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RESEARCH ARTICLE

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Limited short-term benefits of glacial rock flour for enhancing the physical quality of tropical arable soils

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Abstract

There is increasing recognition that the application of fine-grained silicate rock granulates can improve soil productivity by increasing its fertility and ameliorating its physical properties. Although the former has been extensively studied, empirical information on the latter is scarce. Pot and field experiments were conducted at the University of Ghana's Forest and Horticultural Crops Research Centre (FOHCREC), Kade, Ghana, from May 2020 to December 2021 to quantify the short-term effect of the application of Greenlandic glacial rock flour (GRF) on the physical properties of three benchmark arable soils in Ghana, namely an Acrisol (sandy clay loam), a Haplic Ferralsol (sandy loam), and an Arenosol (sand). The pot experiment included three GRF treatments (0, 10, and 20 t ha^{-1}) and the three soil types, while the field experiment was conducted on only the sandy clay loam soil where GRF rates of 10 and 50 t ha^{-1} were compared to the control. Intact 100 cm^3 soil cores were sampled from the soil surface in the field and pot experiments to assess the soil bulk density. We also quantified soil water retention, air and gas transport, and pore morphological characteristics over a range of matric potentials. Both the pot and field experiments showed that adding GRF did not improve soil water retention. Still, the response of gas transport and pore characteristics to changing matric potential was significantly ($p < 0.05$) modified by GRF in some soil types. The results suggested that the effectiveness of the use of GRF to ameliorate soil physical conditions for plant growth may depend on soil type and the soil water matric potential. We concluded that the application of GRF cannot be relied upon as a short-term strategy to significantly improve the structural quality of the tropical soils studied. Rather, GRF should be considered for application to the soils for its other beneficial effects. We recommend that the effects of repeated applications and further build-up of the material in the soil should be investigated to determine the effect of higher relative GRF concentrations on soil hydro-physical properties.

KEYWORDS
air permeability, enhanced rock weathering, glacial rock flour, pore size distribution and morphological characteristics, relative gas diffusivity, soil water retention

1 | INTRODUCTION

Agriculture production in most tropical environments is constrained by low soil fertility due to the highly weathered nature of tropical soils. Also, agricultural intensification to increase food production for the growing population is constrained by the rapid loss of agricultural lands to urbanization (Radwan et al., 2019; Sumbo et al., 2023), mining, and other forms of land use. Intense land competition in the humid tropics has drastically reduced fallow periods widely practiced in the slash-and-burn system of farming leading to widespread soil degradation (Glaser et al., 2002). Different management practices have been suggested to mitigate the degradation of tropical soils and promote plant growth. One such option is the use of chemical fertilizers to improve soil fertility. However, the generally low cation exchange capacity (CEC) and high rainfall in most tropical regions enhance the leaching of the nutrients supplied by chemical fertilizers (Cahn et al., 1993), resulting in nutrient-deficient soils and low crop yield (Glaser et al., 2002). Though research on the use of finely ground and unprocessed rocks as soil amendment dates back several decades (Swoboda, 2016; Swoboda et al., 2022), in recent years, there has been growing interest in the prospects of using rock dust as an amendment in agricultural systems to address soil factors limiting crop growth and yield (Gunnarsen et al., 2023) and induce carbon removal through the enhanced weathering of silicate minerals (Beerling et al., 2020). It is recognized that soil's functional physical and chemical properties are controlled by the fine particle content (Pesch et al., 2022), and thus, the application of mineral rock dust could ameliorate the conditions for soil for plant growth. Glacial rock flour (GRF) is a fine-grained sediment naturally produced by bedrock abrasion during glacial erosion. In Greenland, this material has been washed out from under the glaciers and deposited in fjords where it can be easily collected (Bennike et al., 2019). Recent research has demonstrated that, due to the properties of GRF, particularly its large specific surface area and cation exchange capacity (CEC) (Pesch et al., 2022), its application as an amendment can improve soil hydro-physical properties, especially in coarse-textured soil by enhancing its structure development (Bojesen & Olsen, 2019). Thus, GRF could be used as an alternative to other agricultural amendments or augment the agronomic benefits derived from them. The application of rock dust is expected to improve soil productivity not only through increased nutrient concentration but also through ameliorating soil physical properties (Swoboda, 2016). However, studies on GRF have generally focused on its potential to improve soil fertility, chemical properties, and crop growth traits and yield, whereas evidence of its potential to alter soil physical properties is scarce (Bojesen & Olsen, 2019; Pesch et al., 2022). For example, Gunnarsen et al. (2022) reported that the amendment of GRF to highly weathered tropical acidic soils enhanced the release of silicon but did not significantly improve the availability of soil phosphorus. In another study, Gunnarsen et al. (2023) found that the application of GRF to sandy Danish soil increased maize dry yield by 59 kg ha^{-1}, and potato tuber yield by 90 kg ha^{-1} in the first year of application but did not find any significant residual effect in the subsequent years.

Highlights

- The short-term effects of glacial rock flour (GRF) application on the physical properties of three tropical arable soils were studied.
- The application of GRF did not significantly alter soil water retention.
- The effects of GRF on soil gas transport and pore characteristics varied depending on soil water matric potential.

In Ghana, Acrisols, Haplic Ferralsols, and Arenosols or Quartzipsamments are important agricultural soils. Acrisols are predominant soils in the moist semi-deciduous forest agroecological zone; Haplic Ferralsols in the tropical rain forest (Dwomo & Dedzoe, 2010) and Arenosols or Quartzipsamments are in the semi-arid coastal savanna zone of Ghana, on scattered sandbars and a large sand spit along the coast (Dodor et al., 2018). Despite the agronomic potential of the soils, such as for cultivating food and plantation crops, continuous cropping without replenishing nutrients and unsustainable farm practices have resulted in a rapid decline in soil organic matter and soil fertility (Ghartey et al., 2012). Also, poor soil structure adversely affects fundamental soil functions like water retention and the transport of fluids and gases in the soil (Arthur & Ahmed, 2017; Obour et al., 2019).

Studies on the application of soil amendments are often based on similar conditions, such as soil types, and are usually conducted solely under controlled pot experiments or field conditions, which limits the use of the data as the basis for wider adoption by farmers. Controlled pot experiments help to minimize noise inherent in natural systems and allow researchers to hold constant or vary factors of interest. In contrast, field experiments are more representative of reality. To address the shortcomings outlined above, the present study presents results from controlled (pot) and field experiments. The objective of both experiments was to investigate the effects of GRF on the physical properties of tropical arable soils. Soil hydro-physical properties were quantified in terms of pore morphology, water retention, and air transport. Understanding these properties provides important insights into soil health and functionality for effective soil management. We hypothesize that applying GRF to highly weathered tropical soils will modify the soils' pore size distribution and pore morphology, thereby enhancing its hydro-physical properties.

