Integrated Geo-Mineral Detector and Conventional Laboratory Assessment of Soil Mineralisation Dynamics from Basalt, Dolomite and Granite Rock Dust

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Abstract. The effects of dust from basalt, dolomite, and granite at an application rate of 15 t/ha and ≤ 63 μm on the mineralisation of loamy sand soil were investigated using an integrated geo-mineral detector and a conventional laboratory procedure over a 90-day incubation period. The researchers incubated rock dust in soil samples and recorded phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), cation exchange capacity (CEC), and pH on Day 1 and Day 90. They analysed and interpreted the data using comparative statistics, Pearson correlation analysis, regression analysis, and probability testing at $P < 0.05$. The incorporation of basalt and dolomite significantly improved soil chemical properties compared to granite. After 90 days of incubation, pH increased to 5.20−5.60 with basalt, 5.40−6.00 with dolomite, and 5.10−5.30 with granite. Phosphorus concentrations also increased to 9.80−10.90 mg/kg with basalt, 9.00−9.90 mg/kg with dolomite, and 8.10−9.00 mg/kg with granite. Exchangeable potassium, calcium, and magnesium increased consistently, with dolomite dust producing the highest calcium (5.20−7.40 cmol/kg) and magnesium (3.10−4.00 cmol/kg) values. Basalt produced a more balanced nutrient release. In addition, cation exchange capacity increased to 9.40−10.40 cmol/kg with basalt, 11.30−13.20 cmol/kg with dolomite, and 10.50−10.90 cmol/kg with granite. The correlation between the geo-mineral detector readings and the laboratory assessment was strong, positive, and significant, especially for phosphorus, calcium, magnesium, and pH ($p < 0.05$). The CEC values showed slight variation. This study revealed the effectiveness of basalt and dolomite dust as a slow, consistent source of mineral release to agricultural soils. Also, the study demonstrated the possibility of replacing conventional laboratory procedures with an integrated geo-mineral detector for determining soil fertility and recommended its usage in precision agriculture.

Keywords: Geo-mineral detector; plagioclase feldspar; incubation period; ammonia volatilisation.

INTRODUCTION

The complex mixture of organic matter, organisms, and minerals that makes up soil supports life [1]. The availability of crucial plant minerals determines the productivity of an ecosystem. However, processes such as leaching, denitrification, and ammonia volatilisation were reported to be the end loss these minerals were subjected to. These losses can result in severe environmental degradation, either through natural atmospheric deposition or anthropogenic fertilisation, thereby leading to the emission of gases that are atmospherically active or to contamination of water bodies [2]. The complex interplay between biogeochemical processes and plants determines the availability of soil minerals to plants. The precise use of fertiliser for soil mineralisation

and plant productivity requires proper monitoring of soil-available mineral dynamics to provide the necessary insight into soil nutrient enrichment, environmental change, and natural ecosystem consequences [2].

Different types and sizes of ions are found in soil. Due to this, the dispersing effect of sodium ions is more than that of potassium, and the flocculating effect of calcium is more than that of magnesium. These ions are called base-forming cations. Calcium and sodium ions are readily exchanged in soil, while magnesium and potassium exist as soil mineral constituents permanently incorporated in the soil. Hydrate radiates and significantly affects soil composition. Real-time access to soil minerals via soil sensors is gaining global attention, helping farmers obtain remote, immediate insight into soil conditions. Soil conditions are a crucial factor in production. The measurement of soil nutrients with sensors will help reduce environmental impacts and save resources by enabling precise, on-the-spot application of fertilisers. Cost-effectiveness, rapidity, real-time operation, and nutrient mapping are enabled by sensors [3]. Understanding the relationships among soil properties will provide better insight into the complexity of soil parameters such as structure, texture, water content, and salinity. Soil property data can provide helpful information to support appropriate nutrient and crop management decisions [4].

