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Nature Environment & Pollution Technology

This is a peer-reviewed prepublished version of the paper to be published in Vol. 25, No. 4, December 2026 issue

Original Research

Laboratory Evaluation of Archie's Law in Kaolinite-Rich Land-fill Soil Under the Leachate Influence: A Mineralogical Control and Interpretation Limited by Uncertainty

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Key Words	Landfill contamination, Archie's law, Kaolinite, Electrical resistivity, Granular-clay transitional system
DOI	https://doi.org/10.46488/NEPT.2026.v25i04.D1920 (DOI will be active only after the final publication of the paper)
Citation for the Paper	Rizka, R., Mustofa, M.B., Iskandar, I., Warsa, W. and Santoso, D., 2026. Laboratory evaluation of archie's law in Kaolinite-rich land-fill soil under the leachate influence: A mineralogical control and interpretation limited by uncertainty, *Nature Environment and Pollution Technology*, 25(4), D1920. https://doi.org/10.46488/NEPT.2026.v25i04.D1920

ABSTRACT

Landfill contamination remains a major global environmental challenge, particularly in tropical regions where hydrogeochemical conditions can accelerate subsurface transport processes. However, the reliability of electrical resistivity interpretation in clay-rich and chemically aggressive soils remains highly debated. This laboratory-scale resistivity study evaluated the validity of Archie's Law using kaolinite-dominated soil collected from a tropical landfill, namely the Bakung Landfill, Indonesia, under controlled conditions of no fluid injection (dry condition), saturation with pure water, and saturation with leachate. X-ray diffraction (XRD) analysis indicated that kaolinite was the dominant mineral phase, while scanning electron microscope (SEM) observations revealed discontinuous clay layers that increased pore tortuosity without forming dominant conductive pathways. Despite significant ionic interference from landfill leachate, laboratory resistivity measurements maintained consistent scaling exponents, producing cementation exponent values ranging from 2.22 to 2.53 (R^2 = 0.69–0.81). Statistical analysis was conducted using regression confidence intervals, bootstrap resampling with 10000 iterations, and Monte Carlo uncertainty propagation incorporating realistic laboratory uncertainties (resistivity ±3%; porosity ±2%). The Monte Carlo confidence limits, ranging from 1.80 to 2.95, indicate stable parameter behavior within the granular–clay transitional system. These findings suggest that kaolinite-rich tropical landfill soils represent a transitional electrical system in which laboratory-calibrated Archie parameters remain statistically stable, thereby strengthening the environmental reliability of resistivity-based landfill risk evaluation.

1. INTRODUCTION

Landfills worldwide are increasingly becoming a significant source of environmental pressure on soil and groundwater, primarily through the production of ion-rich leachate containing dissolved organic compounds and heavy metals. Landfill leachate is a highly complex wastewater containing a wide range of organic and inorganic pollutants that can pose significant environmental risks if not properly managed(Rajesh and Saravanakumar, 2025). Subsurface leachate migration can alter the physical and chemical properties of soil, accelerate contaminant transport, and increase the risk of shallow aquifer contamination, particularly when these aquifers serve as water sources for surrounding communities. This risk becomes more critical in tropical regions, where high rainfall intensity and dynamic hydrogeochemical conditions accelerate contaminant mobility within porous media. Therefore, accurate subsurface monitoring is urgently needed for environmental risk management around landfill areas. In this context, electrical resistivity has been developed as an effective monitoring tool because of its ability to non-invasively detect changes in soil physical properties related to porosity, fluid saturation, and ionic conductivity (Pandey & Shukla, 2019; Islam *et al.* 2024). Thus, electrical resistivity has strong potential as a preliminary diagnostic tool for environmental contamination, although its quantitative interpretation still faces fundamental uncertainties.

The relationship between electrical resistivity and the physical properties of porous media was classically described by Archie's law, which relates bulk resistivity to porosity and the degree of fluid saturation through a power-law relationship (Archie, 1942). This model has been widely used in hydrogeology and environmental geophysics to estimate soil parameters such as porosity, volumetric water content, and even permeability (Matsui *et al.* 2016; Rosli *et al.* 2020). However, Archie's formulation was developed under the assumption that electrical conduction is dominated by pore fluid, while the mineral matrix is electrically inert. In soils containing clay minerals or experiencing chemical disturbances caused by leachate contamination, this assumption is often not valid because of the contribution of surface conduction and the effects of the electrical double layer on mineral particles (Godio and Chiampo, 2023). Consequently, the application of Archie's law to clay-rich soils remains a subject of debate in modern environmental geophysics.

Recent experimental studies have shown that soil resistivity response is simultaneously influenced by porosity, fluid saturation, soil mineralogy, and pore fluid chemistry. A laboratory study conducted by Ansari *et al.* (2021) showed that increasing leachate content significantly reduced soil resistivity because of the rise in pore fluid ionic conductivity. Another study conducted by Jia *et al.* (2020) demonstrated that complex resistivity analysis could be used to estimate saturation and permeability in soil systems through laboratory experiments. Furthermore, recent mineralogical characterizations indicate that the composition of clay minerals, such as kaolinite, quartz, and accessory minerals, can control resistivity response through changes in microstructure and pore structure tortuosity (Oumla *et al.* 2022; Ojo *et al.* 2024). Overall, these studies demonstrate that integrating resistivity measurements with mineralogical analysis is crucial for understanding electrical conduction mechanisms in complex soil systems.

Despite these advances, several critical gaps remain in the literature. Most environmental resistivity studies still focus on field-data interpretation without directly linking mineral microstructural control to the petrophysical parameters of Archie's law. Furthermore, only a limited number of studies systematically integrate detailed mineralogical characterization with laboratory resistivity testing under different hydrogeochemical conditions. More importantly, uncertainty quantification of petrophysical parameters using modern statistical approaches such as bootstrapping and Monte Carlo simulation is still rarely applied in soil resistivity studies, even though these methods are essential for producing reliable parameters in environmental risk evaluation (Cuesta-Valero *et al.* 2022). Therefore, a research framework capable of integrating mineralogy, petrophysics, and uncertainty analysis within a single approach is still needed.

