Analysis a mixtures of bentonite, palm kernel shell charcoal and magnesium sulfate ($MgSO_4$) for reducing grounding resistance using rod-type electrodes at varying soil depths

Ferry Rahmat Astianta Bukit, Naemah Mubarakah, Adrian Sinaga
Department of Electrical Engineering, Faculty of Engineering, Universitas Sumatera Utara, Medan, Indonesia

Article Info

Article history:

Received Dec 5, 2025
Revised Jul 29, 2026
Accepted Aug 15, 2026

Keywords:

Bentonite
Grounding system
Magnesium sulfate
Palm shell charcoal
Soil resistivity
Soil treatment

ABSTRACT

A grounding system is an essential electrical safety mechanism designed to protect humans and equipment from disturbances such as lightning-induced surge currents or short circuits. It operates by channeling excess current into the ground through grounding electrodes, thereby reducing the risk of damage and hazards. High grounding resistance can compromise the dissipation of fault currents and overvoltages, leading to safety risks. This study focuses on reducing grounding resistance through chemical soil treatment using bentonite combined with a mixture of magnesium sulfate ($MgSO_4$) and palm shell charcoal. The optimal composition consists of 10% bentonite, 10% native soil, and 80% of the material mixture. Experiments were conducted at electrode depths of 30 cm, 60 cm, 90 cm, and 110 cm. Results showed that the initial resistance of 312.5 Ω at 30 cm depth decreased to 86.1 Ω, and at 110 cm depth, resistance decreased from 186.5 Ω to 53.0 Ω. The average reduction reached 77.4%, indicating that this material combination is highly effective in lowering grounding resistance and improving system performance.

Corresponding Author:

Ferry Rahmat Astianta Bukit
Department of Electrical Engineering, Faculty of Engineering, Universitas Sumatera Utara
Medan, Indonesia
Email: ferrybukit@usu.ac.id

1. INTRODUCTION

Grounding systems protect people and equipment by directing surge currents from lightning or faults into the ground, thereby minimizing damage and hazards [1], [2]. Inadequate grounding systems can damage electrical equipment, disrupt operations, and pose safety risks. Low resistance, which is influenced by soil type, electrode type, depth, and soil composition, ensures effective current dissipation, thus preventing damage [3], [4]. In Indonesia, the PUIL standard sets a safe resistance limit of 5 ohms [5]. Deviation of grounding resistance from the standard requires mitigation efforts, such as increasing the number or depth of electrodes and applying soil treatment with additives such as Bentonite, NaCl, $MgSO_4$, $CuSO_4$, $CaCl_2$, or carbon to reduce soil resistivity around the electrodes [6]–[8]. Palm shell charcoal, produced through the pyrolysis process at temperatures ranging from 500 °C to 1000 °C, contains a high concentration of activated carbon with hygroscopic properties that enhance both water absorption and soil electrical conductivity. Meanwhile, magnesium sulfate ($MgSO_4$) is a salt commonly used in soil treatment for its ability to reduce soil acidity and slow electrode corrosion [9], [10]. Therefore, combining these two materials in this study is expected to improve the grounding system's performance by lowering the soil resistivity surrounding the electrode.

In power systems, grounding is an essential protective measure against equipment-damaging disturbances. It provides a safe path for fault and surge currents, ensuring both equipment integrity and personnel safety. Common implementations include: i) neutral grounding—connecting the system neutral to earth, either solidly or through impedance, to limit overvoltages and maintain protective selectivity; ii) equipment grounding—bonding exposed conductive parts to a grounded protective conductor to keep touch voltage within safe limits during insulation failure; and iii) lightning-protection grounding—diverting lightning and surge currents to the earth to safeguard structures, systems, and connected devices [11], [12]. The success of grounding schemes largely depends on consistently keeping the grounding resistance low. This ensures effective dissipation of fault currents and helps prevent potential rise during abnormal conditions [13], [14]. The surrounding layer of the electrode is also key to grounding performance, as it influences how current enters the soil. Research indicates that a corrosion layer on the electrode surface can raise grounding resistance because it has higher resistivity than the soil. Its thickness is directly linked to increased resistance and ground potential, which can reduce system efficiency over time. Consequently, the material properties and thickness of this layer should be carefully considered in designing grounding systems to ensure stable soil conductivity and dependable long-term operation [13], [14].

To enhance grounding performance in high soil resistivity conditions, researchers have examined various conductive additives. One focus has been on carbon-rich materials like wood charcoal, palm shell charcoal, and waste from palm kernel oil extraction. These studies consistently report reductions in grounding resistance of 68–81%, though effectiveness varies with soil type and electrode setup [15]–[17]. To achieve further improvements, especially in dry soils, some studies have used chemical salts such as magnesium sulfate ($MgSO_4$) or sodium chloride (NaCl). Combined with gypsum, this method can decrease resistance by up to 99% and also slow electrode corrosion [15]–[17]. Bentonite is another extensively studied alternative, either pure or mixed with materials like zeolite, kenaf leaf powder, palm kernel cake, or bunch ash, reducing resistance by 60–97%. Its success depends on concentration, layering method, and local soil characteristics [15]–[17].

Analytical and experimental approaches, including the driven-rod method and the use of soil additives, have long been employed to evaluate grounding system performance, with a focus on optimal resistance values that are crucial for safety and system protection [13], [14]. Integrating this empirical data with computational modeling provides a critical foundation for developing predictive methods applicable to multi-rod configurations. Despite these advancements, theoretical analysis is frequently constrained by the long-standing assumption of uniform soil [15]–[17]. This idealized model, while simplifying calculations, often yields significant discrepancies when compared to actual field conditions, which are inherently heterogeneous or stratified. In response to this gap, subsequent research has shifted focus toward more complex parameters, for instance, highlighting the importance of electrode geometry, demonstrating that adding vertical rods to a grid system can lower total resistance while simultaneously promoting a more uniform potential distribution. Experimental work has confirmed the efficacy of material intervention, proving that combining vertical electrodes with conductive additives, such as fly ash, significantly enhances soil conductivity [18], [19].

The primary objective of this study was to evaluate the extent to which grounding resistance can be reduced through soil treatment using a composite mixture of three materials: bentonite, palm shell charcoal, and magnesium sulfate. Various mixture ratios were examined at different electrode depths to determine the effect of composition and depth on resistance values. Measurements were recorded before and after treatment to objectively assess the actual impact of the mixture.

2. RESEARCH METHOD

2.1. Preparation of grounding pit layout

The experimental layout consisted of twenty test pits as shown in Figure 1 and was systematically designed to study the combined effect of electrode embedment depth and the composition of the soil improvement material (GEM) on grounding performance. The experimental matrix was designed using Roman numerals (I–IV) for four electrode depths (0.3, 0.6, 0.9 and 1.1 m) and letters A–E for five different fill compositions. Each sample was therefore identified by a combination of depth and concentration, e.g. IA, corresponding to the first concentration level at a 0.3 m embedment depth. This coding system allowed for systematic evaluation of each treatment condition and direct comparison between samples exposed to various combinations of embedment depth and material composition.

