Effect of Nano and Conventional Nitrogen Levels and Selected Soil Amendments on Some Soil Properties and Potato Yield

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Abstract

In 2025, a field experiment was conducted at Research Station (1), College of Agriculture, University of Anbar in Al-Buaitha area, Ramadi, Iraq during the spring season. The experiment is conducted in silty loam soil to investigate the effect of selected soil amendments (zeolite, perlite, organic residues of date palm fronds and date palm fronds biochar) each combined with 100% conventional nitrogen (C(n)), 50% conventional nitrogen (C(n)), 100% nano-nitrogen (N(n)) and 50% nano-nitrogen (N(n)). The experiment was set up in Randomized Complete Block Design (RCBD) with 3 replicates, making a total of 75 experimental units. This study was designed to investigate changes in selected soil chemical properties and their relationship to potato yield. The study aimed to evaluate these changes and their subsequent impact on potato production. The results indicated that biochar extracted from palm leaves significantly improved yield parameters, registering the highest average yield per plant (885.46 g/plant) and the highest total yield per experimental unit (21,251.2 kg), while reducing soil pH to 7.67 compared to other treatments. The organic residue from palm leaves resulted in the highest nitrogen concentration in the soil (122.67 mg/kg soil). The use of zeolite resulted in the highest cation exchange capacity (27.29 cmol/kg soil), reflecting its known role in enhancing soil nutrient retention. Regarding nitrogen treatments, the 100% application of nano-nitrogen resulted in superior performance, registering the highest average yield per plant (946.52 g/plant), total yield per experimental unit (22,716.8 kg), and soil nitrogen concentration (144.34 mg/kg of soil). In contrast, the 100% application of conventional nitrogen resulted in the lowest soil pH value (7.73) among the nitrogen treatments. Overall, the integration of nano-nitrogen, particularly at the full recommended dosage, with biochar or other effective soil amendments, has shown clear potential for improving soil fertility indicators and potato productivity in western Iraq.

Keywords: Soil Amendments, Potato, Nano-Nitrogen, Conventional Nitrogen.

Introduction

Soil amendments have become an essential component of modern soil management strategies, particularly in regions where soil degradation, salinity, and nutrient imbalance constrain agricultural productivity. In practical terms, soil amendments are materials incorporated into soil to correct unfavourable physical, chemical, or biological conditions that limit plant growth. These constraints may include salinity, alkalinity, compaction, poor structure, low fertility, or inadequate aeration and drainage. The strategic use of amendments contributes to improving soil aggregation, enhancing particle cohesion in sandy soils, while reducing excessive compaction in heavy clay soils, thereby promoting better water infiltration, aeration, and root penetration. Beyond structural improvement, soil amendments also play a

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significant role in modifying soil chemical properties. Their application can influence soil pH, mitigate the harmful effects of soluble salts, and enhance nutrient availability and retention. Amendments such as zeolite, biochar, and organic residues are particularly recognized for their capacity to improve cation exchange capacity and nutrient-use efficiency. Moreover, organic and biologically active amendments stimulate soil microbial communities, accelerating organic matter decomposition and nutrient cycling processes. These integrated effects ultimately support sustainable soil management and improved crop productivity, especially under arid and semi-arid conditions where soils are often fragile and environmentally stressed [1].

Nitrogen, on the other hand, remains one of the most critical macronutrients governing plant growth and productivity. It is a fundamental constituent of amino acids, proteins, nucleic acids, and chlorophyll, making it indispensable for vegetative growth and photosynthetic activity. In potato (*Solanum tuberosum* L.), nitrogen plays a decisive role in canopy development and leaf area expansion, which directly determine the plant's photosynthetic capacity and subsequent carbohydrate accumulation required for tuber formation. Adequate nitrogen supply enhances leaf area index, improves radiation interception, and ultimately increases both yield quantity and quality. It also influences tuber size, number, protein content, and overall physiological vitality.

