DOI: https://doi.org/10.67042/njss.2026.lqw50lj0

Nigerian Journal of Soil Science
Journal Homepage: www.soilsjournalnigeria.com

Laboratory Assessment of Basalt Dust Incubation on the Physical Properties of Contrasting Soils in Nigeria

Ibrahim Rasheed[a,*]., Akinbile Oluwakunmi Christopher[b], Ewulo Babatunde Sunday[c], Owolabi Ayodele Olumuyiwa[d], Audu Luqman Muhammed[e]

[a,*] Department of Agricultural and Bio-Environmental Engineering Technology, Auchi Polytechnic, Auchi, Edo state, Nigeria.
[b]Department of Agricultural and Environmental Engineering, School of Infrastructure, Manufacturing and Minerals Engineering, Federal University of Technology, Akure
[c]Department of Crop, Soil and Pest Management, College of Agriculture and Agricultural Technology, Federal University of Technology, Akure
[d]Department of Mining Engineering, School of Infrastructure, Manufacturing and Minerals Engineering, Federal University of Technology, Akure
[e]Department of Mechanical Engineering Technology, School of Engineering Technology, Auchi Polytechnic, Auchi, Edo state, Nigeria.

[a,*] corresponding author: *ibbrroo88@gmail.com*

Abstract

The effects of different application rates and particle sizes of basalt dust on the selected physical properties of contrasting soils incubated for 90 days were evaluated in this study. Basalt dust was incubated with two different soil types, and samples of soil were collected for laboratory analysis at day 1, day 30, day 60, and day 90. Air-dried and sieved soil samples collected from Auchi and Agbede towns were treated each with basalt dust from Ikpeshi quarry at the rate of 0, 5, 10, and 15 t ha^{-1} and particle sizes of ≤63µm and ≤125µm fractions. The treatment of soil with basalt dust was significant at ($p < 0.05$) by altering the repacked bulk density, particle density, porosity, and temperature of the incubated soil. The repacked bulk density increased from 1.39-1.71 g cm^{-3} for Auchi loamy sand and 1.16-1.43 g cm^{-3} for Agbede silty loam, while values of 2.27–2.62 g cm^{-3} and 2.04–2.52 g cm^{-3} were evaluated for their particle densities, respectively. Slight improvement in soil porosity was recorded for loamy sand soil of Auchi (42.29%) and silty loam soil of Agbede (47.62%) at 5 – 10 t ha-1 rate of basalt dust. During the incubation period, the average soil temperature rose gradually from about 28.3°C to 31.2°C. The Duncan's Multiple Range Test and two-way analysis of variance (ANOVA) showed that both the main and interaction effects of basalt parameters considered were significant on the selected soils' physical properties. The findings revealed that basalt dust can be used as a soil amendment, helping to improve soil microclimate and physical properties' stability.

Keywords: Olivine, basalt, amphibole, pycnometre, pulverization

Introduction

The productivity of crops and soil health are determined by the physical, chemical, and biological properties of soil (Hu et al., 2024). Example of edaphic factors are texture, pH, moisture content, and nutrient levels, they are classified as soil parameters, and they directly influence crop productivity. Due to poor potential in retaining water, sandy soils are affected by drought, while soils that are

acidic can affect the yield of some crops (Naorem et al., 2023).

A well-developed crop root systems assists soil structure improvement, soil aeration, water holding capacity, and aggregate formation. (Lu et al., 2020). The composition and fraction of soil particles, permeability, and texture determines its water holding capacity, aeration, and fertility (Wei et al., 2023). Soils that are loose and porous excessively affects the growth of a good plant root system, thereby exposing the plant to environmental stress and affecting its productivity. Invariably, these issues will lead to the problems of water retention reduction and leaching of soil nutrients, posing serious problems for plant growth.

Contrarily, the problems of water logging and hypoxia are the results of soil attributes with high compaction and poor permeability, they limit plant root functions and growth, thereby affecting its heath and yield (Manik et al., 2019). Loose and soft textured soils are supportive for the colonization of soil microbes. Long-term soil degradation has resulted in the search for alternatives to sustain soil for agricultural use by preserving soil properties without affecting the environment. Over time, the policy of European agriculture has turned towards the sustainability of the environment at an increasing rate, with the objective of reducing the use of synthetic fertilizer and improving the organic area (European Commission, 2020).

Different anthropogenic activities have resulted in the loss of vegetative cover, which invariably led to the loss of soil productivity, nutrients' availability, and land degradation, among other factors (Pimentel et al., 1995). Soil re-mineralization increases soil fertility by replacing lost minerals due to the problems of erosion, surface runoff, leaching, and excessive farming systems. Synthetic and sustainable farmers have relied on the use of rock dust as an alternative and natural approach to enhance the development of crop root systems, increase crop yields, and promote plant health for different varieties of crops and conditions (Smart et al., 2020). Rock dust consists mainly rocks that have been crushed into fine powder by either artificial or natural means and can be incorporated as a mineralizer to improve soil quality (Akintola et al., 2021). The use of soluble chemical fertilizers is usually restricted due to their role in anion fixation and high cation leaching rates (Brady & Weil, 2017). In turn, the physical and chemical properties of tropical soils suggest high dissolution rates sufficient for silicate rock powder meant for soil mineralization and amendment (Bamberg et al., 2017, Manning & Theodoro, 2020). It is crucial for future studies to include physiochemical properties of topsoil such as texture, pH, and mineralogy, in their investigation, since soil taxa are not adequate, as they typically focus on pedogonic factors that are agronomically less relevant (Sanchez, 2019). There is a lack of adequate laboratory reports quantifying the potential of different application rates and particle sizes of basalt rock dust during incubation on the physical properties of different soil types. Therefore, the objective of this study was to carry out a laboratory investigation on the effects of different application rates and particle sizes of basalt rock dust over for a specified period of time on the physical properties of two contrasting soils in Edo State, Nigeria.

Materials and Methods

Collection of Soil Samples

Samples of soils were collected from two different locations in Edo State, Nigeria, representing different climatic conditions and soil types. Soil samples were collected from three different sub-locations for each of the selected locations in Edo State.in reference to geographic coordinates of 7.080°N, 6.230°E; 7.070°N, 6.240°E, and 7.060°N, 6.230°E for Auchi and 6.840°N, 6.260°E; 6.850°N, 6.270°E; and 6.850°N, 6.260°E for Agbede. The soil samples collected from each of the selected sub-locations were mixed together. The soil samples were collected at 10 cm depth, and this represents the surface layer and zone that is active for plants' rooting and that can be impacted by amendments (Gillman et al.,

2001). Auchi experiences average annual temperatures ranging between 28°C and 32°C with a humid climate. It experiences bimodal rainfall. The average annual rainfall for Agbede town ranges from 180 to 200mm, and elevation is about 152m above sea level (Ozegin et al., 2017).

