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Synergistic Effects of Zeolite and Organic Amendments on Soil Quality in Degraded Northern Guinea Savanna, Nigeria

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Abstract

Background: Land degradation threatens crop productivity, particularly in savanna ecosystems where soils are inherently low in organic matter content and nutrient availability. **Aim:** This study evaluated the synergistic (integrated) effects of zeolite and organic amendments on selected soil chemical and physical properties of degraded Alfisols. **Methods:** A screen-house experiment was conducted in a randomized complete block design with ten treatments replicated three times. Four organic amendments: cow dung (CD), poultry litter (PL), biochar (BC), compost (CM), were applied at 5 t ha^{-1} and a control (CO), these treatments were used alone and in combination with zeolite applied at 5 g kg^{-1} of degraded soil. In all treatments crops were augmented with the recommended NPK rate of sweet corn (*Zea mays* L. saccharata) as the test crop. Soil chemical and physical analyses were conducted using standard procedures after harvest. **Results:** Organic amendments significantly improved soil properties, with the overall performance following CM>PL>CD>BC>CO. Compost increased soil pH, organic carbon (OC), effective cation exchange capacity content (ECEC), saturated hydraulic conductivity (Ksat), and plant available water content (PAWC). Total nitrogen (TN) content increased in the order PL>CM>CD>BC>CO. Zeolite conditioning further enhanced TN, ECEC, Ksat, and PAWC by 30.95%, 9.74%,13.09%, and 13.48% respectively while bulk density (BD) decreased by 3.40% compared to no zeolite-conditioned treatments. **Conclusion:** Overall, compost was the most effective organic amendment, and the integrated use of zeolite with organic amendments provide a practical, restorative strategy for improving nutrient retention and water availability for sustainable sweet corn production on degraded soils.

Keywords: land degradation; nutrient retention; organic amendment; sustainable agriculture; zeolite

1. Introduction

Land degradation is a global concern that threatens ecosystem services, biodiversity, and food security (Jayaraman et al., 2024). Almost half of the world's arable land is currently at a different stage of land degradation due to a combination of physical, chemical, and biological processes that decline soil quality and productivity (Müller et al., 2023; Umoru, 2023; Jayaraman et al., 2024). This problem extends to Africa and Asia continents where land is a natural agricultural resource, supporting 70% of subsistence farming (Umoru, 2023). It is estimated that 46 - 80% of the Africa's arable land is degraded, with 30 - 60 kg nutrients loss per hectare per year (Rapiya et al., 2024). The wide range informs that there is a huge spatial variability in terms of land degree and susceptibility to degradation process which mainly depends on the nature of the soil, types of agroecological zones and anthropogenic activities level. Consequently, the deterioration of soil properties through natural and anthropogenic activities leads to long-term negative impacts on agricultural productivity and sustainability (Gantulga et al., 2023; Bayata, 2024). Reliance on inorganic fertilizers alone can adversely affect soil chemical, physical, and biological functions, including reduced pH, reduced organic matter, disrupted soil aggregation, and weakened moisture retention (Zhuang et al., 2024; Ahmad, 2025; Silvertooth, 2025).

In Nigeria, the soils of the savanna agroecosystem are inherently poor in fertility status, cation exchange capacity and low in activity clays and organic matter content (Jones

& Wild, 1975), which are dominantly sandy in nature, which aggravate nutrients leaching away from the rooting depth of most crops (Yoni et al., 2024). The United Nations Sustainable Development Goals (SDGs), specifically SDG 15.3 (Life on Land), aim to restore degraded land and soils to improve crop productivity, soil and water conservation, and the provision of ecosystem services (United Nations, 2024; Pretorius et al., 2025). Therefore, the use of soil amendments to restore degraded soil is also a promising and sustainable solution for improving soil productivity and the agroecosystem, alongside conservation tillage and crop rotation practices.

The use of soil amendments from both organic and inorganic sources is of great significance in improving not only the chemical properties, but also the physical and biological properties of the soil. Previous studies have shown that applying poultry manure significantly enhances the chemical, biological, and physical characteristics of soil when applied correctly (Agbede et al., 2017; Nweke & Igwe, 2021). In recent years, the use of biochar as soil amendment (Leogrande et al., 2024; Adekiya et al., 2025), as well as compost, has played a crucial role in providing essential nutrients, restoring soil fertility, and re-establishing microbial populations (Leogrande et al., 2024). In addition, the application of amendments could enable carbon storage in soil, converting it into more stable forms and reducing carbon dioxide (CO2) loss to the atmosphere (Gross & Glaser, 2021).

Recent research highlights the significance of long-term amendments such as biochar, compost, cow dung and poultry litter (Dawaki et al., 2019; Kavvadias et al., 2023) due to their stable, recalcitrant carbon. Biochar is the carbonaceous residue of pyrolyzed organic materials or biomass, and it is predominantly stable and recalcitrant (Leogrande et al., 2024). Due to its stability, biochar can be used to increase soil carbon sequestration (Sanchez-Monedero et al., 2018) and improve the fertility of degraded soils. In addition, biochar's highly active surface area and functionality contribute to improving soil quality by positively affecting its chemical, physical, and biological properties. For these reasons, biochar represents a suitable solution for degraded soils to alleviate problems caused by alkalinity, acidity, nutrient deficiency, and water loss (Altobelli et al., 2020). Compost is characterized by a low decomposition rate and by a slow release of organically bound nutrients, making compost less susceptible to large nutrient losses (Leogrande et al., 2024), reduction of erosion and runoff, which enhances infiltration rate and water holding capacity of the soil (Haque et al., 2021; Haftu et al., 2023).

Zeolites as conditioners have gained attention due to their potential to enhance sustainable agricultural ecosystems (Cataldo et al., 2021). The distinctive characteristics of zeolites can vary depending on the natural or synthetic origin of the materials used in their production (Restiawaty et al., 2024). Interestingly, natural zeolites mostly originate from volcanoes and pyrogenic rocks, either extracted in crystalline form or in granular form in sedimentary rocks (Javaid et al., 2024), while synthetic zeolites have been fabricated using hydrothermal techniques from synthetic silicates or natural precursors (Kordala et al., 2024). Zeolites are composed of alumino-silicate tetrahedral units interlinked into a three-dimensional cage-like structure (Munir et al., 2024). Zeolites have distinctive properties, including ion exchange, adsorption, filtration, and catalysis (Mondal et al., 2021; Javaid et al., 2024). In addition, zeolites, owing to their internal crystal structure and unique characteristics, offer practical solutions for enhancing soil properties. Research has highlighted that zeolites reduce nitrate leaching and ammonia volatilization, enhance the slow release of nutrients, and increase cation exchange capacity, thereby restoring soil quality (Cataldo et al., 2021). Studies by Ravali et al. (2020) and Mondal et al. (2021) reported that zeolites can enhance soil bulk density, saturated hydraulic conductivity, infiltration rate, and water-use efficiency by improving soil water-holding capacity and its availability to crops, owing to their highly porous structures. These results support the findings that zeolites have several beneficial effects on soil quality and crop productivity (Baghbani-Arani et al., 2020; Liu et al., 2023). Nevertheless, the amount of organic matter in the soil is unaffected by a single zeolite application (Szerement et al., 2021). To overcome this restriction, combining zeolite with organic fertilisers can increase soil organic carbon content.