2 | MATERIALS AND METHODS

2.1 | Description of the study area

Both the field and pot experiments were conducted at the University of Ghana's Forest and Horticultural Crops Research Centre (FOHCREC), Kade, Ghana. The Research Centre is located at 06° 08′ 37″ N; 00° 54′ 10″ W, at an altitude of 180 m above mean sea level. The study area has a major and minor rainy season within a year. April to July marks the major rainy season period, while the minor rainy season occurs from September to October. The dry season, also called 'Harmattan', spans November to March each year. The annual average rainfall and temperature are 1500 mm and 28°C, respectively. The predominant soils at FOHCREC are Acrisols (WRB, 2015).

2.2 | Physical and chemical characteristics of glacial rock flour used in the study

The Ilulialik GRF used in the study was collected from a marine deposit in Nuuk fjord (64° 45′ 36″ N, 50°, 39′ 36″ W) by the National Geologic Survey of Denmark and Greenland (GEUS). This material has a median grain size of 2.6 μm and a BET-specific surface area of 19.6 $m^2\ g^{-1}$; based on its particle size distribution (37.7% clay, 62.3% silt), its texture would be classified as a silty clay loam (Sarkar, 2021). It is composed of biotite (27.4%), oligoclase/andesine (18.6%), amphibole (14.6%), anorthite (14.1%), quartz (10.5%), Fe-oxide (4.3%), K-feldspar (2.8%), and muscovite (2.4%) (measured with ZEISS Sigma 300VP field emission scanning electron microscopy by the Geological Survey of Denmark and Greenland) (Dietzen & Rosing, 2023; Gunnarsen et al., 2023).

2.3 | Field experiment

The experimental treatments consisted of GRF rates of 0, 10 (GRF_{10}), and 50 (GRF_{50}) t ha^{-1} replicated four times giving a total of 12 experimental plots. These plots measured by 3 m, and they were arranged in a randomized complete block design with 1 m buffer strips between plots and blocks to minimize the chances of GRF movement between plots and blocks. Before sowing for the first experiment, weeds on the plots were manually cleared with cutlass and all tree stumps were removed. Afterwards, GRF was applied by manually broadcasting onto a 1 m^2 section of the soil surface to ensure uniform coverage at rates of 10 and 50 t ha^{-1}. The GRF was then manually incorporated into the upper 15 cm of soil using a hoe.

Maize (*Zea mays*, L.) was sown at plant spacing of 30 cm and row spacing of 60 cm for five consecutive growing seasons running from May 2020 to December 2021. The first three growing seasons were the major, minor, and dry seasons in 2020. The next two growing seasons covered the major and minor seasons of 2021. After harvest for the fifth and last experiment, the land was left uncultivated for 4 months to simulate follow before soil sampling was done.

2.4 | Pot experiment

2.4.1 | Soils, excavation, and experimental design

Two consecutive pot experiments were conducted. The soil samples used in the study were excavated at 15 cm depth from three different benchmark soils in Ghana, namely classified as Arenosols or Quartzipsamments, Acrisols and Haplic Ferralsols, respectively, according to the WRB soil classification. The Arenosols were collected from Anloga in the Volta region, the Acrisols from Kade in the Eastern region, and the Haplic Ferralsols from Ankasa in the Western region. The textures of the Arenosols, Acrisols, and Haplic Ferralsols are sand, sandy clay loam, and sandy loam, respectively. The pots were arranged in a completely randomized design with four replicates of each treatment (0, 10, and 20 t ha^{-1}) for each of the three soil types, for a total of 36 pots.

2.4.2 | Soil and GRF preparation, and filling of pots

The excavated soils were brought to the laboratory, air-dried, and passed through a 2 mm sieve to remove all plant roots and other debris >2 mm. The pots used in the study were made of cylindrical PVC pipes (21 cm in diameter and 30 cm high). These were filled with soil up to 20 cm depth to obtain bulk densities of 1.6, 1.3, and 1.5 g cm^{-3} for the sand, sandy loam, and sandy clay loam soils, respectively (corresponding to field bulk density). GRF (the same as used for the field study) amounts of 34.64 and 69.27 g per pot were mixed into the soil to a depth of 20 cm to obtain GRF rates of 10 (GRF_{10}) and 20 t ha^{-1} (GRF_{20}). Thus, because the pots used for all treatments had the same volume, bulk densities for the GRF-amended soils were slightly higher (0.005 and 0.01 g cm^{-3} higher for GRF_{10} and GRF_{20}, respectively) than the control counterpart at the start of the experiment. The soil-GRF mixture was gently compacted by hand. The control treatment (0 t ha^{-1}) was filled with only soil. Once all the pots were packed, they were saturated with deionized groundwater and allowed to stand for 3 days for excess water to drain. After drainage had ceased, time-domain reflectometry (TDR) probes consisting of two stainless steel rods of 6 mm diameter each, and 20 cm tall were inserted in the middle of each pot. The manual TDR 100 instrument (Campbell Scientific, Logan, Utah, USA) was connected to the probes in the soil, and the soil water content measurements representing field capacity were determined. The moisture levels in the pots were kept close to field capacity by watering the pots back to field capacity whenever the moisture in the pots fell 10% below the field capacity values in the individual pots. The pots were kept under a makeshift shed covered with transparent polyethylene sheets to protect them from the direct impact of rainfall.

2.4.3 | Planting of maize

Maize was sown in the pots and harvested at tasselling (40 days after sowing). The experiment was repeated using the same pots. After the harvest of the second experiment, the pots were kept in the shed for 1 year before soil sampling was done. During this period, the soil water content in the pots was kept at field capacity.

2.5 | Sampling

For the field experiment, bulk and intact 100 cm^3 (6.1 cm diameter, 3.4 cm high) core soil samples were collected from the soil surface for the determination of soil properties. Two cores were sampled from each of the 12 experimental plots. For the pot experiment, a total of 36 soil cores (4 soil cores × 3 GRF rates × 3 soil types) were likewise sampled from the soil surface of each pot.

