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Effect of trachyte and basalt powder on the growth and yield of maize (Zea Mays L.) in the Sudano-Sahelian zone of Cameroon (Central Africa)

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Abstract. The Sudano-Sahelian zone of Cameroon, characterized by a low annual rainfall, faces challenges in soil fertility preservation due to agricultural intensification and unsustainable practices. This study aims to evaluate the effect of trachyte and basalt powders inputs on soil and maize yield in Guiring experimental farm. Fieldwork involved collecting and describing samples of trachyte, basalt, and soil and setting up the experimental design. In the laboratory, the ground rock samples underwent geochemical analysis, and the soil samples were analysed for their mineralogical and physicochemical properties. The experiment followed a completely randomized block design with three repetitions and six treatments (T0, T1, T2, T3, T4 and T5). The soil consists of kaolinite, smectite, sepiolite, and quartz. Its texture is dominated by sand fraction, with a neutral pH (6.98). The organic matter (1.30 to 3.17%) and total nitrogen contents (0.11 to 0.13%) are relatively low. The concentrations of potassium, magnesium, sodium, and calcium vary from 0.10 to 0.40 $cmol_c\ kg^{-1}$, 0.72 to 5.44 $cmol_c\ kg^{-1}$, 0.13 to 0.56 $cmol_c\ kg^{-1}$, and 2.64 to 6 $cmol_c\ kg^{-1}$, respectively. The cation exchange capacity is moderate to high, ranging from 18.70 to 25 $cmol_c\ kg^{-1}$, while the available phosphorus content is high, ranging from 12.60 to 30.30 mg kg^{-1}. The studied soils are moderately suitable for maize cultivation. Fertilization trials showed a significant improvement in maize growth and yield, within plots treated with basalt powder yielding higher (2558.64 kg ha^{-1} and 2931.16 kg ha^{-1}) than those treated with trachyte powder (2362.87 kg $ha^{-1}$and 2763.91 kg ha^{-1}) and the control plots (645.83 kg ha^{-1}). Plots treated with NPK fertilizer recorded the highest yield (3164.45 kg ha^{-1}). Although the treatment with conventional fertiliser resulted in a relative higher yield, the advantage of using rock powders lies in their environmental benefits, long-term effectiveness, and more affordable cost.

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1 Introduction

In recent decades, population growth and food insecurity have led to intensification of agriculture, soil overexploitation, and use of chemical fertilizers (Pham et al., 2018; Jhariya et al., 2021; Khatri et al., 2024). Intensively exploited soils degrade and impoverish rapidly, resulting in a reduction of biological activity, soil acidification and deterioration of soil structure (Kuria et al., 2018; Nanganoa et al., 2019; Rajwar et al., 2021). As a limited resource, it takes between 200 to 1000 years to form a layer of 2.5 cm in thickness, making its exploitation for agricultural purposes fragile due to the increase in the world population and climate change (Moges and Taye, 2016). Soil degradation has become a major global concern due to its harmful effects on biodiversity, agricultural production, and food security (Mekuriaw et al., 2017; Hossain et al., 2020). To maintain soil fertility and productivity, it is necessary to replenish the supply of nutrients (Nkouathio et al., 2008; Garai et al., 2022).

Soil provides physical stability, support for agriculture and contributes to the nutrient cycle, water retention capacity, storage, filtering, buffering, and transformation of compounds (Tsozué et al., 2020a; Toor et al., 2021; Sivaram et al., 2023). Soil health, also known as soil quality, is a key factor in sustainable agriculture, influencing ecosystem quality, such as air and water quality (Are et al., 2018; Tsozué et al., 2020a). Maintaining soil quality is an essential determinant for managing ecosystem services and sustainable soil management (Tsozué et al., 2020a; Wu et al., 2023). Its restoration and assessment require the use of relevant biological, physical, and/or chemical indicators (Tsozué et al., 2020a; Oliveira et al., 2024). It is important to consider current land use and precisely define the type of disturbance that may alter its quality (Peng et al., 2021). In the case of anthropogenic disturbances, land use, including agricultural management systems, strongly influences soil quality, expressed by changes in its physicochemical and biological properties and agricultural yield (Farahani et al., 2019; Tsozué et al., 2020a; Mamabolo et al., 2024).

Intensive agriculture leads to excessive nutrient depletion from the soil, thereby compromising its fertility on a global scale (Padhiary et al., 2024). While nitrogen (N) and phosphorus (P) are often highlighted, potassium (K) also plays a crucial role, and its depletion is becoming an increasing concern (Khan et al., 2023). To address this issue, the use of rock powders has emerged as a sustainable alternative to chemical fertilizers. These natural fertilizers enrich the soil with essential nutrients and enhance its structure, although their performance depends on soil characteristics and climatic conditions (Manning and Theodoro, 2020; Rodrigues et al., 2024b). Numerous studies have explored the use of rock powders for soil fertilization and remineralization. In the Americas, several studies have demonstrated that these mineral powders enhance water retention and soil fertility while contributing to carbon sequestration (Beerling et al., 2018; Theodoro et al., 2021; Lewis et al., 2021; Ramos et al., 2022; Medeiros et al., 2023). In Europe, research has confirmed their positive impact on improving soil fertility and remineralization (Beerling et al., 2018; Vienne et al., 2022). Similarly, in Asia, silicate rocks have shown their ability to increase agricultural productivity (Xiang et al., 2020; Basak et al., 2023; Sniatala et al., 2023). Africa has also embraced this innovation, using rock powders to boost agricultural yields while preserving the environment (Mekuriaw et al., 2017; Muhie, 2022). In Cameroon, in particular, several studies have demonstrated the effectiveness of these powders (Nkouathio et al., 2008; Mein'da et al., 2022; Tetchou et al., 2022). Although crushed rocks offer agronomic and environmental benefits, some limitations remain, including their slow dissolution rate, high logistical costs, and the need for pedological expertise to maximize their effectiveness. Given the growing concerns over soil degradation and nutrient depletion, it becomes crucial to explore sustainable solutions, particularly in regions like the Sudano-Sahelian zone of Cameroon, where challenging climatic conditions contribute to the deterioration of soil fertility.

The Sudano-Sahelian zone of Cameroon, characterized by a low precipitation and a prolonged dry season, faces challenges in preserving soil fertility. Inadequate agricultural practices and pressure on the soil have led to its degradation, resulting in a decline in fertility and agricultural yield (Prasannakumar et al., 2011; Hishe et al., 2017). According to FAO (2013), global food demand is expected to increase by 60% between 2006 and 2050, making imperative, if not essential, to modify or replace agricultural techniques with more sustainable and environmentally friendly practices to preserve the integrity of various environmental components and ensure long-term agricultural sustainability (Nkouathio et al., 2008; Muhie, 2022). One of these techniques involves effectively regenerating soil fertility using appropriate methods that do not impact the environment, including the use of geological materials (Burbano et al., 2022). As the minerals constituting rocks dissolve, the released chemical elements become available to plants (Silva et al., 2005; Manning and Theodoro, 2020; Basak et al., 2023). To address the challenges of soil fertility decline and rising fertilizer costs in the Sudano-Sahelian zone, exploring alternative solutions such as local rock powders becomes essential for sustainable and resilient agriculture.

The rising cost of fertilizers represents a major constraint for farmers, especially in the Sudano-Sahelian zone of Cameroon, limiting their access to these essential inputs (Sinha et al., 2022). This situation has raised global concerns about food shortages, forcing countries reliant on fertilizer imports to find mechanisms and new technological pathways to reduce their dependence on the international market (Xiang et al., 2020; Sniatala et al., 2023). The use of local rock powders, or remineralizers, appears to be a promising alternative (Dalmora et al., 2020; Swoboda et al., 2023). This agroecological approach not only reduces reliance on chemical fertilizers but also sustainably improves soil fertility while being more economical and environmentally friendly (Ramos et al., 2017; Conceição et al., 2020; Swoboda et al., 2022). In light of the challenges posed by increasing fertilizer costs and the need for sustainable agricultural practices, exploring the potential of local geological materials like trachyte and basalt powders to enhance soil fertility and maize production in Cameroon has become a vital research focus.

Maize, one of the most produced and consumed cereals in the world, with about 850 million tons over approximately 162 million hectares, is primarily used for food but also serves for the production of biofuels and the extraction of starch, oil, and other industrial substances. In the northern regions of Cameroon in particular, maize is a staple food in almost every household. In a context marked by soil degradation, the environmental impacts of intensive chemical fertilizers use, and rising input costs, it is essential to assess to what extent the use of local available geological materials such as trachyte and basalt powders can improve soil fertility, promote maize growth and yield, while fostering sustainable and resilient agriculture in the face of climate change. This issue is the focus of studies conducted at the experimental farm of the Agricultural Research Institute for Development (IRAD) in Guiring.

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2 Materials and methods

2.1 Study area

This study was conducted in the locality of Guiring, situated in the Diamaré Division (Maroua III Subdivision) in the Far-North Region of Cameroon, located between 10°32′21.8″ and 10°41′55.7″ North latitude and 14°15′33.8″ and 14°29′42.0″ East longitude (Fig. 1.). The area has a Sudano-Sahelian climate (Suchel, 1987), with a short and irregularly distributed rainy season from June to September, followed by a long dry season lasting from October to May. The average annual rainfall is approximately 792.25 mm, and the average annual temperature reaches 27.7°C (Table 1). According to De Martonne's aridity index (1926), the region experiences four months of rainy season (June to September, with an aridity index > 20) and eight months of dry season (aridity index < 20) (Table 1). The highest temperatures are recorded in April, while the lowest occur in January. The terrain is mainly characterized by a relatively flat topography, marked by several ecological zones, including the Sahelo-Sudanian domain, the elevated Sudanian domain, and the periodically flooded Sahelian domain. The substratum consists of alluvial deposits of Quaternary age (Tament et al., 2015; Gountié et al., 2019). The vegetation consists of scattered trees and shrubs associated with grasses. Among the most representative species are *Acacia seyal*, *Balanites aegyptiaca*, *Faidherbia albida*, and *Ziziphus mauritiana* (Letouzey, 1980).