Nevertheless, despite their unique properties and benefits for sustainable agricultural production, the use of zeolite in combination with organic amendments remains an area that necessitates focused investigation. This study seeks to address an existing knowledge gap. Accordingly, this study aims to explore the integration effects of zeolite and organic amendments on selected soil chemical and physical properties of degraded Alfisols. The findings promise to advance our knowledge and understanding, which also provide possible solutions for restoring the degraded soil. It was hypothesized that the outcomes of this study would contribute to sustainable soil management practices while conserving the waste materials.

2. Methods

2.1 Description of the Study Site

The study site was degraded soil as a result of soil erosion which is located in Area F, Samaru, Zaria (latitude 11°9'51.429″ to 11°9'53.506″ N ,longitude 7°37'25.913″ to 7°37'28.828″ E with elevation of 677 to 696 m above sea level) in the Northern Guinea Savanna ecological zone of Nigeria (Figure 1). A tropical climate with marked rainy and dry seasons characterizes this zone. Samaru is characterized by a monomodal rainfall pattern, with a long-term mean annual rainfall of about 1058.5 ± 161 mm, peaking from March/April to October, with the highest concentration from July to September. Samaru has long-term mean minimum and maximum temperatures of 19.2 °C and 32.4 °C, respectively, and a relative humidity of 51.08% (Institute for Agricultural Research [IAR] - Meteorological Station Unit, 2023).

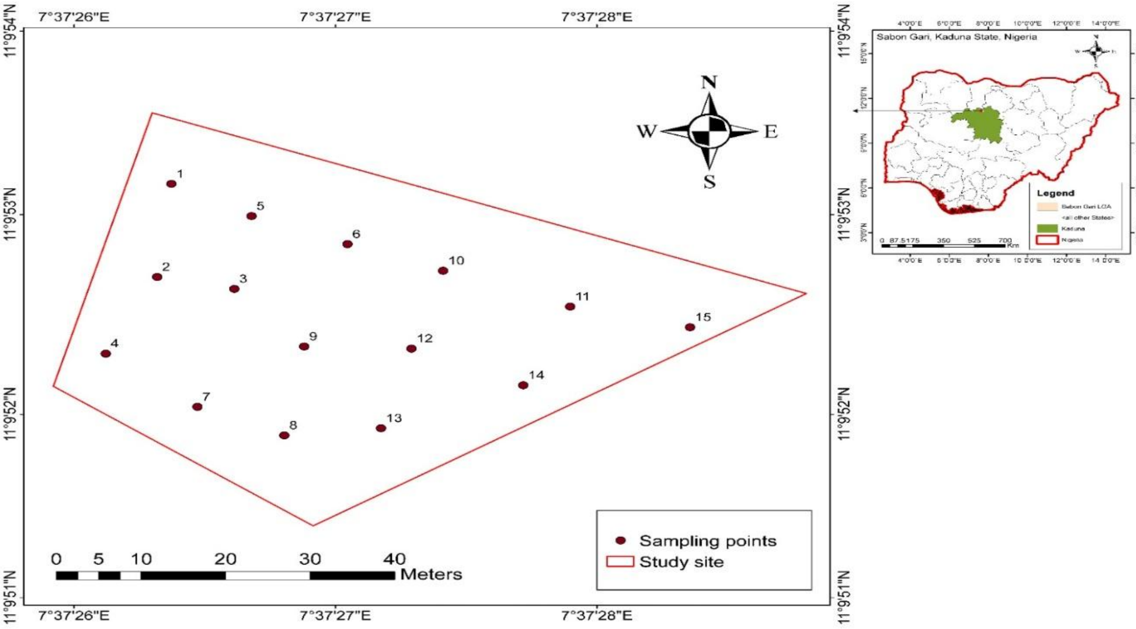

Figure 1. Map of Nigeria showing the study site and sampling points

2.2 Sampling and Analysis of Degraded Soil and Zeolite Prior to Trial Establishment

The disturbed soil samples were collected at a depth of 0-20 cm using an auger, with a simple random sampling technique: the study area was divided into three equal-sized areas, which were then bulked to form the composite samples. The soil and zeolite samples were air dried, crushed and passed through 2 mm sieve for soil chemical and physical properties such as soil pH, electrical conductivity, total nitrogen, available phosphorus, organic carbon, exchangeable bases (calcium, magnesium, sodium, and potassium), exchangeable acidity, and particle size distribution while the undisturbed soil samples were used to determined soil bulk density, and saturated hydraulic conductivity and soil moisture retention characteristics using standard procedures as described in section 2.8.

2.3 Amendments Preparation

2.3.1 Cow dung and Poultry litter preparation

Cow dung and poultry litter were obtained from the Poultry and Livestock Unit of the Department of Animal Science, Faculty of Agriculture, Ahmadu Bello University, Zaria. Both cow dung and poultry litter were air stockpiled and covered with polythene nylon for about three months before applying them to the soil in order to prevent nutrient loss.

2.3.2 Biochar and Compost Preparation

Maize cob biochar was produced in a 60-liter-capacity oven at the Industrial Development Centre (IDC), Zaria, Nigeria. The feedstock (maize cob) was cut into smaller pieces, which were poured into an air-tight stainless-steel container. The container was gently inserted into the oven and its door was locked, which was then pyrolyzed at 600 °C for four hours. Biochar was allowed to cool to ambient temperature within the confines of the oven (Abdu et al., 2021). The total biochar produced was passed through a 2 mm sieve to ensure a uniform particle size with the soil. Compost was produced from feedstocks such as fresh animal manure (cow dung), green Isoberlinia leaves (*Isoberlinia doka*), dried Candahar tree leaves (*Gmelina arborea*), crop residue (rice husk), and phosphate mineral rock.