However, nitrogen management in potato cultivation requires careful balance. Excessive nitrogen application often stimulates luxuriant vegetative growth at the expense of tuber development, delays maturity, and may increase susceptibility to certain diseases. Conversely, nitrogen deficiency leads to stunted growth, chlorosis, reduced leaf expansion, and significant yield decline. Therefore, optimizing nitrogen fertilization—both in terms of source and rate—remains a key determinant of achieving high productivity and maintaining tuber quality [2].

In recent years, the emergence of nano-fertilizers has introduced new perspectives in nutrient management. Nano-nitrogen formulations are designed to enhance nutrient-use efficiency through controlled release mechanisms and improved plant uptake dynamics. Their integration with effective soil amendments may represent a promising approach to improving soil fertility indicators while reducing nutrient losses, particularly under the calcareous and semi-arid soil conditions prevalent in western Iraq.

The application of nano-nitrogen represents one of the most recent advances in fertilizer technology. Unlike conventional nitrogen fertilizers, nano-formulations are characterized by extremely small particle size and a markedly larger surface area, properties that enhance nutrient reactivity and uptake efficiency. This structural advantage allows for a more controlled and gradual release of nitrogen, thereby improving nitrogen use efficiency within the plant system. Consequently, nitrogen losses through leaching or volatilization are reduced, and nutrient availability is sustained for longer periods during critical growth stages. Several studies have reported that nano-nitrogen fertilization enhances vegetative growth, stimulates chlorophyll synthesis, and promotes protein formation, leading to improved photosynthetic performance and, ultimately, higher yield and better crop quality [3].

Potato (*Solanum tuberosum* L.) belongs to the Solanaceae family and is classified as a major tuber crop of global importance. It ranks fourth in economic and nutritional significance after wheat, rice, and maize, underscoring its pivotal role in global food security. As a staple food in many regions, potato provides a rich source of carbohydrates, starch, high-quality proteins, essential amino acids, and important minerals required for human nutrition [4]. Its relatively short growth cycle and high productivity per unit area further enhance its strategic agricultural value.

Given the increasing need to improve nutrient use efficiency under challenging soil conditions, integrating organic and mineral soil amendments with advanced nitrogen fertilization strategies may offer a promising pathway toward sustainable productivity. Therefore, the present study aimed to evaluate the combined effects of selected organic and mineral soil amendments and different levels of nano and conventional nitrogen fertilizers on selected soil properties and potato yield under field conditions.

Material and Methods

Study Site and Land Preparation

The field experiment was conducted during the spring growing season of 2025 at Agricultural Research Station No. (1), College of Agriculture, University of Anbar, located in Ramadi District, Anbar Province, Iraq. The experimental site lies at 33.453749° N latitude and 43.326599° E longitude. The soil of the study area is classified as silty loam (Silt Loam) according to the USDA textural classification system.

Prior to planting, composite soil samples were collected from the surface layer (0–30 cm) at several points across the field to ensure representativeness. The samples were air-dried, gently crushed, and passed through a 2-mm sieve for the determination of selected physical and chemical properties. The baseline characteristics of the soil before planting are presented in Table (1).

Land preparation included primary tillage using a mouldboard Plow to a depth of approximately 30 cm, followed by harrowing to break clods and achieve a fine tilth suitable for tuber development. The field was then carefully levelled and divided into three uniform blocks. Planting was carried out on ridges 6 m in length and 0.75 m in width. The experimental layout consisted of 75 experimental units. To minimize nutrient movement and prevent treatment interference, a 1 m buffer zone was maintained between adjacent plots and a 2 m between blocks.

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Table 1. Selected physical and chemical properties of the experimental soil before planting.