2.6 | Measurements of soil physical properties

The soil water retention curve over a range of matric potentials (−30, −50, −100, −300, −500, and −1000 hPa) was measured on the intact 100 cm^3 soil cores. Measuring soil properties at a range of matric potentials provides comprehensive information about the dynamics of soil water and pore functions at varying moisture conditions for effective soil and water management and maintaining soil quality for agricultural production. To set the matric potentials at −30, −50, and −100 hPa, the soil samples were placed on sandboxes and slowly saturated by capillary action from water to remove all entrapped air in the soil pores before draining the samples to the given matric potentials stepwise. Matric potentials at −300, −500, and −1000 hPa were measured on the soil samples using vacuum pots and pressure plates as described by Dane and Hopmans (2002).

Air permeability (k_a) and gas diffusion (D_p) were measured on the soil cores at each matric potential except for the sand, where D_p was only measured at −30, −50, and −100 hPa matric potentials due to technical challenges. Air permeability was determined following the Forchheimer approach (Schjønning & Koppelgaard, 2017). Gas diffusion was determined following the procedure described by Taylor (1950). The relative gas diffusivity of the soil samples was computed as the ratio of D_p to the gas diffusion in free air (D_0).

After measuring the matric potential at −1000 hPa, the soil cores were oven-dried at 105°C for 24 h to determine the dry bulk density. The dry bulk density of the soil cores was computed as the ratio of the oven-dried mass to the total volume of each soil core. Total porosity was calculated from bulk density and an assumed particle density of 2.65 g cm^{-3}. The gravimetric water content of each matric potential was computed as the mass of moist soil minus the oven-dried mass divided by the oven-dried mass. The volumetric water content at each matric potential was then calculated as the gravimetric water content multiplied by bulk density. The air-filled porosity (ε_a) was computed as the difference between total porosity and volumetric water content at a given matric potential.

2.7 | Modelling pore size distribution and characteristics

The soil pore size distribution was determined from the water retention data by computing the diameter of pores drained at each water potential as:

$$d = \frac{-3000}{\psi}, \quad (1)$$

where d is the equivalent cylindrical pore diameter (μm) and ψ is the soil matric potential (hPa).

Soil pore continuity or pore organization index (PO) was computed as the ratio between k_a and ε_a (Groenevelt et al., 1984). According to Blackwell et al. (1990), soils with similar PO have identical pore size distributions and pore continuities.

The tube model of Ball (1981) was used to compute soil pore tortuosity (τ) as:

$$\tau = \left\{ \frac{\varepsilon_a}{D_p/D_0} \right\}^{1/2}. \quad (2)$$

2.8 | Statistical analysis

The effects of GRF on measured soil hydrologic properties were analysed using linear mixed-effects models conducted with the 'nlme' package (Pinheiro et al., 2017) in R version 4.3.2 (R Core Team, 2023). The one exception to this was the testing of bulk density in the pot experiments, which employed a simple linear model with GRF as the predictor variable as this parameter was only measured once per core and there was no need to account for repeated measurements through a random term. In the field experiment, a linear mixed effects model was still used to test changes in bulk density to account for the blocking in the experimental design and the fact that two cores were taken from each plot, so a random intercept term with plots nested within blocks was included in this model. Data from the three different soil types used in the pot experiment were analysed separately, as was the data from the field experiment.

For response variables, which were measured multiple times per core across a range of matric potentials, including soil water retention, air permeability, relative gas diffusivity, pore organization, and tortuosity, we modelled the response curves with a quadratic regression model incorporating orthogonal polynomial terms through the use of the 'poly' function in the 'nlme' package. The two predictor variables were the absolute value of matric potential (−hPa), which was log-transformed, and the GRF application rate, which was included in the model as an interacting, categorical predictor variable to assess the impact of GRF on the coefficients of the curve of the response of the hydrological property of interest to the varying levels of matric potential. In cases where GRF was observed to have a significant effect, Tukey post hoc comparisons were conducted using the 'emmeans' package (Lenth, 2023) to compare the two treatment levels to the control. The criterion for statistical significance was $\alpha = 0.05$. In the pot experiments, 'pot' was included as a random factor to account for the repeated measurements made on the same sample at different matric potentials (Fishkis et al., 2015). In the field experiment, the random term consisted of a core identifier nested within block to account for the two cores taken from each plot in addition to the randomized block. Residual plots were inspected to ensure normality of residuals. To assess whether the assumption of homogeneity of variances across different treatments was met, we compared the original model with a model that allowed variances to differ between treatments by using the 'weights' function in 'nlme'. If this resulted in a significantly improved model with lower AIC, we retained the 'weights' function in the final model to account for the heterogeneity of variances between treatments.

3 | RESULTS

3.1 | Soil bulk density, water retention, air, and gas transport

GRF application had a significant effect on soil dry bulk density in the pot experiment with the sand soil type ($p = 0.037$, F-test), but had no effect when applied to other soil types or in the field experiment (Figure 1). In the sandy soil, soil bulk density was significantly lower ($p = 0.026$, t-test) in the control pots (1.55 g cm^{-3}) than in the GRF_{20} pots (1.59 g cm^{-3}). The difference between these treatments at the end of the experiment (0.04 g cm^{-3}) was greater than the initial difference due to packing at the beginning of the experiment (0.01 g cm^{-3}). GRF had no impact on the soil water retention curves for any of the soils from the pot or field trials (Figure 2).

The addition of GRF significantly altered k_a in the sandy soils ($p = 0.015$, F-test). Post-hoc comparisons indicated that the GRF_{10} treatment reduced k_a relative to the control ($p = 0.03$, t-test). Likewise, in the sandy clay loam soil, GRF significantly modified k_a at different matric potentials in the pots ($p < 0.001$, F-test) and in the field ($p = 0.001$, F-test) experiments (Figure 3). In the sandy loam soil, k_a for GRF_{10} was more than two-fold higher than GRF_{20} and the control. In the field experiment, increasing the amount of GRF applied resulted in a higher increase in k_a as matric potential increased, resulting in greater differences between treatments at the lowest matric potentials tested. The effect of GRF on k_a in the sandy clay loam soil in the pot experiment was somewhat more convoluted—GRF_{10} consistently had higher k_a than the control at all matric potentials tested, whereas at high matric potentials, GRF_{50} had comparable k_a to the control, but k_a in GRF_{50} increased more rapidly with matric potential, such that at more negative matric potentials, GRF_{50} had the highest k_a.