2.3.3 Zeolite preparation

Zeolite was produced as described by Wardle and Brindley (1972), the process consists of two steps: (i) Metakaolinisation (Chemically activating kaolin clay to metakaolin which was beneficiated from Kankara Local Government Area, Katsina state, Nigeria) and (ii) Zeolitisation (treatment of the metakaolin with aqueous alkali solution to form zeolite). The synthesis for Zeolite-A was carried out according to the procedure by Olaremu et al. (2018), the result was ascertained by comparing it with a commercial Zeolite-A using the X-ray diffraction (XRD) method.

2.4 Soil Amendments Characterization

All the soil amendments (cow dung, poultry litter, compost, biochar) were characterized for pH, measured with a glass-electrode pH meter (Model PHS-3C) at an amendment-to-water (H_2O) ratio of 1:2.5 (*w/v*). In amendments to a 0.01 M $CaCl_2$ solution of 1:2.5 (*w/v*) (McLean, 1982), Total nitrogen was determined by the micro-Kjeldahl digestion method (Bremner, 1982). The soil organic carbon was determined by Walkley-Black dichromate oxidation method as described by Nelson and Sommers (1982), sulphate (S) by Turbidimetric method as described by Tabatabai (1974), while total phosphorus (P) by Vanado-Molybdate method as described by (Association of Official Analytical Chemists

[AOAC], 1970), copper (Cu), iron (Fe), manganese (Mn), calcium (Ca), magnesium (Mg), and zinc (Zn) by wet digestion method as described by AOAC (1970), and measured with atomic absorption spectrometry (Bouck Scientific Model 230) using standard procedures as described by Perkin-Elmer (1968) and total potassium (K) and sodium (Na) were read by flame photometer (Model 410).

2.5 Experimental Procedure

The pot experiment was carried out in a screen house at the Department of Soil Science, Institute for Agricultural Research (IAR), Samaru, Ahmadu Bello University, Zaria, Nigeria (latitude 11°9'52.610̋ N, longitude 7°37'56.633̋ E, elevation 672 m above sea level). Sweet corn (*Zea mays* L. *saccharata), the Sugar King F1 variety, was used as the test crop, a tropical hybrid with* strong plant vigour and a root system (East-West Seed, 2022). A screen-house experiment was conducted in a randomized complete block design with 10 treatments, replicated 3 times. Four organic amendments: cow dung (CD), poultry litter (PL), biochar (BC), compost (CM), were applied at 5 t ha^{-1} and a control (CO), these treatments were used alone and in combination with zeolite applied at 5 g kg^{-1} of degraded soil. In all treatments, crops were augmented with the recommended NPK rate for sweet corn (Zea mays L. saccharata), the test crop.

2.6 Pot Experiment and Cultural Practices

The pot has an area of 2677.84 cm^2 and a volume of 10635.91 cm3, and each pot was filled with 7 kg of 2-mm sieved soil. Water was applied to the pot to field capacity before sowing sweet corn. Sweet corn seed was treated with Apronstar (Lmidacloprid 20% + Metalaxy M20% + Tebuconazole 2% WS) at the rate of 10 g per 4 kg of sweet corn seed. Sowing was done manually using a dibble at a depth of 3-5 cm. 3 sweet corn seeds per pot were sown. Sweet corn seedlings were thinned to one plant or stand per pot at two weeks after sowing**.** Weeding was done as and when due by manual uprooting to maintain the sweet corn in the pot free of weeds.

2.7 Fertilizer Application and Harvesting of Sweet Corn

Fertilizers were applied based on the nutrient (N, P, and K) composition of soil amendments and conditioners. Therefore, the N, P, and K contents of the amendments were supplemented with mineral fertilizer to meet the nutrient requirements for sweet corn production per hectare. The recommended fertilizer rates for corn are 120 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}, and 60 kg K_2O ha^{-1}. Sweet corn was harvested at 4 months, when it reached maturity.

2.8 Soil Sampling and Measurements after Harvesting of Sweet Corn

At the end of the experiment, disturbed soil samples were collected using auger from the amended soils in each pot after harvesting of sweet corn. The soil samples were air dried, crushed and passed through 2 mm sieve for routine soil chemical properties and physical properties. Soil pH was measured with glass electrode pH meter (Model PHS-3C) at soil to water (H_2O) ratio of 1:2.5 (*w/v*) and in soil to 0.01 M $CaCl_2$ solution of 1:2.5 (*w/v*) (Mc lean, 1982), electrical conductivity was measured at a soil to water ratio of 1:2.5 (*w/v*) with electrical conductivity meter (Model EBB/10) (Rhoades, 1982). Total nitrogen was determined by the micro-Kjeldahl digestion method (Bremner, 1982). Available phosphorus was determined by the Bray-1 acid fluoride extraction method (Bray & Kurtz, 1945). Soil organic carbon was determined by the Walkley-Black dichromate oxidation method as described by Nelson and Sommers (1982).

Exchangeable bases are displaced by the neutral 1 M NH_4OAC saturation method (Anderson & Ingram, 1993). The concentrations of sodium and potassium were measured with a flame photometer (Model 410), while calcium and magnesium were determined by titration with ethylenediaminetetraacetic acid (EDTA). Exchangeable acidity was determined as described by Anderson and Ingram (1993). Effective cation exchange capacity was estimated by summation method of all exchangeable bases and exchangeable acidity and particle size distribution using the hydrometer method as described by Gee and Or (2002), also the undisturbed soil samples were collected using core sampler and mallet from each pot and used for determination of soil bulk density by core method as described by Grossman and Reinsch (2002), saturated hydraulic conductivity was determined by using the constant head permeameter method as described by Reynolds et al. (2002) and soil moisture retention characteristics were determined using the pressure plate membrane apparatus at the suctions of 0, -33, and -1500 kPa which termed at saturation, field capacity and permanent wilting point respectively as described by Klute (1986).

2.9 Data Analysis

Data collected in this study were subjected to statistical analysis of variances as described by Snedecor and Cochran (1967), using the Statistical Analysis System computer package version 9.1 (SAS, 2008), and the differences among the treatment means were evaluated using Duncan's Multiple Range Test (DMRT) at 5 % level of probability (Duncan, 1955).