Identification and Collection of Basalt Rock

The basalt rock used for this study was collected from Ikpeshi quarry in Edo State, Nigeria. Rock Identifier, a machine learning application that is specially developed for rock classification, was used for identifying basalt rock among other rocks at the quarry. Basalt rock was characterized with augite, olivine, and calcic plagioclase feldspar (Al-Ahklay, 2018). The following constituents are discovered in Ikpeshi basalt rock sample using X-ray diffraction approach, aluminum oxide, silicon oxide, calcium oxide, phosphorus oxide, potassium oxide, sodium oxide, magnesium oxide, iron oxide, tin oxide, and loss on ignition with the values of 13.12%, 48.32%, 6.19%, 7.63%, 6.76%, 1.42%, 5.05%, 8.02%, 1.48%, and 1.32%, respectively. The major constituents discovered in the Ikpeshi basalt rock are albite, amphibole, olivine, pyroxene, and plagioclase feldspar. Standard endecotts electric sieve shaker (ISO 3310-1) was used to classify basalt rock dust particle into different sizes after basalt rock was subjected to the processes of crushing, bore milling, and pulverizing.

Experimental Design and Incubation Procedure

The study on the incubation procedure was carried out in the soil and water laboratory, Agricultural and Bio-Environmental Engineering Technology, Federal Polytechnic Auchi, Edo State, Nigeria. The effects of basalt dust incorporation, such as different application rates and particle sizes on the selected physical properties of different soils, such as texture, repacked soil bulk density, porosity, and temperature, were investigated. A completely randomized design (CRD) with two-factors' factorial arrangement (4 x 2) was conducted for the study, the factors and their levels considered are 0, 5, 10, and 15 t ha^{-1} (basalt application rate) and ≤63 and ≤125 μm (basalt particle sizes) over 90 days incubation period (Conceiçao et al., 2022; Gillman et al., 2001). The experimental procedures were replicated three times, resulting in twenty four (24) experimental setups. Soil samples collected from each of the locations were air-dried and sieved to 2mm particle sizes and weighed to about 3.6kg for each plastic container meant for incubation. The height of the plastic container is 17.8cm and the diameter is 18.5cm. The total volume of the soil sample in each container was estimated at equivalent value of 4537.048cm^3. The crushed and milled basalt rock was added to each of the already weighed soil samples and mixed thoroughly to ensure uniformity and an equivalent area basis. Distilled water was added at intervals to maintain the moisture of the experimental setups at field capacity to aid soil mineralization. Perforated lids were used to cover each setup for proper incubation till the last day of the experiment.

Determination of Soil Physical Properties

Soil samples were collected at intervals with the aid of laboratory soil corer for analysis. The texture of the contrasting soils was determined by using the hydrometer method as reported by (Bouyoucos, 1962) following the standardized procedure by ISO 11277 (2020). The repacked bulk density of the soil (g cm^{-3}) was determined using the procedure of FAO (2023) in Equation 1.

$$Repacked\ bulk\ density\ (weight\ per\ cubic\ metre) = \frac{Dry\ weight\ of\ soil}{Total\ volume\ of\ the\ soil\ corer} \quad [1]$$

The particle density of the soil was determined using a laboratory pycnometer approach and estimated using Equation 2.

$$d_{pm=\frac{M_a}{(a-b)}} \quad [2]$$

d_{pm} is particle density of the soil in gcm^{-3}.

Brady and Weil (2017) suggested Equation 3 for determining soil porosity

$$P\ (\%) = 1 - (\frac{Bulk\ density}{Particle\ density}) \quad [3]$$

At 5cm depth and 30days interval for incubation period of 90days, a digital soil thermometer was used to determine the soil temperature for each of the experimental set up. (Adebayo et al., 2022; Li et al., 2018).

Statistical Analysis

The research was designed and analyzed considering a completely randomized block design with 4 × 2 factorial arrangement with three replications. Basalt application rate (0, 5, 10, and 15 t ha^{-1}) and basalt particle size (≤63 µm and ≤125 µm) are the main independent factors considered for the study. Incubation period (Day 1, 30, 60 and 90) was not included as a treatment factor in the statistical model, ANOVA was performed independently for each sampling day. Mean separation was carried out using Duncan's Multiple Range Test at $P < 0.05$. Means followed by the same superscript within each sampling day are not significantly different. Two-way analysis of variance (ANOVA) were adopted for each sampling day to determine the effects of different application rates and particle sizes of basalt dust, and their interaction on the selected physical properties of the contrasting soils, such as bulk density, particle density, porosity, and temperature.

The statistical model considered was:

Yijk = µ + Ai + Bj+ (AB)ij + εijk

where:

- Yijk= observed response
- µ = overall mean
- Ai = effect of basalt application rate
- Bj = effect of particle size
- ABij= interaction between rate and particle size
- εijk = experimental error

Pooled Pearson Correlation and multiple regression analysis were conducted to evaluate the relationships between the independent variables (basalt application rate and particle size) and the measured soil physical properties across the reference incubation periods. For the regression analysis, although incubation period was not a treatment factor, it was incorporated as a covariate to account for the time-dependent nature of basalt weathering and its progressive effects on soil physical properties to properly model temporal variability. The individual and combined (interactive) effects of the predictors, as well



A: Collection of Basalt rock *B. Mixing of rock dust with soil* *C. Rock sieve analysis* *D. Basalt incubation with soil*

as their predictive strength, were assessed and interpreted accordingly.

Results of the Experimental Study

Basalt Incubation Effects on Soil Texture

Basalt incubation parameters revealed distinct soil responses with respect to their textural dynamics. The range of 82.72 – 83.83% (sand), 13.58 – 14.21% (silt), and 2.06 – 3.70% (clay) were recorded for the incubated loamy sand collected from Auchi without any change in textural pattern throughout the incubation period. Also, the basalt incubated silty loam soil collected from Agbede remained unchanged throughout the 90day incubation experiment. The silt content of the incubated soil increases and the clay content decreases, most especially for finer basalt dust at increasing dose of basalt dust. This indicates the possible secondary particles' aggregation and enhanced rate of weathering due to the release of cations from silicate rock dust to the soil (Fernandes et al., 2020; Manning, 2018). The improvement in the restructuring and flocculation of finer basalt dust particles are aided by such processes. Comparatively, the modification in textural dynamics of incubated finer texture soil of Agbede is higher compare to that of coarse texture soil of Auchi, signaling the role of rock dust particle size in the arrangement of soil structure and distribution of soil minerals. The prolonged incubation period to 90 days resulted to steady increase in silt content of the soil, and this suggests that weathering of basalt can lead to improved soil structure, soil texture, and soil nutrients (Ramos et al., 2022).

