depth of 4-6m which might be due to the shallow infiltration of wastewater from palm kernel processing activity. On traverse 4, there is good correlation of VLF-EM conductor at 17-22 m with the ERT section, and very low resistivity anomaly from 14.9-22 Ωm extending from 0 to 5.2 m depth and resistivity values 77.9-95m, that shows presence of localized contaminants within this zone. On traverse 5, the VLF-EM conductor from 70-80m (real part +5 near the anomalies) coincides with low resistivity anomaly at 69.2-75.4 Ωm from the ERT section between depth 3.3-7.8 m and resistivity value 79-95 Ωm.

Hydrochemical Validation of Geophysical Anomalies

The combined analysis of hydrochemical and geophysical data significantly improves the confidence in the interpretation of the geophysical anomalies. The ERT and VLF-EM methods identified conductive anomalies that are consistent with the low resistivity values (< 97 Ωm) and high apparent conductivity (35 – 65 mS/m; peak 80 mS/m on Traverse 2). These anomalies were also found to be associated with down-gradient groundwater samples that had EC values of 2,480 – 6,200 µS/cm and TDS of 1,240 – 3,850 mg/L.

The high NH_4^+ levels (4.2 – 18.6 mg/L) detected in the down-gradient groundwater samples provide further confirmation that the conductive anomalies identified by the geophysical methods are contaminated by palm kernel waste. This is in contrast to the background values of NH_4^+ (0.06 mg/L) and total coliform bacteria (< 10 MPN/100 mL) detected in the up-gradient groundwater samples. Similarly, the total coliform bacteria (2,400 – 8,100 MPN/100 mL) and E. coli (450 – 1,800 MPN/100 mL) levels detected in the down-gradient groundwater samples further confirm the presence of contamination by organic waste materials within the conductive anomalies. The absence of significant levels of Pb and Cr suggests that the pollution is not due to industrial effluents but is instead due to organic waste materials.

This study is relevant to the identified societal need of preventing groundwater contamination by identifying the potential sources of contamination and providing a scientific basis for their relocation. International guidelines for the siting of point sources of contamination stipulate a minimum distance of 30 – 100 m from water sources to prevent groundwater contamination (WHO, 2011; UNEP, 2003). Agro-industrial waste disposal sites should therefore be located at a distance of at least 30 – 100 m from water sources. The plumes identified by this study are located close to hand-dug wells and settlements. While the exact distances could not be determined due to the methodology used in this study, the findings suggest that groundwater contamination is likely to occur. As a screening tool, ERI can help identify potential areas of contamination. However, specific recommendations for the relocation of waste disposal sites would require additional hydrochemical and distance measurements, which this study has provided.

Complementary Methods for Future Investigation

While the combined analysis of ERT, VLF-EM and hydrochemical data has improved the confidence in the interpretation of the geophysical anomalies, it is important to recognize that the anomalies could also be caused by clay deposits. Future studies can use Induced Polarization (IP) surveys to distinguish between clay deposits and saline/contaminated groundwater by analyzing the chargeability characteristics of the subsurface. Self-Potential (SP) surveys can also be used to identify flow anomalies that could be associated with the leachate plumes. Shallow piezometric measurements can also help define the flow regime of the groundwater and therefore help assess the rate at which the leachate plumes are likely to migrate. We recommend that future studies consider using these additional methods to complement the findings of this study.

CONCLUSION

ERT and VLF-EM joint application and interpretation with hydrochemical data enabled defining the E. leachate from palm kernel agro-industrial wastes' extent in Oghara, South-South Nigeria. Indeed, ERT detected two distinct anomalous zones of low resistivity (20.3 – 95Ohm-meter) along 5 coinciding traverses, down to 15m depth. VLF-EM identified two conductor clusters shallower than 15m with a mean apparent conductivity of 35 – 65mS/m. The hydrochemical assessment of up and down gradient observation wells confirmed that the electrical conductivity, total dissolved solids, ammonium, iron, manganese, and mesophilic activity in the assigned plumes exceed the thresholds of the NSDWQ and WHO standards for potable water.

The leachate plume is laterally extensive (up to 68m) and vertically oriented towards an underlying shallow aquifer. Notably, the current dumpsite is within close proximity to domestic water sources and residential neighborhoods. As a result, the waste facility poses an elevated health risk to the locals due to leachate pollution. The dumpsite's spatial arrangement does not meet the minimum 50m setback distance recommended by the Nigerian environmental and agricultural policies, as well as the Food and Agriculture Organization. Nevertheless, the combined application of ERT and VLF-EM reduced the ambiguity of contamination in the study area. It is essential to note that without systematic borehole lithology and temporal measurements, the low-resistivity anomalies might be incorrectly associated with native deposits (e.g., clayey horizons or saline formations). Thus, the data should be used for screening assessments.

Therefore, we recommend considering an induced polarization survey, which can be effective in differentiating between clay and saline deposits, combined with a self-potential measurement to evaluate flow conditions. Shallow piezometric observations would help estimate the flow regime and direction, while seasonal measurements and comprehensive chemical analyses would verify temporal trends and provide a quantitative assessment of the pollution in Oghara, South-South Nigeria, and similar regions. Altogether, the study proved that the joint application of ERT, VLF-EM, and targeted hydrochemical analyses can be an effective and non-intrusive method to assess leachate plumes and develop remediation strategies for agro-industrial areas in tropical-savanna zones.

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