To maintain consistency across the experiment, all test pits were excavated and prepared under the same field conditions prior to testing. The pits were of cylindrical shape with 0.08 m diameter and the embedment depth was varied according to the test configuration. To minimize electrical interaction between adjacent grounding systems and to ensure the independence of each measurement, a minimum distance of 1.5 m was maintained between adjacent test pits (minimum < 2 times the electrode depth) [20]. The idea of this experimental setup was to isolate the effect of each variable to evaluate the effect of electrode depth and embankment composition individually and in combination. As a result, the measured grounding resistance can be directly related to the intended treatment conditions, which provides a reliable basis for the analysis of the effectiveness of proposed soil improvement materials. In total, 20 samples were tested across different depths and concentration combinations to assess their effect on ground resistance. The details of these variations are summarised in Tables 1 and 2.

Table 1. Concentration variations

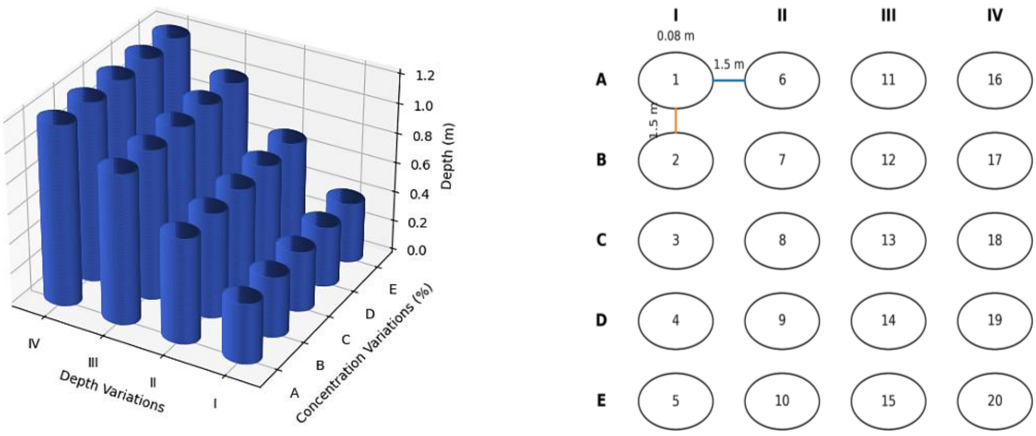
Code	Concentration		
	Native Soil (%)	Bentonite (%)	MgSo4 and Palm Kernel Shell Charcoal (%)
A	10	90	0
B	10	70	20
C	10	50	40
D	10	30	60
E	10	10	80

Table 2. Depth variations

Code	Depth (m)	Diameter (m)
I	0.3	0.08
II	0.6	0.08
III	0.9	0.08
IV	1.1	0.08

2.2. Low resistivity materials

Increasing the number of ground rods does not invariably lead to a significant reduction in grounding resistance. A more efficacious approach involves the utilization of ground enhancement materials (GEMs) to augment the soil's conductivity around the electrode [17], [21]. GEMs are low-resistivity, conductive backfill substances that improve the efficacy of grounding systems. In this research, the GEMs employed comprise bentonite, palm kernel shell charcoal, and magnesium sulfate ($MgSO_4$). The recommended backfill material should possess a resistivity substantially lower than that of the surrounding soil, sustain low resistance over time with minimal fluctuations, and remain chemically stable without reacting with the electrode material. The deployment of these materials substantially boosts the performance and reliability of the grounding system by increasing the soil's conductivity in direct contact with the electrode [22].



(a) (b)

Figure 1. Grounding layout: (a) soil depth variation and (b) sample layout

2.2.1. Bentonite

Bentonite is a natural material frequently utilized as a soil conductivity enhancer due to its capacity to absorb and retain moisture around electrodes. Its hygroscopic properties enable it to effectively decrease ground resistance and sustain stable resistivity, especially amid fluctuations in soil moisture levels. Previous research has demonstrated that bentonite exhibits low resistance during initial testing phases and contributes to the preservation of soil moisture, thereby ensuring the stability of the grounding system. Based on this, bentonite is used as an important reference in this study to explain how natural materials with comparable hygroscopic characteristics can effectively reduce soil resistivity [23].

2.2.2. Magnesium sulfate

Magnesium sulfate is an inorganic compound composed of oxygen, sulfate, and magnesium, and it helps the soil maintain balance by preventing harmful substances from accumulating. In grounding applications, $MgSO_4$ is used to reduce copper saturation at the electrode and slow corrosion, thereby improving the conductivity of the soil surrounding the electrode [24]. Among commonly used salt-based additives, magnesium sulfate is considered the least corrosive, making it a safer option than sodium chloride or copper sulfate. In addition, this compound helps prevent ice formation and lowers soil resistivity, thereby improving the stability and overall performance of the grounding system [10].

2.2.3. Palm kernel shell charcoal

Palm kernel shell charcoal is a solid carbon material produced through pyrolysis, a high-temperature combustion process carried out without oxygen. This process converts the lignocellulosic structure of the shells into a porous carbon form with a strong ability to absorb and retain water and surrounding ions [25]. The abundance of micropores helps maintain soil moisture and creates conductive pathways that allow electric current to flow more easily around the electrode, making it highly effective for grounding systems. In addition, its hygroscopic and chemically stable nature enables it to perform well across a range of environmental conditions. Its high fixed-carbon content and resistance to corrosion make it more durable than other organic materials. Therefore, adding palm kernel shell charcoal to the soil not only reduces resistivity but also improves the durability and reliability of the grounding system as a whole [26], [27].

2.3. Design of backfill material

Figure 2 illustrates the design for backfill material placement in the soil at varying concentrations. The concentration of each component was adjusted to fill the void with additive materials. This study examined the effects of soil depth on resistance values, measured before and after the addition of a bentonite-magnesium sulfate-palm kernel shell charcoal mixture. Variations in both concentration and depth were applied. The aim was to identify the best combination of these three materials at various soil depths in a moist environment. Figure 2 below shows the experimental setup.

The prepared test holes were backfilled with backfill materials consisting of bentonite, palm kernel shell charcoal, and magnesium sulfate ($MgSO_4$). The sample preparation process involved mixing these three materials and dissolving them in water in a single container, using predetermined concentration ratios to ensure a homogeneous mixture before placement into the test holes. Each concentration variation was utilized to analyze the influence of material composition on grounding resistance at various soil depths. Following mixing, the materials were incrementally poured into the holes and compacted to eliminate air pockets around the electrodes. Figure 3 illustrates the mixing process for the ground enhancement materials (GEMs) employed in this study, with the procedure deliberately designed to closely mimic real field conditions, thereby ensuring that the measured results accurately represent the actual performance of the grounding system. After the samples were properly installed and stabilized, resistance measurements were conducted using the three-point method to assess the effectiveness of each material combination in reducing soil resistivity.