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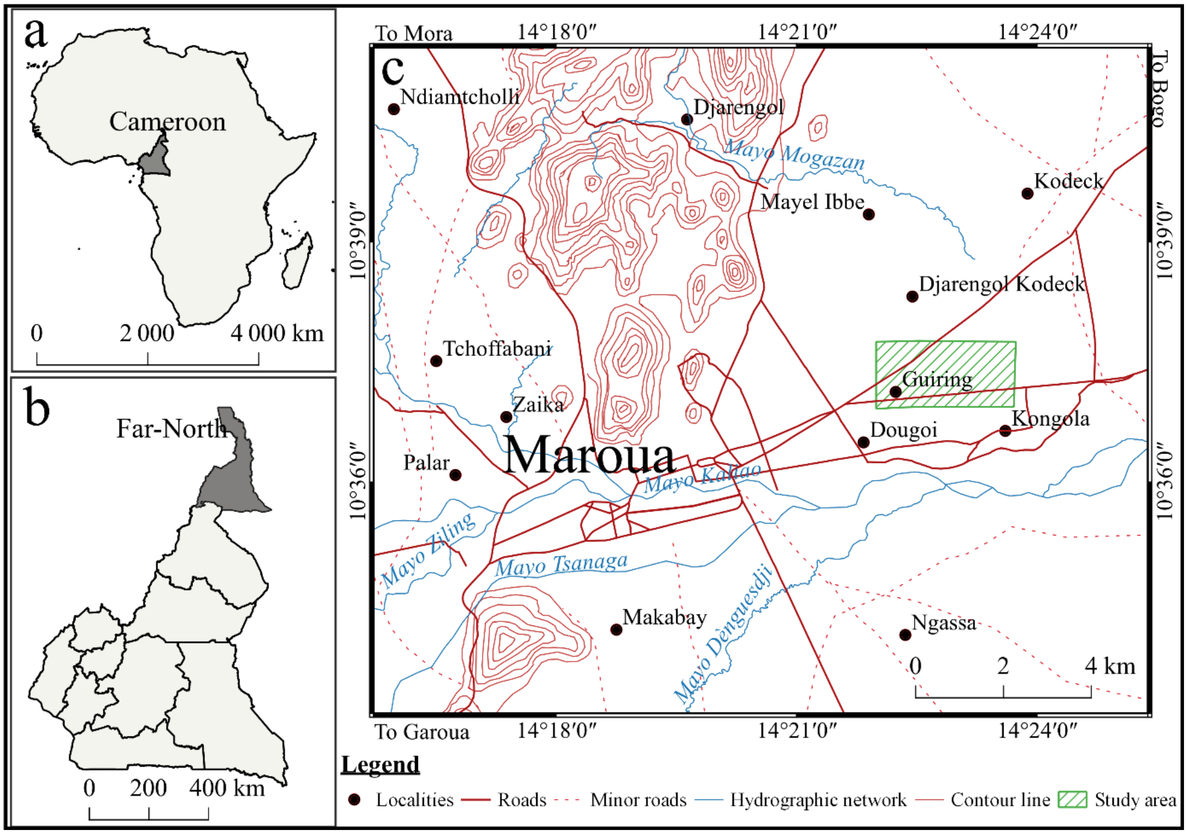

Fig. 1. (a) Location of Cameroon in Africa, **(b)** Location of Far-North region of Cameroon, **(c)** Location of the study area.

Table 1. *Monthly averages of precipitation, temperature, and relative humidity in Maroua-Salack from 1980 to 2020.*

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean	Total
Precipitation (mm)	0	0	0.87	32.10	60.54	105.77	192.77	232.41	118.20	48.79	0.49	0.31	/	792.25
Temperature (°C)	24.20	27.50	30.90	32.90	31.50	28.90	26.50	25.20	25.90	27.50	27.00	24.40	27.70	/
Relative humidity (%)	19	14	11	20	40	60	73	81	79	56	27	23	42	/
Aridity index	0.00	0.00	0.26	8.97	17.49	31.81	63.38	79.22	30.90	15.61	0.16	0.10	20,65	/

2.2 Experimental design, treatments, and plant material

The experimental design is a completely randomized block design with five (05) treatments (T_1, T_2, T_3, T_4, T_5) in addition to the control (T_0) as described in table 2 and three (03) replications, resulting in twenty four (24) experimental plots (Fig. 2.). It was conducted at the experimental site of IRAD in Guiring. Each experimental unit received one of the recommended treatments, T0, T1, T2, T3, T4, and T5 (Table 2). The maize density was 0.80 x 0.25 m, with 2 to 3 seeds needed per hole. Two weeks after sowing, thinning was performed to leave one plant per cluster. The plant material used is the CMS-9015 variety of maize, developed by IRAD. This variety is specifically adapted to the Sudanese-Sahelian zone of Cameroon. Under normal conditions, it produces grain yields ranging from 4 to 4.5 tons per hectare, with a vegetative cycle of 95 days.

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Table 2. *Summary and nature of the experimental treatments.*

Treatment designation	Description of the treatment
T_0	Control plot without fertilizing inputs
T_1	Treatment with trachyte powder (2000 kg ha^{-1}; 1.96 kg/9.6m^2)
T_2	Treatment with trachyte powder (2000 kg ha^{-1}; 1.96 kg/9.6m^2) + urea (104,17 kg ha^{-1}; 100 g/9.6m^2) at 06 weeks
T_3	Treatment with basalt powder (2000 kg ha^{-1}; 1.96 kg/9.6m^2)
T_4	Treatment with basalt powder (2000 kg ha^{-1}; 1.96 kg/9.6m^2) + urea (104,17 kg ha^{-1}; 100 g/9.6m^2) at 06 weeks
T_5	Treatment with NPK fertilizer (208,33 kg ha^{-1}; 200 g/9.6m^2) + urea (104,17 kg ha^{-1}; 100 g/9.6m^2) at 06 weeks

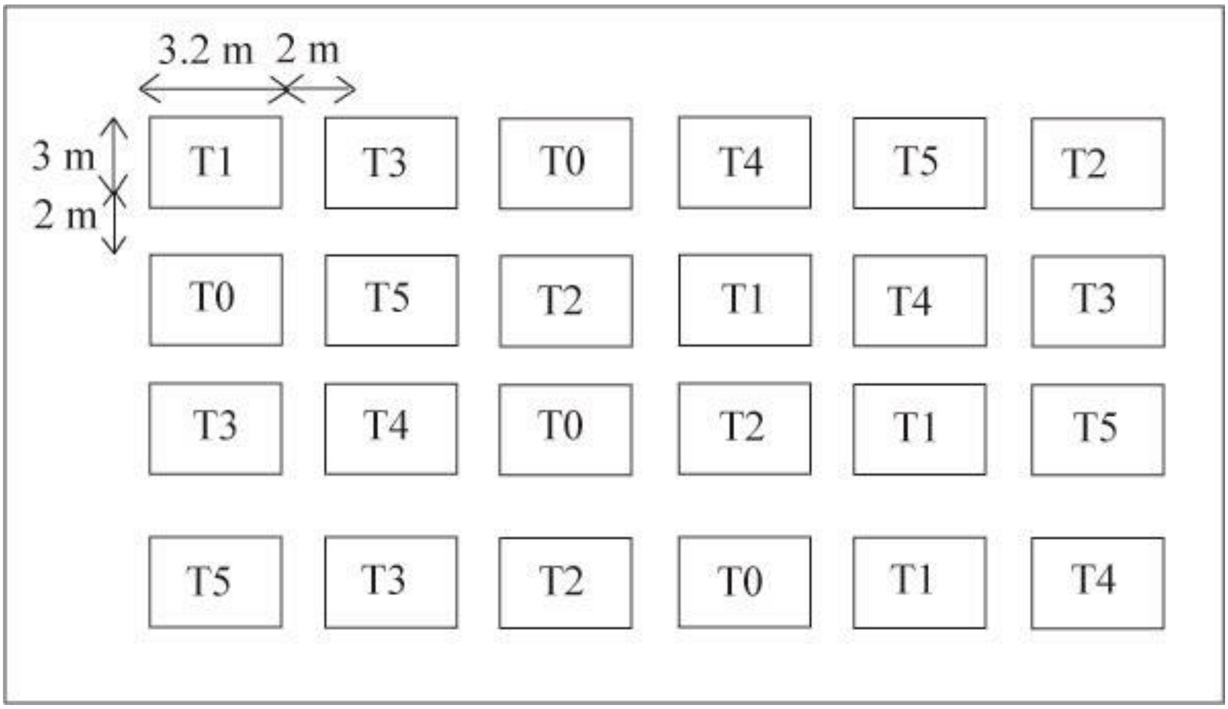

Fig. 2. Completely randomized block design with three replications.

2.3 Rock sampling and analysis

Samples of trachyte (Fig. 3 a) were collected from the localities of Zamai, and that of basalts (Fig. 3 b) from the locality of Gawar. Approximately 500 kg of each type of rock were sampled. These samples were then carefully transported for

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grinding, thin section preparation, petrographic analyses, and geochemical analyses. In total, 3 samples of trachyte and 3 samples of basalts were subjected to petrographic and geochemical analysis in the laboratory.

The rock powders were obtained from a commercial quarry located in the Meri municipality, Douvagar locality, in the Farth-Nord region of Cameroon. The rock was fragmented and passed through a ball mill, then sieved using a 2 mm mesh to obtain powder less than 2 mm (Figs. 3 c and d). In total, 100 kg of trachyte powder and 100 kg of basalt powder were obtained.

The petrographic analysis was carried out on thin sections prepared at the Tokyo Institute of Technology, Japan. The microscopic description was done in the geology laboratory at the University of Maroua using an optic microscope to examine the rock samples in detail. This phase allowed for the precise identification of the different minerals present in each sample, based on their optical and textural characteristics. The observations focused on mineralogical assemblages, grain shapes and the relationships between the various minerals.

For the measurements of trace and major elements, all samples were crushed into millimetre-sized fragments using a jaw crusher, and fragments with saw and hammer marks were carefully separated. After each sample, the jaw crusher was systematically cleaned with compressed air and deionized water. The major elements and some trace elements, including Sc, Co, V, Ni, and Cr, were analysed by X-ray fluorescence (XRF) using a Rigaku RIX2100 at Osaka City University, Graduate School of Science. The trace element concentrations in the samples were determined by ICP-MS at the Tokyo Institute of Technology, Japan, in accordance with the method described by Yokoyama et al. (1999). Approximately 50 mg of rock powder were digested with HNO_3, $HClO_4$, HCl, and HF. Before acid digestion, enriched spikes of 113In and 203Tl were added to the sample to serve as internal standards during measurement. The data reported by Makishima and Nakamura (2006) were used to calibrate the trace element concentrations against the basalt and rhyolite standards JB-3 and JR-1, respectively. The typical analytical reproducibility (2σ) was 4% for Nb and Pb, 5% for Y and Ta, and $<3\%$ for other trace elements.

