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ARTICLE

Enhancing grounding systems: effects of agro-based biochar used as backfill materials

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Abstract

Agro-waste biochar is gradually emerging as a greener and effective means of enhancing the effectiveness of grounding systems. Yet, only a few of such wastes have been empirically assessed as ground enhancing materials. In this study, field-based soil resistivity and resistance to ground (RTG) value monitoring was used to assess the potential of biochar of coconut husk, sawdust, sugarcane bagasse, and rice husk as alternate ground enhancing materials vis-a-vis their susceptibility to seasonal variation and mode of application. The result of this study shows that the applied treatments exerted significant improvement (P-value$\leq$0.05) in soil resistance and zone of influence values with the latter ranging less than 1 m for the clayey soil and equal of more than 2 m in the sandy soil. These effects of the study treatments were significantly influenced by time. A notable finding of this study is that rainfall and high moisture results in physical breakdown of biochar. This has significant implications for the use of treatment and the mode of application of treatment. Treatment, time, and mode of application of treatment played significant and interdependent role in reducing soil resistivity. These factors contributed to over 83% improvement of RTG values. This result suggests that though treatment, time and mode of application of treatment are major factors determining the effectiveness of ground enhancing materials, other confounding variables (e.g. method of carbonizing the waste, physical and chemical properties of the biochar) are also important determinants and must engender future research.

Keywords Grounding system · Backfill material · Soil resistivity · Resistance to ground · Agro-waste · Biochar

Introduction

Ground potential and its resultant effects on electrical systems and human lives abounds because the earth inherently has high resistivity [1, 2]. Thus, achieving low soil resistance is not an easy feat, particularly, when the project area has high volcanic ash and gravel composition or when the ground is craggy [3]. Thus, artificial reduction of soil resistivity in grounding systems is a problem that the scientific community has been occupied with since the early 1940’s [4].

Over the years, physical and chemical-based methods of achieving low ground resistance have been studied and adopted for electrical grounding systems [5]. The physical methods that have been studied the most and adopted (mostly in non-industrial installations) include multi-grounding electrode paralleling (use of multiple rods), ground electrode enlargement (increasing rod diameter), ground electrode deepening (increasing the length), and local soil replacement [5, 6]. Although the application of the above-mentioned physical methods in grounding systems though may result in reduction in resistivity and resistance to ground (RTG) values [2, 7], it is fraught with significant limitations which may render these methods undesirable. According to Mari [7], doubling the length of rod (e.g. 300–600 cm) decreases soil resistance by 45%, however, this percentage gradually reduces as more rods are added. Also, doubling or tripling rod’s diameter does not have significant effect on soil resistivity and RTG values but makes manual or pneumatic burying of earth rods easier. The same author, Mari

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[7], posits that applying multiple rods (e.g. 2 rods) reduces soil resistivity by 41% but further reduction of resistivity after addition of more rods is comparatively small. These reported findings suggest that the aforementioned physical methods are not always effective [3] though they are labor and capital intensive.

Thus, some researchers propose chemical-based treatments [3, 4, 8]. Chemical-based treatments generally involve the replacement of local material with chemical-based low resistivity materials (LRM) like sea water, sodium chloride (NaCl), granite, and bentonite as backfill materials. There are two main schools of thought in the mode of operation of chemical-based LRM. According to Jones [9], using LRM as backfill material for ground electrodes influences the performance of the grounding system by improving the water retention property of the surrounding soil. Chen et al. [3] also posit that LRM used as backfill material increases the electrode diameter, hence causing the ground resistance to decrease. Over the years, encouraging results have been recorded when chemical-based ground enhancing materials (GEM) are used as backfill materials in grounding systems. For instance, Sinchi-sinchi et al. [10] and Martin and Permata [11], reported that using bentonite as LRM induces 60% reduction in resistivity and up to 74% in RTG values. Also, Setiawan et al. [12] reported 62% reduction in resistivity of the local soil after soil treatment with NaCl. Nevertheless, traditional chemical-based treatments are rarely used, especially in long-term projects. This may be attributed to the temporal nature of the effects associated with most of the traditional chemical-based LRM (NaCl and sea water) on resistivity, their associated cost and their corrosive nature [13]. Thus, some researchers have explored the viability of greener options like biochar.

Biochar is a fine-grained charcoal-like material that is produced by burning biomass under air-deprived conditions called pyrolysis [13]. Over the years the use of biochar has gained attention in the construction, agriculture, and the energy sector due to its well documented effects on soil health in general [14–17]. Sultan et al. [14], Abbas et al. [15], and Brista et al. [16] attributed the widespread use of biochar in the agricultural sector to documented cases of: (1) improved production of up to 30%, (2) improved nutrients and trace mineral retention, and (3) improved cation and anion exchange reactions. Likewise, Kaur [17] highlighted the importance of biochar in stabilizing and improving the mechanical properties (like expansivity and compressive strength) of week soil in the construction sector. In recent years, the use of biochar of agro-waste has gained momentum in the energy sector. Research has discovered that biochar possesses suits of traits that enhances electrical conductivity (EC) as observed with traditional ground enhancing materials used as backfill material in grounding systems. These traits include (1) high tendency to absorb and retain water; (2) high mineral content which increases conductivity; (3) long resident time (lasts in soil for hundreds of years); and (4) ability to ameliorate the physical and chemical properties of soil [13, 18–20]. Several of these studies [4, 21–23] have reported impressive results of significant implication to the use of agro-waste as GEM in grounding systems. For example, Karmiathi et al. [21] reported a 76.6% reduction in soil resistivity after treatment with coconut and wood biochar, while Okyere et al. [23] also reported 84% reduction in ground resistance after soil treatment with palm kernel oil cake and cocoa husk biochar. Research attributes these results to the already-mentioned inherent characteristics of the biochar of the studied agro-wastes. For instance, a study by Akoto et al. [24] reported a strong positive association between the studied physicochemical and mechanical properties of soil and agro-wastes (pH, cation exchange capacity (CEC), water holding capacity, bulk density, specific gravity, moisture content, EC, compressive strength, failure load, and flow rate).