Table 1. Textural pattern dynamics of incubated contrasting soils

Basalt (t/ha)	Auchi ≤60µm	Auchi ≤125µm	Agbede ≤60µm	Agbede ≤125µm
0	82.72, 13.58, 3.70(LS)	83.08, 13.83, 3.09(LS)	31.17, 61.04, 7.79(SiL)	33.24, 62.10,4.60(SiL),Day1
5	82.92, 13.63, 3.45(LS)	83.33, 13.98, 2.78(LS)	31.53, 61.62, 6.85(SiL)	33.84, 62.89, 3.27(SiL)
10	83.12, 13.68, 3.20(LS)	83.58, 13.95, 2.47(LS)	31.68, 61.94, 6.38(SiL)	34.09, 62.91, 3.00(SiL)
15	83.32, 13.73, 2.95(LS)	83.83, 14.01, 2.16(LS)	32.10, 62.10, 5.80(SiL)	34.09, 63.12, 2.79(SiL)
0	82.75, 13.60, 3.65(LS)	83.08, 13.95, 2.97(LS)	31.17, 61.10, 7.73(SiL)	33.25, 62.84,3.91(SiL),Day30
5	82.94, 13.73, 3.33(LS)	83.39, 14.00, 2.61(LS)	31.53, 61.70, 6.77(SiL)	33.86, 62.93, 3.21(SiL)
10	83.24, 13.68, 3.08(LS)	83.62, 13.99, 2.39(LS)	31.67, 62.14, 6.19(SiL)	34.09, 63.69, 2.22(SiL)
15	83.30, 13.83, 2.8(LS)	83.85, 14.11, 2.04(LS)	32.14, 62.20, 5.66(SiL)	34.11, 63.84, 2.05(SiL)
0	82.75, 13.60, 3.65(LS)	83.11, 13.98, 2.91(LS)	31.06, 61.30, 7.64(SiL)	33.17, 63.06,3.77(SiL),Day60
5	82.95, 13.78, 3.27(LS)	83.36, 14.04, 2.60(LS)	31.55, 62.11, 6.34(SiL)	33.87, 63.26, 2.87(SiL)
10	83.26, 13.72, 3.02(LS)	83.61, 14.10, 2.29(LS)	31.76, 62.66, 5.58(SiL)	34.21, 64.25, 1.54(SiL)
15	83.35, 13.88, 2.77(LS)	83.74, 14.16, 2.10(LS)	32.32, 62.91, 4.77(SiL)	34.31, 64.55, 1.14(SiL)
0	82.74, 13.79, 3.47(LS)	83.13, 14.04, 2.85(LS)	31.10, 61.44, 7.46(SiL)	33.19, 63.14,3.67(SiL),Day90
5	82.96, 13.81, 3.23(LS)	83.36, 14.10, 2.54(LS)	31.53, 62.27, 6.20(SiL)	33.84, 63.46, 2.70(SiL)
10	83.16, 13.87, 2.97(LS)	83.61, 14.15, 2.24(LS)	31.74, 62.93, 5.33(SiL)	34.14, 64.43, 1.43(SiL)
15	83.21, 14.21, 2.58(LS)	83.73, 14.21, 2.06(LS)	32.30, 63.19, 4.51(SiL)	34.25, 64.43, 1.12(SiL)

The proportion of sand, silt, and clay (%) are represented by the values in the table. LS (Loamy Sand) and SiL (Silty Loam).

Soil bulk density dynamics during incubation (Coarse texture soil)

The repacked bulk density of incubated soil range between 1.39 and 1.71 g cm^{-3} throughout the incubation period (Table 2), indicating gradual compaction and soil mineral organization over the incubation period. The steady increase in the value of repacked soil bulk density with increasing rate of basalt and prolonged incubation period was observed, irrespective of particle size. Across all treatments, The values of the repacked bulk density of incubated coarse textured soil were lowest (1.39–1.51 gcm^{-3})

at day 1, and by day 90, the repacked soil bulk density of the incubated soil increased significantly (1.59–1.71 g cm^{-3}). This increase was attributed to progressive integration of soil minerals, soil aggregation due to weathering of basalt, and cation exchange reactions. The highest value of repacked soil bulk density (1.71g cm^{-3}) was recorded for coarse texture soil (T2) with application rate of 15 t ha^{-1} of basalt dust. This suggests that within the incubated pores of soil, a higher pack of basalt dust was observed. The analysis of variance revealed that basalt incubation parameters considered in the study and their interactions has a significant influence ($p < 0.05$) on the repacked bulk density of incubated loamy sand of Auchi soil. At increasing application rate of basalt, the values of repacked soil bulk density also increases, revealing that increasing application rate of basalt had the most significant effect, increasing overall soil mass due to denser silicate materials.

Table 2: Effects of basalt application rate and basalt particle size on soil bulk density (Auchi)

Basalt Rate(t ha^{-1})	Day1		Day30		Day60		Day90 (Days)	
	T1	T2	T1	T2	T1	T2	T1	T2 (g $cm^{-3)}$
0	1.39^{c}	1.40^{c}	1.48^{c}	1.43^{c}	1.54^{b}	1.51^{b}	1.59^{ab}	1.62^{b}
5	1.40^{c}	1.46^{bc}	1.51^{bc}	1.58^{b}	1.54^{b}	1.58^{b}	1.59^{ab}	1.59^{ab}
10	1.40^{c}	1.50^{b}	1.52^{b}	1.63^{ab}	1.59^{ab}	1.64^{a}	1.63^{ab}	1.66^{a}
15	1.43^{b}	1.51^{b}	1.55^{b}	1.65^{a}	1.65^{a}	1.67^{a}	1.65^{a}	1.71^{a}

Mean values with the same superscript are not significantly different across the table at $P < 0.05$

T1 = ≤63µm basalt particle (fine) and T2 = ≤125µm basalt particle (coarse).