3. Results and Discussion

3.1 Characterization of the study site

The soil chemical and physical properties of the study site are presented in Tables 1 and 2, respectively. In accordance with the ratings of FDALR (1990), the soil pH in water and calcium chloride is moderately acidic and strongly acidic, respectively. The soil's electrical conductivity is non-saline in line with the guidelines of USDA and NRCS (2011). The soil is low in total nitrogen, organic carbon, available phosphorus, exchangeable calcium, sodium and potassium, while exchangeable magnesium is moderate. Furthermore, exchangeable acidity and effective cation exchange capacity are low, in accordance with FDALR (1990) ratings. The soil is sandy loam (SL) in texture, with moderate bulk density in line with the guideline of (USDA & NRCS, 2019), According to the rating of Soil Science Division Staff (2017), saturated hydraulic conductivity is moderately high and soil moisture retention is moderately low.

3.2 Characterization of Amendments and Zeolite

The characterization of the amendments and zeolite used in this study is presented in Tables 3 and 4, respectively. In accordance with the FDALR (1990) rating, the pH of distilled water for biochar, cow dung, and poultry litter was strongly alkaline, whereas that of compost was very strongly alkaline. However, the pH in calcium chloride for biochar was slightly acidic, whereas that of cow dung and poultry litter was moderately alkaline; the pH in $CaCl_2$ for compost was very strongly alkaline. Electrical conductivity (EC) of biochar was non-saline, while EC in compost and poultry litter was very slightly saline, and EC in cow dung was slightly saline (USDA & NRCS, 2011). Results of Total nitrogen (TN) content in amendments show medium TN in biochar, high TN in cow dung and compost, and very high TN in poultry litter.

Table 1. Soil chemical properties of the degraded soil

Properties	Unit	Value
pH (1:2.5 Soil: H_2O)	-	5.82
pH (1:2.5 Soil: 0.01 M $CaCl_2$)	-	5.39
Electrical conductivity	dS m^{-1}	0.13
Total nitrogen	g kg^{-1}	0.53
Organic carbon	g kg^{-1}	3.79
Available phosphorus	mg kg^{-1}	3.09
Exchangeable bases		
Exchangeable calcium	cmol kg^{-1}	4.60
Exchangeable magnesium	cmol kg^{-1}	1.40
Exchangeable sodium	cmol kg^{-1}	0.23
Exchangeable potassium	cmol kg^{-1}	0.16
Exchangeable acidity	cmol kg^{-1}	0.60
Effective cation exchange capacity	cmol kg^{-1}	6.99

Table 2. Soil physical properties of the degraded soil

Properties	Unit	Value
Particle size distribution		
Sand	g kg^{-1}	594
Silt	g kg^{-1}	289
Clay	g kg^{-1}	117
Textural class		Sandy loam
Bulk density	Mg m^{-3}	1.57
Saturated hydraulic conductivity	cm hr^{-1}	0.98
Volumetric moisture content at field capacity	m^3 m^{-3}	0.3326
Volumetric moisture content at permanent wilting point	m^3 m^{-3}	0.2634
Plant available water content	m^3 m^{-3}	0.0692

Following the FDALR (1990) ratings, results revealed that all the amendments (biochar, cow dung, compost, and poultry litter) had very high total organic carbon content, as shown in Table 3. The compost had the highest percentage of total phosphorus content, followed by poultry litter, cow dung and the lowest in biochar. Cow dung had the highest total sulphate, followed by poultry litter and compost, with the least total sulphur observed in biochar. Compost had the highest total iron content, followed by cow dung, then poultry litter, and biochar had the lowest. Poultry litter had the highest manganese ion content, followed by cow dung, then compost, and the lowest was in biochar. Biochar had the highest sodium ion content, followed by cow dung, then poultry litter, and the lowest was in compost. Compost had the highest potassium ion content, followed by poultry litter, then cow dung, and biochar had the lowest. Also, compost had the highest calcium ion content, followed by poultry litter, then cow dung, with the lowest observed in biochar. Poultry litter had the highest magnesium ion content, followed by cow dung, then compost, and the lowest was in biochar. In accordance with the rating of FDALR (1990), the results revealed that the zeolite pH in water and in calcium chloride were very strongly alkaline and strongly alkaline, respectively. The electrical conductivity (EC) of zeolite was very slightly saline (USDA & NRCS, 2011), and the total nitrogen (TN) content in zeolite was medium, with low total organic carbon content. For zeolite, the exchangeable bases were high, while exchangeable acidity was moderate, and the effective cation exchange capacity was very high, in consonance with FDALR (1990) ratings. The zeolite used in this study was silty loam in texture, with 30% sand, 54% silt, and 16% clay.

Table 3. Characterization of amendments

Properties	**Unit**	**Biochar**	**Cow dung**	**Compost**	**Poultry litter**
pH (1:2.5 Amendment: H_2O)	-	8.48	8.71	10.05	9.47
pH (1:2.5 Amendment: 0.01 M $CaCl_2$)	-	7.80	8.41	9.06	8.07
Electrical conductivity	dS m^{-1}	1.40	5.50	3.05	4.00
Total nitrogen	g kg^{-1}	16.71	25.50	26.90	30.50
organic carbon	g kg^{-1}	280.32	340.52	460.63	390.22
Total phosphorus	% P	0.63	0.85	1.42	1.02
Total sulphate ($S0_4^{2-}$**)**	mg kg^{-1}	636.03	1004.25	669.50	836.88
Iron (Fe)	mg kg^{-1}	1951.75	4120.00	4681.25	2959.50
Manganese (Mn)	mg kg^{-1}	134.25	468.25	1166.75	432.50
Sodium (Na)	mg kg^{-1}	9500.00	7500.00	2000.00	5000.00
Potassium (K)	mg kg^{-1}	2500.00	6000.00	20500.00	16500.00
Calcium (Ca)	mg kg^{-1}	1777.75	2310.00	8878.25	5844.25
Magnesium (Mg)	mg kg^{-1}	593.00	682.00	655.25	701.00

Table 4. Characterization of zeolite

Properties	**Unit**	**Value**
pH (1:2.5 Zeolite: H_2O)	-	9.96
pH (1:2.5 Zeolite: 0.01 M $CaCl_2$)	-	8.12
Electrical conductivity	(dS m^{-1})	2.90
Total nitrogen	g kg^{-1})	1.70
Organic carbon	g kg^{-1}	4.33
Exchangeable bases		
Exchangeable sodium	cmol kg^{-1}	1.86
Exchangeable potassium	cmol kg^{-1}	1.15
Exchangeable calcium	cmol kg^{-1}	28.63
Exchangeable magnesium	cmol kg^{-1}	9.57
Exchangeable acidity	cmol kg^{-1}	1.34
Effective cation exchange capacity	cmol kg^{-1}	42.55
Particle size distribution		
Sand	g kg^{-1}	300
Silt	g kg^{-1}	540
Clay	g kg^{-1}	160
Textural class		Silty loam