A notable finding by Akoto et al. [24] is the significant differences in the above-mentioned effects as well as potential effects of other confounding variables like season and the mode of application of the GEM. The effect of seasonal variation on the performance of biochar is well documented with some authors [25, 26] reporting extensively on the often-overlooked effects of rainfall on biochar aging, physical breakdown. This indicates that the selection of agro-waste as GEM should not be done arbitrarily but be based on the total understanding of the effectiveness of the selected agro-wastes as well as their susceptibility to seasonal variation and the mode of application. Regardless, studies on the viability of biochar of agro-waste as GEM are limited at best and often focused on the potential of agro-waste as GEM [1, 3, 13, 24, 27, 28] and not their comparative effectiveness and susceptibility to seasonal variation and mode of application of treatments. This current trend has limited the use of agro-waste-based biochar in grounding systems because decision makers do not have access to enough empirical data to inform decisions on the use of agro-waste-based biochar as GEM in grounding systems. This is quite unfortunate given the potential for agro-waste-based biochar GEM in electrical installations and most importantly, their potential to reduce the waste deficits in developing countries. Thus, this study aims at providing empirical data on the potential of the biochar of some selected agro-wastes as GEM in relation to their susceptibility to seasonal variation and mode of application of treatment.

In this research, authors employed field-based soil resistivity and RTG value monitoring to analyze the potential of agro-waste biochar (coconut husk biochar, sugarcane bagasse biochar, sawdust biochar, and rice husk biochar) as alternative GEM for grounding systems with specific consideration to: (1) the effects of the agro-waste biochar on some essential parameter conductivities (soil resistivity and RTG), (2) the significance of the effects of season and mode of application of treatment on the potency of the agro-waste biochar as GEM, and (3) the relative importance of the effects of treatment, season, and mode of application.

Materials and methods

The two study sites employed for this research are site A (Tanokrom, latitude 4.9133° and longitude 1.7721°) and site B (Whindo, latitude 4.9339° and longitude 1.8136°) located in Takoradi, western region of Ghana. Initial analysis of soil types at the two study sites prior to the commencement of this study suggested that the soil at the study sites A and B were predominantly clayey and sandy respectively.

The western region of Ghana forms part of the semi-deciduous forest and is characterized by matured soil profiles with varying percentage accumulation of clay, sand, and loam [29], a deciding factor in selecting the two study sites. Also, the western region of Ghana is one of the regions with the highest rainfall (1000–1250 mm [30]) and one of the major agric hubs in Ghana. This feat has resulted in a high agro-waste burden in the western region with over 68% of waste generation being organic waste. The ecological problems associated with the high burden of these agro-wastes in the environment necessitate immediate remedial action.

Determination of physicochemical properties of the study GEM and the study sites

The researchers employed standard analytical protocols to determine the physicochemical properties of soil from the two study sites. The physicochemical properties include field capacity, resistivity, effective cation exchange capacity (ECEC), EC, total organic carbon, potassium, phosphorus, pH, and contents of Fe, Zn, Cu, Ni, Pb, and Cd.

Physical properties

Soil samples were dried at room temperature (25 °C) and sieved with a 2 mm sieve. Field capacity of each agro-waste type was determined using the method described in Abbott [31] and Loveday [32], while resistivities of the biochar of agro-wastes were determined following the American Society for Testing and Materials [33]. Moisture content was determined according to the procedures described in Inegbedİon [34].

Chemical properties

Agro-waste biochar and soil samples were dried at room temperature and sieved with a 2 mm sieve. pH and EC were measured according to the method adopted in Walkley and Black [35] in a 1/2.5 (mass/volume) sample-water ratio, whereas ECEC, total organic carbon, potassium, phosphorus were determined according to the method prescribed by Jaremko and Kalembas [36]. The studied heavy metals were analyzed using atomic absorption spectrometer (AAS, Agilent 240AA, Agilent Technologies, CA, USA) according to the protocol adopted by Idera et al. [37] with slight modifications. Samples were weighed (5 g) into conical flasks. For each sample, concentrated sulphuric acid (20 mL) was added and the mixture was allowed to stand for 45 min at room temperature. Five milligrams of nitric acid was then added to the mixture, heated and allowed to cool at room temperature before perchloric acid (5 mL) was added and further heated gradually until the mixture was clear. The mixture was then filtered with Whatman No. 41 filter paper and diluted with double distilled water. Analysis of heavy metals was performed in triplicates after calibrating the AAS with standard solution of the element (Ultra Scientific, at concentration of 1000 μg/mg) to be determined.

The on-site resistivity and RTG measurement were employed instead of the conventional laboratory experimental testing because the on-site testing method is inexpensive, swift, reliable, and non-destructive. Here, the Wenner four-terminal method was adopted. The four probes of the digital earth tester were inserted at equal distance along a profile and resistivity readings recorded as described in Unde and Tathe [38].

Preparation of two study sites

Five plots were demarcated at each study site, with a size of 3 m×20 m and an interval of 3 m. Each plot was then randomly assigned a treatment (coconut husk, rice husk, sugarcane bagasse, sawdust, and control) and further subdivided into two subplots at 2 m apart to prevent any potential interference resulting from leaching of the GEM. Each subplot was then randomly assigned the biochar or concrete form of the assigned treatment.

Preparation of treatments

Collection and preparation of agro-waste Rice husk was collected from rice mill waste streams in Bibiani, western north region and transported to Tamokrom in the western region of Ghana. Coconut husk was transported from Apowa, whilst sugarcane bagasse and sawdust were transported from Beposo and Takoradi respectively to Tanokrom. These agro-wastes were sun dried to less than 10% moisture content. Collection and preparation of agro-waste commenced and ended in December 2021.