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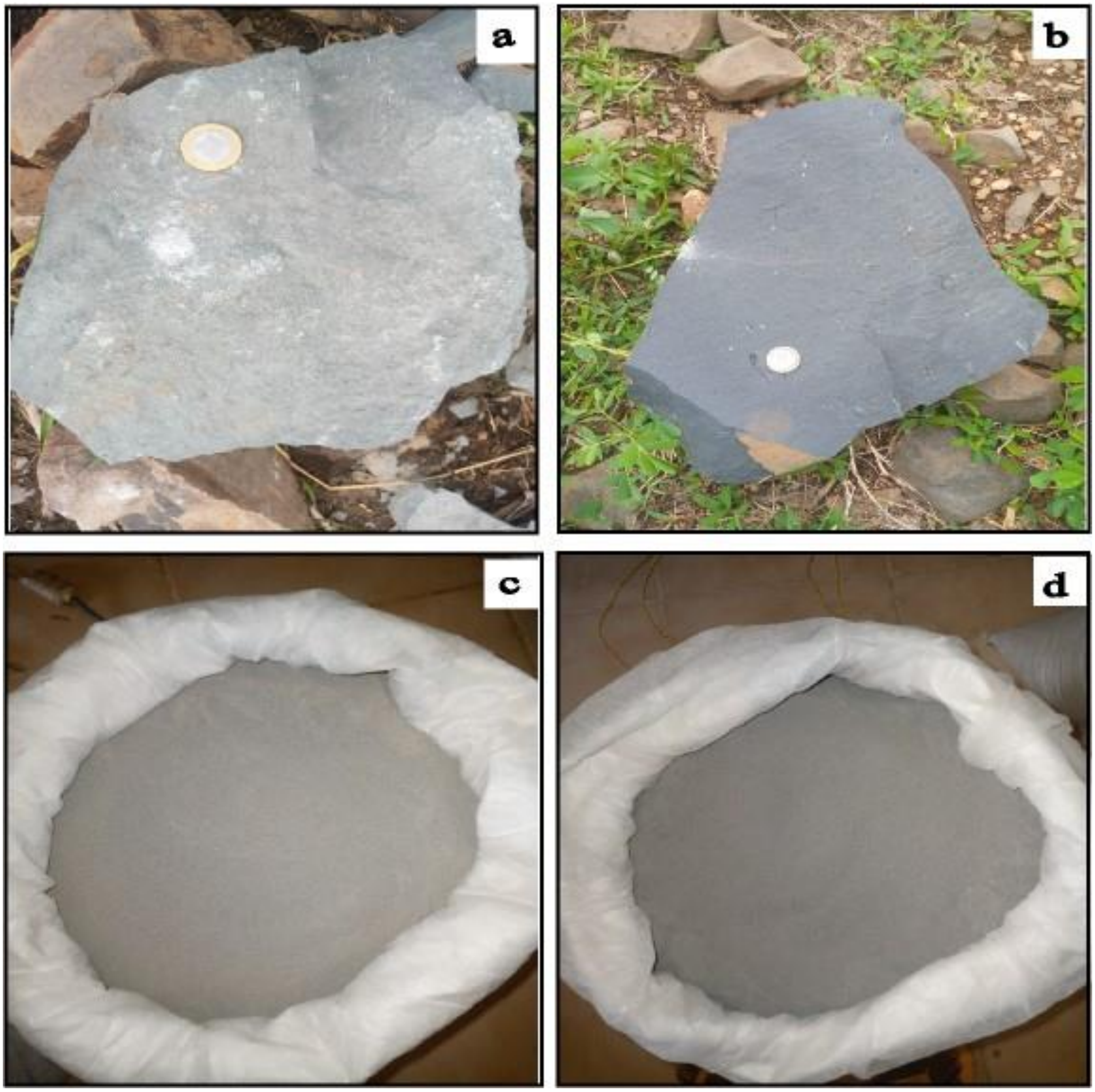

Fig. 3. **Samples and powders of trachyte and basalt: (a)** Trachyte sample from Zamai, **(b)** Basalt sample from Gawar**, (c)** Trachyte powder obtained after grinding, **(d)** Basalt powder obtained after grinding.

2.4 Soil sampling and laboratory analysis

The fieldwork was carried out in two phases. The first phase consisted of direct observation and a detailed description of the study site and its surroundings. In the second phase, a representative soil profile was excavated and described to facilitate soil classification. The soil description took into account several parameters: colour, porosity, texture, coarse elements,

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structure, biological activity, thickness, and the boundaries between horizons. The colour was determined in its dry state using the Munsell Soil Colour Charts (2009). A total of six (06) samples, each weighing approximately 0.5 kg, were collected from the different horizons of the profile. The collected samples were placed in polyethylene bags, carefully labelled, and prepared for laboratory analysis.

In the laboratory, the main analyses focused on mineralogical and physicochemical analyses. Particles size distribution was performed using the Robinson pipette method on air-dried, ground, and 2 mm-sieved samples. The pH was measured in a soil-water suspension, then in a normal potassium chloride solution at 1:2.5 ratio using a glass electrode pH meter. Exchangeable bases (Ca^{2+}, Mg^{2+}, K^+, and Na^+) were extracted from the soil using a pH 7 ammonium acetate solution and measured by atomic absorption spectrophotometry. The sum of exchangeable bases (SBE) was determined by adding the concentrations of Ca^{2+}, Mg^{2+}, K^+, and Na^+. Cation exchange capacity (CEC) was measured using an ammonium acetate solution at pH 7, following a three-step process: washing the soil with alcohol to remove the ammonium solution saturating the pores, determining NH_4^+ by Kjeldahl distillation after quantitative desorption with KCl. The CEC of the clay fraction was calculated from the CEC at pH 7, organic carbon content, and clay percentage. Base saturation (V) was calculated using the formula (SBE/CEC) × 100. Total nitrogen (N) was determined by the Kjeldahl method. Organic carbon (OC) was measured by wet oxidation according to Walkley and Black (1934) using a sodium dichromate and concentrated H_2SO_4 mixture. Organic matter (OM) content was calculated by multiplying the OC by 1.724, and the C/N ratio was determined. Available phosphorus was measured using the Bray no. 2 method (Bray and Kurtz, 1945).

Mineralogical analysis was carried out using infrared (IR) spectroscopy, a non-destructive analytical method widely used to identify and characterize the functional groups present in samples. This technique provides detailed information about the chemical bonds and molecular structures of minerals. Diffuse reflectance IR spectra were recorded in the range of 4000 to 400 cm^{-1} using a Perkin Elmer 2000 FTIR spectrometer (Perkin Elmer, Waltham, MA, USA), equipped with a DTGS (deuterated triglycine sulphate) detector, optimized for high sensitivity and precise resolution. To avoid contamination from atmospheric moisture and ensure the reliability of the results, measurements were carried out under strictly controlled environmental conditions. This method not only allows for the identification of minerals present in the soil but also helps describe their local chemical environments, providing a deeper understanding of the composition and properties of soils.

2.5 Pedoclimatic Assessment

The climatic and pedological assessment of the study area was based on climatic data (precipitation, temperature, relative humidity, and insolation) collected at the Maroua-Salak station between 1980 and 2020, in accordance with the climatic requirements of crops (Sys, 1985; Sys et al., 1993; Issiné et al 2022). A climatic index (CI) was calculated using the parametric formula:

$$I_C = R\text{min} \times \sqrt{\frac{A}{100} \times \frac{B}{100} \times \ldots},$$

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where Rmin is the smallest value, A, B, … are the other parametric values. Adjustments are made if the CI falls between 25 and 92.5.

The pedological assessment used a table of soil characteristics to determine a land quality index (LI), based on similar parametric values using the formula:

$$I_T = R\text{min} \times \sqrt{\frac{A}{100} \times \frac{B}{100} \times \dots},$$

The calculation of the CI and LI allows for an integrated assessment of agroclimatic and soil quality for agricultural production.

2.6 Collection of maize parameters

The growth and yield parameters of maize, including germination rate, plant height, number of leaves per plant, stem diameter, ear length, ear diameter, ear weight, 100-grain weight, and grain yield (kg ha^{-1}), were measured.

The germination rate (GR), assessed 10 days after sowing, is determined using the formula GR = number of germinated seeds × 100 / total number of seeds sown, then multiplying the result by 100 to obtain the germination percentage (Ellis et al., 1986). Plant height was measured using a tape measure, recording the distance from the soil to the top of the stem, with measurements taken every 21 days. These measurements were performed on a representative sample from each plot an average value was considered (Cox and Andrade, 1988). The number of leaves was counted by tallying the leaves deployed on the main stem, with an average estimation made every 3 weeks (Cox and Andrade, 1988). The stem and ear diameter were measured using a calliper respectively before and after harvest (Ngoune Tandzi et al., 2019). The ear length, measured from base to tip, was recorded with a tape measure when the ears were mature. The weight of the ears was obtained by weighing them with a high-precision electronic scale after harvest (Muthaura et al., 2017). The weight of 100 randomly selected dried maize grains was also measured using a precision electronic scale (Soleymani, 2018). The yield per hectare was estimated by harvesting a representative portion of each plot, weighing the harvest, and then extrapolating the results to the hectare scale using a conversion factor (Soleymani, 2018).

2.7 Data Analysis

Statistical analyses focused on the physicochemical properties of soils as well as the growth and yield parameters of maize. The physicochemical properties of soils were subjected to standard statistical analyses, including mean, maximum-minimum values, standard deviation, and coefficient of variation. The Anderson-Darling normality test was used to assess the normality of the distribution. Correlation analysis to evaluate relationships between soil parameters was conducted using Spearman's correlation test. A descriptive analysis of growth and yield parameters of maize was performed to summarize and describe the collected agricultural data using measures of central tendency (mean, median) and dispersion (standard deviation). These analyses were conducted using XLSTAT 2023 version 25.1.141.

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3 Results

3.1 Petrographic and geochemical characteristics of rocks

Petrographically, trachyte outcrop in the form of slabs in the Zamai locality and exhibit an aphyric texture, with rare phenocrysts (≤5%). These scarce phenocrysts are mainly composed of sanidine, sometimes associated with clinopyroxene. Sanidine, characterized by elongated, euhedral prisms reaching up to 0.6 × 1.8 mm, displays simple Carlsbad twins. The trachytes are composed of feldspar microliths, accompanied by a low proportion of clinopyroxene and oxides (Figs. 4 a and b). Basalts outcrop as lava flows, exhibiting well-defined columnar joints and a porphyritic texture. Plagioclase, olivine, and clinopyroxene constitute the phenocrysts (Figs. 4 c and d). Olivine, present in some samples, is often altered to iddingsite. Peridotite xenoliths are also observed in some samples, containing approximately 65% olivine and 35% pyroxene. Plagioclase microliths, associated with clinopyroxene, olivine, and oxides, are the main components of the basalt matrix.