Though GRF treatment did not affect k_a in the sandy loam soil, it did significantly modify the response of relative gas diffusivity (D_p/D_o) in this soil ($p = 0.039$, F-test). GRF_{10} tended to have the highest relative gas diffusivity, followed by the control, with the lowest values observed in the GRF_{20} treatment (Figure 4). These differences between treatments increased with decreasing matric potential.

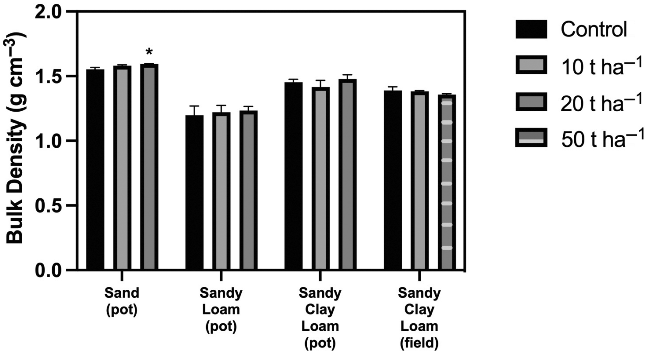

FIGURE 1 Bulk density of soil amended with glacial rock flour (GRF) for the pot and field experiments. 0, 10, 20, and 50 are GRF rates of 0, 10, 20, and 50 t ha^{-1}. Bars indicate standard errors of the mean. * indicates a significant ($p < 0.05$) difference from the control.

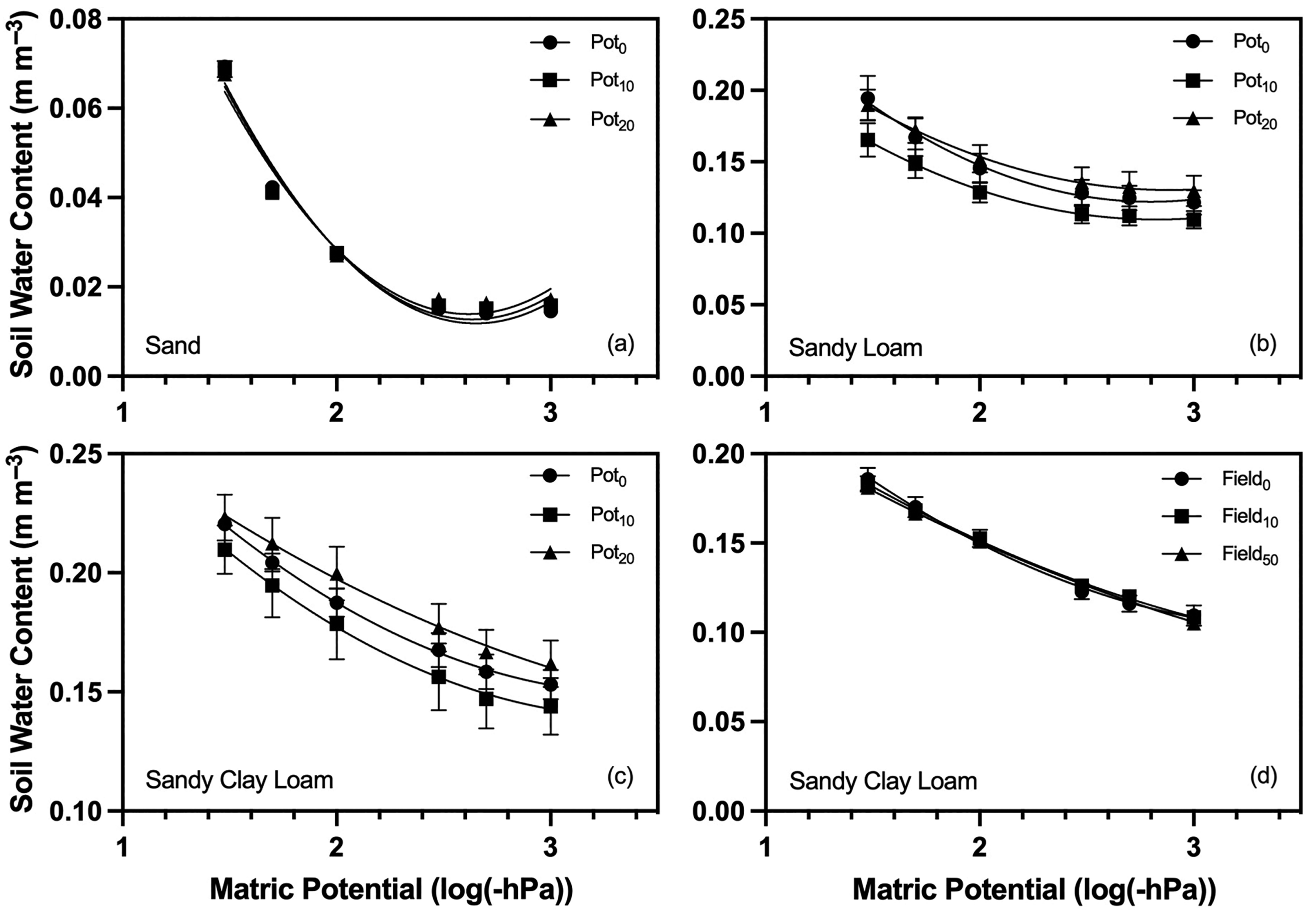

FIGURE 2 Soil water content measured at −30, −50, −100, −300, −500, and −1000 hPa matric potentials and the corresponding fitted curves for soils amended with glacial rock flour for the pot (a, b, and c) and field (d) experiments. 0, 10, 20, and 50 are GRF rates of 0, 10, 20, and 50 t ha^{-1}, respectively. Bars indicate standard errors of the mean. Note the differences in scale on the y-axis.