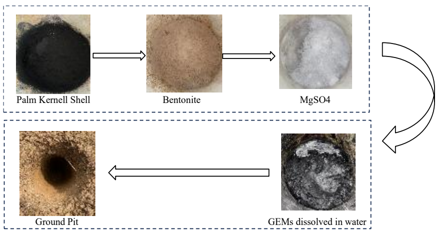


Figure 2. Grounding pit construction

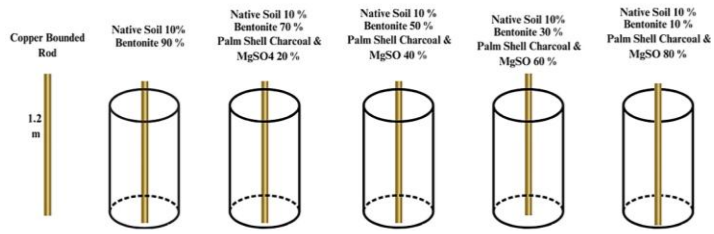


Figure 3. GEMs dissolved in water

3. FIELD MEASUREMENT

3.1. Ground resistance testing

A rod electrode was driven vertically (the driven-rod method) into the soil, and the grounding resistance was measured using the three-point method. The electrode measured 1.2 m in length and 16 mm in diameter and complied with the general requirements for electrical installations [28], [29]. The 3-point method, also known as the “fall of potential” method, involves measuring one grounding electrode (earth electrode) and two additional test electrodes that are electrically independent, usually labeled P (potential) and C (current). These test electrodes do not necessarily need to have the same quality of soil conductivity, but they must be electrically independent of the electrode being measured [30]. Each electrode's earth resistance was measured daily using a Kyoritsu Model 4105A digital earth resistance meter, as shown in Figure 4. Three separate measurements were made for each test pit to ensure the precision of the recorded resistance values. Each test pit was used to ensure the precision of the recorded resistance values.

The results were then recorded in tabular form and further analyzed to assess the site's grounding conditions. The measured resistance is then used to determine the soil resistivity using (1) [30]. For every rod length (L), the measured resistance (R) is used to calculate the apparent resistivity (ρ). Plotting ρ against the corresponding depth (L) shows how soil resistivity changes with depth.

$$\rho = \frac{2\pi LR}{\left[\ln\left(\frac{4L}{a}\right) - 1\right]} \tag{1}$$

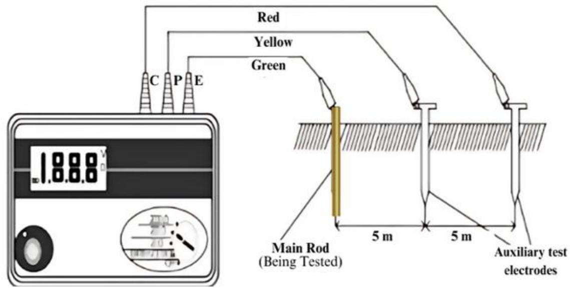


Figure 4. Ground resistance testing

3.2. Soil moisture measurement

Soil moisture significantly influences soil resistivity. An increase in moisture content diminishes resistivity, as water functions as a conductive medium that facilitates the movement of dissolved ions between soil particles, up to a saturation threshold where further water addition yields minimal effect [31], [32]. Therefore, maintaining soil moisture around the electrode—potentially through the incorporation of hygroscopic materials such as bentonite, palm kernel shell charcoal, or magnesium sulfate—constitutes an effective strategy to reduce soil resistivity and improve the overall performance of the grounding system [21]. Consequently, a moisture meter is employed to ensure precise measurements, which are crucial for reliable evaluation of material performance concerning soil characteristics, as illustrated in Figure 5.

Figure 5. Soil moisture measurement

4. RESULTS AND ANALYSIS

The test using the three-point method was conducted at a location with relatively high soil resistance. Additive materials were applied to examine the effect of depth variation on native soil, as well as the influence of adding additives at different depths to achieve a lower resistance value in accordance with Indonesian standards (PUIL 2000), which specifies 5 Ω. The test results were then analyzed to assess the experiment's outcomes. The measurement results are summarised in Table 3.

Table 3. Measured native soil resistance at various depths

No. Sample	Depth (m)	Resistance (Ω)	No. Sample	Depth (m)	Resistance (Ω)
IA-1	0.3	313.7	IIIA-11	0.9	220.3
IB-2	0.3	312.3	IIIB-12	0.9	220.7
IC-3	0.3	313.3	IIIC-13	0.9	221.3
ID-4	0.3	311.7	IIID-14	0.9	222
IE-5	0.3	311.7	IIIE-15	0.9	219.7
IIA-6	0.6	290.3	IVA-16	1.1	186.7
IIB-7	0.6	290	IVB-17	1.1	186
IIC-8	0.6	296	IVC-18	1.1	187.7
IID-9	0.6	291.7	IVD-19	1.1	185.7
IIE-10	0.6	289.7	IVE-20	1.1	186.3

Tests conducted on natural soil indicated that resistance diminished with increasing electrode depth. To further reduce resistance, this study incorporated additives into the samples. The reference resistance values were derived from soil measurements performed without chemical additives, thereby facilitating comparison with the results obtained after additive application. In this manner, the effects of electrode depth and additives on soil resistance can be more comprehensively understood.

4.1. Soil resistance with additive mixtures at depth variations

This resistance measurement was conducted to examine the effect and determine the resistance values using (%) native soil + bentonite + palm kernel shell charcoal + magnesium sulfate ($MgSO_4$) at each depth with varying concentrations. This enables the estimation of the percentage reduction in soil resistance and soil resistivity. The measurement results are summarised in the table below, and the lowest ground resistance was obtained in sample IE-5 with a composition of 10% native soil + 10% bentonite + 80% palm kernel shell charcoal & $MgSO_4$. Sample E consistently showed the lowest resistance value at every depth, with a steady decrease in resistance as the depth increased. The resistance values obtained from the measurements were then used to calculate the soil resistivity by applying (1). The results of all tests are shown in Tables 4-7.

Table 4. Additive mixtures at 0.3 m depth

Sample	First resistance (Ω)	Soil resistivity (Ω-m)	Last resistance (Ω)	Soil resistivity (Ω-m)
IA-1	313.7	147.36	119.9	56.31
IB-2	312.3	146.72	87.1	40.93
IC-3	313.3	147.19	81.9	38.46
ID-4	311.7	146.41	73.9	34.74
IE-5	311.7	146.41	67.5	31.70

Table 5. Additive mixtures at 0.6 m depth

Sample	First resistance (Ω)	Soil resistivity (Ω-m)	Last resistance (Ω)	Soil resistivity (Ω-m)
IIA-6	290.3	136.38	104.0	48.85
IIB-7	290.0	136.23	70.6	33.18
IIC-8	296.0	139.05	63.8	29.96
IID-9	291.7	137.01	61.3	28.81
IIE-10	289.7	136.07	57.3	26.90

Table 6. Additive mixtures at 0.9 m depth

Sample	First resistance (Ω)	Soil resistivity (Ω-m)	Last resistance (Ω)	Soil resistivity (Ω-m)
IIIA-11	220.3	103.50	72.4	34.03
IIIB-12	220.7	103.66	58.1	27.29
IIIC-13	221.3	103.97	55.6	26.13
IIID-14	222.0	104.28	54.1	25.40
IIIE-15	219.7	103.19	51.4	24.14

Table 7. Additive mixtures at 1.1 m depth

Sample	First resistance (Ω)	Soil resistivity (Ω-m)	Last resistance (Ω)	Soil resistivity (Ω-m)
IVA-16	186.7	87.69	62.6	29.41
IVB-17	186.0	87.37	53.7	25.21
IVC-18	187.7	88.16	51.7	24.29
IVD-19	185.7	87.22	49.8	23.38
IVE-20	186.3	87.53	47.4	22.27