Variation in soil repacked bulk density during incubation (silty loam soil)

The result in Table 3 reveals that the repacked bulk density of basalt-incubated silty loam soil (Agbede soil) varied from 1.16 to 1.43 g cm^{-3}, reflecting differences in texture interaction, mineral packing, and response to basalt rate and particle size. Generally, repacked bulk density increased consistently with different application rates of basalt dust, particularly under fine particle size treatment (T1). At all incubation intervals, the untreated plot (0 t ha^{-1}) has the lowest values of bulk density (1.16–1.19 g cm^{-3}), while the highest values of bulk density (1.40–1.43 g cm^{-3}) were obtained in T1 (≤63µm) at an application rate of 15 t ha^{-1}, suggesting a densification or compaction effect that is basalt dose-dependent. Basalt application rate and particle size have significant effect ($p < 0.05$) for the repacked bulk density of incubated silty loam for the incubation period considered (Agbede soil). The relationship between incubated basalt application rate and particle size was significant, suggesting that finer basalt particles (≤ 63µm) exert greater structural effects at low-to-moderate application rates (5 – 10 t ha^{-1}

Table 3: Effects of basalt application rate and basalt particle size on soil bulk density (Agbede)

Basalt Rate(t ha^{-1})	Day1		Day30		Day60		Day90 (Days)	
	T1	T2	T1	T2	T1	T2	T1	T2 (g $cm^{-3)}$
0	1.20^{c}	1.17^{c}	1.22^{c}	1.18^{c}	1.22^{c}	1.16^{c}	1.19^{c}	1.16^{c}
5	1.30^{b}	1.28^{b}	1.31^{b}	1.29^{b}	1.32^{b}	1.29^{b}	1.30^{b}	1.31^{b}
10	1.38^{a}	1.28^{b}	1.40^{a}	1.30^{b}	1.42^{a}	1.29^{b}	1.41^{a}	1.29^{b}
15	1.40^{a}	1.40^{a}	1.42^{a}	1.40^{a}	1.41^{a}	1.39^{a}	1.43^{a}	1.40^{a}

Mean values with the same superscript are not significantly different across the table at $P < 0.05$

T1 = ≤63µm basalt particle (fine) and T2 = ≤125µm basalt particle (coarse).

Variation in soil particle density during incubation (sandy loam soil)

At first day of incubation (Day 1), both particle sizes of basalt (≤ 63µm and ≤ 125µm) revealed soil particle density values that are close (2.41–2.45 g cm^{-3}). However, as incubation period prolongs, the soil treated with 15 t ha^{-1} revealed a steady reduction in particle density value, with the lowest average values (2.28–2.32 g cm^{-3}) at Day60 and Day90. This reduction suggests progressive microaggregate restructuring and mineral weathering over time due to basalt addition, and this tends to increase intra-particle porosity. Across all the particle sizes (Table 5), the coarse basalt (T_2) generally has higher particle density values compared to the fine basalt (T_1), particularly at Day 60 and Day 90, respectively. The increase in residual mineral mass and oil matrix was observed due to slow decomposition of coarse particles of basalt. Conversely, the fine fraction of basalt dust possibly enhanced the reactivity of silicate minerals and weathering rate, resulting in slight reduction in particle density of the soil due to increased porosity and lighter soil aggregates. These outcomes was relatively reported by (Conceiçao et al., 2022; Swoboda et al., 2022). At $P < 0.05$, the analysis of variance revealed that different application rates of basalt had the most pronounced effect on soil particle density for coarse textured soil (loamy sand).

Table 4: Effects of basalt application rate and basalt particle size on soil particle density (Auchi)

Basalt Rate(t ha^{-1})	Day1		Day30		Day60		Day90 (Days)	
	T1	T2	T1	T2	T1	T2	T1	T2 (g $cm^{-3)}$
0	2.41^{ab}	2.45^{ab}	2.37^{b}	2.31^{b}	2.39^{b}	2.47^{ab}	2.42^{ab}	2.57^{a}
5	2.41^{ab}	2.54^{a}	2.40^{ab}	2.53^{a}	2.36^{b}	2.50^{a}	2.43^{ab}	2.52^{a}
10	2.41^{ab}	2.40^{ab}	2.40^{ab}	2.44^{ab}	2.32^{b}	2.59^{a}	2.35^{b}	2.62^{a}
15	2.29^{bc}	2.27^{bc}	2.32^{b}	2.41^{ab}	2.28^{bc}	2.32^{b}	2.31^{b}	2.37^{b}

Mean values with the same superscript are not significantly different across the table at $P < 0.05$

T1 = ≤63µm basalt particle (fine) and T2 = ≤125µm basalt particle (coarse).

Variation in soil particle density during incubation (silty loam soil)

The particle density of incubated silty loam soil revealed slight variations in response to different application rates of basalt and particle sizes over time. The average values of soil particle density ranged from 2.04 to 2.52 g cm^{-3}, indicating soil mineral composition that is relatively dense, typical of ferrallitic soils with moderate quartz and clay proportions. Across all incubation periods, the soil treated with basalt dust of 5 t ha^{-1} (T_1 ≤63µm) has the highest values of particle density (2.52 g cm^{-3}) at Day 60, while the untreated plot (0 t ha^{-1}) had the lowest average values (2.04 – 2.13 g cm^{-3}). This suggests that application of basalt at a moderate rate improved soil mineral compactness through integration of iron-rich fragments and denser silicate materials. The grouping by Duncan Multiple Range Test (DMRT) at $P < 0.05$ revealed that the application rate of basalt dust at 5 t ha^{-1} and particle size of ≤63 µm for treatment (T_1) was statistically different from the coarser fractions (T_2) and control across most incubation periods considered.

Table 5: Effects of basalt application rate and basalt particle size on soil particle density (Agbede)

Basalt Rate	Day1		Day30		Day60		Day90 (Days)	
(t ha^{-1})	T1	T2	T1	T2	T1	T2	T1	T2 (g $cm^{-3)}$

0	31.37^{b}	33.49^{bc}	30.24^{bc}	29.52^{c}	28.10^{c}	27.70^{c}	20.67^{c}	19.63^{c}
5	42.29^{a}	37.50^{ab}	37.54^{ab}	33.18^{b}	38.76^{ab}	31.56^{bc}	36.95^{b}	30.57^{bc}
10	41.86^{a}	42.86^{a}	37.06^{ab}	37.44^{ab}	36.68^{b}	35.63^{b}	36.88^{b}	34.27^{b}
15	41.92^{a}	42.57^{a}	36.78^{ab}	38.00^{ab}	36.74^{b}	34.78^{b}	36.67^{b}	34.52^{b}

Mean values with the same superscript are not significantly different across the table at $P < 0.05$
T1 = ≤63µm basalt particle (fine) and T2 = ≤125µm basalt particle (coarse).

Variation in soil porosity during incubation (loamy sand soil)

Across incubation periods (Table 6), porosity reduced consistently from the first day of incubation to the last day, suggesting rearrangement of soil particles and compaction over time. The significant improvement recorded under moderate application of basalt dust (5 – 10 t ha^{-1}) signifies an application threshold beyond which additional basalt doses does not further improve soil porosity. The improvement in soil particle cohesion and structure was revealed at moderate application of basalt rock dust. The post hoc test using the mean separation by Duncan Multiple Range Test approach (DMRT) revealed that basalt dust application rates at 5 t ha^{-1} and 10 tha^{-1} yielded higher values for soil porosity, particularly at Day 60 when compared to the control.