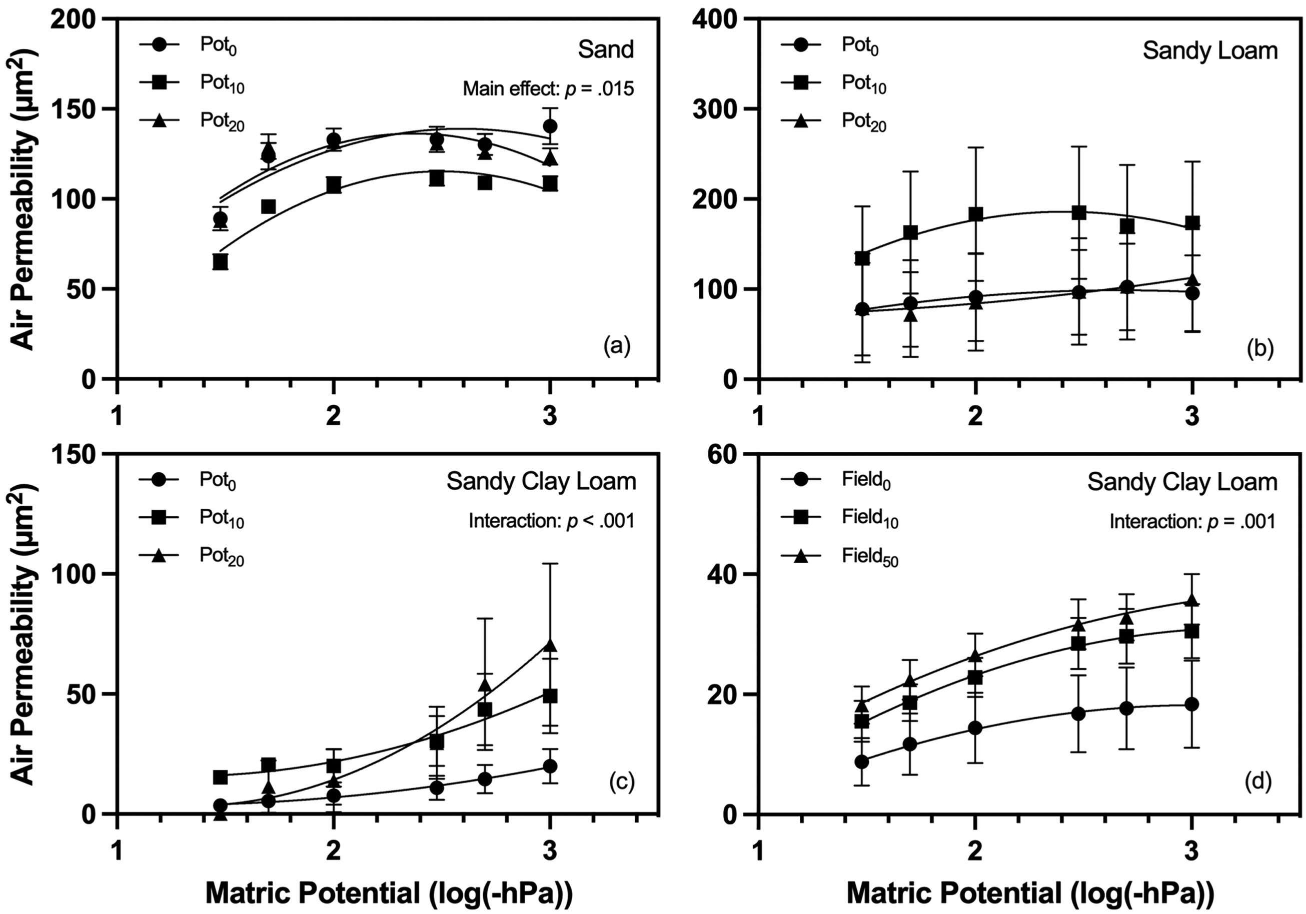

FIGURE 3 Geometric mean of air permeability (k_a) measured at −30, −50, −100, −300, −500 and −1000 hPa matric potentials and the corresponding fitted curves for soils amended with glacial rock flour for the pot (a, b, and c) and field (d) experiments. 0, 10, 20, and 50 are glacial rock flour rates of 0, 10, 20, and 50 t ha^{-1}, respectively. Bars indicate standard errors of the mean. Note the differences in scale on the *y*-axis.

3.2 | Pore morphological characteristics

GRF had a significant effect on the pore organization of sandy soils ($p = 0.009$, *F*-test). Post-hoc tests indicated that GRF_{10} had an overall lower PO than the control ($p = 0.037$, *t*-test). GRF did significantly modify the response of PO of the sandy clay loam soil in pots at decreasing matric potentials ($p < 0.001$, *F*-test) as well as in the field ($p < 0.001$, *F*-test), but it did not have a significant overall effect on this soil type in either experiment (Figure 5). In the field experiment, PO was higher with increasing levels of GRF, and the difference from the control increased with decreasing matric potentials, following the trend established by k_a. In the pot experiment, the trends also followed the pattern of k_a quite closely, with PO values for GRF_{10} consistently higher than the control and the PO of GRF_{20} increasing more rapidly than the other treatments with decreasing matric potential.

GRF application significantly modified the pore tortuosity (τ) across varying matric potentials in the sandy loam pot experiment ($p = 0.021$, *F*-test) as well as the sandy clay loam in the pot experiment ($p < 0.001$, *F*-test) and the field experiment ($p = 0.001$, *F*-test) (Figure 6). This was evident primarily at high matric potentials; however, contrasting trends were observed between the pot experiments and the field experiment. In all experiments, the control plots fell in the middle, but at high matric potentials in the sandy loam and sandy clay loam pot experiments, tortuosity was highest with the GRF_{20} treatment and lowest with GRF_{10}, whereas at high matric potentials in the field experiment, GRF_{10} was higher than the control and GRF_{50} was slightly lower than but similar to the control.

4 | DISCUSSION

Rock dust amendment to soils is reported to ameliorate soil physical properties such as structure and pore space for water and airflow for plant and microbial use