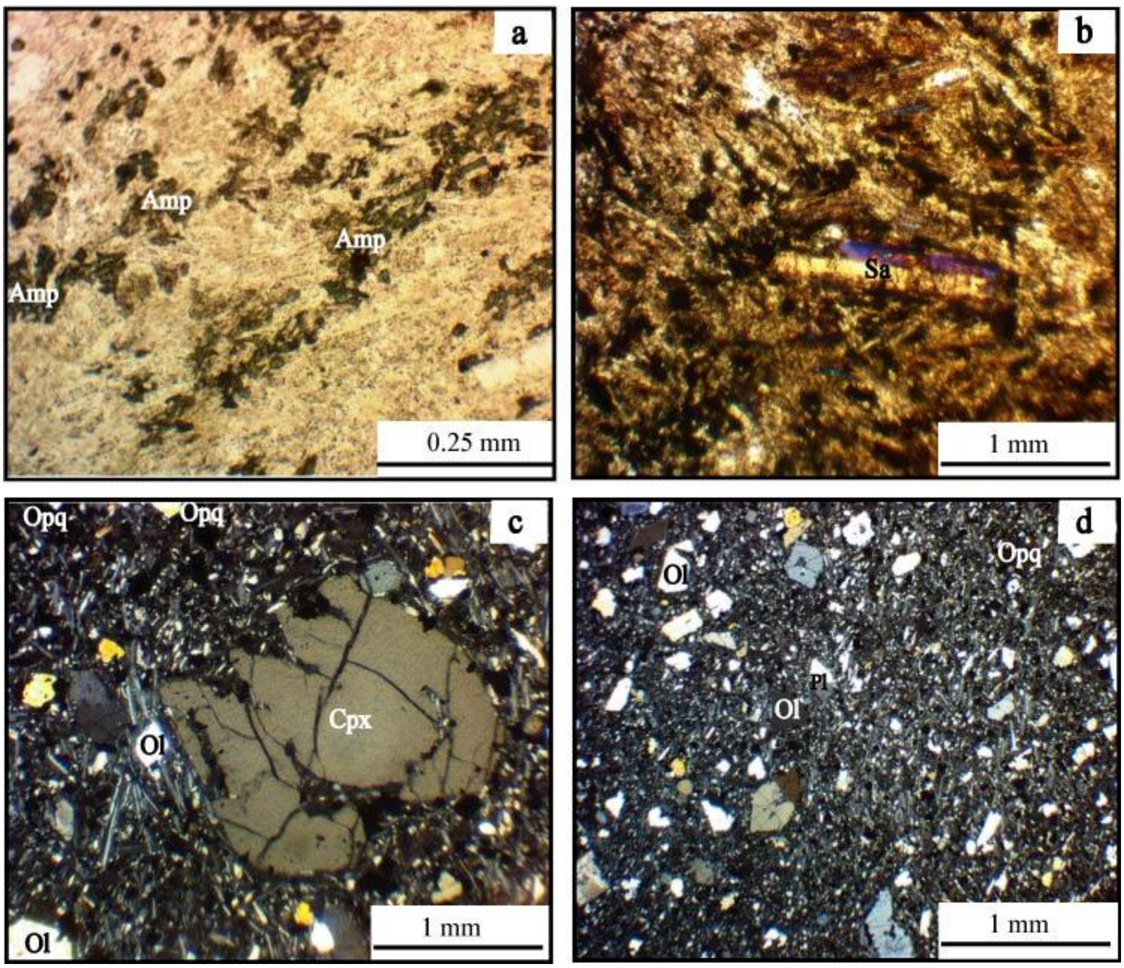

Fig. 4. Photomicrographs of thin sections of representative samples from the study area. **(a)** and **(b)** Aphyric texture of Minawao trachyte showing mineral assemblages. **(c)** and **(d)** Porphyritic texture of Gawar basalt showing mineral assemblages. Ol: olivine. CPx: clinopyroxene. Pl: plagioclase. Opq: opaque minerals. Sa: sanidine. Amp: amphibole. Mineral abbreviations from Whitney and Evans (2010).

From a geochemical perspective, the concentration of major and trace elements in the studied rocks are summarized in Table 3. Trachyte exhibit variations in major element contents across samples. The SiO_2 content ranges between 65.31% and 66.5%. Meanwhile, the TiO_2 content varies from 0.16% to 0.25%. The Al_2O_3 content remains constant at 16.3%, whereas Fe_2O_3 concentrations fluctuate between 4.432 and 5.6%. The contents of CaO and K_2O show variations ranging from 0.63 to 1.12% and 4.66 to 4.82%, respectively. Regarding basalts, notable variations are also observed in the proportions of major elements. The SiO_2 content ranges from 40.86% to 41.34%, while TiO_2 content is between 4.22% and 4.26%. Similarly, the percentage of Al_2O_3 fluctuates between 13.17% and 13.43%. Fe_2O_3 concentrations vary slightly, ranging from 15.33% to 15.44%, while CaO content is between 10.14% and 10.42%, and K_2O ranges from 1.39% to 1.69%. These subtle yet significant differences highlight the important geochemical variations between trachyte and basalt samples, underscoring the diversity of their mineralogical composition.

Trace element concentrations in the trachyte show significant fluctuation. The chromium (Cr) content remains relatively constant at 2 ppm, while other elements such as nickel (Ni), strontium (Sr), rubidium (Rb), yttrium (Y), barium (Ba), and niobium (Nb) exhibit more pronounced variations, ranging from 7.2 to 9.1 ppm, 7.3 to 20.91 ppm, 136.19 to 148.82 ppm, 60.37 to 97.05 ppm, 16.2 to 48.93 ppm, and 194.15 to 197.25 ppm, respectively. In contrast, basalts show much higher concentrations of Cr (176.1 to 183 ppm), Ni (269.6 to 277.7 ppm), Sr (1648.5 to 1685.5 ppm), and Ba (561.1 to 572.7 ppm). However, the basalts have relatively low levels of Rb (18.9 to 23.5 ppm) and Y (22.9 to 23.2 ppm) compared to the trachyte (Table 3). These variations indicate substantial differences in trace elements between trachytes and basalts, reflecting distinct geochemical signatures.

Table 3. *Major (wt.%) and trace (mg kg^{-1}) elements data for the Gawar-Zamay lavas.*

2022		Basalte			Trachyte	
	Gaw1	Gaw2	Gaw3	Zam1	Zam2	Zam3
Longitude	13°49'57.4"E	13°49'55.8"E	13°49'58.2"E	13°53'15.9"E	13°53'17.2"E	13°53'15,7"E
Latitude	10°30'39.1"N	10°30'37.3"N	10°30'38.6"N	10°36'25.5"N	10°36'26.8"N	10°36'26,0"N
Altitude (m.a.s.l)	754	751	753	602	604	605
(wt%)						
SiO2	41.34	41.28	40.86	66.5	66.5	65.31
TiO2	4.26	4.25	4.22	0.16	0.16	0.25
Al2O3	13.43	13.39	13.17	16.3	16.3	16.3
Fe2O3	15.33	15.34	15.44	4.43	4.43	5,6
MnO	0.18	0.18	0.18	0.13	0.14	0.17
MgO	8.5	8.53	8.66	0.04	0.02	0.04
CaO	10.42	10.5	10.14	0.68	0.68	1.12
Na2O	3.46	3.21	3.42	7.07	7.09	6.1
K2O	1.39	1.69	1.67	4.66	4.82	4.82

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P2O5	1.13	1.12	1.12	0.01	0.02	0.02
Total	99.41	99.48	98.87	99.93	99	99
Mg	5.5	55.6	5,8			
(mg kg^{-1})						
Sc	24	21.6	23.5	3	b.d.l.	0.9
V	224.1	222.1	223	b.d.l.	b.d.l.	b.d.l
Cr	178	176.1	183	2	2	2
Co	60.3	59.8	62.1	7.9	7.2	9.1
Ni	271	269.6	271.7	2.4	2.6	1.4
Ga	17	18.1	17.8	39.9	41.7	36.5
Zn	107.7	107.8	104.1	247.6	250.5	208.5
Sr	1668.6	1685.5	1648.5	10.8	7.13	20.91
Rb	18.9	23.5	22.2	148.33	148.82	136.19
Y	23.2	23	22.9	97.05	91.17	60.37
Cs	0.2	0.2	0.2	0.8	0.79	0.3
Ba	572.7	561.1	562.5	48.34	28.93	16.12
La	49.2	48.3	48.1	168.45	160.65	184.76
Ce	106.7	104.9	104.7	420.27	413.43	477.2
Pr	13	12.9	12.8	34.65	33.4	38.1
Nd	56.9	55.9	55.8	125.43	120.77	141.43
Sm	11	10.8	10.8	21.74	21.15	22.02
Eu	3.8	3.7	3.7	1.91	1.84	1.87
Gd	10.7	10.5	10.4	22.93	22.11	22.56
Tb	1.3	1.3	1.3	3	2.89	2.56
Dy	6.4	6.3	6.3	16.48	15.78	12.63
Ho	1.1	1.1	1.1	3.12	2.98	2.28
Er	2.7	2.6	2.6	8.4	8.06	5.98
Tm	0.3	0.3	0.3	1.12	1.08	0.76
Yb	1.9	1.8	1.8	709	6.88	4.95
Lu	0.3	0.3	0.3	1	0.97	0.74
Hf	3.33	3.57	2.94	5.39	33.46	33.35
Ta	3.45	3.48	3.42	1.85	10.75	10.56
Pb	1.8	1.7	1.7	10.51	10.42	7.78
Th	3.8	3.7	3.7	18.61	18.32	12.11
U	1.1	1.1	1.1	4.96	4.91	1.55
Zr	143.8	147.73	125.7	216	1333.53	1314.17
Nb	67.09	67.67	67.24	33.57	197.25	194.15

3.2 Morphological and mineralogical characteristics of the soil

The studied soil, located at latitude 10°33'17" North and longitude 14°22'16" East, and at of 386 m, has a thickness of 270 cm. The relief is flat and the vegetation highly anthropogenized.

The studied soil profile consists of six horizons (Fig. 5.) divided into four distinct textural groups: sandy loam, loamy sand, loamy clayey sand, clayey sand and sandy. The colours range from light yellow-brown (10YR 5/4) to dark brown (7.5YR 3/2), passing through light yellow (10YR 5/4) and up to pale yellow (2.5Y 7/4). Each horizon has a fine, granular structure

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with significant biological and matrix porosity, promoting good permeability and optimal friability. The transitions between horizons are progressive and regular (Table 4).