To address this gap, this study conducted an experimental evaluation of Archie's law in kaolinite-dominated landfill soil collected from a tropical environment, namely the Bakung Landfill in Bandar Lampung. Resistivity measurements were conducted at the laboratory scale under three controlled hydrogeochemical conditions: no fluid injection (dry condition), saturation with pure water, and saturation with leachate. These conditions were designed to evaluate the porosity–resistivity and saturation–resistivity relationships in kaolinite-rich soil. Mineralogical analysis using X-ray diffraction (XRD) and microstructural characterization using a scanning electron microscope (SEM) were performed to identify mineralogical controls on electrical conduction mechanisms. The stability of Archie's parameters was then evaluated through deterministic regression combined with bootstrap resampling and Monte Carlo simulation. By integrating petrophysical, mineralogical, and uncertainty quantification approaches within a single laboratory experimental framework, this study provides mineralogically calibrated Archie's parameters for tropical landfill soil and offers a more transparent and risk-based basis for resistivity interpretation in environmental contamination monitoring.

2. MATERIALS AND METHODS

2.1. Materials

2.1.1. Soil

The soil used in this study was collected from the Bakung Landfill in Bandar Lampung. Seven soil samples, namely L1B, L2A, L2B, L3A, L4A, L4B, and L5A, were collected for laboratory analysis. The samples were subsequently dried in a dry heat oven at 110°C for 24 hours to ensure complete drying and the removal of residual fluids. The physicochemical parameters of the soil samples are presented in Table 1.

Table 1: The physicochemical parameters of the soil samples

Sample ID	pH	Humidity (%)	Temp (^{0}C)
L1B	6.00	68.00	32.00
L2A	5.50	63.00	33.00
L2B	5.00	71.00	36.00
L3A	5.50	78.00	27.00
L4A	7.00	79.00	30.00

Sample ID	pH	Humidity (%)	Temp (^{0}C)
L4B	7.00	77.00	28.00
L5A	7.00	67.00	29.00

2.1.2. Water

The water used in this study consisted of pure water and leachate collected from the Bakung Landfill. These two types of water were used to compare soil saturation conditions under pure water and leachate exposure. The physicochemical parameters measured for both pure water and leachate included temperature, pH, resistance, salinity, hardness, conductivity, and total dissolved solids (TDS), as presented in Table 2.

Tabel 2: The data of water quality pure water and leachate

Parameter	Pure water	Leachate
Temperature	25.2 ^{0}C	25 ^{0}C
pH	7.1	8.27
Resistance	6008 Ω	86.70 Ω
Salt	0%	0.6 %
Hardness	83.2 ppm	5750 ppm
Conductivity	165.4 µS/cm	11440 µS/cm
TDS	109.8 ppm	7640 ppm

2.2. Methods

2.2.1. Geoelectrical Resistivity Test

Seven soil samples collected from the Bakung Landfill, Lampung, Indonesia, were used in this study. Each sample was subjected to three treatment conditions: no fluid injection (dry condition), saturation with pure water, and saturation with leachate. Prior to testing, the soil samples were sieved using a USA Standard test sieve (ASTM E11) and oven-dried at 110°C for 24 hours. The prepared samples were then placed into glass cylinders with a height of 10 cm and a diameter of 3.8 cm.

Electrical resistivity measurements for each soil sample were conducted using the four-electrode method with a sample holder consisting of four metal electrodes arranged at nearly equal spacing, following Australian Standard AS 1289.4.4.1-1997 (Pandey and Shukla, 2019). The resistivity measurement system consisted of a resistivity meter connected to two multimeters, a 12 V battery, and a four-electrode sample holder. The components were interconnected using cables according to positive and negative electrical polarity to measure electric voltage and current during the testing process. The DC input was connected to the resistivity meter to display voltage and current values throughout the measurements. The use of the four-electrode configuration minimized the influence of contact resistance on the measurement results. The electrodes consisted of C1 and C2 as current electrodes, and P1 and P2 as potential electrodes (Fig. 1).

Fig. 1: Soil resistivity measurement

2.2.2. Initial Soil Resistivity Measurement

Initial soil resistivity measurements were conducted on untreated soil samples. The measurement system consisted of a resistivity meter (microcontroller-based) connected to a sample holder. Soil from each container was divided into three smaller samples and placed into the sample holder for testing. The resistivity of each sample was measured four times, and the average value was subsequently calculated.

2.2.3. Resistivity Measurement Using Saturation with Pure Water and Saturation with Landfill Leachate

This measurement was conducted to evaluate the porosity–resistivity and saturation–resistivity relationships of the soil samples. Resistivity testing is commonly performed under fully saturated conditions. However, dry-condition measurements were also included in this study to support the interpretation of the overall resistivity response. The resulting porosity values ranged from 49.59% - 61.98%.

Dry soil was placed into each sample holder with different porosity levels. Resistivity measurements were conducted in two stages. The first measurement was performed under no fluid injection (dry condition), whereas the second measurement was carried out after the injection of pure water and landfill leachate at saturation intervals of 10%, 25%, 40%, 55%, 70%, 85%, and 100% (fully saturated), depending on the porosity of each sample holder. Repeated measurements were conducted over approximately three days until stable resistivity values were obtained.

2.2.4. Porosity Measurement

Porosity refers to the empty space contained within a rock or soil material. Its value is expressed as a percentage (%) and is calculated by dividing the pore volume by the total rock volume. Porosity measurements were conducted using the following equation (Fetter, 1994):

$$\phi = \frac{V_{pore}}{V_{bulk}} = \frac{V_{bulk} - V_{solid}}{V_{bulk}} \times 100\% \quad (1)$$

$$V_{solid} = \frac{m}{\rho} \quad (2)$$

where V_{pore} is the total pore volume of the rock, V_{bulk} is the total volume of the rock affected by fluid content, V_{solid} is the volume of the solid mineral component in the rock, m is the mass of the rock sample, and ρ is the rock density.

2.2.5. Archie's Law Calculation

The relationship between resistivity, saturation, and porosity in the samples was calculated using Archie's Law (1942), as follows:

$$f=\frac{\rho_0}{\rho_w}=aSw^{-n} \quad (3)$$

where the resistivity of the soil containing water is directly proportional to the resistivity of the groundwater. In this equation, f represents the formation factor, ρ_0 is the resistivity of the soil at 100% saturation, and ρ_w is the resistivity of the saturating fluid.