3.3 Effect of Amendments and Zeolite on Soil Chemical Properties of a Degraded Soil

In Table 5, the application of amendments showed a significant (P≤0.01) difference in soil pH (H2O and CaCl2), reducing soil acidity and increasing soil pH toward neutrality. The increase in soil pH water is by 17.28%, 16.06%, 15.36% and 12.04% in soils amended with compost, poultry litter, cow dung, and biochar, respectively, relative to unamended soil. Soil pH in $CaCl_2$ was statistically similar in all amended soils. The pH of CaCl2 increased on average by 17.73% in all the amended soils compared to the unamended soil. The increase in soil pH from the application of soil amendments may be due to the alkaline nature of all the amendments, thereby reducing soil acidity and shifting the pH from strongly acidic to slightly acidic, in addition to their good buffering capacity. This corroborates with the findings of Kavvadias et al. (2023) who reported that addition of compost in soil improved soil pH due to the alkaline nature. Similarly, for soil amended with poultry litter (Adekiya et al., 2019; Agbede & Oyewumi, 2022), and soil amended with cow dung (Minardi et al., 2020;Santoso et al., 2022), an increase in soil pH in soil amended with biochar may be due to the relatively high ash content of biochar owing to the presence of a high amount of carbonates, which can neutralize acidity in soil (Ghorbani et al., 2022). The moderately and strongly acidic levels of soil pH in water and $CaCl_2$, respectively, in unamended soil could be ascribed to the application of inorganic fertilizer alone and the leaching of basic cations due to the absence of OM.

The results of electrical conductivity (EC) showed significant (P≤0.01) increases of 131.03% in soils amended with biochar and cow dung, 103.45% in soils amended with poultry litter, and 86.21% in soils amended with compost, compared with unamended soil. The EC was below the threshold value for saline soil (4 dS m-1) in both the amended and unamended soils. Therefore, all the amended soils and unamended soils are termed as non-saline soils.

Table 5. Effect of amendment and zeolite on some soil chemical properties of the degraded soil

	pH $_{H2O}$	**pH$_{CaCl2}$**	**Electrical conductivity (dS m^{-1})**	**Organic carbon (g kg^{-1})**	**Total nitrogen (g kg^{-1})**	**Available phosphorus (mg kg^{-1})**
Amendment (A)						
Cow dung	6.61ab	6.10a	0.65a	14.60b	1.78b	13.47c
Compost	6.72a	6.19a	0.54b	18.02a	2.52a	18.82a
Biochar	6.42b	6.01a	0.68a	11.17c	1.68b	10.59d
Poultry litter	6.65ab	6.15a	0.59ab	15.54b	2.57a	17.35b
No amendment	5.73c	5.19b	0.29c	3.36d	1.16c	3.44e
SE±	0.090	0.065	0.034	0.400	0.055	0.270
SL	**	**	**	**	**	**
Conditioner (C)						
Zeolite	6.48	5.97	0.54	12.72	2.20a	13.43a
No zeolite	6.37	5.88	0.56	12.36	1.68b	12.03b
SE±	0.057	0.041	0.021	0.253	0.035	0.171
SL	NS	NS	NS	NS	**	**
Interaction						
A X C	NS	NS	NS	NS	NS	NS

Means followed by the same letter (s) within the same treatment group in a column are not significant at 5% level of probability using Duncan Multiple Range Test (DMRT), NS= Not significant, ** =Significant at 1% level of probability, SE ± = Standard error, SL= Significance level.

Application of amendments increases organic carbon (OC) content by 436.31%, 362.50%, 334.52% and 232.44% in soils amended with compost, poultry litter, cow dung and biochar, respectively, compared to unamended soil**.** The substantial increase in OC content in compost-treated soil could be attributed to the relatively high humic material content in compost manure, which, in turn, would contribute to organic matter (OM) content and improve the soil fertility status of the degraded soil. The compost amendment used in this study had higher OC content than all other amendments. This corroborates the findings of Rosalina et al. (2019) and Kavvadias et al. (2023), who reported that compost manure with high organic matter content accelerated biological activities and improved soil productivity (Das et al., 2017). This implies that soil amended with compost would retain and release more nutrients and exchangeable ions in the soil solution. Both increased OC content in soils amended with poultry litter and cow dung were similarly reported by Frank et al. (2020) and Agbede & Oyewumi (2022), respectively. An increase in OC could be ascribed to the relatively high temperature (600 °C) at which maize cob pyrolyzed and to the nutritive content of the biochar used (Ouyang et al., 2014; El-Naggar et al., 2018). Low OC content in unamended soil could be attributed to the application of mineral fertilizer alone (without organic amendments), which is not carbon-based material.

Soil amended with poultry litter had higher total nitrogen (TN) content, followed by compost, then cow dung and biochar by 121.55%, 117.24%, 53.45% and 44.83%, respectively, compared to unamended soil. The highest TN in soil amended with poultry litter could be attributed to the high N content and low C:N ratio (12.79) in poultry litter compared to other amendments (Adekiya et al., 2019; Agbede & Oyewumi, 2022). Furthermore, other amendments applied in this study, including compost and cow dung, significantly increased total nitrogen content compared to unamended soil due to their nutrient content (Santoso et al., 2022; Kavvadias et al., 2023). Moderately low TN in soil treated with biochar may be attributed to the relatively high temperature of 600 °C at which the biochar was pyrolyzed, which causes the volatilization of N from the biochar amendment (Adekiya et al., 2019). The lowest TN in the unamended soil could be attributed to the leaching of nitrogen due to its fast release from mineral fertilizer applied to the soil and its high mobility in the soil, leading to its loss beyond the crop.

Soil treated with compost, poultry litter, cow dung, and biochar showed increases in available phosphorus (AP) content of 447.09%, 404.36%, 291.57%, and 207.85%, respectively, compared to the unamended soil, which had the lowest AP content. The improvement in AP in soil amended with compost may be due to the high content of humic substances derived from compost mineralization, which also increased exchangeable Ca, Mg, and K (Rosalina et al., 2019; Kavvadias et al., 2023). Moreover, the increase in AP by application of soil amendments could be attributed to the mineralization of organic P and production of organic acids, which make the soil P more available and reduce P fixation (Frank et al., 2020; Agbede & Oyewumi, 2022), compared to the unamended soil where only mineral fertilizer was applied.