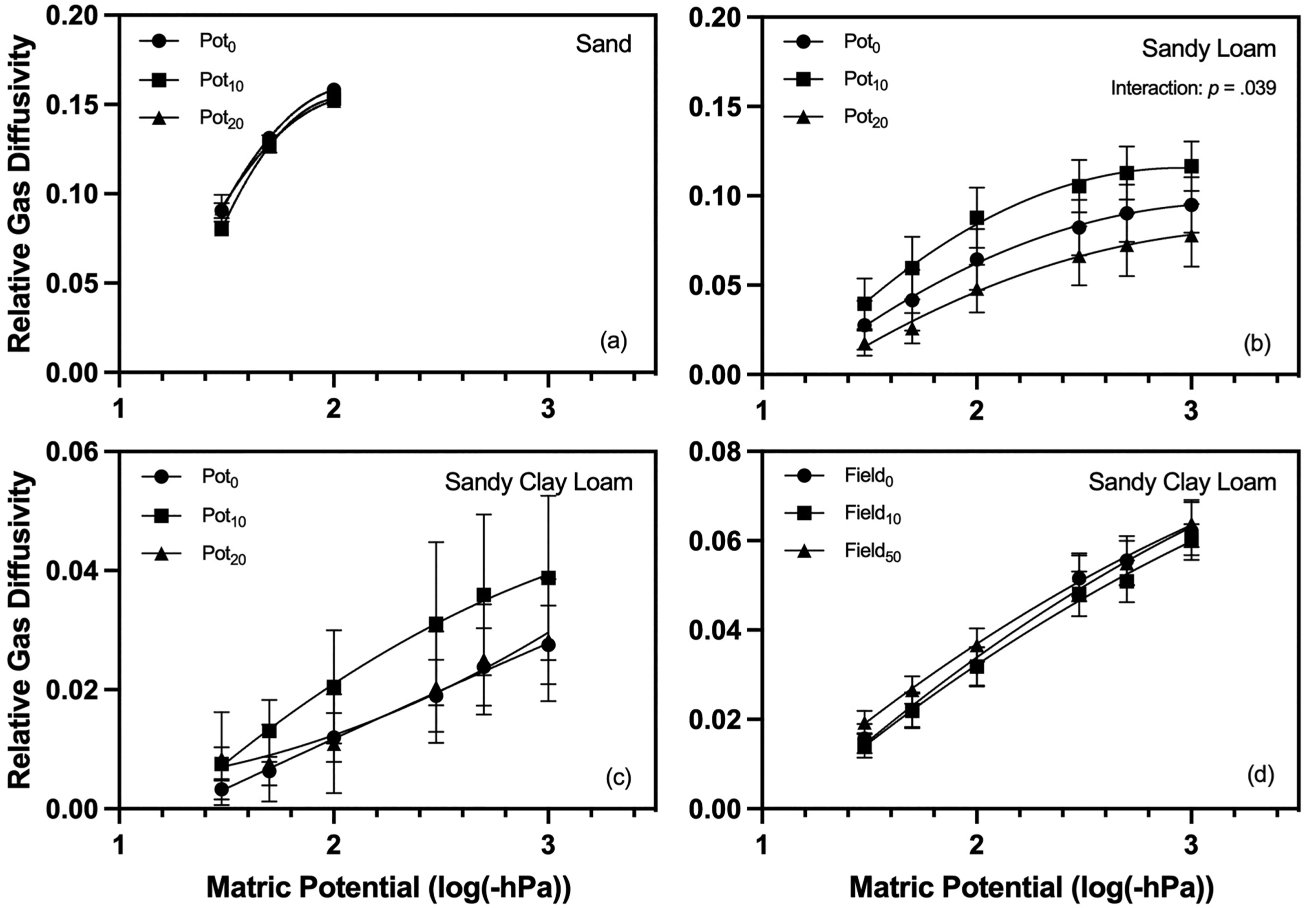

FIGURE 4 Relative gas diffusivity measured at −30, −50, −100, −300, −500 and −1000 hPa matric potentials and the corresponding fitted curves for soils amended with glacial rock flour for the pot (a, b, and c) and field (d) experiments. 0, 10, 20, and 50 are glacial rock flour rates of 0, 10, 20, and 50 t ha^{-1}, respectively. Bars indicate standard errors of the mean. Note the differences in scale on the *y*-axis.

(Swoboda, 2016). Findings from the present study showed that the effect of GRF on the bulk density of the tested tropical soils in the pot and field experiments was only significant in sandy soils, where bulk density increased with the application of GRF. However, the bulk densities of all treatments were lower than the value at which the columns were initially packed, and the higher value for GRF_{20} was the result of a lower reduction in bulk density over the course of the experiments relative to the control.

Soil water retention, k_a, and D_p/D_o largely depend on soil texture and structure (Chamindu Deepagoda et al., 2013). The soil water retention curves were unaffected by GRF application, thus indicating that the application of GRF did not alter soil water availability at the trialled application rates. This is not entirely surprising, as even at the 50 t ha^{-1} application rate, GRF comprised only 1.6% of the soil mass, which is unlikely to be sufficient to modify the soil texture class.

These results suggest that the use of GRF to improve the physical properties of the tropical soils investigated may vary based on the soil type. We found that while effects on the PO and k_a of the sand and sandy clay loam soils were observed, these properties were not affected in the sandy loam. On the other hand, the sandy loam was the only soil type for which an effect on relative gas diffusivity was observed such that GRF_{10} increased D_p/D_o compared to the control, while the opposite effect was found for GRF_{20} versus the control. The results may have been due to the tendency of GRF_{20} to increase pore tortuosity at the matric potentials measured (Figure 6). An increase in pore tortuosity can decrease D_p/D_o due to the elongation of the pathways for gas transport (Schjønning et al., 2002). However, the observed increase in D_p/D_o for the GRF_{10} needs to be further investigated especially in field conditions to understand its practical relevance better. The inconsistency in the effects of GRF across varying matric potentials for the tested soils is probably due to the differential changes in soil pore characteristics. For example, Pesch et al. (2022) reported that applying GRF altered the pore size distribution of sandy soil in South Greenland.