Archie (1942) further expressed the relationship between porosity and the formation factor using the following equation:

$$f=\frac{a}{\phi^m} \quad (4)$$

where a and m are experimentally determined constants that vary according to grain size, grain sorting, and rock texture.

By combining Equations (3) and (4), the following Archie resistivity equation is obtained:

$$S_w=\left(\frac{1}{f}\right)^{\frac{1}{n}} \quad (5)$$

$$Sw^n=\frac{a\rho_w}{\phi^m\rho_0} \quad (6)$$

$$\rho=a\rho_w\phi^{-m}Sw^{-n} \quad (7)$$

Where:

ρ_0 : soil resistivity when the soil is at maximum saturation (Ωm)

ρ : soil resistivity when the water has a certain saturation or water content (Ωm)

a : turbulence factor

m : cementation exponent

n : saturation exponent

ρ_w : water resistivity (Ωm)

Φ : porosity (%)

Sw : water saturation or water content in the soil (%)

2.2.6. Soil Mineralogy Determination

A scanning electron microscope (SEM) was used to obtain detailed information regarding the soil components from the Bakung Landfill. The analysis aimed to identify the presence of clay minerals within the soil samples. For SEM analysis, 10 g of each sample was crushed to a particle size of <5 μm and observed at magnifications of up to 10000x.

Soil mineralogy was also analyzed using X-ray diffraction (XRD). XRD is a method that utilizes electromagnetic radiation with short wavelengths based on interatomic or crystal lattice spacing. The analysis was conducted to identify the chemical characteristics and dominant mineral types present in the soil samples.

3. RESULTS

3.1. Mineralogical and Microstructural Characterization

X-ray diffraction (XRD) analysis showed that the soil samples collected from the Bakung Landfill were dominated by kaolinite, with minor amounts of quartz and accessory minerals such as cristobalite and muscovite (Fig. 2). No significant expansive clay minerals, such as smectite, were identified. The dominance of kaolinite indicates a non-swelling 1:1 clay mineral system with relatively low cation exchange capacity. The abundance of quartz suggests the presence of a sandy matrix, while muscovite and iron oxides may contribute to local conduction heterogeneity.

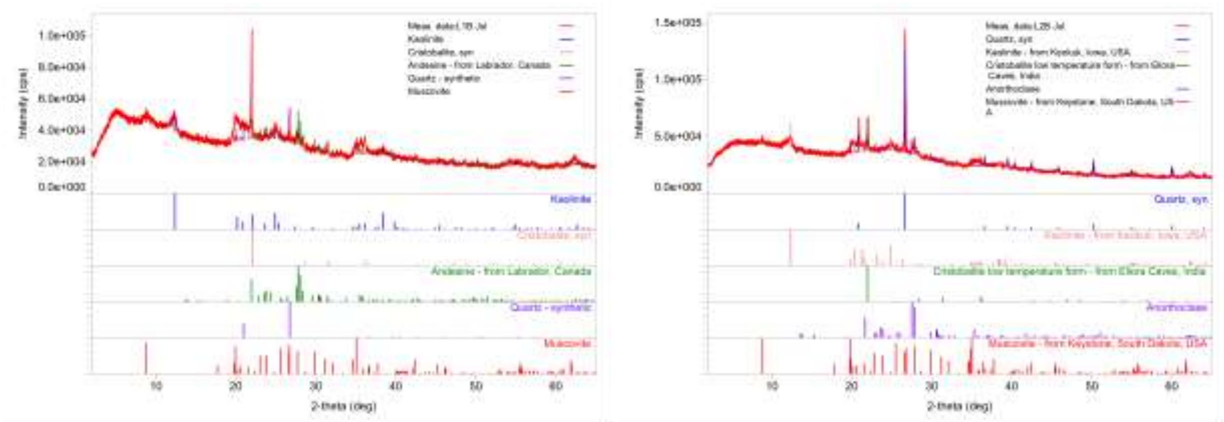

Fig 2. The results of X-Ray Diffraction (XRD) on the sample

Scanning electron microscope (SEM) observations revealed a heterogeneous microstructure characterized by granular particles coated with soft clay material (Fig. 3). Kaolinite also appeared as discontinuous layers along grain boundaries and within microporous domains. Microporosity was clearly observed, particularly within fine-grained aggregates, indicating increased tortuosity within the pore network.