The traditional farming system uses a repeated-cultivation approach without balanced replenishment of soil nutrients. Usually, farming systems rely heavily on chemical fertilisers, with restrictions to only nitrogen, phosphorus, and potassium as their constituents, while the importance of other essential macro- and micronutrients is neglected. Over time, the use of this fertiliser alone led to over-depletion of soil nutrients, affecting the objectives of sustainable agricultural practices, crop productivity, and food security. In other words, the extensive use of industrial inputs, intensive soil manipulation, mechanisation, and irrigation, known as the Green Revolution, has been a significant concept in mass food production. Researchers recommended this approach as an alternative to address concerns arising from the global crisis, including population growth, food production, and availability [5]. However, the balance of the agricultural sector was disrupted by the use of chemical fertilisers, exacerbating the risk posed by low-fertility soils due to increased soil acidity

and reduced levels of soil phosphorus and potassium. This further encourages dependence on chemical fertilisers.

The remineralisation of agricultural soils can be achieved naturally and cost-effectively using inexpensive materials such as rock dust [5]. It provides essential trace elements and minerals needed for soil nutrient balance. Farmers and researchers commonly use different rock dusts, such as limestone, granite, basalt, and volcanic rock, to replace nutrients lost from the soil. Basalt, an igneous rock, contains minerals such as magnesium, calcium, zinc, iron, and manganese. Granite, another rock used to improve soil mineralisation, contains minerals such as silica, potassium, and phosphorus.

On the other hand, minerals such as calcium carbonate (limestone) help supply calcium for plant growth and raise soil pH. The volcanic ash, a significant source of volcanic rock dust, carries trace elements and minerals due to volcanic activity over millions of years. Basalt provides unique benefits to soil and plants, including minerals such as SiO_2, $Al2O_3$, Fe_2O_3, MnO, MgO, Na_2O, K_2O, and CaO [6]. Rock dust can meet the mineral needs of different agricultural soils. The hypothesis of stone meal technology was that significant mineral products could be derived from crushed rock samples. Among other rocks, basalt was suitable for soil mineralisation because of its availability and nutrient composition, including potassium, calcium, magnesium, and silica [7]. Also, it contains an assembly of minerals, such as plagioclase and pyroxenes, and an amorphous matrix that provides the dissolution rate required to meet crop needs in the field [8].

This study aimed to evaluate and compare the dissolution rates and soil mineralisation potential of different rock dusts, such as basalt, dolomite, and granite, over time, and to estimate nutrient release using a geo-mineral detector to validate its reliability for soil fertility. The researchers compared data from the soil geo-mineral detector with results from the conventional laboratory approach to validate the detector's reliability for soil geo-mineral sampling. Understanding the dissolution of rock minerals helps researchers optimise soil amendments, enhance nutrient cycling, and promote sustainable agricultural practices. Previously, most research focused on adopting conventional laboratory procedures for soil analysis. This approach was observed to be time-consuming, affected by intermittent power

supply, and somewhat unreliable due to a lack of technical know-how, creating a gap in in-situ and nutrient-sensor-based field measurement of soil minerals incorporated with different rock dusts.

METHODS

Study Site. The researchers conducted this study at Auchi Polytechnic in Edo State, Nigeria, and used the Mineral and Petroleum Resources Engineering Technology laboratory for the analysis. Auchi has predominantly sandy loam and loamy sand soils and experiences a tropical climate. The area lies at 7.04° N, 6.28° E.

Rock Samples. Basalt, granite, and dolomite are the different rock types used for the study. The researchers crushed the rocks in a laboratory jaw crusher, milled and sieved them to ≤ 63 µm, and homogenised the resulting material. They then used X-ray fluorescence and X-ray diffraction to determine the elemental and mineral composition of the selected rocks.

Experimental Setup. The effects of dust of basalt, dolomite, and granite on the chemical properties (phosphorus, potassium, calcium, magnesium, and pH) of a loamy sand soil for an incubation period of 90 days. The researchers set up the incubation process using four experimental treatments with three replicates. They incubated the rock dusts in soil at a rate of 15 t/ha, with particle size ≤ 63 µm. They mixed the rock dust and soil at a 3:1 ratio and incubated the mixtures in plastic containers. The rock dust samples and soil mixture were properly agitated and mixed to ensure homogeneity before incubation. The mixtures were incubated at the reference incubation temperature of 28-32 °C, with distilled water added to the setup at intervals to maintain field capacity for 90 days. The essence of adding distilled water to the experimental setup was to speed up the mineralisation rate of the rock dust–soil mixture. The researchers treated the plastic containers separately according to the experimental factor to avoid potential sample destruction and disturbance of other incubated samples. The plastic container used for the incubation process had a height of 17.8 cm, a diameter of 18.5 cm, and an overall surface area of 0.01767 m^2. The researchers filled the plastic containers (experimental setup) with 3.60 kg of loamy sand collected from the Auchi soil to avoid bias. They measured the average weight of the empty plastic container as 0.10 kg.