Application of zeolite did not show any significant effect on most of the chemical properties evaluated except for TN and AP, which were significantly ($P \leq 0.01$) improved, where application of zeolite influenced 30.95% and 11.64% more TN and AP, respectively, compared to the soil with no zeolite (Table 5). However, the TN was moderately high and medium for zeolite- and no-zeolite-conditioned soil, respectively, while the available phosphorus was moderate for both zeolite- and no-zeolite-conditioned soil, following the ratings of FDALR (1990). The no significant effect of zeolite on pH, EC and OC may be due to the relatively low rates of 5g zeolite per kg soil applied in this study. Santoso et al. (2022) reported that the application of zeolite increased soil pH, TN, and AP especially when zeolite was applied at 10, 15 and 20 g per Kg of soil. A decrease in soil acidity, indicated by both pH in water and CaCl2 in zeolite-conditioned soil, may be attributed to the alkaline nature of the zeolite applied in this study. Several studies such as Filcheva & Tsadilas (2002); Ramesh et al. (2015); Santoso et al. (2022) indicated that addition of zeolite typically resulted in an increase in soil pH, because zeolites are marginally alkaline, while decrease in EC in soil amended with zeolite could be ascribed to zeolite molecular sieve structure and high cation-exchange capacity, which enables zeolite to exchange ions with its environment, thus resulting in decrease in soil EC (Doni et al., 2020). The addition of zeolite results in lower EC values in soil solution due to greater K-ion adsorption compared to Na ions (Lahori et al., 2020; Munralini.

The slight increase in organic carbon (OC) content when zeolite was applied to soil may be attributed to the ability of zeolite to sequester carbon especially when combined with organic materials by trapping carbon dioxide from the atmosphere into it is porous structure which has potential to trap, exchange, or release molecules and ions with the organic materials at the exchange site (Santoso et al., 2022; Kavvadias et al., 2023). An increase in TN content in soil amended with zeolite could be attributed to the retention properties of zeolite, which allows zeolite to reduce leaching and loss of essential nutrients. This corroborates the findings of Ali et al. (2022) and Kavvadias et al. (2023), who reported that the application of amendments and zeolites has the potential to retain ammonia through ammonium adsorption and reduce nutrient loss due to zeolites' porous structure and absorbent nature. However, the increase in available phosphorus may be attributed to the high exchange capacity of zeolite (Ramesh & Reddy, 2011). Zeolites have high exchange capacity, which increases the availability of phosphorus for uptake while decreasing this element's pollution load (Litaor et al., 2017; Rosalina et al., 2019).

3.4 Effect of Amendment and Zeolite on Soil Exchangeable Bases, Exchangeable Acidity, and Effective Cation Exchange Capacity of a Degraded Soil

Analysis of variance revealed that all organic amendments applied significantly ($P \leq 0.01$) improved exchangeable bases and effective cation exchange capacity (ECEC) compared to the unamended soil in Table 6. The results revealed that soil exchangeable calcium concentration improved in soils amended with compost, poultry litter, cow dung, and biochar by 163.45%, 94.78%, 75.70%, and 52.61%, respectively, compared to unamended soil. Exchangeable magnesium improved in soil treated with compost, poultry litter, cow dung, and biochar by 134.97%, 99.00%, 81.12% and 60.14%, respectively, compared to unamended soil. Soils treated with compost, poultry litter, cow dung and biochar had an increase of exchangeable potassium by 410%, 305%, 270% and 195%, respectively, compared to unamended soil. The ability of compost to adsorb cations due to its high net negative surface charge and adsorption affinity of cations may be the reason for the increase in exchangeable Ca, Mg, and K in soil amended with compost, thus increasing the availability of cationic species in compost-amended soil (Latifah et al., 2016). While an increase in exchangeable Ca, Mg, and K in soil amended with poultry manure could be ascribed to the nutrients released during the breakdown of the manure. Research has shown that adding poultry manure to soil increases its OC, N, P, K, Ca, and Mg content (Almaz et al., 2017; Adekiya et al., 2020).

The improved buffer capacity of the soil due to the high organic matter content of the manure applied may increase the exchangeable Ca, Mg, and K in soil amended with cow dung (Meelu & Gill, 2001;Frank et al., 2020). The ability of biochar to adsorb cations due to its high net negative surface charge and adsorption affinity of cations may increase exchangeable Ca, Mg, and K in soil amended with biochar (Zaidun et al., 2019). The low exchangeable Ca, Mg, Na and K in unamended soil may be attributed to the leaching of basic cations in low-organic-matter soil. Application of amendment influenced exchangeable sodium in soil treated with cow dung, biochar, poultry litter and compost compared to unamended soil by 173.08%, 169.23%, 142.31% and 96.15%, respectively. The enhancement in exchangeable Na in all the amended soils may be ascribed to the better buffering capacity of the soil owing to the high organic matter content of the manure added, which enhanced the soil fertility (Mahdy, 2011; Gautam et al., 2021).

Table 6. Effect of amendment and zeolite on soil exchangeable bases, acidity and effective cation exchange capacity of the degraded soil

	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	EA	ECEC
	← ------------------------------		cmol kg^{-1}		------------------------------→	
Amendment (A)						
Cow dung	8.75c	2.59b	0.71a	0.74bc	0.39b	13.18c
Compost	13.12a	3.36a	0.51b	1.02a	0.24c	18.25a
Biochar	7.60d	2.29c	0.70a	0.59c	0.45b	11.62d
Poultry litter	9.70b	2.72b	0.63ab	0.81b	0.31c	14.16b
No amendment	4.98e	1.43d	0.26c	0.20d	1.04a	7.92e
SE±	0.193	0.069	0.058	0.051	0.028	0.265
SL	**	**	**	**	**	**
Conditioner (C)						
Zeolite	9.29a	2.62a	0.57	0.72	0.45b	13.63a
No zeolite	8.37b	2.34b	0.55	0.63	0.52a	12.42b
SE±	0.122	0.044	0.037	0.032	0.018	0.168
SL	**	**	NS	NS	*	**
Interaction						
A X C	NS	NS	NS	NS	NS	NS

Means followed by the same letter(s) within the same treatment group in a column are not significant at 5% level of probability using Duncan Multiple Range Test (DMRT), NS = Not significant, *= Significant at 5% level of probability, **= Significant at 1% level of probability, SE± = Standard error, SL= Significance level.