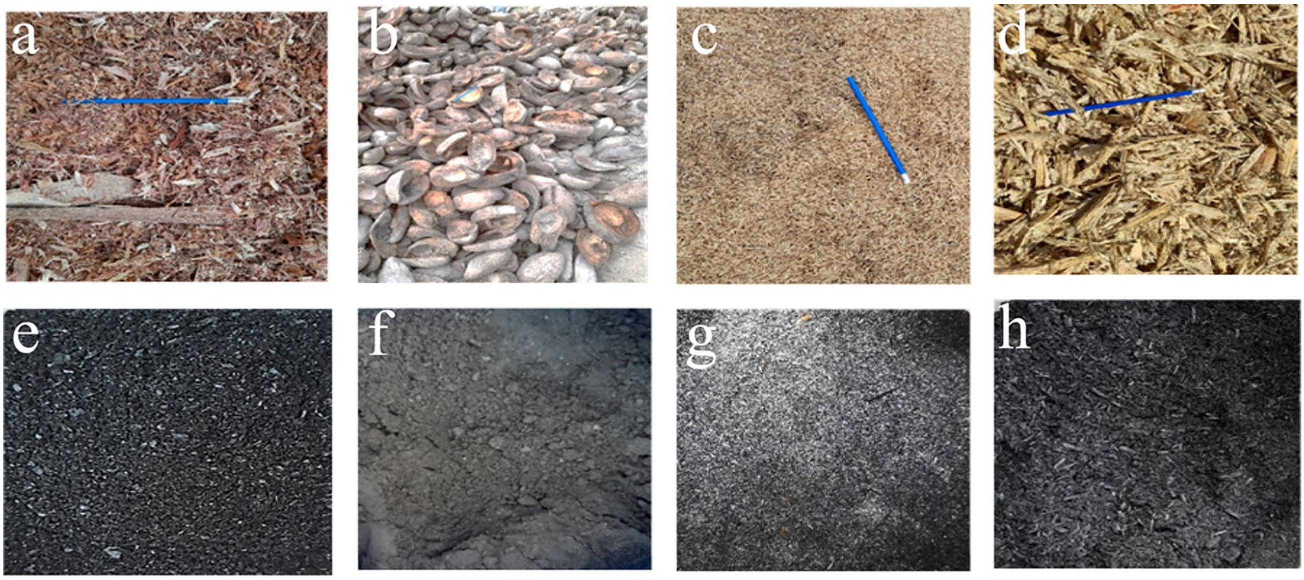

Fig. 1 Raw state and biochar state of agro-wastes. **a** and **e**: sawdust and sawdust biochar; **b** and **f**: coconut husk and coconut husk biochar; **c** and **g**: rice husk and rice husk biochar; **d** and **h**: sugarcane bagasse and sugarcane bagasse biochar

Production of biochar Biochar (Fig. 1) was produced from the agro-waste using a locally made Elsa barrel-type pyrolyser as described by Billa et al. [39] with the only modification being the capacity of the barrel used (100 L compared to the 250 L described in the cited publication). Here the sun-dried agro-waste was placed in the barrel, then a small amount of kerosene was introduced and ignited. The steel plate lid was then used to cover the open end of the barrel and the chimney was added. This ensured that the feed stock was exposed to a low amount of oxygen. The low oxygen content in the system prevented the complete burning of the feedstock and produced biochar through the process of carbonization. The biochar was poured on a clean surface and the flame in the biochar safely extinguished with clean water. The biochar of each agro-waste type was then crushed to fine particle size. The pyrolysis process was carried out over a period of 7 d due to the large amount of waste and the limited number of available Esla barrels. The average temperature in the barrel was 500 °C.

The green concretes of the agro-waste were produced with agro-waste biochar and cement ratio of 4:1 by volume.

Field set-up and application of treatment

Two circular augured holes of 0.2 m diameter and 0.5 m depth were dug on each subplot at 2 m apart. A plastic pipe, 0.2 m diameter and 0.6 m long, was inserted into each hole after a one end-threaded copper coated rod, 12.4 mm diameter rod and 1.0 m long, was driven (0.5 m) deep into each of the holes.

According to Lim et al. [40], the earth rods used in grounding systems must be installed deep enough to reach the permanent moisture level of soil. Also, Faudzi et al. [28] reports that: (1) copper rods are excellent conductors of electricity and resistant to corrosion, (2) the minimum specification for diameter of the copper grounding rod is 12 mm. These documented data informed the type of rod and rod specification used in this study.

The augured holes (except for the control) were each backfilled with the biochar or concrete form of the assigned treatment (rice husk, coconut husk, sawdust and sugarcane bagasse) and compacted. The setup was left for 14 d for the concrete to be cured before data collection commenced on the 11th March 2022.

Data measurement

Data for this study was collected twice a month for a year, that is, from March 2022 to March 2023.

Resistance to ground

In a straight line from each planted rod, the 62% method was applied. At 12.4 m, that is, 62% of the 20 m (the length of the plot), a second rod is planted, and a third rod is planted at the 20 m mark. The earth resistance tester probe's potential terminal 1 (P1) was connected to the locus rod. Potential terminal 2 (P2) to the 62% point and current terminal 2 (C2) to the last rod at 20 m. The RTG values for each treatment type were monitored with the digital earth tester (STANDARD 4236 ER 4, Taiwan, China).

Resistivity

The Wenner four-terminal method was employed. On each of the study sites, four rods were placed 3 m apart. Leads from the digital earth tester were then connected to the potential terminals 1 and 2 and current terminals 1 and 2 in line with the arrangement of the rods. These readings were taken five times at different locations and the average for the day was recorded.