Soil Sensor Calibration and Laboratory Analysis. Soil chemical parameters were measured using a 7-in-1 integrated geo-mineral detector (Model SEM225, JXCT IoT, Shandong, China). The geo-mineral detector was integrated using a developed algorithm in Python to detect and estimate parameters such as soil temperature (°C), soil moisture level (%), electrical conductivity (µS cm^{-1}), pH, and rapid indicator estimates of available nitrogen (N), phosphorus (P), and potassium (K). The detector was designed for in-situ measurement of soil minerals and operates using the RS-485/Modbus communication protocol. The detector was calibrated for a laboratory-scale field measurement before deployment [9]. Calibration was performed using a certified solution for the reference concentration range for nitrate nitrogen (NO_3^--N), phosphate phosphorus (PO_4^{3-}-P), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and pH with consideration to standard buffer solutions at pH 4.0, 7.0, and 10.0. The researchers calibrated electrical conductivity using potassium chloride (KCl) standards of known ionic strength. They plotted reference concentrations against sensor output values to generate calibration curves and derived linear correction factors that they applied during data processing. The cross-validation of sensor readings on a scale of 15% of samples using standard laboratory methods was adopted to address the variability in geo-mineral detector absolute values, including extraction of phosphorus with Mehlich-3, extraction of exchangeable potassium with ammonium acetate, and determination of nitrate nitrogen (NO_3^-N) with a colourimetric procedure [10, 11]. The laboratory readings were used as a reference to assess the reliability of the geo-mineral detector indices. Ca^{2+} and Mg^{2+} exchangeable bases were extracted with 1N NH_4OAc, and their concentration was determined using an atomic absorption spectrophotometer. The researchers measured soil acidity and alkalinity using a glass-electrode pH meter following the 1:2.5 soil-to-$CaCl_2$ suspension procedure [12].

Field Measurements and Sampling Design. The researchers inserted the geomineral detector into the active root zone of the soil (0–15 cm) for annual crops and took in situ readings on Day 1 and Day 90. At each sampling point, they allowed the detector output to stabilise for 2–3 minutes on the Arduino screen before recording NPK, moisture, temperature, electrical conductivity, and pH. To reduce variability – particularly in soil

moisture and temperature – the researchers collected all readings between 08:00 and 10:00 a.m.

Data Analysis. The dissolution dynamics of the applied rock minerals were quantified by measuring changes in soil sample elemental concentrations after the 90-day incubation. The researchers visualised temporal variations in mineral release using trendline plots generated in Microsoft Excel 365. They validated measurements from the geo-mineral detector against conventional laboratory techniques using Pearson's correlation coefficient (r), linear regression (r^2), and analysis of variance (ANOVA) to test for statistical significance at $p < 0.05$.

Plate 1 – Crushed basalt, dolomite, and granite rocks

Plate 2 – Soil analysis with integrated geo-mineral detector

Plate 3 – Calibration of the geo-mineral detector

Plate 4 – Field assessment of the detector

RESULTS AND DISCUSSION

Composition of the Reference Rocks. The mineralogical and geochemical constituents of the rock samples considered in this study reveal three unique lithological attributes which align with global standards. The granite shows a typical felsic composition: SiO_2 (76.48%), Al_2O_3 (10.13%), Na_2O (2.76%), and K_2O (4.38%), comparable to the high-silica characterisation of granites reported by [13, 14]. The dolomite is dominated by CaO (47.41%) and MgO (20.67%) and is predominantly low in silica, alumina, and LOI (1.11%), which aligns with pure dolostones reported by [15]. A high Fe–Mg and moderate silica composition was reported for basalt. One of the ancient rocks is basalt, and it is rich in trace minerals, calcium, magnesium, and iron without groundwater leaching. Basalt rock dust was reported to be safe and non-toxic to soil, plants, and aquatic animals [16]. The results of the X-ray diffraction (XRD) procedure for mineralogical characterisation of Ikpeshi basalt revealed plagioclase feldspar, olivine, pyroxene, amphibole, and albite as its constituents. The percentage composition of Ikpeshi basalt minerals is in the order of silicon oxide (48.32%), aluminium oxide (13.12%), iron oxide (8.02%), phosphorus oxide (7.63%), potassium oxide (6.76%), and calcium oxide (6.19%). Minerals such as magnesium oxide (5.05%), tin oxide (1.48%), sodium oxide (1.42%), and the value for loss on ignition (1.32%) were also evaluated as part of the rock's composition. The results revealed that Ikpeshi basalt aggregate is suitable as a soil mineraliser because of its oxides and elemental composition. The mineralogical, geochemical, and elemental composition of Ikpeshi rocks reveal granite as an assembly of felsic intrusive rocks, dolomite with high-purity sedimentary rocks, and mantle-derived basalt, providing a reliable reference for geological and agricultural use.