Table 6: Effects of Basalt Application Rate and Basalt Particle Size on Soil Porosity (Auchi)

Basalt Rate	Day1		Day30		Day60		Day90 (Days)	
(t ha^{-1})	T1	T2	T1	T2	T1	T2	T1	T2 (%)
0	2.13^{c}	2.10^{c}	2.12^{c}	2.11^{c}	2.10^{c}	2.07^{c}	2.04^{c}	2.05^{c}
5	2.48^{a}	2.32^{b}	2.49^{a}	2.32^{b}	2.52^{a}	2.31^{b}	2.47^{a}	2.32^{b}
10	2.42^{a}	2.31^{b}	2.42^{a}	2.32^{b}	2.42^{a}	2.32^{b}	2.43^{a}	2.31^{b}
15	2.46^{a}	2.47^{a}	2.47^{a}	2.46^{a}	2.48^{a}	2.45^{a}	2.49^{a}	2.47^{a}

Mean values with the same superscript are not significantly different across the table at $P < 0.05$
T1 = ≤63µm basalt particle (fine) and T2 = ≤125µm basalt particle (coarse).

Variation in soil porosity during incubation (silty loam soil)

The porosity of incubated silty loam soil collected from Agbede was affected by the application rate and particle size of basalt rock dust over time. The soil porosity ranged between 41.32% and 47.62% across the incubation period and treatments adopted. At Day 1, the highest value of soil porosity (47.58%) was observed under 5 t ha^{-1} basalt (T1) and the lowest value of soil porosity (42.98%) was observed at 10 t ha^{-1} basalt (T1) for the same day. The trend was similar on Day 30 of incubation, where 5 t ha^{-1} (T1) has the porosity value (47.39%), suggesting improved pore continuity and soil structure at moderate application rates of basalt dust. Porosity values reduced slightly generally across treatments, with increasing periods of incubation suggesting a gradual process of mineral stabilization or soil compaction as periods of incubation progresses.

Table 7: Effects of basalt application rate and basalt particle size on soil porosity (Agbede)

Basalt Rate	Day1		Day30		Day60		Day90 (Days)	
(t ha^{-1})	T1	T2	T1	T2	T1	T2	T1	T2 (%)
0	43.66^{b}	44.29^{ab}	42.45^{b}	44.08^{ab}	41.90^{b}	43.96^{ab}	41.67^{b}	43.41^{ab}
5	47.58^{a}	44.83^{ab}	47.39^{a}	44.40^{ab}	47.62^{a}	44.16^{ab}	46.96^{a}	43.53^{ab}
10	42.98^{b}	44.59^{ab}	42.15^{b}	43.97^{ab}	41.32^{b}	44.40^{ab}	41.98^{b}	44.16^{ab}

15	43.09^{b}	43.32^{b}	42.51^{b}	43.09^{b}	43.15^{b}	43.27^{b}	42.57^{b}	43.32^{b}

Mean values with the same superscript are not significantly different across the table at $P < 0.05$
T1 = ≤63µm basalt particle (fine) and T2 = ≤125µm basalt particle (coarse).

Variation in soil temperature during incubation (sandy loam soil)

A consistent increase in soil temperature was recorded at incubation period of 90 day. This suggests enhanced exothermic process for biological oxidation and mineral release in the soil due to basalt incorporation. Higher soil temperatures were maintained by the fine-milled basalt dust (≤ 63µm) compared to the coarse milled basalt dust (≤ 125µm), likely due to increase surface area and improved chemical reactivity, which encourage heat generation through release of nutrient. The soil temperature dynamics suggests that the soil microclimate was modified by the application of basalt dust through improved decomposition of soil organic matter and thermal conductivity. Basalt application at the rate of (15 t ha^{-1}) revealed the most pronounced warming effect.

Table 8: Effects of basalt application rate and basalt particle size on soil temperature (Auchi)

Basalt Rate	Day1		Day30		Day60		Day90 (Days)	
(t ha^{-1})	T1	T2	T1	T2	T1	T2	T1	T2 (^{0}C)
0	29.60^{ab}	28.40^{b}	28.70^{b}	28.70^{b}	28.70^{b}	28.50^{b}	28.50^{b}	29.40^{b}
5	29.00^{b}	28.60^{b}	28.60^{b}	28.80^{b}	28.30^{b}	28.80^{b}	30.00^{ab}	29.10^{b}
10	29.40^{b}	29.50^{ab}	28.80^{b}	29.70^{ab}	28.30^{b}	28.00^{b}	29.20^{b}	29.40^{b}
15	30.30^{a}	29.60^{a}	30.30^{a}	30.80^{a}	28.50^{b}	28.00^{b}	30.90^{a}	31.20^{a}

Mean values with the same superscript are not significantly different across the table at $P < 0.05$
T1 = ≤63µm basalt particle (fine) and T2 = ≤125µm basalt particle (coarse).

Variation in soil temperature during incubation (silty loam soil)

The values of soil temperature ranged from 28.34°C to 30.26°C across treatments and periods of incubation. A general observation suggests that temperature increases with incubation period, most especially under fine-milled basalt treatments (T1). At day 1, the highest temperature (30.20°C) was recorded for soils treated with 15 t ha^{-1} of fine basalt (T1), while the lowest temperature (29.10°C) was recorded for soil treated with 5 t ha^{-1} (T1). As incubation progresses, relatively higher temperatures were maintained for soil incubated with fine basalt at application rates of 10 and 15 t ha^{-1} compared to coarse basalt (T2). This suggests that the particles of finer basalt improved mineral weathering and microbial activity within the soil microclimate and slightly led to increased soil temperature, possibly due to improved aeration and exothermic mineral dissolution. By days 60 and 90, temperature increase was consistent (30.19–30.26°C) for fine basalt at 10 t ha^{-1} (T1), signifying a micro-thermally stabilized environment that may improve enzymatic reactions and root zone metabolism. The two-way ANOVA revealed that basalt rate and particle size significantly affected the temperature of the incubated silty loam over time (Agbede soil) at $p < 0.05$. The interactive effect of the two parameters, most especially basalt rate and particle size was significant ($p < 0.05$).