Data analysis

The mean RTG values and resistivity values were calculated for each month. Also, the monthly zone of influence for each treatment type was calculated by Eq. (1) [41]

$$R_{\mathrm{b}} = \frac{1}{2\pi l}\left[\rho\left(\ln\frac{8l}{D_{\mathrm{b}}}-1\right)+R_{\mathrm{l}}\left(\ln\frac{8l}{d}-1\right)-R_{\mathrm{l}}\left(\ln\frac{8l}{D_{\mathrm{b}}}-1\right)\right], \quad (1)$$

where R_{b} is the earth resistance of electrode with conductive backfill (Ω); ρ is the resistivity of the local soil (Ω m); D_{b} is the diameter of conductive backfill (m); R_{l} is the resistivity of the backfill material (Ω m); l is the length of electrodes (m); d is the diameter of earth rod (m).

The Bartlett and multivariate normality tests (MVN package) analysis suggested that the data set did not meet the assumptions for using parametric tests. Thus, non-parametric analysis (Kruskal-Walli's test) was used to determine the effect of GEM (agro-wastes) on resistivity, RTG values and the zone of influence. Tukey's honestly significant difference (HSD) test was performed to statistically evaluate the extent of the effect of the different agro-waste and their mode of application (biochar or concrete) on the performance of ground electrodes.

Simple linear regression analysis was also employed to quantify and compare the effects of treatments and time on the RTG and the zone of influence. The relative effects of treatment, time, and mode of treatment on the RTG were quantified using the 'relaimpo' version 3.6.3 package in the *R* statistical software [42]. Data analysis and plotting were done with GraphPad Prism 9.0 (Dotmatics, UK) and *R* statistical software (R Foundation, Vienna, Austria).

Results

Baseline characteristics of soils from the study sites

Site A was slightly basic and site B was slightly acidic with the recorded pH for both study sites within the recommended threshold limits (Table 1). The recorded CEC values for both study sites were higher than the typical CEC value for soil in the coastal regions with site A recording higher CEC value of 120.909 mmol/kg compared to 24.242 mmol/kg for site B. Field capacity recorded for both study sites was also significantly lower than the recommended 16%. Also, total organic carbon, potassium, and phosphorus content in soil from both study sites were lower than recommended levels, though site A recording higher levels of potassium and phosphorus relative to site B.

Mean heavy metal concentrations of the five heavy metals were significantly lower than their threshold limits (*P*-value>0.05). Fe was the most dominant heavy metal for both sites while Ni and Cd were the least heavy metals in sites A and B, respectively.

Table 1 Baseline soil properties of the study sites

Soil parameter	Site A (Tanakrom)	Site B (Whindo)	Threshold limit	Reference
pH	8.15	5.65	6.0–7.5	[43]
ECEC (mmol/kg)	120.9	24.2	20.0	[44]
EC (μs/cm)	125.20	35.80	<4000	[45]
Total organic carbon (%)	0.36	1.20	20	[43]
Potassium (mmol/kg)	0.9	0.5	>50	[43]
Phosphorus (mmol/kg)	0.7	0.3	20–40	[43]
Fe (mg/kg)	76.68	18.27	5000	[43]
Zn (mg/kg)	0.96	0.57	50	[46]
Cu (mg/kg)	0.97	0.66	36	[46]
Pb (mg/kg)	1.60	0.25	85	[46]
Cd (mg/kg)	0.10	0.04	0.80	[46]
Ni (mg/kg)	0.05	0.05	35	[46]
Field capacity (%)	4.86	9.03	16	[47]

Table 2 Effects of agro-waste-based GEM (coconut husk, sugarcane bagasse, rice husk, and sawdust) on RTG

Soil type	Mode of application	Treatment type					Values for mode of application		Values for treatment	
		Control	Coconut husk	Sugarcane bagasse	Sawdust	Rice husk	*P*-value	*F*-value	*P*-value	*F*-value
Clay	Biochar	112.70^{a} (2.10)	50.30^{b} (1.20)	33.05^{c} (0.80)	65.15^{d} (0.90)	47.40^{b} (0.30)	0.900	0.03	7.19×10^{-8}	1438.50
	Concrete	112.70^{a} (2.10)	48.95^{b} (0.60)	34.85^{c} (0.60)	63.45^{d} (0.50)	59.00^{e} (1.00)			1.37×10^{-8}	1146.20
Sandy	Biochar	216.50^{a} (1.70)	260.50^{b} (0.70)	471.70^{c} (2.70)	370.55^{d} (44.30)	479.95^{c} (1.50)	0.002	13.10	1.00×10^{-4}	72.60
	Concrete	216.50^{a} (1.70)	150.60^{b} (1.30)	139.90^{c} (0.30)	160.10^{d} (1.60)	340.65^{e} (0.50)			1.13×10^{-9}	7808.00

Notes: Values are means (Ω) of six replicates with standard deviation in parenthesis.

For each mode of treatment application, different letters represent significant differences in RTG for the different treatments

Effects of agro-waste-based GEM on RTG values of grounding systems

The agro-waste-based treatments exerted significant effects (P-value≤0.05) on RTG values relative to the control (Table 2). The extent of the effect depended on the agro-waste treatment type, soil type and the mode of application of the treatment.

Averagely, the RTG values were higher in the sandy soil compared to the clay soil and application of treatments (biochar and concrete) exerted significant but mixed effects on the RTG values. For instance, the application of the biochar of coconut husk, sugarcane bagasse, sawdust, and rice husk reduced the RTG values in the clay soil (site A) but failed in the sandy soil (site B) compared to the control.

Sugarcane bagasse biochar exerted the most effect on RTG values, recording an RTG value of 33.05 compared to 112.70 recorded for the control. Clearly, coconut biochar was the most effective GEM for site B, though the recorded RTG values were still higher than the control.

The mode of application of treatment also exerted significant but mixed effects on the RTG values. For instance, there was a clear and significant difference (P-value≤0.05) in the RTG values of the ground systems with concrete form of the agro-waste biochar compared to their counterpart with the biochar form of the agro-waste in the sandy soil but not the clay soil (P-value>0.05).