Table 1 – Geochemical composition of Ikpeshi basalt, dolomite and granite rock (%)

Location	Ikpeshi Basalt	Ikpeshi Dolomite	Ikpeshi Granite
SiO_2	48.32	1.81	76.48
Al_2O_3	13.12	0.42	10.13
Fe_2O_3	8.02	0.43	0.74
CaO	6.19	47.41	0.63
MgO	5.05	20.67	0.29
Na_2O	1.42	0.18	2.76
K_2O	6.76	0.77	4.38
SO_3	0.20	-	-
P_2O_5	7.63	0.86	0.0002
TiO_2	1.48	0.11	0.19
LOI	1.32	1.11	0.78

Notes: Dynamics of Incubated Rock Dust – Soil Mixture

Figure 1 showed that, over the 90-day incubation period, soil pH increased significantly across treatments, with differences among rock types.
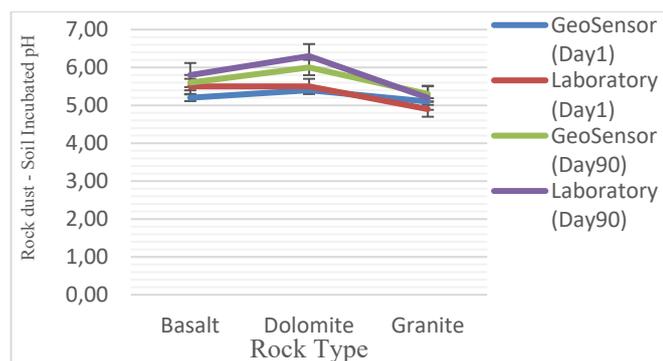

Figure 1 – Rock dust – loamy sand incubated pH

The highest pH values were recorded for dolomite at Day 1 (5.40 by geo-mineral detector; 5.50 in the laboratory) and Day 90 (6.00 by geo-mineral detector; 6.30 in the laboratory), indicating its potential for soil liming due to its high calcium and magnesium carbonate content. A moderate improvement in soil pH was observed with basalt incubation at Day 1 (5.20 by geo-mineral detector; 5.50 in the laboratory) and Day 90 (5.60 by geo-mineral detector; 5.80 in the laboratory), due to its gradual release of basic cations during weathering [17-19]. The lowest pH values were recorded for granite throughout the incubation period (5.10 by geo-mineral detector and 4.90 in the laboratory) for Day 1 and (5.30 by geo-mineral detector and 5.20 in the laboratory) for Day 90, indicating limited liming potential

[20]. Despite improvements in soil acidity across all treatments, none fell within the FAO-recommended pH range of 6.5–8.5, suggesting that more extended incubation periods and higher application rates may be required. Dolomite is the best rock material for improving soil pH, according to authors [21, 22], followed by basalt and granite, respectively.

Phosphorus Dynamics of Incubated Rock Dust – Soil Mixture. Phosphorus concentrations increased consistently across treatments from Day 1 to Day 90, suggesting progressive mineral weathering and dissolution (Figure 2).
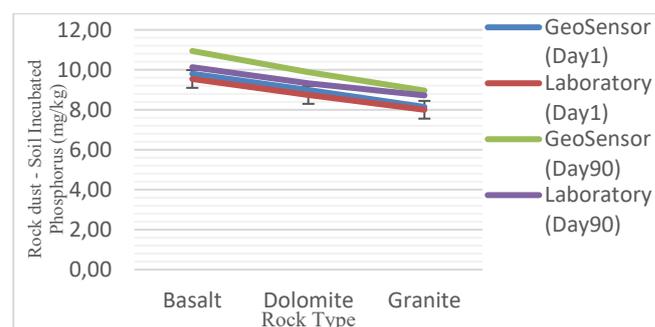