The measurements from the table of additive mixtures at various depths underscore the comparison between the initial soil resistance and the subsequent resistance. Figure 6 illustrates that the addition of more palm kernel shell charcoal and $MgSO_4$ consistently diminishes the ground resistance, demonstrating that the evaluated treatment was highly effective in substantially reducing both soil resistance and resistivity, as evidenced by the significant disparity between the "initial" and "post-treatment" curves. The preliminary data also indicate that the native soil at the test site was heterogeneous, with deeper layers exhibiting increased conductivity. This trend likely reflects an escalation in soil moisture content with depth. Moreover, within each depth category, the efficacy of the treatment improved progressively from sample A to E, suggesting a potential influence of exposure duration or additive concentration. Consequently, the lowest resistance was attained under the optimal combination of parameters: applying the treatment to the deepest soil layer in group IV (1.1 m) and permitting the longest reaction period in Sample E. For instance, sample IB-2, with a 20% mixture, recorded a resistance of 87.1 Ω, whereas sample IE-5, with an 80% mixture, further decreased to 67.5 Ω. This clearly demonstrates an inverse trend: as the concentration of additives increases, the resistance decreases.

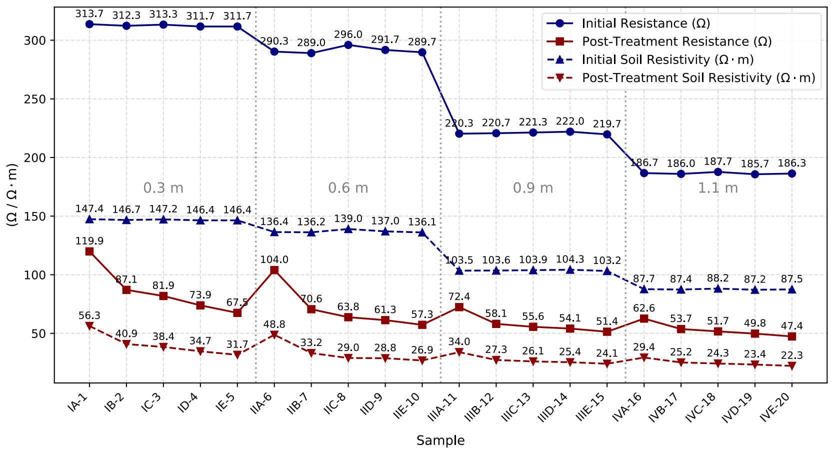


Figure 6. Comparison of soil resistance with additive mixtures at depth variations

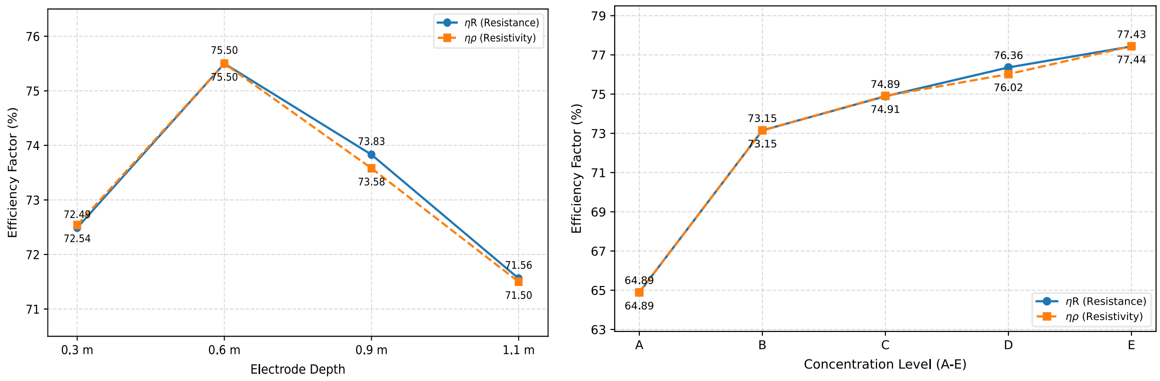
4.2. Relationship of depth and concentration in soil backfill mixtures

In general, the data indicate that increasing the electrode depth consistently reduces the average resistance value. The average final resistance decreases from approximately 86.1 Ω at a depth of 0.3 m to 71.4 Ω at 0.6 m, 58.3 Ω at 0.9 m, and 53.0 Ω at 1.1 m. This trend is consistent with the characteristics of stratified soil, where deeper layers tend to exhibit higher moisture content, greater density, and more stable dissolved ion concentrations [33], [34]. For all depth groups, samples with higher treatment levels exhibit lower resistance than those with lower levels. This pattern indicates that increasing the proportion of bentonite, palm shell charcoal, and magnesium sulfate ($MgSO_4$) improves conductivity around the electrode by enhancing moisture retention and increasing the concentration of ions participating in electrical conduction. This improves conductivity around the electrode by enhancing moisture retention and increasing the concentration of ions participating in electrical conduction. The performance of the enhancing compounds is characterized by their ability to decrease the grounding resistance. Accordingly, the relative efficiency factor can be expressed by (2) [35], [36]. Where R_0 is the initial resistance or resistivity before treatment, and R_1 is the value after treatment. The value of η is expressed as a percentage and directly represents the relative reduction from the initial condition.

$$\eta = 1 - \frac{R_1}{R_0} \quad (2)$$

The result obtained from Figure 7(a) shows the average efficiency factor values for all mixture concentrations at each depth, where the efficiency factor (η) for resistance (ηR) and soil resistivity ($\eta \rho$) ranges between approximately 71–76% at all electrode depths, indicating that the additive treatment produces a high and relatively uniform reduction compared to the initial condition. The maximum value is obtained at a depth of 0.6 m, $\eta R \approx 75.50\%$ $\eta \rho \approx 75.50\%$, suggesting the presence of an optimum depth at which the chemical properties of the soil most effectively support the performance of the mixture. The nearly overlapping trends of ηR and ηρ further confirm that the reduction in electrode resistance is primarily due to improved soil resistivity in the vicinity of the electrode [37], [38].

Figure 7(b) illustrates the mean efficiency factor values across all depths at each mixture concentration. This condition elevated the efficiency factors (ηR and $\eta \rho$) from approximately 64.9% to approximately 77.4%, thereby demonstrating that higher additive concentrations enhance the performance of the grounding system. The strong correlation between ηR and $\eta \rho$ at each concentration level indicates that the reduction in electrode resistance occurs concurrently with the decrease in soil resistivity. Conversely, the observed plateauing trend at elevated concentrations suggests a practical threshold beyond which additional increments result in diminishing improvements in efficiency [39], [40].



(a) (b)

Figure 7. Variation of the efficiency factors (ηR and ηρ) under different electrode depths and concentration levels: (a) effect of electrode depth and (b) effect of concentration level

The superior performance of sample E can be attributed to the complementary functions of its three constituent materials. Bentonite acts as a hygroscopic medium, absorbing and retaining water around the electrodes to maintain stable soil moisture and prevent rapid increases in soil resistivity under dry conditions. Palm kernel shell charcoal provides a porous carbon structure with interconnected micropores that facilitate moisture retention while forming electrically conductive pathways within the surrounding soil. Meanwhile, $MgSO_4$ dissolves into Mg^{2+} and SO_4^{2-} ions, increasing ion mobility and reducing the electrical resistance of the soil electrolyte.