Effect of agro-waste-based GEM on zone of influence

Like the trend observed with the RTG values, treatment and mode of application of treatment exerted significant (P-value≤0.05) but varied effects on the zone of influence (Table 3). Sugarcane bagasse (biochar and concrete) extended the zone of influence more in the clay soil. Apparently, the zone of influence of the agro-waste was significantly higher in the sandy soil across treatment with all the treatment types recording more than 1.0 m zone of influence. However, there was a significant difference in the effect of the treatment based on the mode of application. Notably,

Table 3 Effects of agro-based GEM (coconut husk, sugarcane husk, rice husk and sawdust) on the zone of influence

Soil type	Mode of application	Treatment type					Values for mode of application		Values for treatment	
		Control	Coconut husk	Sugarcane bagasse	Sawdust	Rice husk	*P*-value	*F*-value	*P*-value	*F*-value
Clay	Biochar	0.00112^{a} (0.00)	0.07871^{b} (0.00)	0.00002^{c} (0.00)	0.00231^{a} (0.00)	0.00112^{a} (0.00)	0.6	0.2	1.31×10^{-7}	1167.0
	Concrete	0.00153^{a} (0.00)	0.05070^{b} (0.00)	0.00005^{c} (0.00)	0.00013^{a} (0.00)	0.00153^{a} (0.00)			5.71×10^{-6}	256.5
Sandy	Biochar	3.20000^{a} (0.01)	1.10001^{b} (0.01)	2.20001^{c} (0.5)	1.00001^{b} (0.04)	3.20000^{a} (0.01)	0.004	10.6	2.00×10^{-4}	48.2
	Concrete	3.70001^{a} (0.01)	3.80001^{a} (0.00)	3.70000^{a} (0.01)	2.50000^{b} (0.03)	3.70001^{a} (0.01)			3.90×10^{-8}	1889.7

Notes: Values are means (m) of six replicates with standard deviation in parenthesis.

For each mode of treatment application, different letters represent significant differences in the zone of influence for the different treatments

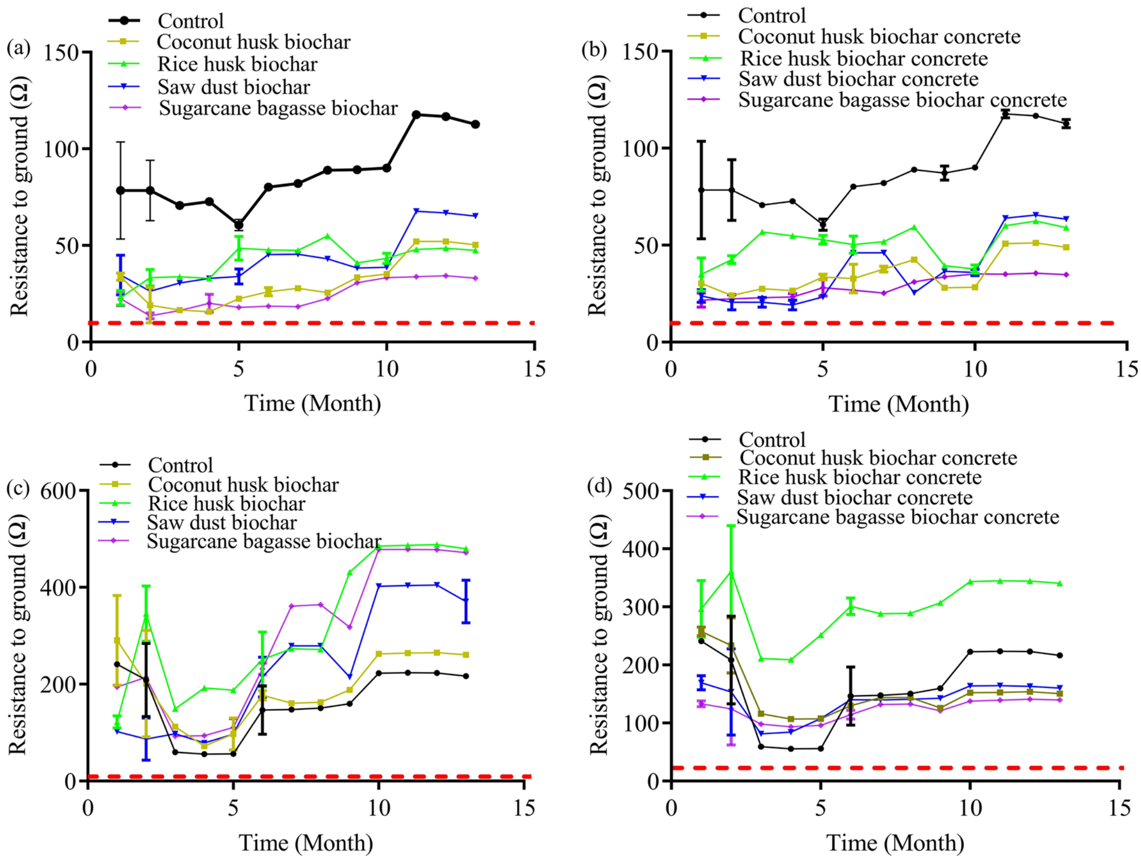

Fig. 2 Effects of time and treatment on the RTG values of grounding systems. **a** site A biochar, effect of treatment $= 2.2 \times 10^{-16***}$ and effect of time $= 2.2 \times 10^{-16***}$; **b** site A concrete, effect of treatment $= 2.2 \times 10^{-16***}$ and effect of time $= 2.2 \times 10^{-16***}$; **c** site B biochar, effect of treatment $= 0.05^{***}$ and effect of time $= 0.04^{***}$; **d** site B concrete, effect of treatment $= 2.2 \times 10^{-16***}$ and effect of time $= 2.2 \times 10^{-9***}$. Red dashes represent threshold resistance to ground values (10 Ω), *** represents the data when the effect is the most significant

the concrete form of the agro-waste recorded significantly higher zone of influence compared to the biochar form in the predominantly clayey soil but not the sandy soil.