Analysis of variance revealed a significant ($P \leq 0.05$) difference in exchangeable acidity (EA) due to the application of soil amendments. Exchangeable acidity significantly ($P \leq 0.05$) decreased by 62.50%, 76.92%, 56.73% and 70.19%, in cow dung, compost, biochar and poultry litter treated soils respectively, relative to the unamended soil. The reduction in exchangeable acidity (EA) of amended soils may ascribed to organic amendments application which decreases soil acidity owing to release of basic cations from OM which may decrease exchangeable aluminium ions in the soil, and in turn increase the soil cations exchange capacity (Zaidun et al., 2019). High EA in unamended soil may be attributed to leaching of basic cations in low organic matter soil, resulting into increase in aluminium and hydrogen ions at soil exchange site. Highly significant ($P \leq 0.01$) difference was observed in ECEC as a result of amendment application. There was 130.43%, 78.79%, 66.41%, 46.72% increment in ECEC in soil amended with compost, poultry litter, cow dung, and biochar respectively compared to the unamended soil. The increase in ECEC was attributed to the buffering capacity of organic amendments applied (Meelu & Gill, 2001; Frank et al., 2020).

Statistical analysis revealed that application of zeolite had a highly significant ($P \leq 0.01$) influence on exchangeable calcium, magnesium, exchangeable acidity, and effective cation exchange capacity. However, exchangeable sodium and potassium were not significantly influenced by zeolite application. There were 10.99%, 11.97%, and 9.74% increases in exchangeable Ca, Mg, and ECEC, respectively, compared to no-zeolite-conditioned soil. In addition, a significant ($P \leq 0.05$) decrease of 13.46% in exchangeable acidity was observed in zeolite-conditioned soil relative to soil with no zeolite. No significant interaction was observed between amendment and conditioner for all the exchangeable bases, exchangeable acidity and effective cation exchange capacity. Increased exchangeable cations, such as Ca and Mg, in soil that received zeolite could be attributed to zeolite's unique chemical properties, including high cation exchange capacity and strong cation affinity (Gholamhoseini et al., 2013; Jarosz et al., 2022).

The reduction in EA in soil conditioned with zeolite may be due to the increase in basic cations, especially Ca, which chelated these ions to decrease exchangeable acidity, exchangeable Al, and exchangeable Fe (Latifah et al., 2016). Furthermore, zeolite contains aluminosilicate, which may produce OH^- if hydrolysis occurs, OH^- is bound to acid cations as the acid cations decrease, soil pH increases and basic cations increase (Zaidun et al., 2019; Minardi et al., 2020). The increase in ECEC in soil amended with zeolite could be attributed to the zeolite's high cation exchange capacity. These results were consistent with the results obtained by Latifah et al. (2016); Zaidun et al. (2019); Minardi et al. (2020), who reported that the increase in ECEC with the application of zeolite could be attributed to the high ECEC of zeolite applied.

3.5 Effect of Amendment and Conditioner on Selected Soil Physical Properties of a Degraded Soil

Analysis of variance revealed that all organic amendments applied significantly ($P \leq 0.01$) improved the bulk density (BD), saturated hydraulic conductivity (Ksat), and soil moisture retentions at saturation (SAT), field capacity (FC), permanent wilting point (PWP) and plant available water content (PAWC) compared to the unamended soil in Table 7. Results showed a significant ($P \leq 0.01$) decrease in BD in soil amended with compost, poultry litter, cow dung, and biochar by 22.45%, 18.37%, 17.01%, and 8.84%, respectively, compared to unamended soil. The decrease in BD in all the amended soils with organic amendments could be attributed to the addition of OM from the application of organic materials (organic amendments), thereby increasing total pore spaces and lowering BD. Organic matter lowers soil bulk density; this occurs when soil mineral fractions (soil solid phase) are diluted with organic matter, thereby reducing the mass of soil solids per unit volume (Hudson, 1994; Zhou et al., 2020; Lawal & Adamu, 2022). The highest BD in unamended soil is observed due to the lowest organic carbon content as a result of mineral fertilizer application alone.

Saturated hydraulic conductivity (Ks) increases in soil amended with compost, poultry litter, cow dung, and biochar by 256.94%, 196.86%, 145.66%, and 80.80%, respectively, compared to unamended soil. Increased Ks in soils amended with compost and poultry litter may be due to increased total pore volume and pore-size distribution, and decreased bulk density and organic carbon content. All of the amended soils had improved Ks which could be attributed to the favorable distribution of pore spaces and improved aggregate stability when compared to the unamended soil (Alaboz et al., 2021; Feng et al., 2021; Kranz et al., 2023), also improved Ks enhances drainage system in the soil thereby reduces the risk of surface runoff and soil erosion (Layek et al., 2023). Therefore, the lowest Ks in unamended soil could be due to a decrease in total porosity, higher bulk density and low organic carbon content, which conferred poor soil structure.

Soil moisture retentions at saturation (SAT) increase in soil amended with compost, poultry litter, cow dung, and biochar by 72.39%, 16.58%, 62.82%, and 59.27% respectively compared to unamended soil, at field capacity (FC) in soil amended with compost, poultry litter, cow dung, and biochar by 82.03%, 53.24%, 78.67 and 72.04% respectively compared to unamended soil, at permanent wilting point (PWP) moisture content increase in soils amended with biochar, cow dung, compost, and poultry litter by 60.00%, 51.31%, 44.38%, and 0.15% respectively compared to unamended soil. The plant available water content (PAWC) increased in soil amended with compost, poultry litter, cow dung, and biochar by 126.81%, 115.83%, 111.25%, and 86.46%, respectively, relative to unamended soil. Generally, the increase in soil moisture retention at all the suction points in all the amended soils could be ascribed to high OM matter content of the amendments used in this study. Additionally, all the values of PAWC obtained in this study ranged from 0.20 - 0.25 m^3 m^{-3} for amended soils, indicating that all PAWC ≥ 0.20 m^3 m^{-3} are within "ideal" for optimal root growth and function (Hall et al., 1977; Cockroft & Olsson, 1997) while that of unamended soil (0.11 m^3 m^{-3}) is within the range of 0.10 ≤ PAWC< 0.15 m^3 m^{-3} which is "limited" for proper root growth (Hall et al., 1977; Warrick, 2002; White, 2006).