Table 9: Effects of basalt application rate and basalt particle size on soil temperature (Agbede)

Basalt Rate	Day1		Day30		Day60		Day90	
(t ha^{-1})	T1	T2	T1	T2	T1	T2	T1	T2 (^{0}C)

0	29.70^{ab}	29.40^{b}	29.50^{ab}	29.40^{b}	29.00^{b}	28.93^{b}	29.04^{b}	29.61^{ab}
5	29.10^{b}	29.20^{b}	28.60^{c}	29.30^{b}	28.45^{c}	29.79^{ab}	28.34^{c}	29.62^{ab}
10	29.30^{b}	29.30^{b}	30.00^{a}	29.40^{b}	30.19^{a}	29.50^{ab}	30.26^{a}	29.46^{ab}
15	30.20^{a}	29.90^{a}	30.00^{a}	29.20^{b}	29.65^{ab}	28.95^{b}	30.04^{a}	28.91^{b}

Mean values with the same superscript are not significantly different across the table at $P < 0.05$

T1 = ≤63µm basalt particle (fine) and T2 = ≤125µm basalt particle (coarse).

Pooled Correlation Analysis for the Selected Physical Properties of Incubated Loamy Sand and Silty Loam Soil Pooled correlation analysis (Incubated loamy sand physical parameters)

A negative correlation value that is strong and highly significant ($r = –0.82$, $p < 0.01$) was estimated for soil bulk density and porosity of incubated loamy sand, revealing a significant decrease in soil porosity at any increase in bulk density, a significant decrease in total porosity of the soil was also recorded. The compaction effect of basalt application on soil structure was validated by the inverse relationship between soil bulk density and porosity, which invariably affect the soil's potential to retain water and air adequately. The value of correlation between soil particle density and porosity revealed a significant and positive effect ($r = 0.465$, $p < 0.05$).

Table 10. Result on correlation values for physical parameters of incubated loamy sand

Parameters	Bulk Density (gcm^{-3})	Particle Density (gcm^{-3})	Porosity (%)	Temperature (^0C)
Bulk Density ($g\ cm^{-3}$)	1	0.125	-0.82**	0.195
Particle Density ($g\ cm^{-3}$)		1	0.465*	-0.203
Porosity (%)			1	-0.284
Temperature (^0C)				1

Note: Significance of *p < 0.05* and *p < 0.01 are indicated by* * and **

Pooled correlation analysis (Incubated silty loam physical parameters)

At $P < 0.01$, the bulk and particle density of soil revealed a correlation that is highly significant and positively strong, while porosity and temperature revealed a are not significant statistically ($p < 0.05$). correlation value that is strong negatively ($p < 0.01$). Positive and moderate relationship was estimated for repacked bulk density and temperature, indicating that increase in soil temperature lead to increase in soil compaction (Table 11). Other relationships

Table 11. Result on correlation values for physical parameters of incubated silty loam

Parameters	Bulk Density (gcm^{-3})	Particle Density (gcm^{-3})	Porosity (%)	Temperature (^0C)
Bulk Density (gcm^{-3})	1	0.894**	-0.203	0.361*
Particle Density (gcm^{-3})		1	0.255	0.050
Porosity (%)			1	-0.648**
Temperature (^0C)				1

Note: Significance of *p < 0.05* and *p < 0.01 are indicated by* * and **

Pooled regression analysis for incubated loamy sand and silty loam soils

Pooled or multiple regression analysis for basalt incubated soil physical parameters (loamy sand)

The selected physical properties of incubated loamy sand (Auchi soil) was significantly influenced by basalt application rate according to pooled regression analysis (Table 12). About 86% of the variation was influenced by basalt application rate, particle size, and incubation period while the highest model fit ($R^2 = 0.863$, $P < 0.01$) was attributed to soil bulk density. Rock powder

has the potential to enhance soil moisture in agroforestry, and soil moisture is one of the physical attributes of soil that influences its bulk density (Medeiros et al., 2024).

Table 12: Effects of basalt application rate, particle size, and incubation period on the physical properties of loamy sand (Auchi soil)

Parameters	R^2	P-Values	Basalt Treatment Parameters		
			Application Rate (t ha^{-1}) (P-Value)	Particle Size (μm) (P-Value)	Incubation Period (Days) (P-Value)
BD (g cm^{-3})	0.863	<0.001**	<0.001**	0.002*	<0.001**
PD (g cm^{-3})	0.445	0.001*	0.008*	0.002*	0.172
Porosity (%)	0.745	<0.001**	<0.001**	0.456	<0.001**
Temperature (^{0}C)	0.233	0.056	0.072	0.892	0.785

Note: Significance and high significance are indicated by * and **

Pooled or multiple regression analysis for basalt incubated soil physical parameters (silty loam)

The bulk and particle density of the soil (0.901 and 0.669) are affected significantly by basalt application rate according to the regression analysis in Table 13. Little effect was estimated on soil porosity and temperature for silty loam. Richardson (2024) reported that basalt rock incorporation to soil will improve soil aggregate over time due to basalt rock addition.

Table 13: Effects of basalt application rate, particle size, and incubation period on the physical properties of silty loam (Agbede soil)

Parameters	R^2	Model P-Values	Basalt Treatment Parameters		
			Application Rate (t ha^{-1}) (P-Value)	Particle Size (μm) (P-Value)	Incubation Period (Days) (P-Value)
BD (g cm^{-3})	0.901	<0.001**	<0.001**	<0.001*	0.558
PD (g cm^{-3})	0.699	<0.001**	<0.001**	0.023*	0.748
Porosity (%)	0.081	0.494	0.256	0.688	0.337
Temperature (^{0}C)	0.133	0.254	0.065	0.589	0.586

*Note: Significance and high significance are indicated by * and ***

Discussion of Results

Effects of basalt application rates and particle sizes on loamy sand soil of Auchi

At increasing application rates of basalt, the incubated loamy sand of Auchi exhibited structural modification that was progressive across the 90-day incubation period (Tables 2, 4, 6, and 8). With increasing application rate of basalt, bulk density (BD) increased generally, most especially at 10 and 15 t ha^{-1}, while a corresponding reduction in porosity was observed. Variation in the value of soil particle density (PD) was recorded with increasing rates of basalt application, revealing the incorporation of dense basalt minerals into the matrix of the soil.

Typically, the particle density of basalt typically is between 2.8–3.0 g cm^{-3}, which is higher than the constituents of many sandy soil. Thus, higher application rate of basalt increased the density of the solid-phase of the soil system. Hillel (1998) reported that the total porosity of soil is determined by the bulk and particle density of the soil:

This study revealed that increases in soil bulk density at higher application rates of basalt were accompanied by moderate stabilization or increases in the particle density of the soil, resulting in an overall reduction in total porosity of the soil. Weak aggregation and

large macropores are the attributes of the loamy sand textural pattern, the soil was reported to be sensitive to improved packing of particles. Brady & Weil (2017) reported that coarse-textured soils are more responsive structurally to changes in the composition of the solid phase because their pore system is dominated by packing arrangement rather than stable aggregation.