The simultaneous presence of these three mechanisms creates a synergistic effect rather than an additive effect on individual components. Bentonite retains the moisture required for ion conduction, charcoal enhances electron transport through the conductive carbon network, and $MgSO_4$ continuously supplies mobile ions for charge transfer. As a result, the composite filler exhibits lower resistivity and better electrical stability than either material alone.

4.3. Measurement of grounding resistance using multiple rod electrodes

In the design of grounding systems, a single rod electrode is often insufficient to obtain the required safety resistance; thus, multiple rods are generally installed in parallel. However, theoretical studies have shown that the total resistance of a bundle of rods does not decrease linearly with the number of rods due to mutual interference, or mutual resistance, between the electrodes. This gives rise to a large diminishing returns effect. If all the rods are in the same small space, each additional rod makes less of a difference than the previous one. Such behavior has been much commented upon in the scholarly literature.

Previous grounding resistance measurements revealed two principal trends. Firstly, increasing the burial depth of the rod electrode generally resulted in lower resistance values, signifying that deeper installations benefit from soil layers with higher moisture content and more advantageous electrical properties. Secondly, the application of soil treatment utilizing a mixture of palm shell charcoal, bentonite, and magnesium sulfate ($MgSO_4$) consistently produced a significant reduction in resistance across all test conditions, with the most optimal performance observed for mixture level E. The most notable reductions were observed at depths of 0.3 m and 0.6 m, indicating that at these depths, the combined effects of the additive mixture—enhanced moisture retention, improved ion availability, and better contact conditions around the electrode—are most effectively utilized. In the present study, these findings are further extended through an evaluation of a grounding system employing multiple rod electrodes installed at depths of 0.3 m and 0.6 m with the mixture composition corresponding to level E. This approach allows for a more comprehensive examination of the previously identified optimal configuration within a multi-electrode arrangement.

Figure 8(a) demonstrates that the grounding resistance of the native soil remains comparatively high at a depth of 0.3 meters. Consequently, in this phase of the study, a configuration comprising five double-rod electrodes arranged in parallel within a single row is utilized to assess the potential reduction in grounding resistance that can be achieved through the implementation of a multi-electrode system. Figure 8(b) illustrates that at a depth of 0.6 meters, the grounding resistance of the native soil remains comparatively high, although slightly lower than at 0.3 meters. Consequently, a configuration of double-rod electrodes arranged in parallel within a single row, comprising a total of five rods, is subsequently utilized to assess the reduction in grounding resistance that can be attained through the implementation of a multi-electrode system.

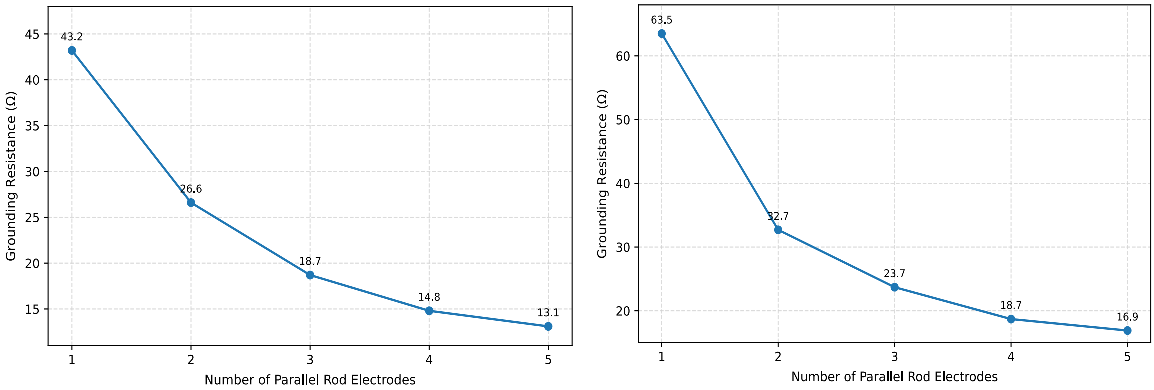


Figure 8. Grounding resistance: (a) at 0.3 m and (b) 0.6 m depth with a parallel rod configuration

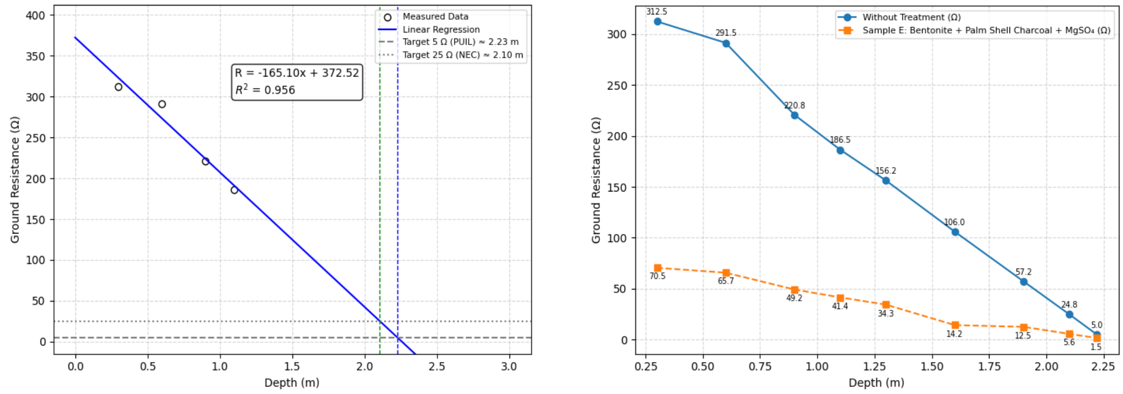
4.4. Optimum values of ground resistance

Measurements were performed in different conditions (different electrode depth, soil treatment, double-rod configuration using the most efficient mixture (level E)). The results show that the soil properties have been changed and the number of electrodes has been increased, which caused a significant decrease in the grounding resistance in comparison with the native soil. But the measured values are still below the recommended standards. For safety and reliability, the Indonesian PUIL standard requires a grounding resistance of 5 Ω or less [5]. However, the NEC requires the resistance to earth for a single rod electrode shall not be more than 25 Ω; if the resistance is more than 25 Ω, then at least one more grounding electrode (such as a second rod) shall be installed [41], [42]. The purpose of this requirement is to be practical to field implementation without need for complex measurement procedures. Therefore, computational analysis is required to further assess the measurement results and to determine the most effective configuration of the grounding system.

4.4.1. Analysis of experimental data of depth and concentration variations

The analysis of Figure 6 shows that the lowest resistance was obtained at a depth of 1.1 m with an average of 53 Ω. This is a big drop but not the 5 Ω standard needed. Hence, a further analysis was performed by linear regression on the mean depth and concentration data. The purpose of this analysis is to estimate the depth at which ground resistance can be reduced to the 5 Ω target value [5]. Figure 9(a) shows the linear regression analysis. The electrode burial depth needed to satisfy the Indonesian standard of 5 Ω is approximately 2.23 m. The depth required to satisfy the NEC limit of 25 Ω is approximately 2.10 m.