Table 7. Effect of amendment and conditioner on selected soil physical properties of degraded soil

			Soil Water Potential			
	BD	**Ksat**	**SAT**	**FC**	**PWP**	**PAWC**
	Mg m^{-3}	**cm day^{-1}**	**0**	**-33**	**-1500**	
			< ---------------------- KPa		-------------------------->	
			Volumetric moisture content (m^3 m^{-3})			
Amendment (A)						
Cow dung	1.22c	30.09ab	0.5785a	0.4276a	0.1967a	0.2309a
Compost	1.14d	43.31a	0.6125a	0.4356a	0.1877a	0.2479a
Biochar	1.34b	21.94bc	0.5659a	0.4117a	0.2080a	0.2038a
Poultry litter	1.17d	36.02ab	0.5211a	0.3667a	0.1302a	0.2359a
No amendment	1.47a	12.13c	0.3553b	0.2393b	0.1300a	0.1093b
SE±	0.017	6.992	0.04713	0.04279	0.03827	0.03869
SL	*	*	*	*	*	**
Conditioner (C)						
Zeolite	1.24b	30.84a	0.5613a	0.4067a	0.1853a	0.2214a
No zeolite	1.29a	27.27a	0.5036a	0.3557a	0.1606a	0.1951a
SE±	0.007	3.020	0.02035	0.01845	0.01653	0.01671
SL	*	NS	NS	NS	NS	NS
Interaction						
A X C	NS	NS	NS	NS	NS	NS

Means with the same letters within the same treatment group in a column are not statistically different at 5% probability level, = standard error, NS = not significant, * = significant at p ≤ 0.05, ** = significant at p ≤ 0.01, BD = bulk density, Ksat = saturated hydraulic conductivity, SAT=Saturation, FC=field capacity, PWP = permanent wilting point, PAWC = plant-available water content, SE± = Standard error, SL= Significance level.

The increase in PAWC for amended soils could be ascribed to high amounts of organic matter content, which enhances gradual water release due to the spongy nature of organic matter. Şeker & Manirakiza (2020), Haque et al. (2021), and Haftu et al. (2023) found that application of compost led to the reduction of erosion and runoff, and enhanced infiltration rate and water holding capacity of the soil. Also, improved moisture retention in soil amended with poultry litter and cow dung could be attributed to organic material particles of the manure entering large soil pores and creating more of smaller-diameter pores, which improved the soil water retention capacities and availability (Hudson, 1994; Feng et al., 2021; Alaboz et al., 2021). Similarly, improved moisture retention in soil amended with biochar may be ascribed to the nature of biochar in increasing soil micropores due to the high internal microporosity of biochar and because smaller biochar particles size can fill inter pores between coarse soil particles, which decreases the average pore size thereby allowing, small soil pores to hold more water against gravity than large soil pores (Blanco-Canqui, 2017; Botková et al., 2023; Layek et al., 2023), while lowest soil moisture retention in unamended soil was attributed to low organic carbon content due to sole application of mineral fertilizer (Alghamdi et al., 2020; Castellini et al., 2022).

The study revealed that the application of zeolite had no significant effect on all the evaluated soil physical properties except BD. Soil treated with zeolite had a 3.40% decrease in BD relative to no zeolite-conditioned soil. Though there was an increase in Ksat, SAT, FC, PWP and PAWC by 13. 09%, 11.46%, 14.34%, 15.58, and 13.48% respectively relative to no zeolite conditioned soil. Generally, an increase in total porosity as a result of zeolite application may be responsible for the decrease in bulk density due to the improved pore spaces in the soil system (Rosalina et al., 2019; El-Sherpiny et al., 2020). Razmi & Sepaskhah (2012) observed that application of 8 g of zeolite per kg of soil improved soil porosity and pore size, thus leading to an increase in saturated hydraulic conductivity, while a higher application rate of 12 g of zeolite per kg of soil had a negative impact on pore size and porosity of the soil, which led to a decrease in saturated hydraulic conductivity. Increase in soil moisture retention with zeolite application could be ascribed to the porous nature of zeolite, which retains more water and makes it available to crops (Karami et al., 2020; Ravali et al., 2020; Belviso et al., 2022) opined that a moderate rate of zeolites improves water-use efficiency by increasing the soil water-holding capacity and its availability to crops due to their extraordinarily porous structure and moderate quantity of zeolite applied.

4. Limitations and Future Directions

This study was conducted as a screen-house pot experiment, which limits root exploration, rainfall-driven hydrology processes, and long-term biogeochemical dynamics that would occur under field conditions. Therefore, extrapolation to on-farm degraded landscapes should be made cautiously.

The experiment evaluated a single zeolite dose (5 g kg^{-1} soil) and a single organic amendment rate (5 t ha^{-1}). Soil responses may differ under alternative application rates, different zeolite sources, and other organic residue qualities and decomposition stages. Future research should (i) test zeolite–amendment integration under field conditions across multiple degraded soil types and textures, (ii) evaluate additional zeolite rates and amendment quality gradients, and (iii) investigate longer-term outcomes on nutrient cycling and leaching.

5. Conclusions

Proper use of high-quality soil amendments, especially long-term organic amendments such as compost, as well as biochar, will enhance the performance of degraded soil in terms of nutrient status, water retention and fertility. The findings of this study show that application of organic amendments, particularly compost, effectively improved the chemical and physical properties of degraded soil, while zeolite demonstrated moderate effects by complementing the organic amendments in enhancing the soil fertility. The integration of organic amendments and zeolite offers a promising strategy for restoring soil quality, reducing nutrient leaching, and enhancing water retention and availability to sweet corn while achieving sustainable crop production and waste materials management practices. In order to establish conclusive evidence regarding the influence of the zeolite application doped with organic amendments on soil properties of degraded soil, it is necessary to know the nutritional composition status of organic amendments and zeolite for better sustainable restoration, conduct long-term trials on different types of soil as well as the different types of soil texture and structure for intensive maize cultivation.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the authors did not use any artificial intelligence (AI) tools in the writing, editing, or proofreading process and assume full responsibility for the content of the publication.

Authorship Contribution Statement

Auwal Bello Adamu: conceptualization, methodology, validation, sampling and formal analysis, investigation, data curation, writing original draft, visualization; Halima Mohammed Lawal: Supervision, methodology, writing - review & editing; Jabir Haruna Abdulkareem: Supervision, validation, writing - review & editing; Ayami Musa Modu: Zeolite synthesis and analysis, investigation, writing, review & editing; Sharhabil Musa Yahaya: validation, formal analysis, investigation, writing, review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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