Particle size also affected the structural adjustment of the soil. Considering different incubation periods, the coarser fraction (≤125 μm) produced bulk density and particle density that is slightly higher in values compared with the finer fraction (≤63 μm) of basalt, especially at higher rates of application of basalt. Coarser particles likely contributed more directly to mechanical packing, while finer dust of basalt dispersed at the initial stage within pore spaces of incubated soil before consolidation. The geometry of basalt rock particles and surface area are known to affect both soil-mineral interactions and the structural rearrangement of the soil (White & Brantley, 2003).

Moderate changes in temperature were recorded for incubated loamy sand of Auchi but tended to increase at the highest application rate of basalt (15 t ha^{-1}). As soil bulk density increased, porosity reduced, and improvement was recorded for particle contacts, thereby improving thermal conductivity of the incubated soil. Hillel (2004) reported that the heat transfer efficiency of soils with higher bulk density always increases due to reduced air-filled pores and improved solid-phase continuity. Thus, in the incubated loamy sand of Auchi, increasing the application rate of basalt resulted in increased bulk and particle density, reduced porosity, and slightly improved temperature of the soil through enhanced thermal conduction.

The thermal and structural responses of loamy sand of Auchi soil indicate that application of basalt affected both the packing density (BD) and solid fraction (PD), leading to significant reductions in soil pore space and moderate changes in the dynamics of soil temperature.

Effects of basalt application rates and particle sizes on silty loam of Agbede

In contrast, the incubated silty loam of Agbede recorded a more moderate soil structural response to basalt application (Tables 3, 5, 7, and 9). Progressively, bulk density increased with increasing rate of basalt, while a significant increase in particle density of silty loam occured at 5–15 t ha^{-1} incorporation with basalt. However, the extent of reduction in soil porosity for incubated soil was smaller compared to what was recorded in the loamy sand.

The link between soil bulk density, particle density, and porosity aligns with soil physical theory (Hillel, 1998), but the extent of porosity reduction was less revealing compared to incubated loamy sand of Auchi. This suggests that for incubated silty loam of Agbede, changes in soil particle density did not translate into the collapse of proportional pore due to aggregation-mediated structural resilience.

The effect of particle size was less revealing in the incubated silty loam of Agbede. The differences between fine and coarse basalt fractions in influencing bulk density and particle density were insignificant. This establishes the fact that finer-textured soils and intrinsic soil aggregation exerts more control over the arrangement of soil pores than the geometry of particle amendment alone.

The variation in temperature for Agbede soil were relatively small across treatments. Although, at higher application rates during the incubation study, slight increases in soil temperature were observed, the changes in the incubated soil temperature were less consistent than in loamy sand soil of Auchi. Hillel (2004) reported that soil bulk density and porosity have a great effects on the soil heat flow; the soil pores of silty loam soil of Agbede that are relatively stable moderated thermal fluctuations within the soil. Thus, in the incubated silty loam of Agbede, the application rate of basalt increased particle density and bulk density of the soil moderately, but porosity and temperature

were dramatically less affected due to soil structural stability that is inherent.

Comparative effects of basalt application rates and particle sizes on the incubated contrasting soils

The responses of the contrasting incubated soils of Auchi and Agbede revealed the importance of soil textural pattern in mediating the effects of basalt amendment. In the incubated loamy sand of Auchi. Generally, the bulk and particle density of the soil increases, and a reduction in soil porosity and a slight increase in soil temperature were recorded, revealing structural sensitivity to mineral loading. In the silty loam of Agbede, although the increase in application rate of basalt increased the bulk and particle density of the incubated soil, soil structural buffering, limited reduction in soil pores, and minimized thermal shifts were recorded.

These findings confirm that the physical effects of basalt application on incubated soils strongly depend on soil textural pattern and also depend on the interactions among the selected properties of the soil, such as bulk density, particle density, and the dynamics of soil pores.

Discussion on correlation and regression analysis

The pooled correlation analysis revealed textural differences that are clear with respect to incubated soils' physical properties' response to basalt amendment. For incubated loamy sand of Auchi (Table 10), the bulk density (BD) of the soil was strongly and negatively correlated with soil porosity, revealing an inverse in soil properties' structural relationship between the two parameters, which was expected scientifically. Particle density (PD) revealed a moderate relationship with soil porosity, while temperature recorded correlation level that is weak with other soil properties, revealing a thermal influence that is minimal on the structural attributes of the loamy sand of Auchi.

In silty loam (Table 11), stronger interactions were observed. Soil bulk density and particle density were highly correlated, revealing mineralogical control over compaction dynamics. The soil porosity was negatively and strongly correlated with temperature, suggesting that finer soil fractions were more sensitive and reactive to structural adjustments that were thermally-induced.

The multiple regression analysis estimated that treatment with basalt influenced density parameters of the soil significantly. In loamy sand (Table 12), bulk density and porosity were strongly described by application rate and incubation period, signifying weathering effects that are progressive and consistent with the kinetics of silicate dissolution. In contrast, temperature revealed weak responses.

In silty loam (Table 13), high model fit was recorded by the bulk density of the soil; this was increased majorly by the application rate of basalt rather than the period of incubation, suggesting stabilization potential that is rapid in fine-textured soil. Porosity and temperature were weakly predicted, revealing structural buffering capacity. The results of the findings demonstrate that basalt amendment significantly alters soil physical properties, but the magnitude and controlling factors are texture-dependent. The response of loamy sand to basalt treatment was time-driven, while the response of silty loam to basalt treatment was rate-driven, signifying the relevance of soil texture towards improving weathering applications.

Conclusion

The physical properties of incubated loamy sand (Auchi soil) and silty loam (Agbede soil) are significantly improved by basalt application rates and particle sizes over the reference incubation periods, according to the findings of this study. The soil porosity and structural aggregation are significantly improved by finely milled particles and a moderate application rate of basalt dust. Also, improvement was noticed in the dissolution of silicate minerals due to a slight increase in incubation temperature, thereby

enhancing soil structure and secondary mineral formation. Therefore, the temperature resilience, stability, and long-term productivity of tropical soils can be improved by basalt dust as a sustainable and mineral-based soil amendment. However, the validation of basalt's role for improving soil physical properties under natural temperature regimes and moisture fluctuations in an open field experiment is crucial to corroborate these laboratory findings.

Acknowledgements

The authors acknowledge the Department of Agricultural and BioEnvironmental Engineering, Auchi Polytechnic, for making the laboratory of Soil and Water Engineering accessible for the purpose of this research. Also, Eguje Nigeria Enterprise at Ikpeshi town quarry section, Edo State, Nigeria is acknowledged for assisting with identification and provision of basalt rock sample. Also, the Tertiary Education Trust Funds of Nigeria (TeTFund) under the coordination of Auchi Polytechnic Auchi Edo State Nigeria is also highly appreciated for providing the funds for executing this study.