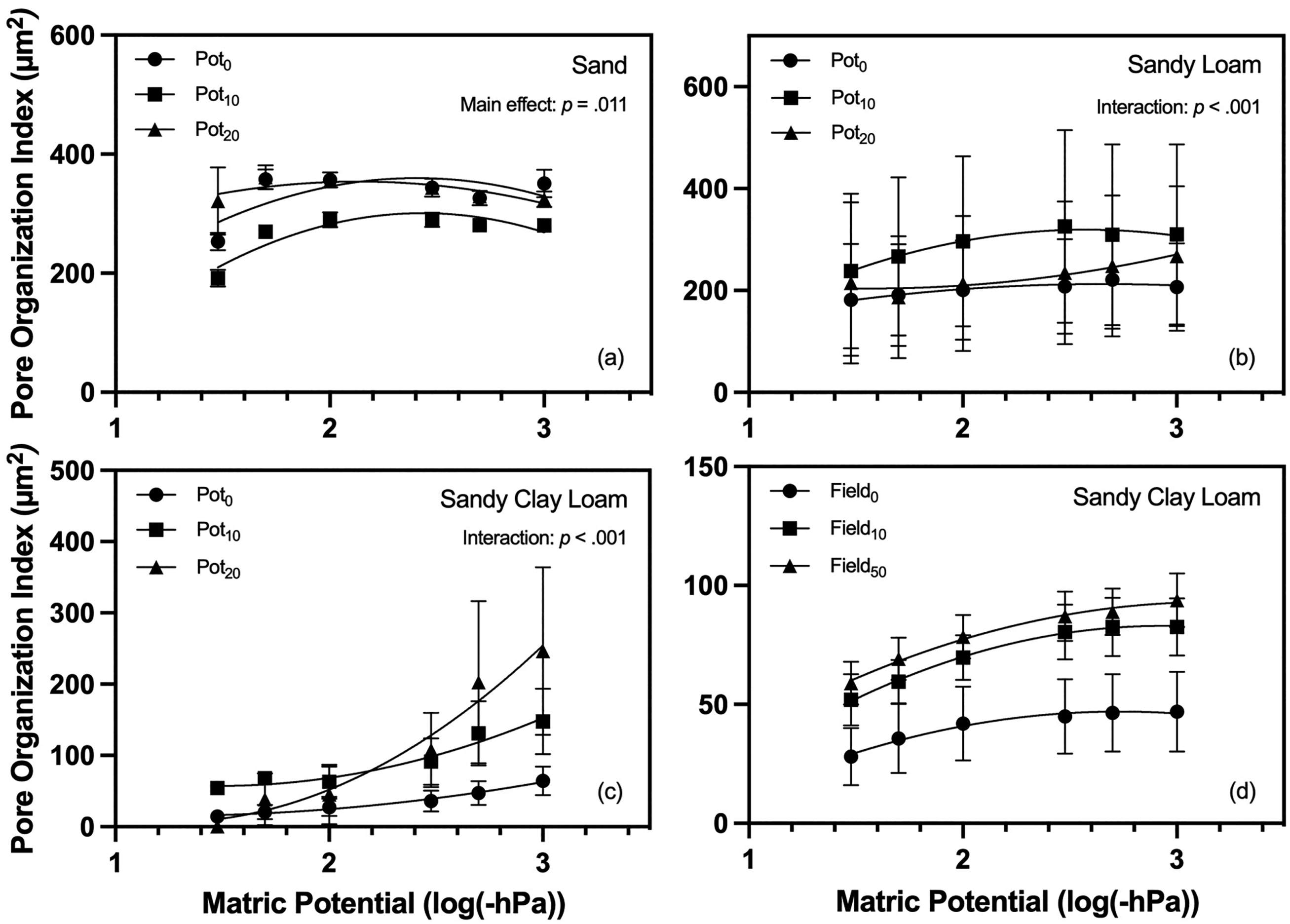

FIGURE 5 Geometric mean of pore organization index at −30, −50, −100, −300, −500, and −1000 hPa matric potentials and the corresponding fitted curves for soils amended with glacial rock flour for the pot (a, b, and c) and field (d) experiments. 0, 10, 20, and 50 are glacial rock flour rates of 0, 10, 20, and 50 t ha^{-1}, respectively. Bars indicate standard errors of the mean. Note the differences in scale on the *y*-axis.

Air permeability highly depends on pore diameter while D_p/D_o is controlled by the tortuosity and connectivity of soil pores (Arthur et al., 2012; Schjønning et al., 2002). An air permeability value of 1 μm^2 is generally considered the lower threshold for soils to conduct airflow. In general, soils with k_a of 1 μm^2 or less are considered effectively impermeable (Ball et al., 1988). Regarding this threshold, the permeability of tested soils at the matric potentials measured was above the threshold (Figure 3). The GRF tended to improve k_a in the sandy clay loam soils, especially at low matric potential suggesting the opening of the large pores for the conduction of flow with decreasing soil water content. Given the generally low k_a of the sandy clay loam soil at −30 to −1000 hPa matric potentials (Obour et al., 2019), the observed increase in k_a at about 100% magnitude for the GRF amended treatments at any given matric potential measured compared to the control, especially in the field experiment, indicates that GRF may have the potential to increase k_a in this soil. However, further studies are needed to reaffirm the results before practical adoption.

In contrast, GRF significantly decreased k_a and PO with the GRF_{10} but not GRF_{20} treatment in the sandy soil, suggesting that low application rates may be disrupting the natural pore structure, for example, by reducing the volume of large pores due to the infilling and clogging effect, which reduces the range of soil pore size distribution. A reduced pore size distribution could have implications for soil functions such as aeration and carbon processes (Kravchenko & Guber, 2017), nutrient availability, and biological dynamics, for example, microbial diversity and root penetration (Rabot et al., 2018). The lack of change in these parameters in the sandy soil with GRF_{20} could imply that a relatively higher application rate can prevent selective clogging of the soil pores acting as a reinforcing agent in the soil matrix, thereby causing less interference to the soil's natural pore system. The results suggest that GRF amendment may have a threshold effect, which has