Effect of time and treatment on RTG values

The recorded RTG values across soil type, treatment, and mode of application of treatment were better than the recommended threshold RTG values (Fig. 2). Time and treatment played a significant but mixed role in reducing RTG values. For the clay soil, treatment and time reduced the RTG values more than the control. The effect of treatment on RTG values were similar in the initial stage of this study. However, the effect of rice husk biochar and sawdust biochar dwindled over time and the recorded RTG values for the grounding system with the biochar of rice husk and sawdust were higher than those of coconut husk and sugarcane bagasse. For the clay soil, the RTG values recorded for grounding system with sugarcane bagasse biochar as backfill materials were the lowest throughout the study period regardless of the mode of application. On the other hand, RTG values were higher in the sandy soil and application of treatment did not improve RTG values over time.

Clearly, mode of application also exerted significant effect on the sustained RTG values overtime. Except for rice husk biochar (concrete), the variation in the recorded RTG values for grounding systems with concrete form of the treatment was fairly constant throughout the study period relative to the biochar form which varied widely with time and treatment.

Clearly, time, treatment, and soil type significantly affected the recorded RTG values though the magnitude of significance varied. Soil type was the most dominant factor, followed by treatment and time.

Effect of time and treatment on zone of influence of agro-waste as GEM

The zone of influence of the study treatments, especially the biochar varied significantly with time (Fig. 3). Apart

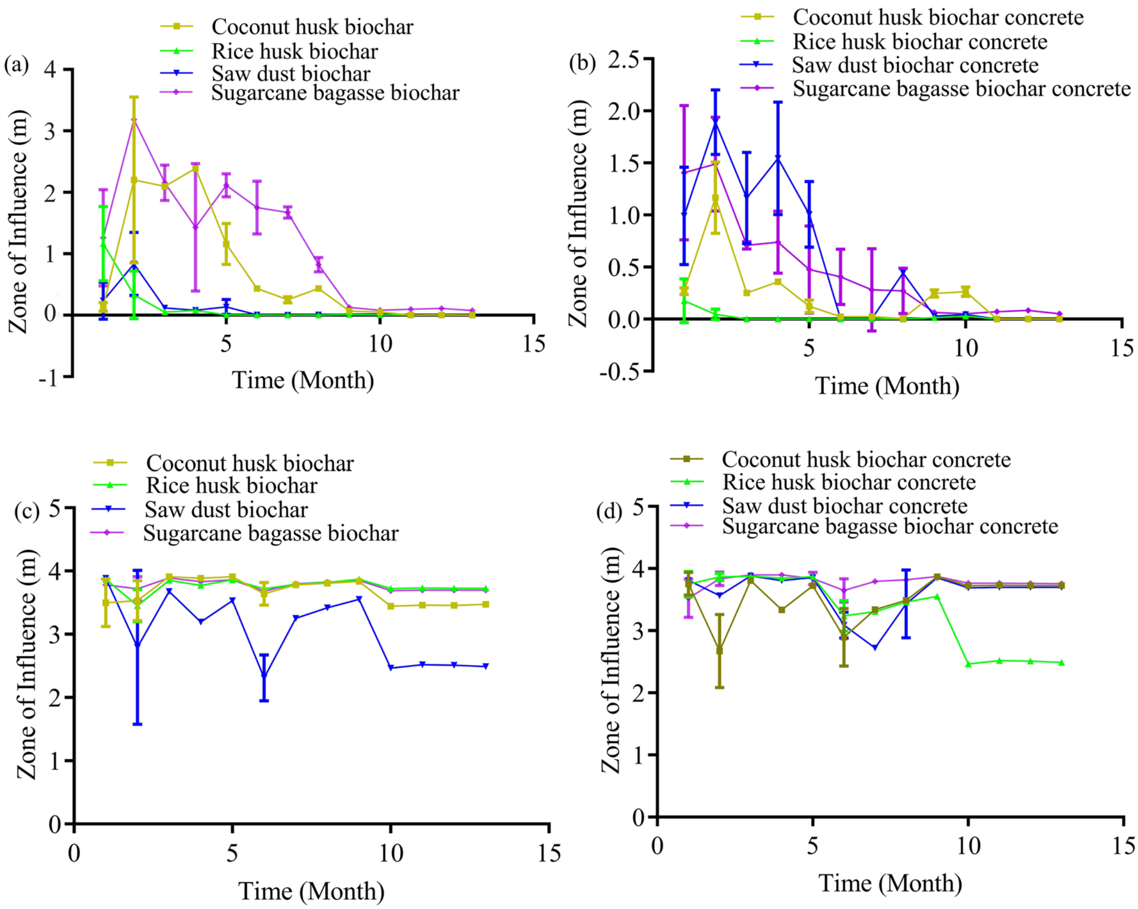

Fig. 3 The effects of time and treatment on the zone of influence of agro-wastes used as GEM during grounding. **a** site A biochar, effect of treatment = $2.2 \times 10^{-16***}$ and effect of time = $2.2 \times 10^{-16***}$; **b** site A concrete, effect of treatment = $3.086 \times 10^{-13***}$ and effect of time = $2.2 \times 10^{-16***}$; **c** site B biochar, effect of treatment = $1.418 \times 10^{-14***}$ and effect of time = $2.2 \times 10^{-16***}$; **d** site B concrete, effect of treatment = $2.2 \times 10^{-16***}$ and effect of time = $1.515 \times 10^{-7***}$. *** represents the data when the effect is the most significant

from sawdust, the recorded zone of influence for the clay soil was more than 1 m for all treatment. However, the zone of influence for the agro-waste reduced significantly with time. Notably, variation of zone of influence for the different modes of application were not that different and the recorded zone of influence for all treatment were less than 0.2 m by the 10th month of this study. An opposite trend was observed for the sandy soil with zone of influence not varying widely with time for all treatments. The recorded zone of influence for the treatments was significantly higher in the sandy soil relative to the clay soil.