References

Adebayo, O. C., Lawal, Y. B., Obasi-Oma, O. R., Ojo, J. S. (2022). Effect of near-earth surface temperature on soil temperature at 5 cm depth. Physical Science International Journal, 26(3), 45–54.

Akintola, A., Adewale, J., Ogunleye, M. (2021). Influence of granulated granite stone mixture on growth of Treculia africana Decne seedlings. Journal of Applied Agricultural Science and Technology, 18(2), 104–111.

Al-Akhaly, I. (2018). Engineering properties of basalt coarse aggregates in Hamdan area, North West Sana'a, Yemen. Journal of Geological Engineering, 42, 159–174.

Bamberg, A. L., Silva, C. A., Carvalho, A. M. X., Fonseca, A. F. (2017). Effect of rock powder and organic fertilizer on soil chemical properties and plant growth. Revista Brasileira de Ciência do Solo, 41, e0160219.

Beerling, D. J., Kantzas, E. P., Lomas, M. R., Wade, P., Eufrasio, R. M., Renforth, P., Sarkar, B., Andrews, M. G., James, R. H., Pearce, C. R., Mercure, J.-F., Pollitt, H., Holden, P. B., Edwards, N. R., Khanna, M., Koh, L., Quegan, S., Pidgeon, N. F., Janssens, I. A., Hansen, J., Banwart, S. A. (2020). Potential for large-scale CO_2 removal via enhanced rock weathering with croplands. Nature, 583, 242–248.

Bouyoucos, G. J. (1962). Hydrometer method improved for making particle size analyses of soils. Agronomy Journal, 54(5), 464–465.

Brady, N. C., Weil, R. R. (2017). The nature and properties of soils (15th ed.). Pearson Education Limited, USA. 1086p.

Conceição, L. T., Silva, G. N., Holsback, H. M. S., Oliveira, C. de F., Marcante, N. C., Martins, É. de S., Santos, F. L. de S., Santos, E. F. (2022). Potential of basalt dust to improve soil fertility and crop nutrition. Journal of Agriculture and Food Research, 10, Article 100443.

European Commission (2020). European Green Deal. (Retrieved November 16, 2022), Brussel-Belgium. pp. 24.

FAO (2023). Standard operating procedure for soil bulk density, cylinder method. Rome-Italy, pp. 17.

Fernandes, M. M., Silva, D. F., Nogueira, L. S. (2020). Soil mineral weathering responses to basalt application in tropical systems. Catena, 195, 104826.

Gillman, G. P., Burkett, D. C., Coventry, R. J. (2001). A laboratory study of application of basalt dust to highly weathered soils: Effect on soil cation chemistry. Australian Journal of Soil Research, 40(5), 955–972.

Hillel, D. (1998). *Environmental soil physics*. Academic Press.

Hillel, D. (2004). Introduction to environmental soil physics. Elsevier.

Hu, Z., Delgado-Baquerizo, M., Fanin, N., Chen, X., Zhou, Y., Du, G., Hu, F., Jiang, L., Hu, S., Liu, M. (2024). Nutrient-induced acidification modulates soil biodiversity–function relationships. Nature Communications, 15(1):2858.

International Organization for Standardization (2020). ISO 11277: Soil quality determination of particle size distribution in mineral soil material, Method by sieving and sedimentation, Geneva, Switzerland, pp 38.

Li, Y., He, J., Chen, X., Zhang, X. (2018). Soil temperature and moisture dynamics under different tillage systems in a dryland wheat field. Soil and Tillage Research, 178, 104–112.

Lu, J., Zhang, Q., Werner, A. D., Li, Y., Jiang, S., Tan, Z. (2020). Root-induced changes of soil hydraulic properties: A review. Journal of Hydrology, 589, 125203.

Manik, S. M. N., Pengilley, G., Dean, G., Field, B., Shabala, S., Zhou, M. (2019). Soil and crop management practices to minimize the impact of waterlogging on crop productivity. Frontiers in Plant Science, 10, 140.

Manning, D. A. C. (2018). Mineral sources of plant nutrients: Chemical weathering of silicate minerals. Applied Geochemistry, 96, 127–134.

Manning, D. A. C., Theodoro, S. H. (2020). Enabling food security through use of local rocks and minerals. The Extractive Industries and Society, 7(2), 480–487.

Medeiros, F. d. P., de Carvalho, A. M. X., Ramos, C. G., Dotto, G. L., Cardoso, I. M., Theodoro, S. H. (2024). Rock powder enhances soil nutrition and coffee quality in agroforestry systems. Sustainability, 16(1), 354.

Naorem, A., Singh, R., Devi, S., Nongkhlaw, R. (2023). Soil constraints in an arid environment Challenges, prospects, and implications. Agronomy, 13(2), 220.

Ozegin, K. O., Ataman, J. O., Okolie, E. C. (2017). Prospecting for Metallic Mineral Deposits using Integrated Electromagnetic and Electrical Resistivity Tomography in Agbede, Edo State Nigeria. Scientia Africana, 16(2), 269–281.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R., Blair, R. (1995). Environmental and economic costs of soil erosion and conservation benefits. Science, 267(5201), 1117–1123.

Ramos, M. F., Silva, A. C., Nogueira, L. S. (2022). Rock dust weathering and its implications for soil texture and fertility. Geoderma, 406, 115547.

Richardson, J. B. (2024). Basalt rock dust amendment on soil health properties and inorganic nutrients: Laboratory and field study at two organic farm soils in New England, USA. Agriculture, 14(2), 312.

Sanchez, P. A. (2019). Properties and Management of Soils in the Tropics. Cambridge University Press, UK. 666p.

Smart, M. O., Akintola, O. O., Adesida, O. A., Adeoye, A. S. (2020). Effects of rock dusts on the early growth of cocoa (Theobroma cacao L.), In: Proceedings of the 3rd Commonwealth Forestry Association Conference [Paper presentation]. Commonwealth Forestry Association, Nigeria, pp. 146 -151.

Swoboda, P., Döring, T. F., Hamer, M. (2022). Remineralizing soils? The agricultural usage of silicate rock powders: A review. Science of the Total Environment, 807, 150976.

Wei, B., Peng, Y., Lin, L., Zhang, D., Ma, L., Jiang, L., Li, Y., He, T., Wang, Z. (2023). Drivers of biochar-mediated improvement of soil water retention capacity based on soil texture: A meta-analysis. Geoderma, 437, 116591.

White, A. F., Brantley, S. L. (2003). The effect of time on silicate mineral

weathering rates. *Chemical Geology*, *202*(3–4), 479–506.