Based on the measurement results, the mixture used in sample E was identified as the most effective and consistent across all depths. Consequently, sample E was adopted as the reference for further analysis, based on the resistance-reduction trend in Figure 6, to estimate the depth or electrode configuration required to achieve grounding resistance values of 5 Ω and 25 Ω. Figure 9(b) shows that, following the resistance-reduction trend observed for sample E, the depth at which the untreated soil (without additive materials) is predicted to reach about 5 Ω is approximately 2.23 m, resistance reduction trend observed for sample E, a depth of approximately 2.23 m is the point at which the untreated soil (without additive materials) is predicted to reach about 5 Ω, consistent with the regression model in Figure 9(a). At the same depth, the treatment using the bentonite–palm shell charcoal–$MgSO_4$ mixture in sample E further reduces the resistance to around 1.5 Ω, demonstrating a substantial improvement in grounding performance compared with the native soil condition.

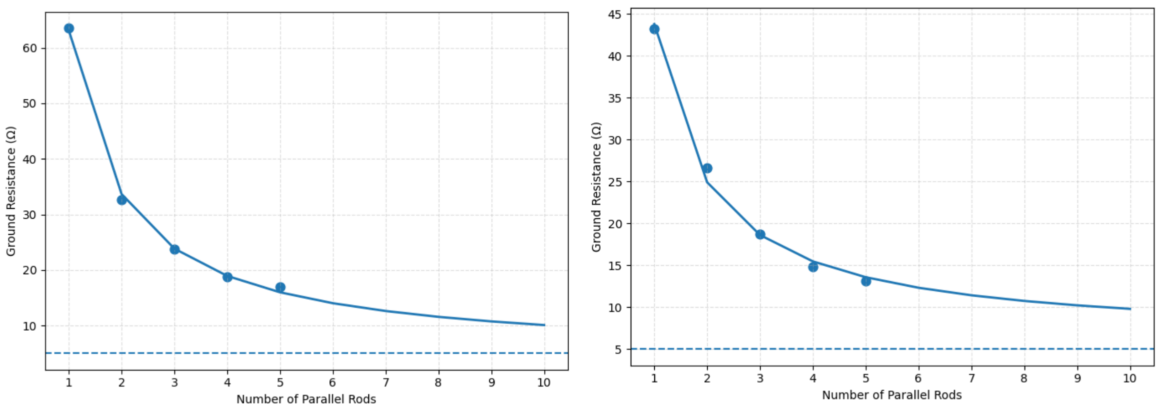


(a) (b)

Figure 9. Prediction of the required depth under different conditions: (a) for 5 Ω and 25 Ω and (b) versus concentration for 5 Ω in sample E

4.4.2. Analysis of experimental data using multiple rods

Grounding resistance vs number of electrode rods is not linear. Rather, there are diminishing returns with the addition of each rod. This is in line with the theory of mutual resistance, which states that when electrodes are close to each other, the current distribution fields interact with each other and the resistance reduction is less effective with the increasing number of rods. Figures 10(a) and 10(b) depict the influence of adding electrodes on the grounding resistance for sample E at 0.3 m and 0.6 m depths, respectively, where the returns are diminishing. The maximum resistance reduction is achieved with up to about five rod electrodes, and then the resistance continues to decrease, but the incremental improvements gradually diminish and tend to approach a saturation point.



(a) (b)

Figure 10. Parallel rods: (a) at depth 0.3 m and (b) at depth 0.6 m

5. CONCLUSION

This study empirically demonstrates that the combination of bentonite, palm kernel shell charcoal, and magnesium sulfate ($MgSO_4$) serves as an effective soil enhancement material for reducing grounding resistance in soils with high resistivity. The systematic increase in electrode embedment depth consistently diminished the grounding resistance and apparent soil resistivity, while the addition of the proposed filler material further amplified this effect. Among all tested formulations, a mixture comprising 10% native soil, 10% bentonite, and 80% palm kernel shell charcoal–$MgSO_4$ (Sample E) achieved optimal overall performance, resulting in an average reduction in grounding resistance of 77.4% relative to untreated soil. The findings suggest that the synergistic mechanism—comprising bentonite-mediated moisture retention, palm kernel shell charcoal's conductive pathway, and the enhanced ionic conductivity of $MgSO_4$—substantially improves current dissipation around the grounding electrode.

The proposed material mix offers a practical, cost-effective way to improve grounding systems, especially in tropical regions with high soil resistivity. Bentonite, $MgSO_4$, and palm kernel shell charcoal are easily available, making it simple to integrate into standard installations without major changes. Research shows that using optimized filler materials with deeper electrodes or multi-rod setups can further reduce grounding resistance in substations, renewable energy systems, industrial sites, and lightning protection.

The proposed approach also promotes sustainability through the utilization of palm kernel shell charcoal, an agricultural byproduct that enhances the value of biomass waste while decreasing dependence on traditional chemical grounding enhancement materials. Compared to highly corrosive additives such as sodium chloride, $MgSO_4$ provides a less aggressive chemical environment for the grounding electrodes while maintaining effective electrical conductivity. Nevertheless, environmental considerations related to potential sulfate dissolution should be thoroughly assessed prior to large-scale deployment, especially under long-term field operating conditions. Although the mixture improves grounding performance, resistance values still don't meet standards under current conditions. Further optimization—such as deeper electrode installation, adding parallel electrodes, or alternative configurations—is necessary to achieve very low grounding resistance. Future research should assess the long-term durability of the filler material, considering seasonal environmental changes such as moisture, $MgSO_4$ dissolution, and corrosion. Comparative studies with other grounding materials and additives like biochar and carbon nanomaterials are recommended to enhance performance, sustainability, and cost-effectiveness.

ACKNOWLEDGMENTS

We would like to express our deepest gratitude to the Faculty of Engineering, Universitas Sumatera Utara, especially to the research team at the Department of Electrical Engineering, for their comprehensive support in completing this research.

FUNDING INFORMATION

The authors state no funding is involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Ferry Rahmat Astianta Bukit	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓		✓
Naemah Mubarakah		✓		✓	✓	✓	✓			✓			✓	
Adrian Sinaga			✓			✓		✓	✓		✓		✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author, [FRAB]. The data, which contain information that could compromise the privacy of research participants, are not publicly available due to certain restrictions.

REFERENCES

[1] D. Arias-Cazco and L. Cruz-Panchi, "Multi-objective optimization for safety in the grounding of ac substations," *IEEE Latin America Transactions*, vol. 23, no. 7, pp. 592–599, Jul. 2025, doi: 10.1109/TLA.2025.11045670.

[2] O. E. Gouda, A. Z. El Dein, E. Tag-Eldin, M. Lehtonen, and M. M. F. Darwish, "Proposed approach to investigate the current and voltage distributions of isolated and grounded systems during earth fault conditions," *IEEE Access*, vol. 11, pp. 98362–98375, 2023, doi: 10.1109/ACCESS.2023.3312058.