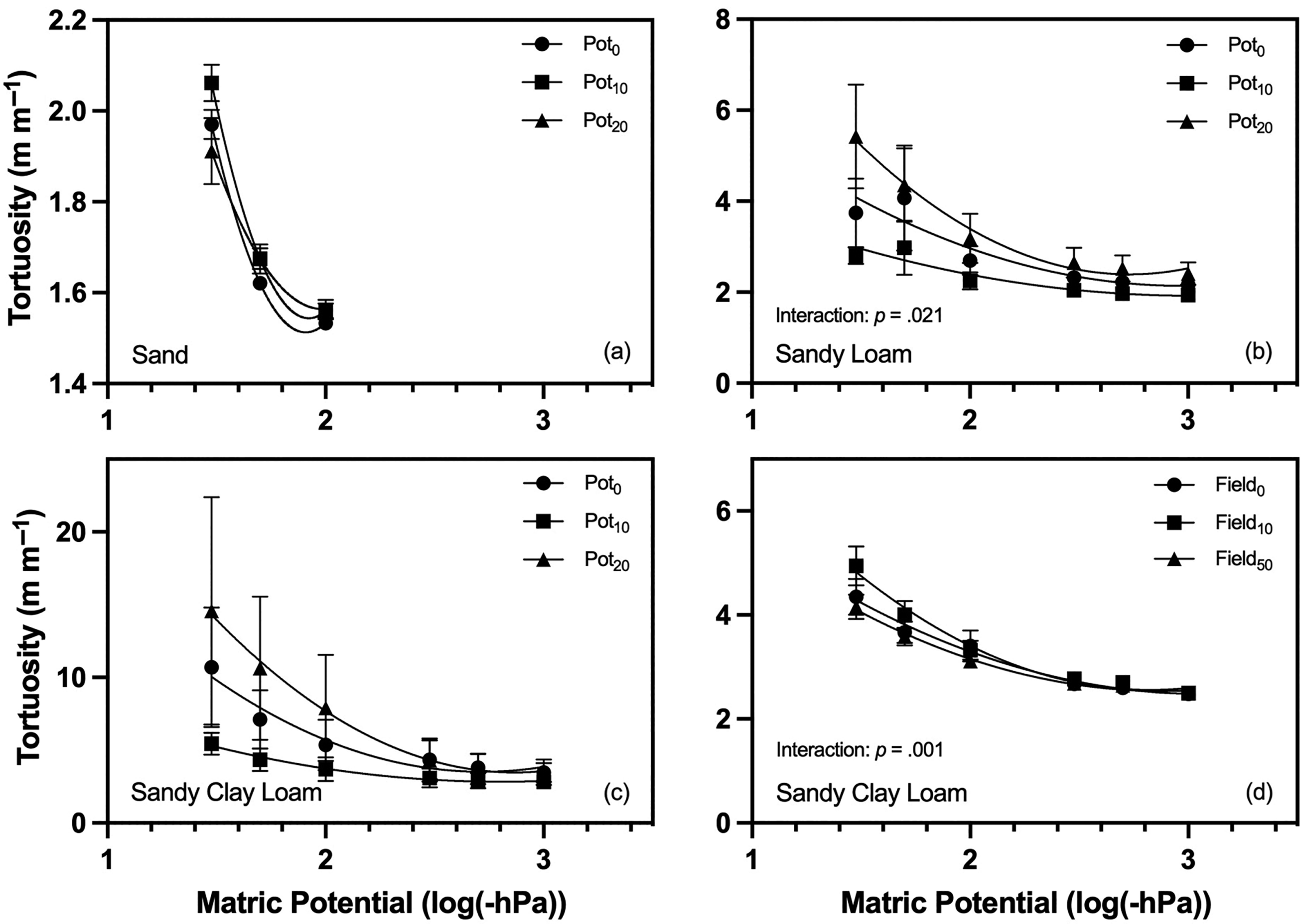

FIGURE 6 Estimates of pore tortuosity derived from the tube model of Ball (1981) at −30, −50, −100, −300, −500, and −1000 hPa matric potentials and the corresponding fitted curves for soils amended with glacial rock flour for the pot (a, b, and c) and field (d) experiments. 0, 10, 20, and 50 are GRF rates of 0, 10, 20, and 50 Mg ha^{-1}, respectively. Bars indicate standard errors of the mean. Note the differences in scale on the *y*-axis.

practical relevance for avoiding the GRF-induced disruption of soil's natural pore structure. However, given that this decrease was only observed in sandy soils, which have exceedingly high k_a, potential decreases of this scale are likely not of practical concern. We are, however, mindful that this is the first study on GRF amendment to Ghanaian soils. Further studies on other benchmark soils involving single and repeated applications are necessary before recommending the use of GRF as an amendment on a large scale to improve soil physical properties for agricultural production in Ghana.

Finding that applying GRF to tropical soils can significantly impact gas transport within the soil is particularly relevant when these minerals are applied to remove atmospheric CO_2 through enhanced rock weathering (Deng et al., 2023). GRF can alter soil physical properties such as porosity and air permeability to influence soil aeration and gas diffusion rates, which could have potential implications for carbon uptake and greenhouse gas fluxes. When gas diffusion is restricted, CO_2 generated by the decomposition of soil organic matter can accumulate in the soil (Piñol et al., 1995) resulting in elevated concentrations of gaseous and dissolved CO_2. This would result in higher concentrations of carbonic acid in the soil solution, which could further enhance the weathering rate of applied silicate minerals. Conversely, higher rates of gas diffusivity are associated with lower soil partial pressure of CO_2 (pCO_2), so improved air permeability could potentially slow the weathering and carbon uptake rate. However, increased k_a may be advantageous when considering the fluxes of other greenhouse gases. Coarser soils with better gas diffusivity tend to have higher rates of methane consumption (Dörr et al., 1993), whereas increasing tortuosity has been linked with reduced methane oxidation rates (Boeckx et al., 1997). Decreased k_a can also limit aeration and create anaerobic conditions, potentially increasing the production and release of nitrous oxide (Jamali et al., 2016).

Further research is therefore needed to improve our understanding of the effects of silicate mineral applications on the interplay between soil physical properties and biogeochemical processes, which is essential for a comprehensive evaluation of the environmental implications of enhanced weathering as a climate mitigation strategy.

5 | CONCLUSIONS

Evidence from the study showed that soil amendment with GRF imposed under controlled (pot) or field conditions did not seem to offer an immediate meaningful alteration to the soil water retention properties, but did modify some other soil physical properties, namely air permeability, pore organization, and tortuosity in some soils. This study therefore provided initial insights into the potential effects of GRF amendments on gas transport, which can, in turn, have implications for soil greenhouse gas fluxes. We concluded that success in using GRF to ameliorate soil physical conditions for plant growth may depend on the soil type. Based on these findings, we advocate that GRF should be considered for application to the soils for its other beneficial effects. It is recommended that the effects of repeated applications and further build-up of the material in the soil should be investigated to determine the effects of higher relative concentrations on soil physical properties.

AUTHOR CONTRIBUTIONS

Peter Bilson Obour: Conceptualization; formal analysis; data curation; writing – original draft; writing – review and editing. **Christiana Dietzen:** Conceptualization; data curation; formal analysis; writing – original draft; writing – review and editing; project administration. **Eric Oppong Danso:** Conceptualization; methodology; data curation; writing – original draft; writing – review and editing; formal analysis; investigation. **Emmanuel Arthur:** Conceptualization; data curation; formal analysis; writing – original draft; writing – review and editing; supervision. **Michael Osei Adu:** Data curation; writing – original draft; writing – review and editing; formal analysis. **Minik Thorleif Rosing:** Conceptualization; writing – review and editing; supervision; project administration; funding acquisition; resources.

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CONFLICT OF INTEREST STATEMENT

Minik Thorleif Rosing is Chairman of the Board for Rock Flour Company, a Danish Start-up company aiming at developing Glacial Rock Flour for climate change mitigation and global food security. The Rock Flour Company has not influenced the study and has no commercial interests in the research reported here.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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