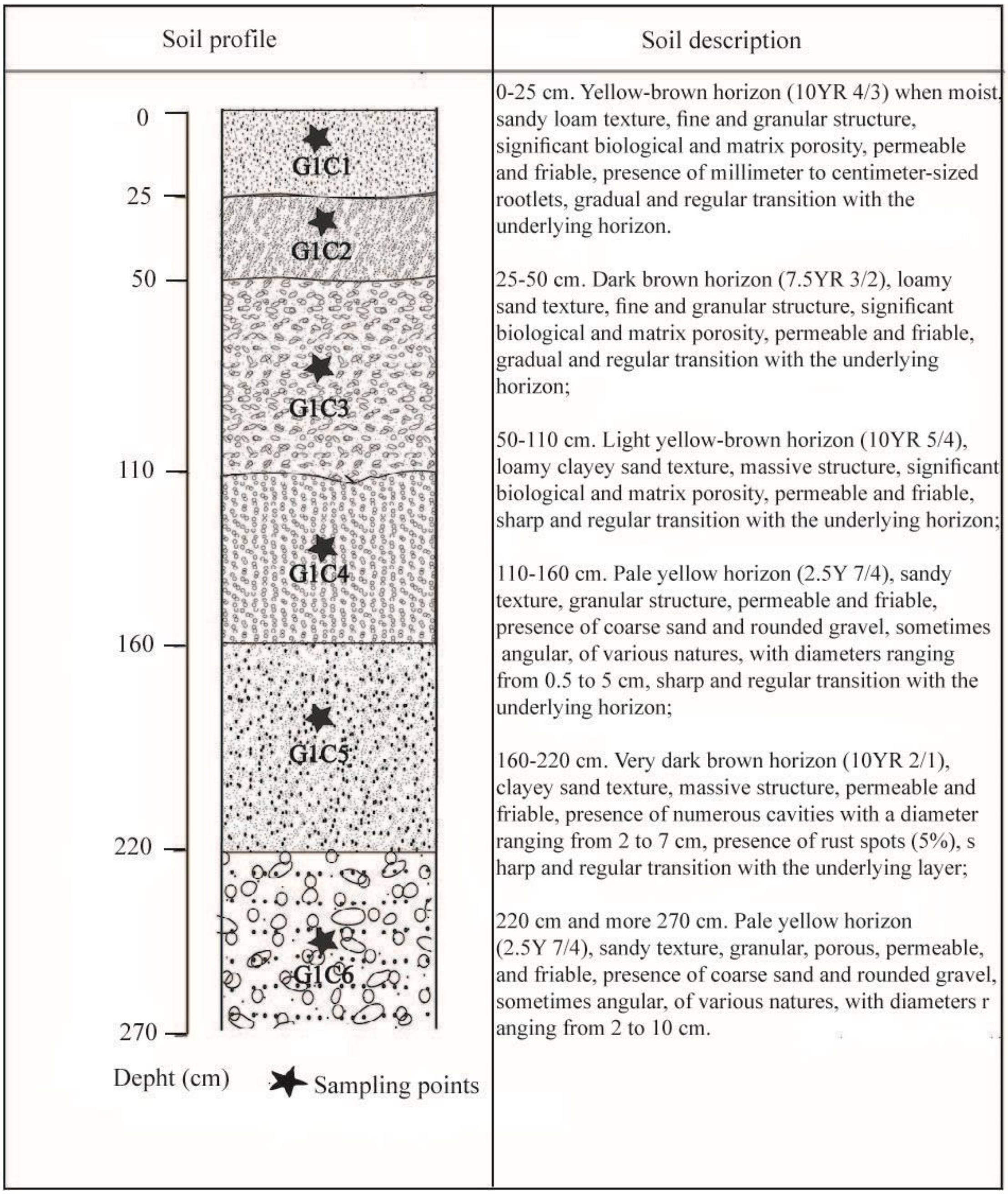

Fig. 5. Macroscopic organization of the soil in the study area.

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***Table 4**. Morphological and physical characteristics of the soil profile.*

Site	Depth(cm)	Colour (Moist)	Structure	Consistency		Rock fragments	Boundary	Textural class
				Dry	Wet			
Guiring	0-25	10YR 4/3	f&wg	s	s & p	n	g	sandy loam
	25-50	7.5YR 3/2	f&wm	s	s & p	c	g	loamy sand
	50-110	10YR 5/4	m&mma	h	s & p	m	g	loamy clayey sand
	110-160	2.5Y 7/4	c&sabk	l	s & p	d	c	sandy
	160-220	10YR 2/1	m&sma	h	s & p	m	c	loamy clayey sand
	220-270	2.5Y 7/4	c&sabk	l	s & p	d	g	sandy

Soil characteristics

Structure			Consistency		Rock fragments	Boundary
Size	Type	Grade	Dry	Wet		
vf = very fine (G5 mm) f = fine (5–10 mm) m = medium (10–20 mm) c = coarse (20–50 mm) vc = very coarse (>50 mm)	g = granular abk = angular blocky sbk = subangular blocky l=lumpy ma=massive	w = weak (peds barely observable) m = moderate (peds observable) s = strong (peds clearly observable)	l = loose s = soft h = hard	s = sticky p = plastic	n = none (0%) m = many (15%–40%) v = very few (0%–2%) a = abundant (40%–80%) c = common (5%–15%) d = dominant (>80%)	g = gradual c = clear

Mineralogically, the infrared spectra of the soil, illustrated in Fig. 6, reveal the presence of kaolinite, smectites, sepiolite, and quartz. In the high-frequency region, the hydroxyl groups display two bands at 3774 – 3622 cm^{-1}, corresponding to the stretching vibrations of the OH^- groups characteristic of kaolinite according to Famer (1964) and Frost et al. (1998). The low intensity absorption band located at 1621 cm^{-1} is attributed to water molecules, possibly associated with smectites. Sepiolite is primarily distinguished by the band at 531 cm^{-1}. The presence of quartz is manifested by the peaks at 1003, 774, 693, 531, and 459 cm^{-1}, which correspond to Si-O vibrations.

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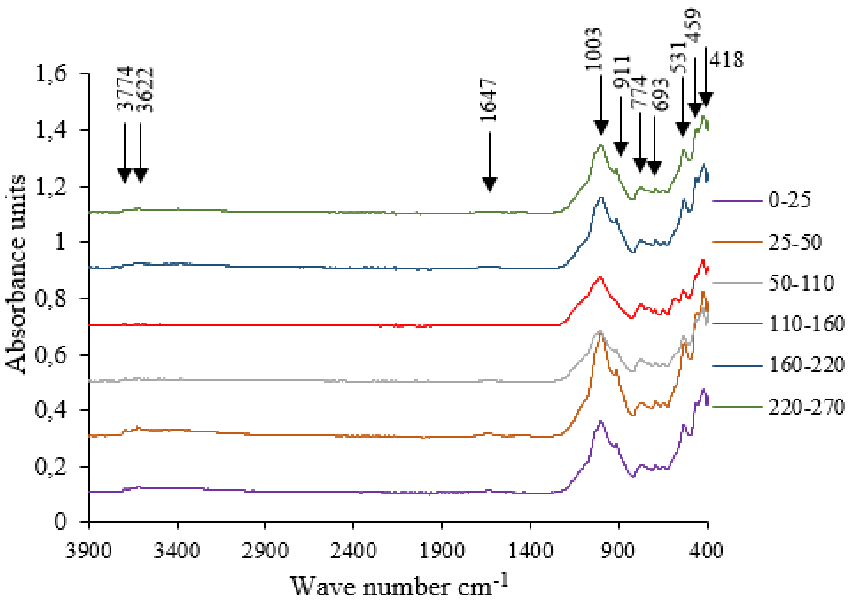

Fig. 6. Infrared spectra of the studied soil.

3.3 Physicochemical characteristics of the soils

The particle size distribution is dominated by sand fraction with proportions varying from 62% to 82%, corresponding to a mean value of 76.17 ± 9.17% (Table 5). Clay constitutes the second important particle size fraction, with proportions ranging from 13% to 23%, with a mean value of 16.33 ± 5.16 %. Silt fraction appears to be the least abundant, with proportions varying from 5% to 15%, with an average of 9.17 ± 4.92%. Sand is strongly negatively correlated with clay ($r = -0.99$, $p < 0.05$). Silt has a moderate positive correlation with clay ($r = 0.53$, $p < 0.05$) and a negative correlation with sand ($r = -0.57$, $p < 0.05$) (Table 6).

The analysed soils exhibit a pH ranging from acidic to slightly basic (6.80 to 7.20), with an average of 6.98. No correlation was observed between pH and other elements, except for clay ($r = 0.91$, $p < 0.05$). The organic matter (OM) and total nitrogen (N) contents are relatively low, with values ranging from 1.30% to 3.17%, and 0.11% to 0.13%, with averages of 2.57 ± 0.67%, and 1.12 ± 0.01% (Table 5). The C/N ratio, relatively low, varies from 6 to 16, with an average of 12.33 ± 3.61. Base saturation (V) varies between 23.60% and 42.41%, with an average value of 34.28% (Table 5).

The exchangeable bases (Ca^{2+}, Mg^{2+}, K^+, and Na^+) exhibit notable variation across the soil profile. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations are low to moderate, with values ranging from 2.64 to 6.00 $cmol_c\ kg^{-1}$ in the case of Ca^{2+} and 0.72 to 5.44 $cmol_c\ kg^{-1}$ for Mg^{2+}, with respective averages of 3.88 ± 1.49 and 2.45 ± 1.58 $cmol_c\ kg^{-1}$ (Table 5). Regarding potassium (K^+) and sodium (Na^+), their contents are very low to low, oscillating between 0.10 and 0.40 $cmol_c\ kg^{-1}$ for K^+ and between 0.10 and 0.60 $cmol_c\ kg^{-1}$ for Na^+, with respective averages of 0.18 ± 0.12 and 0.28 ± 0.17 $cmol_c\ kg^{-1}$ (Table 5). Mg^{2+} shows a positive correlation with clay ($r = 0.62$, $p < 0.05$) and pH H_2O ($r = 0.66$, $p < 0.05$). K^+ is strongly correlated with clay ($r = 0.76$, $p < 0.05$) and moderately with pH H_2O ($r = 0.65$, $p < 0.05$). The sum of exchangeable bases (SEB) ranges from 5.10 to 8.90 cmol·kg^{-1}, with an average value of 6.88 ± 1.66 cmol$_c$ kg^{-1} (Table 5). This SEB shows a moderately positive correlation with clay content ($r = 0.79$, $p < 0.05$). The cation exchange capacity (CEC) displays relatively high values, ranging from 18.70 to 25.00 cmol$_c$ kg^{-1}, with an average of 22.05 ± 2.52 cmol$_c$ kg^{-1} (Table 5). It shows a strong correlation with the clay fraction ($r = 0.82$, $p < 0.05$), as well as with pH H_2O ($r = 0.84$, $p < 0.05$). It is also moderately correlated with potassium (K^+) ($r = 0.75$, $p < 0.05$) (Table 6). Phosphorus (P) shows concentrations ranging from low to medium, with values between 12.60 and 30.30 mg kg^{-1}, and an average of 19.00 ± 6.95 mg kg^{-1} (Table 5). Phosphorus shows a strong correlation with clay content ($r = 0.92$, $p < 0.05$) and with CEC ($r = 0.81$, $p < 0.05$) (Table 6). Base saturation (V) presents values ranging from 23.60% to 42.41%, with an average of 31.11 ± 7.42%. Electrical conductivity varies from 0.02 to 1.20 dS/m, with an average of 0.27 ± 0.46 dS/m (Table 5). The latter is strongly correlated with Na, with a coefficient of $r = 0.92$ ($p < 0.05$).

Morphologically, the study soil profile is characterized by an alternation of different soil texture which are sandy loam, loamy sand, loamy clayey sand, clayey sand and sandy, in line with the alluvial nature of the parent rock. This alternation of soil texture is confirmed by the zigzag evolution of the percentage of different particle size distribution fraction noted in table 5. These characteristics correspond to those of Fluvisols. Base saturation ratio in all soil horizons is below 50%, leading to the choice of Dystric as principal qualifier. The light colour of soil and the organic matter content (<3%) lead to classify the studied soils as Ochric Dystric Fluvisols according to the IUSS Working Group WRB (2022).