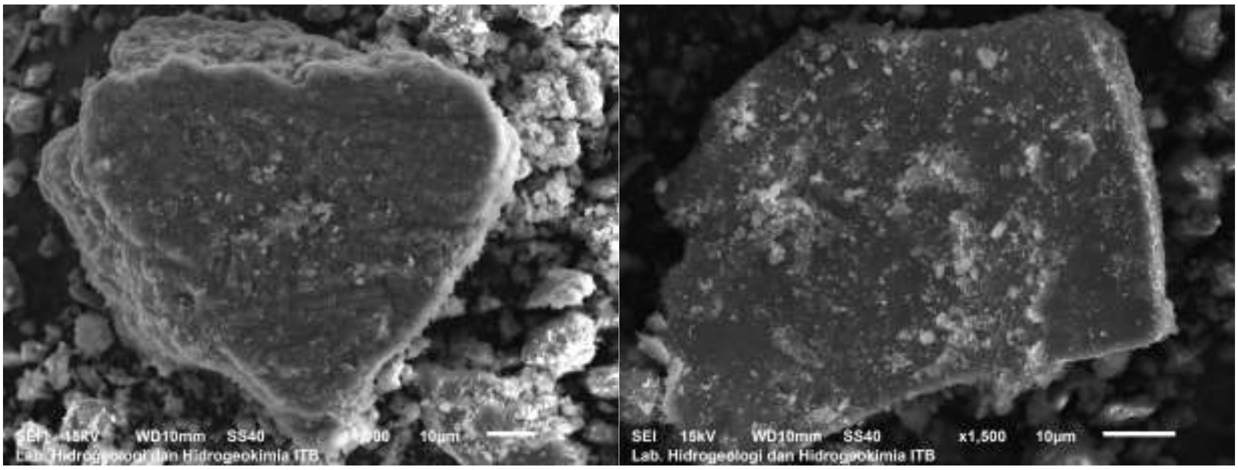

Fig 3. The results of Scanning Electron Microscopy (SEM) on the samples

Mineralogical analysis (Fig. 4) indicates that kaolinite is the dominant mineral component, comprising approximately 35.6% of the sample composition, followed by quartz at 34.5%, muscovite at 14.2%, cristobalite at 3.6%, and smaller proportions of goethite (2.2%), magnesioferrite (2.4%), andesine (2.5%), anorthoclase (2.3%), albite (1.3%), labradorite (1.2%), and hydrotalcite (0.1%). These values were estimated using a semi-quantitative approach based on the intensity of major peaks in the XRD patterns. Prominent peaks were identified for kaolinite at 12.3° and 24.8° 2θ, while quartz showed a strong peak at approximately 26.6° 2θ.

Scanning electron microscope observations at the microscale revealed that clay particles were unevenly distributed and frequently formed aggregates. This condition created a complex pore network with tortuous fluid-flow pathways. Such a microstructure directly affects the electrical resistivity response because the presence of kaolinite and the heterogeneous pore geometry tend to increase the cementation exponent (m) by producing more complex electrical conduction pathways. This interpretation corresponds with the resistivity measurements, which produced mmm values ranging from 2.219 to 2.534, highlighting the influence of microstructural heterogeneity on the porosity–resistivity relationship. In addition, the presence of relatively inert non-clay minerals such as quartz also affects current distribution, resulting in a resistivity response controlled by both pore-fluid conduction and pore geometry.

However, it should be noted that this mineralogical analysis remains semi-quantitative and does not directly measure surface conduction contributions. Therefore, the interpretation of the relationship between mineralogy and Archie's parameters still requires further validation through additional analyses, such as cation exchange capacity (CEC) measurements or complex resistivity testing.

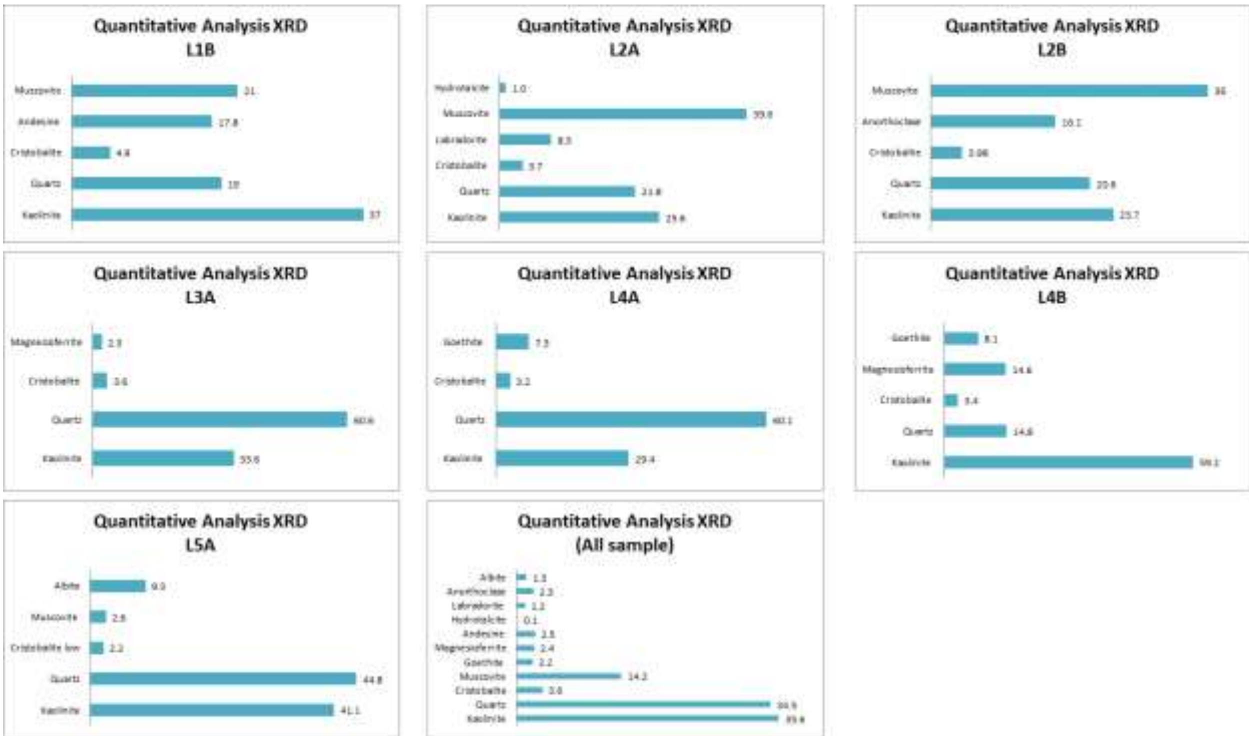

Fig 4. The quantitative analysis XRD on the samples

3.2. The Results of Porosity–Resistivity and Saturation–Resistivity with Uncertainty Evaluation

Laboratory resistivity measurements showed a consistent decrease in resistivity following a power-law relationship with increasing porosity under no fluid injection (dry condition) (Fig. 5), saturation with pure water (Fig. 6), and saturation with leachate (Fig. 7). The laboratory results presented in Fig. 5 show higher resistivity values under dry conditions because of the reduced conductive pathways associated with air-filled pores. The increase in the cementation exponent (m) reflects greater tortuosity and lower connectivity of the conductive pathways. Despite variability in saturation conditions, the power-law relationship remained statistically robust, indicating that structural controls dominated the electrical behavior of the samples. These findings suggest that saturation conditions significantly influence resistivity response in clay–granular transition systems.

Fig. 6 illustrates that the regression follows a power-law pattern consistent with Archie's formulation, producing cementation exponent (m) values within the expected range for granular to layered clay-based media. The logarithmic trend shows decreasing resistivity with increasing porosity, reflecting enhanced fluid-pore connectivity. The relatively high R^2 values indicate stable pore-fluid-dominated conduction, whereas the minor data scatter may be associated with the microstructural heterogeneity observed in the SEM analysis. This behavior confirms that, in kaolinite-dominated systems saturated with low-ionic fluids, electrical conduction is primarily controlled by the bulk pore-fluid system rather than by surface conduction mechanisms.