There was not much difference in the zone of influence for the treatments regardless of the mode of application, for a particular soil type. However, results show that treatment was a more dominant factor compared to time.

The study results show that generally, soil type is an important determinant of the zone of influence of the applied treatment followed by time and treatment type.

Relative importance of the effects of treatment, mode of treatment application, and time on RTG values

Time, treatment, and mode of application are major factors contributing to the variations in RTG values with the three variables accounting for 83.37% of the total variations in the RTG values (Fig. 4a).

Treatment was the most dominant study factor, accounting for 54.7% of the variations in RTG values ralative to the 38.6% and 6.7% recorded for the mode of application and time, respectively.

The four study treatments contributed a total of 87.93% variations in RTG values (Fig. 4b). Coconut husk biochar was the most effective among the study treatment, contributing 55% reduction in RTG values compared with 26%, 16%, and 3% recorded for rice husk biochar, sawdust biochar and sugarcane bagasse biochar, respectively.

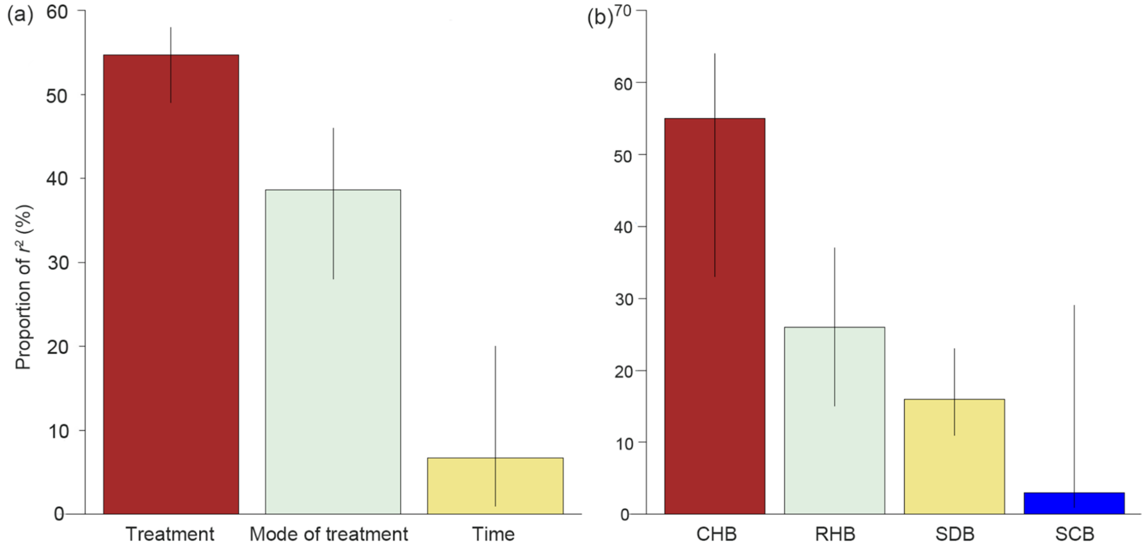

Fig. 4 Relative importance of the effects of time, treatment and mode of application of treatment to RTG values (N=576). r^2 for Figs. 4a and 4b are 83.37% and 87.93% respectively. CHB, RHB, SDB, and SCB represent coconut husk biochar, rice husk biochar, sawdust biochar, and sugarcane bagasse biochar, respectively

Discussion

Effects of soil type on soil resistance

The main importance of grounding systems is the collection, drainage, and dissipation of fault current into the earth to restrict the potential gradient within the permissible limits [48]. Thus, it is important that there is no resistance to the flow of dissipated current to the earth. Hence, detailed knowledge of the soil structure in the territory where the project will be sited is considered as an indispensable condition for proper design of grounding systems [48, 49]. Results of the baseline study suggests that site A has significantly high ECEC (120.9 mmol/kg) and EC (125.20 µs/cm) relative to the 24.2 mmol/kg and 35.80 µs/cm recorded for ECEC and EC for soil from site B. Also, site A which was determined to be predominantly clay, had a relatively high field capacity of 9.03%.

ECEC, EC, and field capacity have strong correlation with the resistivity of soil [50–52]. The recorded high ECEC and EC in soil from site A suggest relatively low soil resistivity as confirmed by the relatively low RTG values recorded for site A soil (112.70 Ω) compared to their counterpart from site B (216.50 Ω). Soil type significantly influences the behavior of applied biochar treatments [27, 48, 49]. For instance, Zu et al. [25] and Wang et al. [26] posit that soil with high moisture content and high clayey content are likely to have low resistivity and are unlikely to leach out the applied biochar treatment. Thus, barring any confounding phenomenon, it is likely for the effects that the applied biochar in clayey soils (site A) lasts longer relative to sandy soil (site B) [25–27, 49].

Effects of treatment on soil resistivity

Application of GEM during grounding is common [4, 53, 54]. These materials have low resistance, hence, create low resistance path for EC or alter the physicochemical properties like water holding, CEC, and EC of soil [13, 24, 55]. Studies have shown that backfilling earth electrodes with GEM, either chemical-based or agro-waste-based, results in significant reduction in soil resistance [8, 22, 23, 28, 56]. For instance, Nyuykonge et al. [13] report the reduced soil resistance from 242 Ω to 27 Ω after application of biochar. Also, Faudzi et al. [28] report significant decrease in soil resistance (from 19.3 Ω to 17.3 Ω) after application of palm oil ash.