Table 5. *Physicochemical characteristics and summary statistics of the soil profile.*

Depth cm / statistics	0-25	25-50	50-110	110-160	160-220	220-270	Min	Max	Mean	SD	CV
Sand (%)	82.00	82.00	67.00	88.00	62.00	88.00	62.00	82.00	76.17	9.17	0.12
Silt (%)	15.00	5.00	10.00	8.00	15.00	8.00	5.00	15.00	9.17	4.92	0.54
Clay (%)	13.00	13.00	23.00	5.00	23.00	5.00	5.00	23.00	16.33	5.16	0.32
pH_{H2O}	6.80	7.00	7.20	6.80	7.20	6.90	6.80	7.20	6.98	0.18	0.03
pH_{KCl}	4.40	4.20	6.30	6.60	4.60	5.50	4.20	6.60	5.27	1.02	0.19
OC (%)	0.75	1.84	1.66	1.66	1.36	1.66	0.75	1.84	1.49	0.39	0.26
OM (%)	1.30	3.17	2.86	2.86	2.34	2.86	1.30	3.17	2.57	0.67	0.26
N (%)	0.13	0.13	0.11	0.13	0.12	0.11	0.11	0.13	0.12	0.01	0.09
C/N	6.00	14.00	16.00	12.00	11.00	15.00	6.00	16.00	12.33	3.61	0.29
Ca (cmol$_c$ kg^{-1})	2.96	2.64	2.72	5.52	6.00	3.44	2.64	6.00	3.88	1.49	0.38
Mg (cmol$_c$ kg^{-1})	2.24	2.48	5.44	0.72	2.00	1.84	0.72	5.44	2.45	1.58	0.65
K (cmol$_c$ kg^{-1})	0.15	0.11	0.42	0.13	0.18	0.11	0.10	0.40	0.18	0.12	0.64
Na (cmol$_c$ kg^{-1})	0.22	0.22	0.31	0.56	0.13	0.31	0.13	0.56	0.29	0.17	0.61
SBE (cmol$_c$ kg^{-1})	5.57	5.45	8.88	7.94	8.32	5.10	5.10	8.90	6.88	1.66	0.24
CEC (cmol$_c$ kg^{-1})	20.80	23.17	25.00	18.72	24.38	20.19	18.70	25.00	22.05	2.52	0.11
P (mg kg^{-1})	13.10	12.58	24.29	17.52	30.28	16.22	12.60	30.30	19.00	6.95	0.37
V(%)	26.77	23.60	34.52	42.41	34.12	25.26	23.60	42.41	31.11	7.42	23.53

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CE (mS cm^{-1})	0.07	0.02	0.18	1.18	0.04	0.08	0.02	1.20	0.27	0.46	1.73

Table 6. *Spearman correlation matrix for linear relationships between soil profile properties.*

	Sand	Silt	Clay	pH$_{H2O}$	pH$_{KCl}$	OC	OM	N	C/N	Ca	Mg)	K	Na	SBE	CEC	P	V	CE
Sand	1																	
Silt	-0.57	1																
Clay	-0.99*	0.53	1															
pH$_{H2O}$	-0.90*	0.31	0.91	1														
pH$_{KCl}$	-0.05	-0.40	0.14	-0.05	1													
OC	0.00	-0.81*	0.04	0.29	0.40	1												
OM	0.00	-0.81*	0.04	0.29	0.40	0.99*	1											
N	0.56	-0.21	-0.63	-0.58	-0.32	-0.06	-0.06	1										
C/N	-0.17	-0.66	0.25	0.46	0.46	0.91*	0.91*	-0.46	1									
Ca	-0.37	0.17	0.25	0.07	0.21	-0.01	-0.01	0.22	-0.19	1								
Mg	-0.49	0.21	0.62	0.66	0.13	0.11	0.11	-0.69	0.42	-0.58	1							
K	-0.64	0.28	0.76	0.65	0.44	0.08	0.08	-0.71	0.36	-0.24	0.90*	1						
Na	0.44	-0.62	-0.38	-0.52	0.83	0.35	0.35	0.22	0.22	0.20	-0.29	-0.04	1					
SBE	-0.76	0.28	0.79	0.59	0.55	0.15	0.15	-0.31	0.20	0.50	0.36	0.69	0.20	1				
CEC	-0.79	0.42	0.82*	0.94*	-0.27	0.13	0.13	-0.47	0.30	-0.18	0.75	0.65	-0.67	0.43	1			
P	-0.96*	0.47	0.92*	0.80*	0.21	0.06	0.06	-0.52	0.19	0.58	0.29	0.52	-0.25	0.81*	0.60	1		
V	-0.34	0.02	0.35	0.07	0.73	0.12	0.12	0.04	0.03	0.69	-0.11	0.31	0.63	0.83*	-0.14	0.50	1	
CE	0.27	-0.41	-0.26	-0.45	0.72	0.22	0.22	0.41	0.00	0.50	-0.44	-0.11	0.92	0.37	-0.62	-0.07	0.81*	1

*****Significant at $p < 0.05$.

3.4 Suitability of the studied soil for maize cultivation

The study area presents very favourable climatic conditions for the growth and yield of maize. The average temperature of 26.6 °C during the growing cycle presents a slight limitation for the production of maize (S1-1) (Table 7). The precipitation during the growing cycle, approximately 649 mm, has no limitation for the cultivation of maize. The climatic index of 91.41 (S1-0) indicates that there are no major limitations for maize cultivation in this area. This means that climatic conditions are favourable, suggesting the possibility of achieving optimal yields. The low slope (1%), presents a slight limitation (S1-1). The risk of flooding is non-existent (FO), and drainage is of good quality, indicating that there are no constraints related to soil moisture (S1-0) (Table 8). The soil texture, of the sandy-loamy type (SL), classified as S2, has proven to be a moderate limitation with a parametric value of 67.4. The soil depth, greater than 100 cm, is very suitable (S1-0), which is optimal for root development. Presence of coarse fragments displays a slight limitation (S1.1), with a parametric value of 96.3 for maize production (Table 8). The apparent cation exchange capacity (CEC) of the soil, classified as S1-1, indicates a slight limitation, with a parametric value of 90. Base saturation and organic carbon content, both classified as S2, reveal moderate limitations, with respective parametric values of 75.2 and 72.8. The soil pH (S1-1) and the electrical conductivity is suitable (S1-0) for the production of maize although there is a slight limitation related to pH (Table 8). The overall land suitability index is 62.37, which classifies it as S2sf, indicating moderate suitability for cultivation, primarily due to constraints related to the soil's physical properties and fertility.

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Table 7. *Climatic suitability evaluation for the production of Maize using simple limitation and parametric methods.*

Characteristics	Values	Classes	Limitations	Parametric values
Precipitation				
Precipitation during crop cycle (mm)	649.18	S1-0	0	100
Precipitation during 3rd cycle (mm)	232.41	S1-0	0	100
Temperature				
Mean temperature during crop cycle (°C)	26.6	S1-1	1	95
Mean maximum temperature during crop cycle (°C)	31.8	S1-1	1	86.9
Mean minimum temperature during crop cycle (°C)	23	S1-1	1	93
Relative humidity during crop cycle (%)	73.25	S1-0	0	100
n/N during crop cycle	62.6	S1-1	0	100
Calculated climatic index (CR)		S1-1		91.41

Table 8. *Land suitability evaluation for the maize production using simple limitation and parametric methods.*

Characteristics	Values	Classes	Limitations	Parametric values
Topography (t)				
Slope (%)	1	S1-1	1	93.2
Wetness (w)				
Flooding	FO	S1-0	0	100
Drainage	Good	S1-0	0	100
Physical soil characteristics (s)				
Texture/structure	SL	S2	2	67.4
Soil depth (cm)	> 100	S1-0	0	100
Coarse fragments (%)		S1-1	1	96.3
Soil fertility characteristics (f)				
Apparent CEC ($cmol_c$ kg^{-1} clay)	22.05	S1-1	1	90
Base saturation (%)	31.3	S2	2	75.2
Organic carbon (%)	0.75	S2	2	72.8
pH-H_2O	6.98	S1-1	1	94
CE	0.27	S1-0	0	100
Suitability and calculated land index (Is)		S2sf		62.37

3.4 Evaluation of the effect of trachyte and basalt powder on the growth and yield of maize

3.4.1 Effect of trachyte and basalt powder on maize growth parameters

The maize growth parameters include the germination rate, plant height, number of leaves, stem diameter, as well as ear length and ear diameter.

Germination was observed in all plots starting from the 5th day after sowing. After 10 days, the recorded germination rate reached 92.18%, indicating good uniformity and a of plant growth across all experimental plots.

The plant height ranges from 147.32±2.09 cm for treatment T0 to 215.12±2.09 cm for treatment T5, with the latter showing the tallest plants, while T0 (control) shows the shortest height. Treatments T1 (175.15±2.09 cm), T2 (181.47±2.09 cm), T3 (179.57±2.09 cm), and T4 (194.85±2.09 cm) show no significant differences among them, although all are higher than T0. However, treatment T5 (215.12 cm) is significantly taller than all other treatments. A progressive increase in plant height is observed with inputs of trachyte and basalt powders (Table 9).

The evolution of the number of leaves based on treatments shows that treatment T5, with an average of 22 leaves per plant (22±1), yields the best results, showing a significant difference compared to the other treatments. In contrast, treatment T0, with 18 leaves per plant (18±1), recorded the lowest number of leaves. Treatments T1, T2, and T4 produced similar results, each with an average of 20 leaves per plant (20±1). Treatment T3, with an average of 19 leaves per plant (19±1), is slightly lower than T1, T2, and T4, but still significantly higher than T0.

The stem diameter shows a significant increase depending on the treatments (Table 9). T0 recorded the smallest stem diameter (1.54±0.07 cm), serving as the reference without any treatment influence. T1 and T2 had stem diameters of 2.52±0.07 cm and 2.67±0.07 cm, respectively, both larger than T0. Similarly, T3 recorded a stem diameter of 2.56±0.07 cm, and T4 reached 2.72±0.07 cm, both showing wider diameters than T0. T5 exhibited the largest diameter at 3.03±0.07 cm. The plots treated with trachyte and basalt powder clearly stand out from the control plot (T0).

The evolution of ear length shows a significant increase as the treatments are applied (Table 9). Treatment T0, with an ear length of 8.55±0.9 cm, presents the shortest ears and stands out significantly from all other treatments. T1 (13.03±0.9 cm) and T2 (13.98±0.9 cm) display noticeably longer ears than those of T0. For treatments T3 and T4, the ear length increases to 13.45±0.9 cm and 14.07±0.9 cm, respectively. Under the influence of treatment T5, the length reaches its maximum at 15.65±0.9 cm, a value significantly higher than the others (Table 9).

The ear diameter shows a statistically significant increase with the application of the different treatments (Table 9). Treatment T0, with an average diameter of 3.00±0.08 cm, produces the smallest ears. T1 (3.54±0.08 cm) and T2 (3.86±0.08 cm) show a noticeable increase compared to T0. Treatment T3 (3.76±0.08 cm) and T4, with a diameter of 4.20±0.08 cm, also show significant increases, surpassing T0. Under the effect of treatment T5, the diameter reaches its maximum at 4.99±0.08 cm, a value significantly higher than those observed for the other treatments.

3.4.2 Effect of trachyte and basalt powder on maize yield parameters

Several parameters help assess the overall productivity of maize, including the weight of the ears, the weight of 100 maize grains, and the total yield in kilograms per hectare (kg ha^{-1}).