Fig. 7 shows that resistivity values decreased because of the higher ionic content of the leachate, resulting in increased bulk conductivity. Although the power-law relationship remained observable, the greater dispersion of the data reflects chemical heterogeneity and local microstructural variability. The cementation exponent (m) remained within physically realistic limits, indicating that Archie's law is still applicable in kaolinite-rich soils despite the influence of leachate.

The porosity–resistivity relationship under no fluid injection (dry condition) (Fig. 5) shows a power-law pattern with cementation exponent (m) values ranging from approximately 2.3 to 2.5 and coefficients of determination (R^2) between 0.69 and 0.75. Resistivity decreases significantly with increasing porosity, where samples with porosity values of approximately 45–50% exhibit higher resistivity than samples with porosity approaching 60%.

Under saturation with pure water (Fig. 6), the cementation exponent (m) ranges from approximately 2.2 to 2.4, with R^2 values of approximately 0.75–0.81. The absolute resistivity values are lower than those observed under unsaturated conditions at similar porosity levels. Under saturation with leachate (Fig. 7), resistivity decreases further, with mmm values ranging from approximately 2.3 to 2.5 and R^2 values of approximately 0.70–0.78. Although the absolute resistivity values are lower than those under pure water saturation, the porosity–resistivity relationship continues to follow a consistent power-law trend.

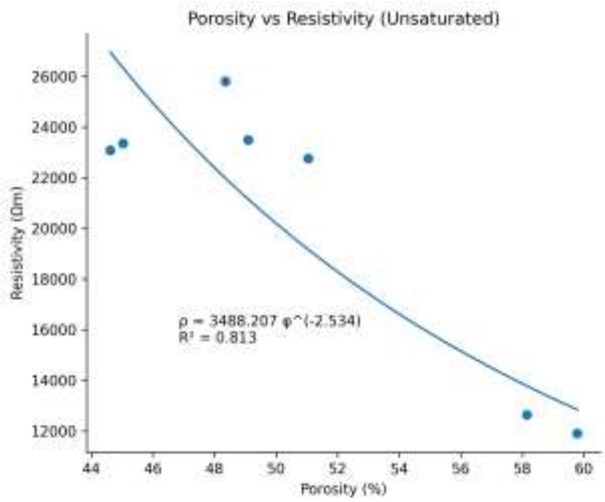

Fig. 5 Laboratory-derived relationship between porosity (%) and bulk resistivity (Ωm) under no fluid injection (dry condition)

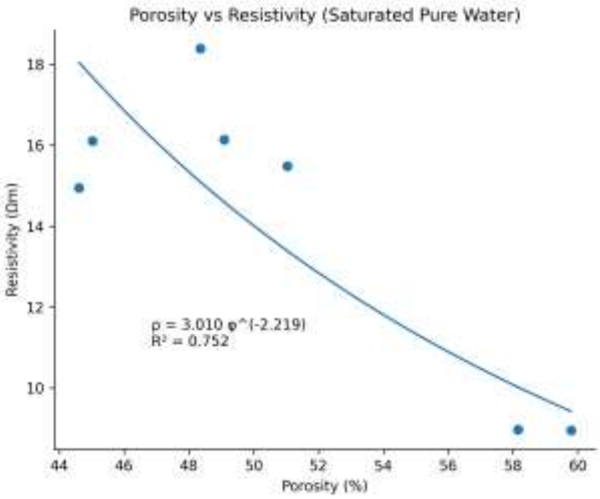

Fig. 6 Laboratory-derived relationship between porosity (%) and bulk resistivity (Ωm) under saturation with pure water

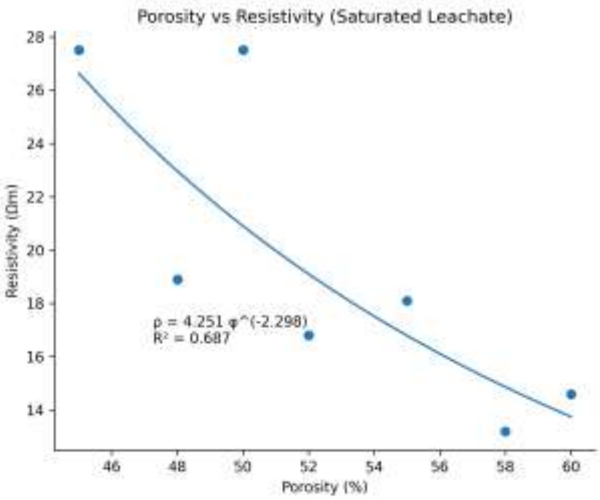

Fig. 7 Laboratory-derived relationship between porosity (%) and bulk resistivity (Ωm) under saturation with leachate

The saturation–resistivity relationship under pure water saturation conditions (Fig. 8) shows saturation exponent (n) values ranging from approximately -2.340 to -2.640, with R^2 values of approximately 0.935–0.987. Under leachate-saturated conditions (Fig. 9), resistivity decreases further, with saturation exponent (n) values ranging from approximately -2.686 to -3.580 and R^2 values of approximately 0.798–0.981. Although the absolute resistivity values are lower than those under pure water saturation, the saturation–resistivity relationship continues to follow a consistent trend.