Figure 2 – Rock dust – loamy sand incubated phosphorus concentration

The researchers recorded the highest phosphorus concentrations in basalt dust incubations on Day 1 (9.80 mg/kg using the geo-mineral detector and 9.54 mg/kg using laboratory analysis) and on Day 90 (10.94 mg/kg using the geo-mineral detector and 10.13 mg/kg using laboratory analysis), which previous studies according to authors [17, 23] also classify as relatively high. They observed a moderate phosphorus release from dolomite on Day 1 (8.99 mg/kg using the geo-mineral detector and 8.74 mg/kg in the laboratory) and on Day 90 (9.88 mg/kg using the geo-mineral detector and 9.32 mg/kg in the laboratory). The researchers attributed this moderate release to dolomite's lower inherent phosphorus content, as reported by the authors [24], although improved mineral reactivity enhanced phosphorus availability. The concentration of phosphorus was lowest for granite dust incubation soil (8.14 by geo-mineral detector; 8.00 mg/kg in the laboratory) for Day 1 and (8.96 by geo-mineral detector; 8.72 mg/kg in the laboratory) for Day 90, due to its poor nutrient composition and slow weathering attribute [21]. Although the phosphorus concentration improved over time, the values for all treatments remained

below the FAO-recommended threshold (20 mg/kg) for optimal soil fertility, suggesting that combined fertilisation strategies or higher application rates may be required [25, 26]. Basalt released the most available soil phosphorus, followed by dolomite, while granite contributed insignificantly throughout the study period.

Potassium Dynamics of Incubated Rock Dust – Soil Mixture. Figure 3 revealed a slight increase in potassium concentration over the 90-day incubation period for all rock–soil treatments, with basalt recording the highest values.
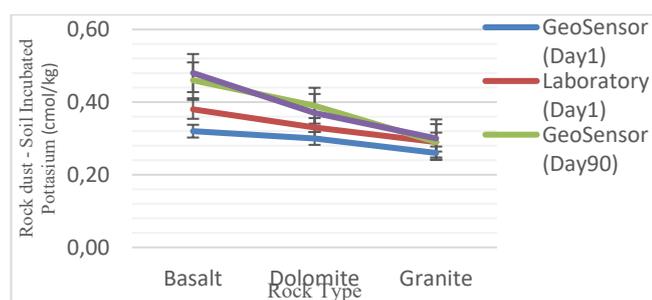

Figure 3 – Rock dust – loamy sand incubated potassium concentration

The soil amended with basalt has increased potassium levels (0.32–0.38 cmol/kg) for both the geo-mineral detector and the conventional laboratory evaluation at Day 1 and (0.46–0.48 cmol/kg) for both assessments at Day 90, revealing its relatively improved potassium-bearing content according to authors [19, 27] and rapid rate of weathering compared to other rocks. Moderate release of potassium was observed in dolomite (0.30–0.33 cmol/kg) by Day 1 for geo-mineral detector and laboratory evaluation, and (0.37–0.39 cmol/kg) by Day 90; this was due to its low inherent potassium content and its dominance by calcium- and magnesium-carbonates, according to the authors [28], who reported insoluble silicates formed of quartz and potassium feldspar (orthoclase). The lowest values were recorded for granites (0.26–0.29 cmol/kg) by the geo-mineral detector and by laboratory estimate for Day 1 (0.29–0.30 cmol/kg) for Day 90 of incubation; this was due to a slow dissolution rate and the locking of potassium within resistant feldspar minerals. Despite the increase, all treatments' potassium levels were below the FAO-recommended range (0.6–1.2 cmol/kg) for adequate soil fertility according to authors [26], suggesting that rock dust alone may not provide suf-

ficient potassium to meet plant needs in the short term. Nutrients were released faster from basalt than from granite due to its mafic composition, whereas carbonate rocks such as dolomite contributed little to potassium release to soil during incubation.