The weight of the ears increases significantly according to the treatments, indicating a positive response over time, resulting from the dissolution of the rock powder (Table 9). Treatment T0, with a weight of 31.74±6.82 g, is significantly lower than

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all the others. Under treatment T1, the weight doubles, reaching 75.49±6.82 g, and T2 (93.46±6.82 g) also shows a notable improvement compared to T0. Treatment T3 (82.06±6.82 g) and T4 (97.45±6.82 g), are statistically significant compared to T0. Treatment T5, with a weight of 131.96±6.82 g, shows a substantial and significant increase compared to all other treatments.

The variation in the weight of 100 grains shows that treatment T0, with a weight of 18.85±2.18 g, is significantly lower than all the other treatments. Treatments T1 (24.21±2.18 g) and T2 (27.64±2.18 g) exhibit notable increases compared to T0, Treatments T3 (26.01±2.18 g) and T4 (29.35±2.18) also show significantly higher values than T0. Treatment T5, with an average weight of 32.02±2.18 g for 100 grains, significantly outperforms all other treatments (Table 9).

The yield in kg ha-1 based on the treatments is presented in Table 9. Treatment T0, with a yield of 645.83±27.02 kg ha^{-1}, shows the lowest level among all treatments. In contrast, treatments T1 (2362.87±27.02 kg ha^{-1}) and T2 (2763.91±27.02 kg ha^{-1}) recorded significantly higher yields, demonstrating notable improvement compared to T0 due to the application of trachyte powder. Similarly, treatment T3 (2558.64±27.02 kg ha^{-1}) and treatment T4 (2931.16±27.02 kg ha^{-1}) reveal significant increases, highlighting the positive impact of basalt powder on maize yield. Treatment T5, with a maximum yield of 3164.45±27.02 kg ha^{-1}, statistically outperforms all other treatments. Globally, it is noted that application of basalt powder has more positive effect on maize yields than trachyte powder while adding urea to these treatments increase the maize yield.

***Table 9.** Statistical analysis of the effect of basalt and trachyte powder on the growth and yield of Maize.*

Traetment	**T0**	**T1**	**T2**	**T3**	**T4**	**T5**
Plant height (cm)	147,32±12,09a	175,15±12,9b	181.47±12.09b	179.57±12.09b	194.85±12.09c	215.12±12.09d
Number of leaves	18±1a	20±1b	20±1b	19±1c	20±1b	22±1d
Stem diameter (cm)	1.54±0.07a	2.52±0.07b	2.67±0.07c	2.56±0.07b	2.72±0.07d	3.03±0.07e
Ear length (cm)	8.55±0.9a	13.03±0.9b	13.98±0.9c	13.45±0.9bd	14.07±0.9e	15.65±0.99f
Ear diameter (cm)	3.00±0.08a	3.54±0.08b	3.86±0.08c	3.76±0.08cd	4.20±0.08e	4.99±0.08f
Ear weight (g)	31.74±6.82a	75.49±6.82b	93.460±6.82c	82.06±6.82d	97.45±6.82ce	131.96±6.82f
Weight of 100 grain (g)	18.85±2.18a	24.21±2.18b	27.64±02.18c	26.01±2.18cd	29.35±2.18ce	32.02±2.188f
Yield (kg ha^{-1})	645.83±27.02a	2362.87±27.02b	2763.91±27.02c	2558.64±27.02d	2931.16±27.02e	3164.45±27.02f

T_0: Control plot without treatment; **T_1**: Treatment with trachyte powder (1.96 kg of trachyte powder for 9.6m^2); **T_2**: Treatment with trachyte powder (1.96 kg of trachyte powder for 9.6m^2) + urea (100g for 9.6m^2) at 06 weeks; **T_3**: Treatment with basalt powder (1.96 kg of basalt powder for 9.6m^2); **T_4**: Treatment with basalt powder (1.96 kg of trachyte powder for 9.6m^2) + urea (100g for 9.6 m^2) at 06 weeks. **T_5**: Treatment with NPK fertilizer (200g for 9.6 m^2) + urea (100g for 9.6 m^2) at 06 weeks.

Mean value followed by the letters in the same line are not statistically different.

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4 Discussion

4.1 Physical and mineralogical characteristics of soils

Particle size analyses revealed that the upper part of the soil profile primarily consists of a sandy-loam horizon, characterized by a high sand content ranging from 67 to 82%. The underlying horizons exhibit a succession of sandy and sandy-clay textures, with similar sand proportions. These observations are consistent with those observed in Fluvisols from various arid regions around the world (Romanens et al., 2019). This succession may reflect successive episodes of alluvial deposits, as well as long periods of drought, indicating pedogenetic evolution under hydrological influence. The predominance of sand fractions warrants particular attention, as it can negatively affect water and nutrient retention capacities while directly impacting plant root development, as also noted by Basga et al. (2018) and Tsozué et al. (2020a). Nevertheless, the limited presence of silt particles may help mitigate these effects by enhancing infiltration and slightly increasing the soil's water and nutrient retention capacity, as suggested by Lu et al. (2020) and Tsozué et al. (2021). The clay fraction, ranging from 13% to 18%, plays a significant role in the soil's structural stability and fertility. According to Kome et al. (2019) and Gautam et al. (2022), an adequate clay proportion can enhance both nutrient availability and water retention in the soil.

From a mineralogical perspective, the studied soils are predominantly composed of quartz, along with clay minerals such as kaolinite, smectites, and sepiolite. Kaolinite, an indicator of advanced weathering processes in tropical environments, results from climatic conditions that promote the leaching of basic cations and the neoformation of secondary minerals. These findings are consistent with the work of Tsozué et al. (2020b) and Lyu and Lu (2024). In contrast, the presence of smectite suggests moderate pedoclimatic conditions with variable humidity, which enhance cation exchange capacity and water retention. However, due to its swelling and shrinking behaviour, smectite could cause drainage problems and surface water stagnation, limiting agricultural use for certain sensitive crops (Hopmans et al., 2021). Sepiolite, on the other hand, is characteristic of semi-arid environments with low leaching rates (Bannari et al., 2021). According to Easwaran et al. (2024), this mineral is notable for its remarkable ability to retain water and nutrients, making it particularly beneficial for soils in arid areas or regions prone to drought. Additionally, the significant presence of quartz in the studied soils reflects the influence of alluvial parent material or exogenous inputs. These factors play a crucial role in shaping the textural and structural characteristics of the soil profiles, as observed by Tsozué et al. (2017) and Kemnitz and Lucke (2019).

4.2 Physicochemical characteristics of the studied soils

From a physicochemical perspective, the pH reveals low acidity, ranging between 6.80 and 7.20. These values are typical of soils under a Sudano-Sahelian climate, consistent with the chemical conditions observed in this region (Tsozué et al., 2020a; Tamto Mamdem et al., 2024). According to Tsozué et al. (2021) and Thiaw et al. (2024), this pH level could influence the availability of nutrients for plants. The slight acidification, particularly in the surface layer, can be attributed to the leaching of bases and the use of chemical fertilizers and pesticides (Pahalvi et al., 2021; Sarkar et al., 2024). The strong correlation between pH and cation exchange capacity highlights the importance of regulating pH to optimize CEC and, consequently, improve the availability of essential nutrients for crops. These findings are consistent with those of Santos et al. (2023) regarding acidic soils in the amazonian region. According to Poggi et al. (2023), pH variations must be considered when selecting crops based on their tolerance. Organic matter plays a key role in soil fertility; its low proportion could be explained by several factors, including the semi-arid climate characteristic of the study area and the sandy texture of the soils. Comparable results have been reported by Plaza et al. (2018) and De Alencar et al. (2023) in the semi-arid regions of Brazil. The high correlation between OM and the C/N ratio shows that OM plays a crucial role in nutrient cycles and soil structure, which are important for ensuring sustainable agricultural productivity (Yang et al., 2024). Abdelhak (2022) highlighted that the low concentration of OM could result from the overexploitation of agricultural lands and intensive grazing after harvest. Arif et al. (2021) and Choudhury et al. (2024) emphasized in their research that improved management practices, such as adding organic matter, crop rotation, or using cover crops to improve soil fertility and overall health, could be corrective measures. The very low C/N ratio indicates rapid mineralization, likely related to high temperatures and the sandy texture of the soils. Similar results have been reported by Chen et al. (2024) in soils rich in organic carbon. The low content of available phosphorus in the soil could be attributed to its fixation on the clay-humic complex, a phenomenon strongly influenced by the clay content, pH, and calcium levels. Joshi et al. (2021) and Lotse Tedontsah et al. (2022) demonstrated that these factors play a key role in phosphorus availability, which is essential for crop growth and yield. The relatively high CEC is a crucial indicator of soil fertility, illustrating its ability to retain and exchange nutrients, essential for plant growth. According to Obi et al. (2020), this suggests that the soil can sustainably provide nutrients. High concentrations of Ca^{2+} and Mg^{2+}, especially at depth, indicate a good reserve of nutrients for plants (Hechmi et al., 2023). In contrast, the relatively low K^{+} content could limit plant growth, as potassium is important for photosynthesis and water regulation (Johnson et al., 2022). The moderate Na^{+} concentration would be beneficial in preventing salinity issues (Hussain et al., 2021). These exchangeable bases play a vital role in plant health and improving agricultural yields. The strong positive correlation between Mg and K is a favourable sign for soil quality and productivity. Verma et al. (2024), in their work, emphasized the importance of integrated nutrient management to optimize agricultural production. Electrical conductivity is a key indicator of soil salinity. Since the measured values are low, this would not favour optimal absorption of water and nutrients by plant roots (Golia, 2023).

4.3 Kinetics of nutrient element release from trachyte and basalt powders

The release of nutrients from trachyte and basalt powders is a key topic in pedology and geochemistry, particularly in biogeochemical weathering (Podia et al., 2023). These processes enhance the bioavailability of essential plant nutrients (Medeiros et al., 2023). Mineral hydration from water input causes swelling and disintegration, releasing cations like K, Ca, and Mg (Ramos et al., 2022; Wakeel, 2013).