[3] A. H. Amadi *et al.*, "A review of soil resistivity testing for enhanced corrosion control: overcoming limitations through integrated geophysical approaches and alternative methodologies," *Measurement*, vol. 242, p. 116214, Jan. 2025, doi: 10.1016/j.measurement.2024.116214.

[4] F. Sadeghian, S. Jahandari, A. Haddad, H. Rasekh, and J. Li, "Effects of variations of voltage and ph value on the shear strength of soil and durability of different electrodes and piles during electrokinetic phenomenon," *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 14, no. 2, pp. 625–636, Apr. 2022, doi: 10.1016/j.jrmge.2021.07.017.

[5] Badan Standarisasi Indonesia, "Persyaratan umum instalasi listrik 2000 (puil 2000)," 2000.

[6] F. M. S. Sinchi, F. A. P. Quizhpi, H. P. C. Guillen, and S. N. N. Quinde, "Soil treatment to reduce grounding resistance by applying low-resistivity material (lrm) and chemical ground electrode in different grounding systems configurations," *2018 IEEE International Autumn Meeting on Power, Electronics and Computing, ROPEC 2018*, 2018, doi: 10.1109/ROPEC.2018.8661403.

[7] I. G. N. S. Hernanda, A. B. Ksatria, I. M. Y. Negara, I. P. C. Suardana, D. A. Asfani, and P. J. Mirnafandi, "Effect of grounding rods position and fly ash material on grounding resistance in limestone soil," in *2022 International Seminar on Intelligent Technology and Its Applications (ISITIA)*, IEEE, Jul. 2022, pp. 371–376, doi: 10.1109/ISITIA56226.2022.9855301.

[8] B. Anggoro and D. B. Irman, "The characteristics of soil which is treated by salt solution, and water as the basic of grounding diagnostics," in *2012 IEEE International Conference on Condition Monitoring and Diagnosis*, IEEE, Sep. 2012, pp. 1007–1012, doi: 10.1109/CMD.2012.6416326.

[9] B. Gidudu and E. M. N. Chirwa, "The role of ph, electrodes, surfactants, and electrolytes in electrokinetic remediation of contaminated soil," *Molecules*, vol. 27, no. 21, p. 7381, Oct. 2022, doi: 10.3390/molecules27217381.

[10] N. Basak *et al.*, "Soil management for salt-affected soil," in *Agricultural Soil Sustainability and Carbon Management*, Elsevier, 2023, pp. 99–128. doi: 10.1016/B978-0-323-95911-7.00011-6.

[11] R. A. de Araujo, W. L. M. de Azevedo, A. S. Rosa, and J. P. Filho, "Dynamic monitoring of temporary protective grounding state in power system routines," *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 7, p. 100431, Mar. 2024, doi: 10.1016/j.prime.2024.100431.

[12] M. W. Altaf, M. T. Arif, S. N. Islam, and M. E. Haque, "Microgrid protection challenges and mitigation approaches–a comprehensive review," *IEEE Access*, vol. 10, pp. 38895–38922, 2022, doi: 10.1109/ACCESS.2022.3165011.

[13] E. D. Ellinas, G. Lianos, V. T. Kontargyri, C. A. Christodoulou, and I. F. Gonos, "Performance evaluation of grounding systems of medium-voltage concrete poles: a comprehensive analysis," *Applied Sciences*, vol. 14, no. 9, p. 3758, Apr. 2024, doi: 10.3390/app14093758.

[14] L. Grcev, B. Markovski, and M. Todorovski, "Lightning performance of multiple horizontal, vertical and inclined grounding electrodes," *IEEE Transactions on Power Delivery*, vol. 37, no. 5, pp. 3782–3791, Oct. 2022, doi: 10.1109/TPWRD.2021.3137361.

[15] S. A. Saleh, D. Jewett, and S. A. R. Panetta, "The analysis, modeling, and capabilities of grounding system designs," *IEEE Transactions on Industry Applications*, vol. 58, no. 5, pp. 5908–5920, Sep. 2022, doi: 10.1109/TIA.2022.3186290.

[16] Z. Li, Y. Chu, G. Cai, C. Yan, S. Liu, and A. Han, "Evaluation of penetration-depth and voltage effects in four-electrode resistivity testing of geotechnical media," *Measurement*, vol. 257, p. 118727, Jan. 2026, doi: 10.1016/j.measurement.2025.118727.

[17] B. AbuBakar, C.-L. Wooi, S.-F. Khor, N. H. N. Ali, Y. L. Then, and H. N. Afrouzi, "Overview of grounding system improvements: design, simulation, grounding enhancement materials," in *2025 IEEE 8th International Conference on Electrical, Control and Computer Engineering (InECCE)*, IEEE, Aug. 2025, pp. 127–132, doi: 10.1109/InECCE64959.2025.11150870.

[18] H. Siregar, Y. Siregar, T. P. Manurung, R. Simanjuntak, F. A. Fradiska, and M. Iqbal, "Analysis of the utilization of gypsum powder composition and fly ash for improving grounding resistance at variations in electrode depth," in *2025 International Conference on Technology and Policy in Energy and Electric Power (ICT-PEP)*, IEEE, Sep. 2025, pp. 235–239, doi: 10.1109/ICT-PEP67281.2025.11232156.

[19] W. F. H. Wan Ahmad and Y. Nagappan, "Moisture retaining test of biochar, coco coir peat, palm kernel oil cake and charcoal dust mixtures for grounding system purposes," in *2024 IEEE Sustainable Power and Energy Conference (iSPEC)*, IEEE, Nov. 2024, pp. 445–450, doi: 10.1109/iSPEC59716.2024.10892518.

[20] F. R. A. Bukit and M. Hidayat, "Analysis of the effect of addition of bentonite zeolite bunch ash and coconut kernel oil as earthing media," in *2023 7th International Conference on Electrical, Telecommunication and Computer Engineering (ELTICOM)*, IEEE, Dec. 2023, pp. 218–223, doi: 10.1109/ELTICOM61905.2023.10443150.

[21] H. Martínez Ángeles *et al.*, "Ground enhancement materials for grounding systems: a systematic review of factors, technologies and advances," *Technologies*, vol. 14, no. 1, p. 49, Jan. 2026, doi: 10.3390/technologies14010049.

[22] O. Kherif, S. Robson, A. Haddad, and D. Thorpe, "On the optimization of grounding design of rods covered by low resistivity materials," in *2022 57th International Universities Power Engineering Conference (UPEC)*, IEEE, Aug. 2022, pp. 1–6, doi: 10.1109/UPEC55022.2022.9917937.

[23] W. F. H. W. Ahmad, N. Marudin, J. Jasni, and M. Z. A. Ab-Kadir, "Performance of bentonite and zeolite mixtures as grounding enhancement materials," in *2023 12th Asia-Pacific International Conference on Lightning (APL)*, IEEE, Jun. 2023, pp. 1–5, doi: 10.1109/APL57308.2023.10182022.

[24] A. A. Abildina *et al.*, "Corrosion behavior of magnesium in aqueous sulfate-containing electrolytes," *Journal of Magnesium and Alloys*, vol. 11, no. 6, pp. 2125–2141, Jun. 2023, doi: 10.1016/j.jma.2023.06.001.