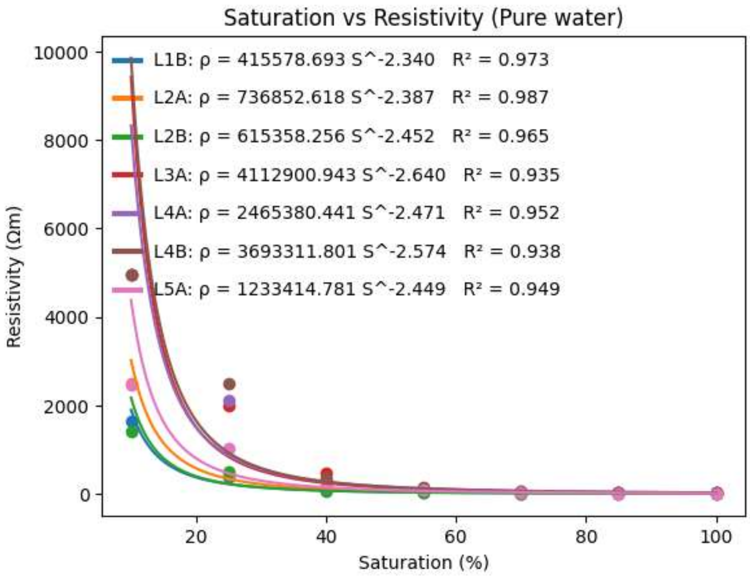

Fig. 8 Laboratory-derived relationship between saturation (%) and bulk resistivity (Ωm) under saturation with pure water

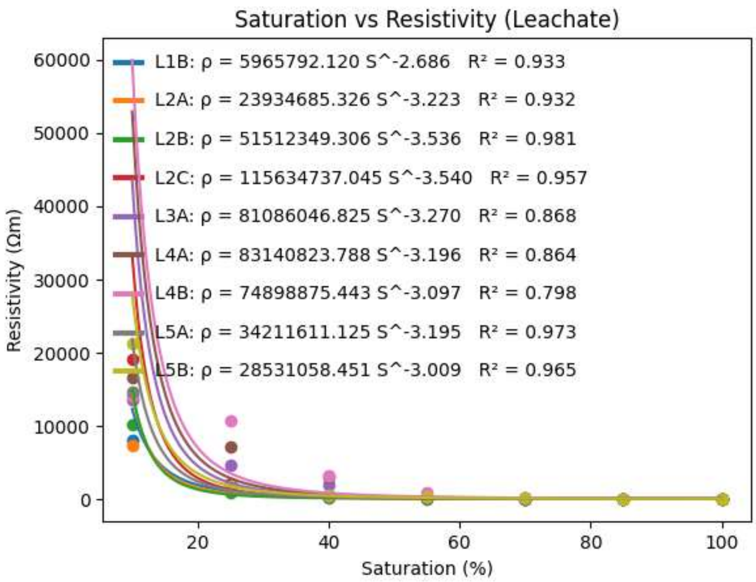

Fig. 9 Laboratory-derived relationship between saturation (%) and bulk resistivity (Ωm) under saturation with leachate

Bootstrap resampling (10000 iterations) shows that the estimated cementation exponent (m) is statistically stable (Fig. 10). The bootstrap distributions of the cementation exponent under unsaturated, pure water-saturated, and leachate-saturated conditions exhibit unimodal patterns that are approximately normally distributed. The mean bootstrap values for each condition are close to those obtained from deterministic regression. The 95% confidence intervals (CI), calculated from the 2.5th and 97.5th percentiles, indicate a limited range of parameter variation and do not produce extreme values beyond physically reasonable limits.

Monte Carlo simulation conducted with uncertainty propagation measurements (±2% porosity and ±3% resistivity) produced narrower parameter distributions than the bootstrap analysis. The mean values obtained from the Monte Carlo simulation were consistent with the initial regression results, while the 95% confidence intervals (CI) indicated relatively small ranges of variation under the three saturation conditions. Overall, both the bootstrap and Monte Carlo methods produced stable parameter estimates for all tested conditions (Fig. 11). The values of m, n, R^2, confidence intervals, bootstrap results, and Monte Carlo results are presented in Table 3.

Tabel 3: Comparison m, n, R^2, confidential interval, bootstrap, and Monte Carlo results

Condition	m	n	m R^2	m 95% CI low	m 95% CI high	m Bootstrap 2.5%	m Bootstrap 97.5%	m Monte Carlo 2.5%	m Monte Carlo 97.5%
Pure Water	2.219	-2.473	0.752	0.754	3.683	-0.552	3.610	1.801	2.618
Leachate	2.298	-3.194	0.687	0.517	4.079	1.127	3.790	1.806	2.753
Unsaturated	2.534	-	0.813	1.135	3.933	-0.243	3.832	2.080	2.964

4. DISCUSSION

4.1. Resistivity as a Representation of Soil Physical Properties

The laboratory results indicate that the electrical resistivity of kaolinite-rich soil from the Bakung Landfill has a systematic relationship with porosity and degree of saturation. These findings are consistent with previous studies showing that resistivity can be used indirectly to estimate soil physical parameters such as porosity, bulk density, and volumetric water content (Al-qaysi and Sadrekarimi, 2015; Rosli *et al*. 2020). This correlation is generally explained by Archie's formulation, in which resistivity increases as porosity and saturation decrease because of the reduced continuity of fluid-conduction pathways (Mustofa *et al.* 2022).

The relationship between resistivity and soil particle size has also been reported in soil-site investigation studies by Chik and Islam (2012), who showed that grain-size distribution and soil texture influence flow-path geometry and electrical resistance. In the context of the Bakung Landfill, the dominance of kaolinite identified through XRD analysis and the plate-like microstructure observed in the SEM images indicate increased tortuosity without forming a continuous conductive matrix. This interpretation is consistent with the findings of Oh and Park (2018), who emphasized that mineralogy and pore-water chemistry jointly control the resistivity response in saturated soils.