Calcium Dynamics of Incubated Rock Dust – Soil Mixture. Across all treatments, calcium concentration increased during the 90-day incubation, with dolomite releasing the highest concentration (Figure 4).
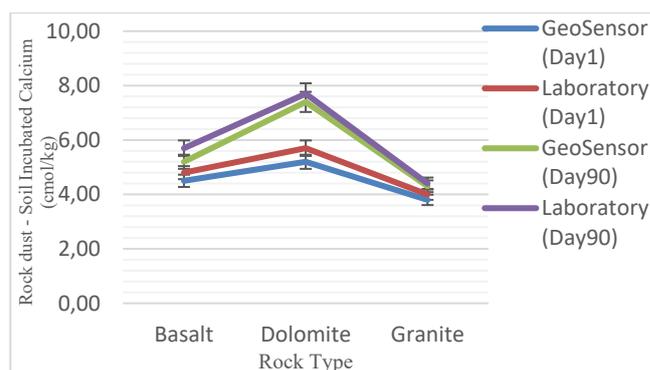

Figure 4 – Rock dust – loamy sand incubated calcium concentration

The therapy with soil amended with dolomite dust recorded the highest values of calcium at both Day 1 (5.20–5.70 cmol/kg by geo-mineral detector reading and conventional laboratory evaluation) and Day 90 (7.40–7.70 cmol/kg by geo-mineral detector and conventional laboratory readings, respectively), validating dolomite as a source of calcium and magnesium carbonate mineral according to authors [28] and releasing Ca^{2+} readily during dissolution [29]. The release of calcium also increases for basalt (4.50–4.80 cmol/kg by Day 1 for both geo-mineral detector and laboratory readings to 5.20–5.70 cmol/kg by Day 90 for geo-mineral detector and laboratory evaluation, respectively), suggesting the presence of silicate minerals with calcium composition, such as plagioclase and pyroxenes that gradually weather under soil conditions [16]. The lowest calcium release was recorded for granite (3.80–4.00 cmol/kg from Day 1 of incubation to 4.30–4.40 cmol/kg from Day 90 of incubation), due to its slow weathering rate and low calcium content [30]. Despite the increase in calcium concentration across all treatments, all recorded values are below the FAO range (10–20 cmol/kg) reported by the authors [26], suggesting that higher application rates or longer weathering

periods are required for the reference rocks. Dolomite had the highest calcium concentration, followed by basalt and granite.

Magnesium Dynamics of Incubated Rock Dust – Soil Mixture. From Day 1 to Day 90, magnesium concentration increased across all treatments, indicating progressive nutrient release and mineral dissolution over the incubation period. Dolomite released the highest amount of magnesium (3.14 by geo-mineral detector reading; 3.20 cmol/kg in the laboratory) for Day 1 and (4.00 by geo-mineral detector reading; 3.89 cmol/kg in the laboratory) for Day 90, aligning with magnesium as one of its major mineral compositions for soil mineralisation [28]. A moderate increase in magnesium concentration was revealed by basalt (2.28 by geo-mineral detector; 2.33 cmol/kg in the laboratory) for Day 1 and (2.97 by geo-mineral detector reading; 3.11 cmol/kg in the laboratory) for Day 90, revealing its mafic mineralogy role, which gradually weathers under moist conditions [31, 32]. The lowest concentration of magnesium (Mg^{2+}) was released by granite (1.64 by geo-mineral detector and 1.71 cmol/kg recorded in the laboratory) for Day 1 and (1.93 by geo-mineral detector and 2.10 cmol/kg in the laboratory) for Day 90, aligning with its limited magnesium composition and felsic nature [30]. However, soil mineralisation with basalt and granite dust for magnesium release remained slightly below the FAO standards (3.0–8.0 cmol/kg) for optimum soil fertility [26]. The magnesium values of soils amended with dolomite approached the lower threshold of the standard by Day 90, suggesting its suitability for alleviating magnesium deficiency in tropical soils. The strong agreement between the geo-mineral detector and laboratory values confirms the reliability of the geo-mineral detector for monitoring the dynamics of soil nutrients during the incubation window for the rock-soil mixture (Figure 5).
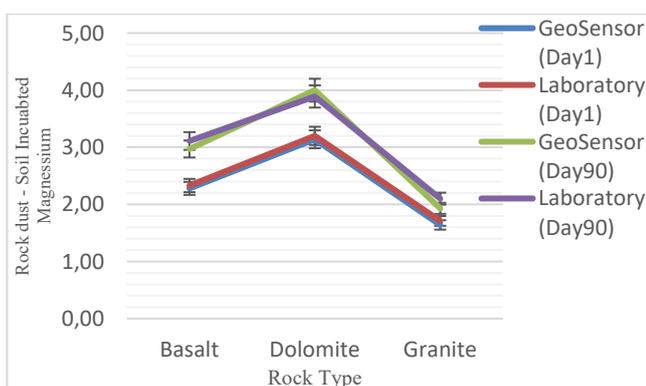