[25] J. Andas, M. L. A. Rahman, and M. S. M. Yahya, "Preparation and characterization of activated carbon from palm kernel shell," *IOP Conference Series: Materials Science and Engineering*, vol. 226, p. 012156, Aug. 2017, doi: 10.1088/1757-899X/226/1/012156.

[26] C. L. Lee, K. L. Chin, P. S. H'ng, M. S. Hafizuddin, and P. S. Khoo, "Activation temperature and particle size of palm kernel shell vs. the surface properties of activated carbon," *BioResources*, vol. 18, no. 1, pp. 1714–1730, Jan. 2023, doi: 10.15376/biores.18.1.1714-1730.

[27] M. S. M. Zaini, M. Arshad, and S. S. A. Syed-Hassan, "Adsorption isotherm and kinetic study of methane on palm kernel shell-derived activated carbon," *Journal of Bioresources and Bioproducts*, vol. 8, no. 1, pp. 66–77, Feb. 2023, doi: 10.1016/j.jobab.2022.11.002.

[28] Z. Ben Zaied, F. Slaoui-Hasnaoui, and S. Georges, "Modeling and simulation of the potential of four grounding electrodes using the finite element method," in *2023 Fifth International Conference on Advances in Computational Tools for Engineering Applications (ACTEA)*, IEEE, Jul. 2023, pp. 162–166, doi: 10.1109/ACTEA58025.2023.10194160.

[29] A. Suratman, M. S. Yunus, N. Mohamad Nor, and M. Othman, "Steady-state and impulse impedance values for ground electrodes treated with enhancement materials," in *2026 International Conference on Electric Power and Renewable Energy (EPREC)*, IEEE, Jan. 2026, pp. 1–4, doi: 10.1109/EPREC66546.2026.11412106.

[30] M. Abdel-Salam, A. Eid, and H. H. El-Hawary, "A novel method for calculating resistance of grounding schemes buried in homogenous and two-layer soils based on current sphere simulation technique and concept of images," *IEEE Transactions on Power Delivery*, vol. 40, no. 3, pp. 1587–1596, Jun. 2025, doi: 10.1109/TPWRD.2025.3555103.

[31] G. Hong, S. Choi, D.-Y. Yoo, T. Oh, Y. Song, and J. H. Yeon, "Moisture dependence of electrical resistivity in under-percolated cement-based composites with multi-walled carbon nanotubes," *Journal of Materials Research and Technology*, vol. 16, pp. 47–58, Jan. 2022, doi: 10.1016/j.jmrt.2021.11.151.

[32] P. de A. Carísio, C. F. T. Soares, O. A. Mendoza Reales, E. de M. R. Fairbairn, and R. D. Toledo Filho, "Effect of moisture on electrical resistivity and self-sensing behavior of a cement paste," *Journal of Materials in Civil Engineering*, vol. 36, no. 8, Aug. 2024, doi: 10.1061/JMCEE7.MTENG-17356.

[33] C. Huang, C. Zhao, Y. Sun, and S. Guan, "Mechanical response and numerical simulation of liquid soil abutment backfill," *International Journal of Transportation Science and Technology*, vol. 17, pp. 1–20, Mar. 2025, doi: 10.1016/j.ijtst.2024.02.001.

[34] A. Al-Taie, E. Yaghoubi, M. Disfani, S. Fragomeni, and E. Gmehling, "Field performance evaluation of recycled aggregate blends used for backfilling deep excavated trenches," *International Journal of Geomechanics*, vol. 24, no. 2, Feb. 2024, doi: 10.1061/IJGNAI.GMENG-7588.

[35] M. Wahba, M. Abdel-Salam, M. Nayel, and H. A. Ziedan, "A comprehensive review on soil-enhancement materials additive to grounding system," in *2023 24th International Middle East Power System Conference (MEPCON)*, IEEE, Dec. 2023, pp. 1–8, doi: 10.1109/MEPCON58725.2023.10462409.

[36] F. Sinchi-Sinchi, C. Coronel-Naranjo, A. Barragán-Escandón, and F. Quizhpi-Palomeque, "Soil treatment to reduce grounding resistance by applying low-resistivity material (LRM) implemented in different grounding systems configurations and in soils with different resistivities," *Applied Sciences*, vol. 12, no. 9, p. 4788, May 2022, doi: 10.3390/app12094788.

[37] U. Muhammad, F. Aman, and N. Mohamad Nor, "Impulse characteristics of soil treated with enhancement materials and various moisture contents," *Applied Sciences*, vol. 14, no. 2, p. 547, Jan. 2024, doi: 10.3390/app14020547.

[38] S. N. Onyedikachi, C. Gomes, and J. van Coller, "Equations for predicting the volumetric water content affecting the resistivity of soil in the vicinity of a driven earth electrode in variably saturated homogeneous soil," in *2022 36th International Conference on Lightning Protection (ICLP)*, IEEE, Oct. 2022, pp. 1–6, doi: 10.1109/ICLP56858.2022.9942536.

[39] W. Li *et al.*, "Unlocking efficiency: minimizing energy loss in electrocatalysts for water splitting," *Advanced Materials*, vol. 36, no. 42, Oct. 2024, doi: 10.1002/adma.202404658.

[40] H. H. Hizamul-Din, N. M. Nor, N. N. Ahmad, N. F. Idris, and A. Mahmud, "Investigations on the performance of various horizontal ground electrodes," *Energies*, vol. 14, no. 4, p. 1036, Feb. 2021, doi: 10.3390/en14041036.

[41] M. D. Kavimandan, "Electrical grounding impedance and gap(s) in IEEE STD. 80, NESC® , or NEC® - a project case," in *2024 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, IEEE, May 2024, pp. 1–4, doi: 10.1109/TD47997.2024.10555991.

[42] D. R. Stockin, "Design and testing of facilities ground," in *Electrical Overstress/Electrostatic Discharge Symposium Proceedings 2000 (IEEE Cat. No.00TH8476)*, ESD Assoc, pp. 368–374, doi: 10.1109/EOSESD.2000.890104.

BIOGRAPHIES OF AUTHORS

Ferry Rahmat Astianta Bukit did his undergraduate work at Universitas Sumatera Utara in Medan, North Sumatera, Indonesia. He received a Bachelor of Electrical Engineering in 2011. After a while, he worked for a private company. He continued taking a master's program in electrical engineering at Institut Teknologi Bandung, Bandung, West Java, Indonesia, from 2013-2015. Until now, he has been lecturing at Universitas Sumatera Utara. He can be contacted at email: ferrybukit@usu.ac.id.

Naemah Mubarakah works at the University of North Sumatra in Medan, North Sumatra, Indonesia. She earned her bachelor's degree in electrical engineering in 2003. In 2009, she completed her master's program in electrical engineering at the Sepuluh Nopember Institute of Technology, Surabaya, East Java, Indonesia, and obtained her doctoral degree in 2025 from the University of North Sumatra. She can be contacted at email: naemah@usu.ac.id.

Adrian Sinaga received his B.Eng. degree in electrical engineering from Universitas Sumatera Utara, Medan, Indonesia, in 2025. His bachelor's thesis focuses on grounding systems and soil resistivity using backfill materials. He can be contacted at email: riannsng@gmail.com.