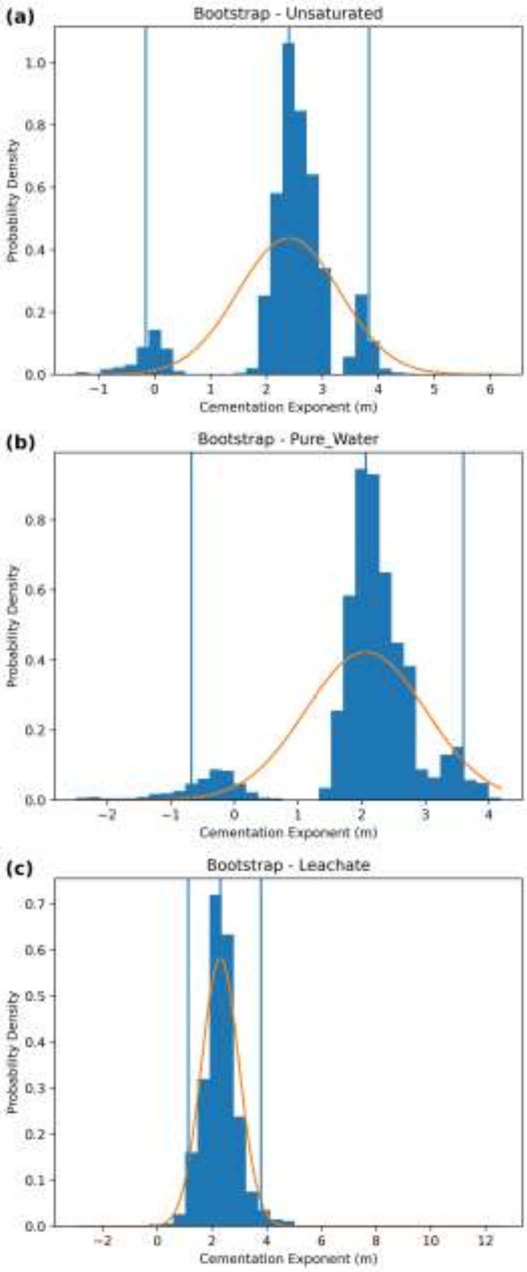

Fig. 10 Bootstrap distribution of the cementation exponent (m) under (a) no fluid injection (dry condition), (b) saturation with pure water, and (c) saturation with leachate

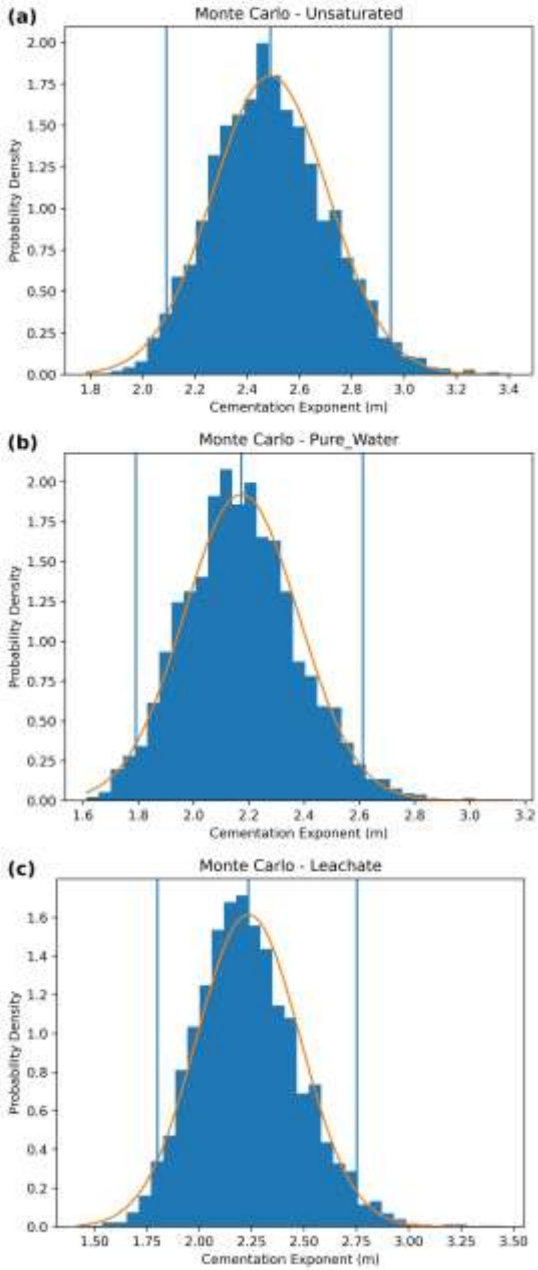

Fig. 11 Monte Carlo-derived uncertainty distribution of the cementation exponent (m) under (a) no fluid injection (dry condition), (b) saturation with pure water, (c) saturation with leachate

4.2. The Role of Kaolinite in Conduction Mechanisms

Based on the XRD and SEM analyses, the soil samples were confirmed to contain clay minerals dominated by kaolinite. Clay minerals generally form through the chemical weathering of silicate minerals involving reactions with carbonic acid, resulting in silicate hydration processes. The presence of silicate-derived clay minerals may contribute to retardation processes within the soil system. In landfill environments, clay minerals can also function as natural damping or buffering materials against leachate migration.

Kaolinite generally exhibits lower surface conductivity than expansive clay minerals. A study on the behavior of kaolinite as a landfill barrier material by Cuevas *et al.* (2009) indicated that non-expansive clay minerals tend to maintain pore-fluid-dominated conduction rather than surface conduction. Similar findings were reported by Oumla *et al.* (2022) and Ojo *et al*. (2024), who emphasized the importance of mineralogical and physicochemical characteristics in controlling the electrical response of clay-rich materials.

The cementation exponent (m) values obtained in this study fall within a transitional range, indicating increased tortuosity caused by kaolinite particle coatings without suggesting dominant surface conduction. This interpretation is consistent with the conceptual approaches proposed by Matsui *et al.* (2016) and Sawayama *et al.* (2023), who related resistivity behavior to tortuosity and percolation flow pathways. Therefore, these results suggest that electrical conduction in the Bakung Landfill soil is still primarily controlled by pore-fluid pathways despite the influence of clay minerals.

4.3. The Effect of Leachate on Resistivity Response

Saturation with leachate resulted in lower absolute resistivity values compared with pure water saturation, but it did not produce drastic changes in the saturation exponent values. This phenomenon is consistent with laboratory studies showing that increased salinity enhances pore-fluid conductivity without fundamentally altering pore-structure geometry (Oh and Park, 2018; Ansari *et al.* 2021).

A study by Carpenter *et al.* (2009) on formation factors under leachate and waste saturation conditions also showed that, despite the decrease in total resistivity, the porosity–resistivity relationship could still be explained using Archie's approach with appropriate calibration. Wang *et al.* (2020) further reported that microstructural changes caused by leachate exposure may affect soil permeability and structural properties; however, these effects are more strongly associated with changes in absolute resistivity values than with fundamental changes in power-law scaling behavior.