Figure 5 – Rock dust – loamy sand incubated magnesium concentration

Cation Exchange capacity (CEC) Dynamics of incubated Rock Dust – Soil Mixture. Improved soil chemical activity and progressive mineral weathering over time were observed in soil cation exchange capacity across all treatments (Figure 6).
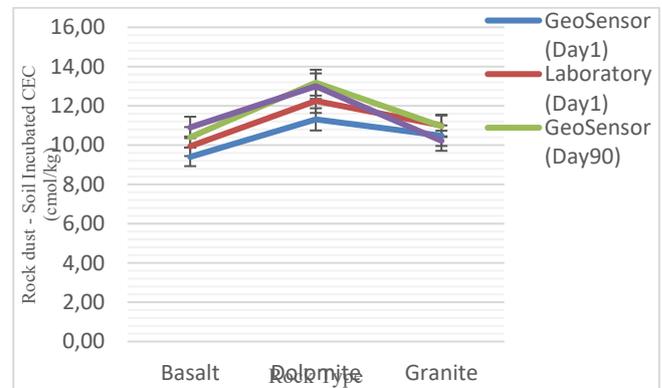

Figure 6 – Rock dust – loamy sand incubated cation exchange capacity (CEC)

The highest cation exchange capacity was recorded for dolomite (11.31–13.18 cmol/kg by geo-mineral detector and 12.25–13.00 cmol/kg in the laboratory), due to its high carbonate content and fine particle size, which promote the development of surface charge during dissolution [29]. Basalt revealed a moderate increase in cation exchange capacity (9.40 – 10.40 cmol/kg geo-mineral detector; 9.94 – 10.90 cmol/kg in the laboratory), suggesting the slow release of exchange sites from the weathering of calcium- and magnesium-rich silicates such as olivine and pyroxenes [19, 23, 33, 34]. A relatively stable value was recorded for granite (10.48–10.96 cmol/kg by geo-mineral detector and 11.00–10.22 cmol/kg in the laboratory), consistent with its limited contribution to exchangeable cations and its low weathering rate due to its quartz- and feldspar-dominated composition. Both basalt and dolomite rock minerals approached the FAO-recommended range (10–25 cmol/kg), indicating their suitability for improving soil fertility. At the same time, the close agreement between the geo-mineral detector readings and conventional laboratory results demonstrated the sensor's reliability during long-term incubation of rock minerals in agricultural soils.

Statistical Interpretation. The correlation and variation analysis between the geo-mineral detector readings and the conventional laboratory approach revealed a strong, consistent relation-

ship across all soil chemical parameters during the 90-day incubation period (Table 2).

Table 2 – Correlation and regression analysis for geo-mineral detector and laboratory chemical parameters for rock dust incubated soil

Parameters	Days	R	R^2	p-value
pH	Day 1	0.755929	0.571429	0.454371
	Day 90	0.990938	0.981957	0.085772
Phosphorus (P)	Day 1	0.999338	0.998676	0.023174
	Day 90	0.998989	0.997978	0.028633
Potassium (K)	Day 1	0.967868	0.936768	0.161821
	Day 90	0.973863	0.948408	0.145874
Calcium (Ca)	Day 1	0.999424	0.998848	0.021612
	Day 90	0.993316	0.986677	0.073645
Magnesium (Mg)	Day 1	0.999927	0.999854	0.007699
	Day 90	0.997462	0.994931	0.045365
Cation Exchange Capacity (CEC)	Day 1	0.99246	0.984977	0.078227
	Day 90	0.909618	0.827405	0.272748

The variation among treatments was influenced by the incubation period. Still, the general results demonstrate that the geo-mineral detector provides a reliable approximation of laboratory-based measurements for monitoring the chemical changes in soil induced by basalt, dolomite, and granite rock amendments.