The results of this study suggest that treatment exerts significant but mixed effects on soil resistance. Treatment with coconut husk biochar (CC), sugarcane bagasse biochar (SC), sawdust biochar (SD), and rice husk biochar (RH) resulted in reductions of soil resistance by 44.0%, 29.3%, 57.8%, and 42.0%, respectively, when applied to the predominantly clay soil. However, treatment with biochar of the agro-waste was not effective in the sandy soil. Here, CC, SC, SD, and RH which were effective in reducing RTG values in the clay soil failed to significantly reduce the same parameter in the predominantly sandy soil.

Coarse and porous soil has high soil resistivity [38, 57]. These types of soil usually have low moisture content because they are porous and easily lose water, dissolved ions, and applied GEM [58, 59]. Soil water influences the mobility of electrical charges because soil chemical properties like humus, cation, anions, soil minerals, and salts which are linked to EC in soils are predominantly dissolved in soil water [4, 27, 60].

Thus, the failure of the applied treatments to reduce RTG values of the sandy soil though effective in reducing resistivity in the predominantly clayey soil may be attributed to the loss of the applied treatment through leaching as also confirmed by the wider zone of influence of all treatments with the sandy soil compared to the clay soil.

In applying GEM as backfill materials for grounding system, it is important that for the proper functioning of the earthing system and the general health of the environment the applied backfill materials are inert and last for long period [13]. However, a noteworthy finding of this study is that the soil type may in some instances (sandy, coarse soil with high porosity) be an important determinant of the durability of the applied treatment. Thus, in such instances when managers choose to use biochar as low resistance materials, it is vital to find ways of immobilizing applied treatment so that they are not leached out.

One such method is using green concrete technology, that is, using the selected agro-waste-based biochar for concrete and subsequently use the by-product (green concrete) as backfill materials.

Effect of mode of application

Biochar can last for hundreds of years before losing its soil enhancing role [13]. The results of this study suggest that in very porous soil, such as sand or coarse soil, applied biochar is easily washed out, rendering the grounding system ineffective. In addition, high rainfall and high soil moisture content also trigger physical breakdown of biochar [25, 26]. The use of agro-waste-based green concrete has been proposed as a viable alternative of preserving agro-waste-based biochar GEM in grounding systems [20, 54, 61].

According to Hasni et al. [61] and Cordon et al. [62], combining the structural capacity of concrete with the properties of GEM like steel fiber and granite improves the EC properties of concretes. The results of this study support this finding. Here, the mode of application of treatment exerted significant effect on the recorded RTG values. This trend being more obvious in the sandy soil. Clearly, set-up treated with the concrete form of the agro-waste in the sandy soil recorded significantly lower RTG values compared to their counterparts with biochar of the same agro-waste over the study period. This trend suggests that concretizing the biochar of agro-wastes immobilizes the treatment and prevent it from being leached out. While the results of this study suggest that such leaching of biochar in clay soil is limited, application of such technology in clay soil in long term grounding systems may be effective in maintaining the integrity and effectiveness of grounding systems.

Effects of time

The performance of most GEM has been linked with moisture content in soil [4, 27, 60]. The results of this study, especially the first six months of the study, seem to confirm this finding. It is also noteworthy that high moisture content in soil resulting from rainfall is also an important but often-overlooked mechanism for biochar aging, physical breakdown [25, 26]. According to Zu et al. [25], during rainfall events, biochar undergoes molecular transformation (oxidation, dissolution, and fragmentation) at molecular level. This phenomenon may be attributable to the significant reduction in the resistivity reducing effects (especially in the clayey soil) of the biochar on soil resistivity after the study period corresponding to the rainfall season in the study area. This has significant implications for the use of biochar as GEM in grounding systems as well as their mode of application. One of the most favorable characteristics of biochar as GEM is its long resident time in soil [13]. A notable finding of this study is a potential compromise, through leaching or physical breakdown, of the above-mentioned characteristics in areas with high rainfall patterns. Hence, novel ways of immobilizing applied biochar in grounding systems need to be found, especially when applied to porous soil or soil exposed to high amount of rainfall.

Notably also, it is the recorded zone of influence for the clayey soil (<1 m) relative to the sandy soil (≥2 m) reported in this study. This suggests that the reduced effect of the applied biochar in the clayey soil overtime was mostly attributable to the physical breakdown of biochar as posited by Zu et al. [25].

Treatment, time, and the mode of application of treatment are important factors affecting the effectiveness of agro-waste-based GEM used as backfill materials during grounding. In this study, these three factors explained 83.37% of the changes in RTG values. Treatment was the most important factor followed by mode of application and time as also reported by Zu et al. [25] and Nyuykonge et al. [13]. Clearly, the effects of treatment, time, and mode of application of treatments are interdependent [25, 26]. For instance, in this study authors reported coconut husk biochar as an effective GEM. However, this treatment was not effective in reducing RTG values in the sandy soil because the nature of the soil and mode of application of treatment made it easier for treatment to leach out, rendering the applied treatment ineffective.

Conclusions

Agro-waste-based GEM are viable alternatives to chemical-based GEM as backfill materials for grounding systems. The recorded significant (*P*-value≤0.05) improvement in soil resistivity values as well as the zone of influence, ranging less than 1 m for the clayey soil and equal or more than 2 m in the sandy soil, is a strong testament. These effects of the study treatments were significantly influenced by time. A notable finding of this study is that rainfall and high moisture content result in physical breakdown of biochar. This has significant implications for the use of treatment and the mode of application of treatment. Treatment, time, and mode of application of treatment played significant and interdependent roles in reducing soil resistivity with these factors contributing to over 83% improvement of RTG values.

Apparently, other confounding variables (e.g. method of carbonizing the waste, physical and chemical properties of the biochar) are also at play and significantly affect the effectiveness of GEM and must guide future research in GEMs.

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Declarations

Competing interest The authors declare no competing interests.

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