In an environmental context, these findings are important because they indicate that a decrease in resistivity caused by leachate does not automatically imply increased contaminant migration. Instead, the resistivity response should be interpreted together with porosity and saturation parameters to obtain a more reliable understanding of subsurface contamination conditions.

4.4. Sensitivity Analysis and Mineralogical Implications

The sensitivity analysis indicates that uncertainty in the petrophysical parameters of the kaolinite-rich soil from the Bakung Landfill is more strongly influenced by pore-structure heterogeneity than by laboratory measurement error. The wider bootstrap distribution compared with the Monte Carlo distribution confirms that microstructural variability, rather than instrumental noise, is the primary source of uncertainty. This type of uncertainty quantification approach has been recommended in recent geoscience literature to produce defensible parameters for environmental applications (Cuesta-Valero *et al.* 2022).

Mineralogically, the dominance of kaolinite places this system within a transitional conduction regime. Particle coating by kaolinite increases tortuosity and slightly modifies the cementation exponent (m), but it does not produce dominant surface-conductive pathways. Recent studies have shown that kaolinite, compared with expansive clay minerals, tends to maintain pore-fluid-dominated conduction under moderate salinity conditions (Emelianov *et al.* 2024).

The increase in salinity caused by leachate significantly reduces absolute resistivity values but does not drastically alter the scaling exponent, indicating that pore geometry remains the primary controlling factor. This finding is consistent with recent experimental studies showing that changes in fluid chemistry mainly influence resistivity magnitude rather than the fundamental structure of the pore network (Gabr *et al.* 2024).

4.5. Limitation and Implication

The limited number of samples (n = 7) imposes substantial constraints on the reliability of the Archie parameters, particularly the cementation exponent (m) and saturation exponent (n), which are commonly derived from log–log regression relationships between formation factor and saturation. Although bootstrap resampling and Monte Carlo simulation were applied to evaluate parameter variability, these approaches do not eliminate the limitations associated with the underlying data structure. As a result, they may produce statistical confidence that appears stronger than the actual representativeness of the experimental dataset.

In clay-rich soils such as the kaolinite-dominated landfill soil examined in this study, small variations in pore structure, surface conduction behavior, and pore-fluid composition can significantly influence bulk electrical resistivity and affect the fitting of Archie parameters. Therefore, the reported uncertainty ranges should be interpreted as indicators of parameter sensitivity within the experimental dataset rather than as universally applicable values.

To address this limitation, the study presents explicit parameter results for each condition, including m, n, R^2, and confidence intervals. Nevertheless, further investigations involving larger datasets and more diverse environmental conditions are still required to verify the broader applicability of the observed relationships.

Environmentally, the results have three main implications, as follows:

a. Electrical resistivity is a valid monitoring tool for kaolinite-rich landfill soils, provided that local laboratory calibration is performed.

b. Resistivity interpretation must consider leachate chemistry rather than relying solely on absolute resistivity values.

c. Uncertainty analysis using bootstrap and Monte Carlo approaches is important for environmental risk-based decision-making because it provides confidence limits for petrophysical parameters used in inversion modeling and contaminant migration estimation.

Thus, the kaolinite-rich soil at the Bakung Landfill can be categorized as a transitional electrical system in which Archie's law remains applicable within the tested range of leachate chemistry, while the statistical approach provides a more defensible basis for environmental monitoring interpretation.

5. CONCLUSIONS

This study demonstrates that kaolinite-dominated tropical landfill soil from the Bakung Landfill preserves the porosity–resistivity and saturation–resistivity power-law relationships consistent with Archie's law, even under the influence of realistic leachate chemistry. The cementation exponent (m) and saturation exponent (n) fall within the transitional granular–clay system range and show strong statistical stability based on bootstrap and Monte Carlo analyses. The decrease in resistivity induced by leachate is primarily controlled by the increase in pore-fluid conductivity rather than by fundamental changes in soil microstructure.

XRD and SEM characterizations indicate that kaolinite increases tortuosity without forming dominant surface-conductive pathways, which helps explain the relative microstructural stability of the Archie parameters. The uncertainty analysis further suggests that parameter variability is more strongly influenced by sample heterogeneity than by instrumental error, while all confidence intervals remain within physically realistic limits.

The limitations of this study include the laboratory-scale experimental design, the limited number of samples, and the restricted range of leachate chemistry conditions, which did not include extreme salinity environments. Therefore, further field validation and multi-salinity experiments are recommended to identify the transition threshold of surface conduction behavior.

Strategically, this study strengthens the scientific basis for the application of resistivity as an environmental monitoring tool in kaolinite-rich tropical landfill soils. By providing mineralogically calibrated Archie parameters together with quantified uncertainty estimates, this study supports a transition from descriptive resistivity interpretation toward a more transparent, quantitative, and risk-based evaluation framework for groundwater protection and sustainable remediation planning.

Author Contributions: Conceptualization, Rizka; methodology, Rizka, Irwan Iskandar, Muhammad Bisri Mustofa; software, Rizka; hardware, Muhammad Bisri Mustofa; validation, Rizka, Muhammad Bisri Mustofa, Irwan Iskandar; formal

analysis, Rizka; investigation, Rizka; resources, Irwan Iskandar; data accuration, Muhammad Bisri Mustofa; writing of original draft, Rizka; writing review and editing, Rizka; visualization, Rizka; Supervision, Djoko Santoso, Warsa.

Funding: This research was funded by the Institut Teknologi Sumatera.

6. ACKNOWLEDGMENTS

We would like to thank the support provided to the Sumatra Institute of Technology. We also thank the assistants of the Geophysics Laboratory of the University of Indonesia and the assistants of the Hydrogeology and Hydrogeochemical Laboratory of the Bandung Institute of Technology for their laboratory facilities and analysis.

Conflicts of Interest: "The authors declare no conflicts of interest." It is essential to identify and disclose any personal circumstances or interests that may be perceived as influencing the representation or interpretation of the reported research results. Additionally, any involvement of funders in the design of the study, data collection, analysis, interpretation, manuscript writing, or decision to publish must be clearly stated. If there was no role for the funders, please include the statement: "The funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results."

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