The release of nutrients from trachyte and basalt powders is governed by interdependent physical, chemical, and biological processes (Swoboda et al., 2022). Mineralogical composition plays a fundamental role in nutrient dynamics. Basalt, rich in plagioclase feldspars, pyroxenes, and olivine, provides Ca, Mg, Fe, and trace elements. Its high reactivity stems from mafic minerals, which are more easily altered (Korndörfer et al., 2002; Ghasera and Rashid, 2024). In contrast, trachyte, mainly composed of alkali feldspars, is a major K source but has lower reactivity due to its felsic nature (Meena and Biswas, 2014; Mbissik et al., 2021). Particle size significantly influences mineral dissolution and nutrient release. Studies by Duarte et al. (2013), Burbano et al. (2021), and Rodrigues et al. (2024b) highlight that finer particles increase the specific surface area, accelerating dissolution. Meena and Biswas (2014) demonstrated that rock phosphate and mica release cations more rapidly when finely ground and combined with compost. Wakeel (2013) further emphasized that acidic soils enhance silicate solubilization, an effect amplified by particle fragmentation. Optimizing rock powder size thus improves agronomic efficiency by promoting sustained nutrient release. Soil pH and redox conditions also affect element solubility: acidic pH favours silicate dissolution and K, Mg, and Fe release, while reducing conditions increase Fe and Mn mobility (Wakeel, 2013; Vondráčková et al., 2017). Organic matter and microbial activity play key roles in mineral weathering (Rout et al., 2024). *Bacillus mucilaginosus* produces organic acids that enhance nutrient solubilization (Yang et al., 2016). Root exudates and mycorrhizal associations further improve K and Mg bioavailability, facilitating plant uptake (Ma and Yamaji, 2006; Menna and Biswas, 2014). This microbial activity, coupled with mycorrhizal interactions, enhances mineral breakdown and nutrient uptake (Menna and Biswas, 2014). These symbioses boost root access to nutrients and activate biological processes that promote silicate dissolution (Yadegari et al., 2024). These combined mechanisms make trachyte and basalt powders particularly effective in nutrient-deficient soils, facilitating the release of K, Ca, and Mg. Climatic conditions also influence nutrient release. Basak and Biswas (2009) found that high humidity promotes mineral alteration and microbial activity, while excessive rainfall can cause nutrient leaching (Lima et al., 2010). Nutrient interactions with soil minerals impact accessibility. Clays adsorb cations, limiting their immediate availability, but organic amendments enhance soil cation exchange capacity, reducing leaching (Duarte et al., 2013). An integrated soil management approach, combining organic amendments with optimized environmental conditions, is essential to maximize nutrient efficiency from minerals.

4.4 Suitability of the soils from Guiring to maize production

The climate of the study area offers particularly favourable conditions for maize growth and yield, as evidenced by annual rainfall and the climatic index. These factors highlight the importance of climate in this region, without presenting major constraints for maize cultivation. However, potential variations due to climate change could disrupt rainfall patterns and temperatures, necessitating continuous monitoring to anticipate and mitigate their impacts (Liu et al., 2024). In this context, Rocha et al. (2020) recommend water management strategies such as irrigation during dry periods to ensure stable agricultural productivity. Conversely, some edaphic parameters pose moderate limitations, including the sandy-loam texture and low base saturation, which affect water retention and nutrient availability (Verdoodt et al., 2003; Tsozué et al., 2015;

Issiné et al., 2022; Scanlan et al., 2022). To address these limitations, adapted management practices are essential. Adding organic matter, such as compost or crop residues, and using cover crops like legumes can improve soil structure and water retention capacity (Obi et al., 2020). Additionally, the application of lime or dolomite could increase calcium and magnesium saturation, while potassium fertilizers can correct low potassium availability (Hechmi et al., 2023). Improving soil texture is also a critical strategy. Adding clay or biochar, identified by Hussain et al. (2021) as an effective solution, enhances water retention and cation exchange capacity, both of which are fundamental properties for the fertility of sandy soils. The use of organic fertilizers is similarly effective in overcoming fertility limitations while promoting sustainable soil management (Van Leeuwen et al., 2015; Das et al., 2024; Robinson, 2024). Finally, trachyte and basalt powders, used as natural amendments, represent a promising alternative for improving soil fertility, especially in semi-arid regions where soils are often degraded by nutrient depletion and poor structure which can not optimize high nutrients release fertilizers such as NPK and urea. Derived from the weathering or grinding of silicate or carbonate rocks, these powders gradually release essential minerals such as calcium, magnesium, and potassium, thereby increasing exchangeable bases and cation saturation (Swoboda et al., 2022; Basak et al., 2023). Similarly, as demonstrated by Manning and Theodoro (2020) and Ramos et al. (2022), they enhance nutrient retention, improve soil mineral composition, increase cation exchange capacity, and contribute to sustainable agricultural fertility management. As slow-release mineral sources, these powders also help restore nutrient balances, improve water retention, and revitalize soil microbial activity (Anda et al., 2015; Guo et al., 2023). This is particularly relevant in semi-arid zones, where conventional fertilizers are often ineffective due to rapid nutrient leaching and unfavourable climatic conditions (Ramos et al., 2022; Cardozo et al., 2024). By stimulating microbial activity, they enhance long-term soil health and support sustainable agricultural practices (Ramos et al., 2022). This combination of integrated solutions could transform semi-arid soils into productive and resilient resources, adapted to the challenges posed by climate change and edaphic constraints.

4.5 Effect of trachyte and basalt powder on maize growth and yield

Trachyte powder, with relatively high concentrations of K_2O and Na_2O, proves beneficial for soil fertilization, as these elements promote plant growth, particularly potassium, which is essential for photosynthesis and water regulation. Nevertheless, its low levels of Fe and Mg limit its direct nutrient contribution for maize, which primarily requires nitrogen, phosphorus, and potassium for its growth (Reimann et al., 2018; Linhares et al., 2021). In contrast, basalts, characterized by high concentrations of Fe_2O_3, CaO, TiO_2, and P_2O_5, while exhibiting reduced levels of SiO_2 and Al_2O_3, can serve as a natural nutrient source (Oppon et al., 2023). They are particularly suited to enriching soils deficient in these elements, thereby improving soil fertility and productivity (Kagou Dongmo et al., 2018; Luchese et al., 2021; Conceição et al., 2022).

The results show that the application of rock powders and conventional fertilizers led to an increase in essential parameters related to maize growth and yield, including plant height, stem diameter, ear diameter, length, and weight, 100-grain weight, and overall yield, compared to the control. Plots treated solely with trachyte and basalt powders exhibited significantly

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higher growth compared to control plots (Ramos et al., 2017, 2022; Reis et al., 2024). These results highlight the potential of these powders as effective amendments for improving maize growth, particularly due to their contents of K_2O, P_2O_5, CaO, and Fe_2O_3. Several studies confirm the beneficial effects of applying rock powders for remineralisation and soil amendment in agriculture, including Mein'da et al. (2022) on the use of pyroclastic powders on ferrallitic soils in the Adamaoua region, Ramos et al. (2015, 2017, 2021, 2022), Oliveira et al. (2020), and Luchese et al. (2023) on volcanic rock powders for soil fertilisation in Brazil. The application of these powders positively impacted maize growth parameters, particularly vegetative development and vigour. This improvement could influence photosynthesis, biomass production, and even seed quality, contributing to increased productivity and yield (Oliveira et al., 2020; Viana et al., 2021; Bamberg et al., 2022; Luchese et al., 2023). These findings confirm that the use of trachyte and basalt powders can sustainably improve soil fertility by supplying both macronutrients (N, P, K, Ca, Mg, S) and micronutrients (Fe, Mn, Zn, Cu, B). This contributes to improved crop quality and yields, consistent with the conclusions of Swoboda et al. (2022) and Luchese et al. (2023). In light of the growing impacts of climate change, soil degradation, rising fertilizer costs for farmers, and crop health issues, rock powders represent a promising alternative to conventional fertilizers (Nkouathio et al., 2008; Burbano et al., 2022; Swoboda et al., 2022).

The results also show that overall maize yield improved significantly, increasing from 645 kg ha^{-1} the control plot to 2763 kg ha^{-1} in the plot treated with trachyte powder and 2931 kg ha^{-1} in the plot amended with basalt powder. These findings emphasize the potential of trachyte and basalt powders to boost maize yields (Tamfuh et al., 2020; Ramos et al., 2020; Mbissik et al., 2023). Although the highest yield was obtained with the application of conventional fertilizers (3164 kg ha^{-1}), trachyte and basalt powders could be more advantageous due to their local availability, lower cost, and positive effects on the soil. They release nutrients slowly and sustainably over multiple seasons, unlike conventional fertilizers, which provide nutrients rapidly but for a short duration. These rock powders act as a natural and sustainable source of essential nutrients for plants, gradually releasing minerals into the soil. They help improve soil fertility without causing pollution or harming biodiversity. Moreover, their use has no negative environmental impact, unlike chemical fertilizers, which can alter ecosystems and affect water and soil quality (Nkouathio et al., 2008; Lopes et al., 2014; Oliveira et al., 2020; Luchese et al., 2023).

5 Conclusion

This study aims to evaluate the effect of using trachyte and basalt powders on maize growth and yield in the Guiring area. Geochemically, the Zamai trachytes are rich in silica and potassium, while the basalts are distinguished by their high content of iron, magnesium, and calcium. The soils in Guiring, dominated by a high sand content (62-82%) and low clay (13-23%) and silt (5-15%) contents. Mineralogically, these soils are composed of kaolinite, smectites, sepiolite, and quartz. The pH ranges from 6.80 to 7.20, organic matter (1.30-3.17%), and total nitrogen (0.11-0.13%) are low, with a low C/N ratio. The cation exchange capacity (18.70-25.00 $cmol_c\ kg^{-1}$ is high, while exchangeable bases (Ca^{2+}, Mg^{2+}, K^+, Na^+) and phosphorus

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are low to moderate, with base saturation varying between 23.60 and 42.41%. The study area has very favorable climatic conditions for maize growth. Soil texture, base saturation, and organic carbon content are classified as S2, indicating moderate limitations. Soil depth (S1-0) is highly suitable, and coarse fragments (S1-1) are slightly suitable. Cation exchange capacity and pH also show slight limitations (S1-1). Overall, the land suitability index is 62.37, classifying it as S2sf, indicating moderate suitability for maize cultivation. Growth and yield parameters show significant improvement based on the treatments applied. The control treatment (T0) shows the lowest yield, with 645.83 kg ha^{-1}. Treatments T1 (2362.87 kg ha^{-1}) and T2 (2763.91 kg ha^{-1}) showed notable improvements with trachyte powder application. Treatments T3 (2558.64 kg ha^{-1}) and T4 (2931.16 kg ha^{-1}) highlight the positive effect of basalt powder. Treatment T5 achieves the maximum yield of 3164.45 kg ha^{-1}, surpassing all other treatments highlighting an importance of associating urea to rocks powders. Although chemical fertilizers provide maximum yields in the short term, trachyte and basalt powders offer a sustainable and cost-effective alternative, improving soils while ensuring competitive yields. Their use is particularly beneficial for resilient and environmentally friendly agriculture.

Author contributions

All the authors substantially contributed to this article. The conceptualization of the study was done by Désiré Tsozué and Bienvenu Sidsi, with input from Claudine Vounba, Simon Djakba Basga. The data acquisition, investigation, methodology, and visualization for the paper were performed by Désiré Tsozué, Bienvenu Sidsi, Claudine Vounba Simon, Djakba Basga, with substantial input from Aubin Nzeugang Nzeukou and Merlin Gountie Dedzo. Bienvenu Sidsi and Claudine Vounba wrote the initial draft, and Désiré Tsozué and Simon Djakba Basga were involved in the reviewing, editing, and the validation of the paper. All authors read and agreed to the final version of the manuscript.

Data availability

The research data will be freely available on request from the corresponding author.

Declarations Competing interests

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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