A moderate correlation (R = 0.76; R^2 = 0.57) was estimated on Day 1 for the pH of the mixture, suggesting that only 57% of the variability in the pH of the laboratory evaluation was attributed to the geo-mineral detector readings at the beginning of incubation. However, a significant relationship was recorded by Day 90 of incubation (R = 0.99; R^2 = 0.98), suggesting that the geo-mineral detector correctly predicted the soil pH dynamics over time. Progress in stabilising the rock-soil mixture chemistry during incubation led to improved pH.

The analysis identified one of the strongest relationships in phosphorus (P) levels across both sampling periods. On Day 1, Pearson correlation and regression results (R = 0.999; R^2 = 0.999) showed perfect agreement, with a statistically significant p-value of 0.023, indicating that geo-mineral detector readings explained more than 99% of the variation in laboratory-measured phosphorus levels. Similarly, on Day-90, a high correlation (R = 0.999; R^2 = 0.998; p = 0.029) was observed, demonstrating the reliability of the geo-mineral detector in capturing available soil

phosphorus as mineral weathering progressed. These results validate that the rapid geo-mineral detector, through in-situ measurement, can monitor the weathering of phosphorus in soil over time.

A similar trend was recorded for potassium (K) with strong correlations (R = 0.97; R^2 = 0.94) on Day 1 and (R = 0.97; R^2 = 0.95) on Day 90. At (p > 0.05), the estimates were not statistically significant; the high regression (R^2) values indicate that the sensor could still predict more than 90% of the variation in laboratory values of potassium.

Calcium (Ca) and magnesium (Mg) are the significant indicators of soil nutrient improvement and rock dissolution, and they revealed perfect agreement between the two methods. On Day 1, calcium (R = 0.999; R^2 = 0.999; p = 0.022) demonstrated a near-perfect, robust correlation. The researchers estimated the same trend on Day 90 (R = 0.999; R^2 = 0.987). Magnesium exhibited the strongest overall relationship on Day 1 and on Day 90, respectively. The results confirm that the geo-mineral detector detected divalent cation release from rock dust more readily.

A robust correlation was observed for cation exchange capacity (CEC) on Day 1 (R = 0.992; R^2 = 0.985), but agreement decreased by Day 90 (R = 0.910; R^2 = 0.827; p = 0.273); this may be due to an increase in soil heterogeneity and soil colloidal interactions as weathering progressed, potentially triggering the ionic activity of the geo-mineral detector relative to the laboratory extractions.

Overall, these findings demonstrated that the geo-mineral detector provided a scientifically reliable alternative to the conventional laboratory analytical approach for monitoring soil chemical properties during rock dust-soil incubation. A strong to near-perfect correlation (R > 0.95) was observed for most parameters considered, and high predictive accuracy (R^2 > 0.90), especially for P, Ca, Mg, and K, was also observed. Slight deviations in pH at the early stage and CEC at the late stage may reflect natural soil chemical variability rather than limitations of the sensor. These results support the use of geomineral detectors as rapid, low-cost tools for assessing soil fertility improvements associated with rock dust application in sustainable agriculture.

CONCLUSIONS

The variations in soil minerals were influenced by incubating basalt, dolomite, and granite rock dust in soil. They were evaluated using an integrated geo-mineral detector and a laboratory analytical procedure over a 90-day incubation period. Basalt and dolomite improved soil chemical properties more effectively than granite. The study reported the role of rock dusts as slow but consistent soil mineralisers, with dolomite showing the most substantial liming effect, while basalt provided a more balanced soil nutrient enrichment. The measurements between the geo-mineral detector and the laboratory analysis procedure revealed a strong agreement, particularly for phosphorus, calcium, magnesium, and pH at later incubation stages, confirming the reliability of the in-situ geo-mineral detection approach for monitoring soil mineralisation dynamics. This study recommended assessing agricultural soil fertility and implementing precision nutrient management using practical, efficient tools. The integration of a geomineral detector into soil chemical property monitoring and the adoption of basalt and dolomite rock dust to improve soil liming and mineralisation demonstrated a promising approach. Crop response assessment, long-term field validation, and further refinement of geo-mineral detection calibration to assess the complex properties of the geo-mineral-soil mixture should be the focus of subsequent research.

Conflict of Interests

The authors declare that they have no conflict of interest related to this study.

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