Unit	Value	Property	Unit	Value	Property
$Mg\ m^{-3}$	1.30	Bulk density	$dS\ m^{-1}$	3.22	Electrical conductivity (EC)
$Mg\ m^{-3}$	2.54	Particle density	—	7.80	Soil pH
%	22.5	Sand	$g\ kg^{-1}$	6.30	Organic matter
%	61.5	Silt	$g\ kg^{-1}$	125.0	Calcium carbonate ($CaCO_3$)
%	16.0	Clay	$g\ kg^{-1}$	5.20	Gypsum
—	Silty loam	Soil texture class	$mg\ kg^{-1}$	25.0	Available nitrogen
$cmol\ kg^{-1}$ soil	18.0	Cation exchange capacity (CEC)	$mg\ kg^{-1}$	9.5	Available phosphorus
—	—	—	$mg\ kg^{-1}$	180.0	Available potassium

Experimental Factors and Experimental Design

The experiment was conducted using a Randomized Complete Block Design (RCBD) in a factorial arrangement to evaluate the interaction between nitrogen fertilization strategies and selected soil amendments. The first factor consisted of nitrogen source and level, including four fertilization treatments in addition to an unfertilized control. These treatments were: 100% conventional nitrogen (N_1), 50% conventional nitrogen (N_2), 100% nano-nitrogen (N_3), 50% nano-nitrogen (N_4), and a control treatment without nitrogen addition (N_0). The application rates were calculated based on the locally recommended nitrogen requirement for potato production under similar soil and climatic conditions.

The second factor included soil amendments applied at a rate of 5 Mg ha^{-1}. The amendments comprised zeolite (A_1), perlite (A_2), date palm frond residues (A_3), and biochar derived from date palm fronds (A_4), in addition to a non-amended control (A_0).

The combination of the five nitrogen treatments and five amendment treatments resulted in 25 treatment combinations. Each treatment was replicated three times, yielding a total of 75 experimental units (25 × 3). Treatments were randomly distributed within each block to minimize spatial variability and experimental error [5].

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The nano-chelated nitrogen fertilizer used in this study was supplied by KHADRA Company, specialized in nano-fertilizer production. The product contained 17% nitrogen in nano-chelated form and was applied according to the designated treatment levels.

Table 2. Selected chemical properties of amendments

Unit	Date palm biochar	Date palm frond residues	Perlite	Zeolite	Property
dS m^{-1}	7.5	10.0	1.32	0.68	EC
—	7.3	7.4	6.5–7.5	7.60	pH
cmol kg^{-1}	43.0	21.7	24.1	74.2	CEC
%	5.60	8.13	—	—	Total N
mg kg^{-1}	6.10	3.50	—	—	Available P
mg kg^{-1}	112.28	220.8	—	—	Available K

Crop Planting and Management

Planting: Potato tubers of the Burren variety were planted on January 25, 2025. Tubers were harvested two weeks prior to planting to break dormancy. Only visually healthy tubers, free from mechanical damage or decay, were selected for planting. Tubers were planted in a single row per experimental unit at a spacing of 25 cm between tubers, with 24 tubers per experimental unit.

Crop Management: Irrigation: Irrigation was applied using a fixed sprinkler system to maintain soil moisture in the root zone at near field capacity. The irrigation schedule was adjusted based on water loss measured by an evaporation pan [6].

Weeding: Manual weeding was performed whenever necessary to maintain weed-free conditions in the experimental plots.

Disease Control: Late blight (Phytophthora infestans) was controlled using a protective fungicide applied in two sprays: the first spray 45 days after emergence, followed by a second spray 10 days later to prevent initial infections.

Measured Parameters: Yield per Plant (kg $plant^{-1}$):

Yield per plant was calculated from the total yield of the experimental unit using the following formula:

$$\text{Yield per plant } (kg\ plant^{-1}) = \frac{\text{Total yield of the experimental unit } (kg)}{Number \text{ of plants in the experimental unit } (kg)}$$

$$\text{Total yield of the experimental unit } (kg) = \text{yield per plant} \times \text{Number of Plants}$$

Nitrogen: Total nitrogen in soil samples was determined using the micro-Kjeldahl method after digestion with 10 M sodium hydroxide (NaOH), followed by titration with 0.04 N hydrochloric acid (HCl) [7].

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Soil pH: Soil pH was measured in a 1:1 soil-to-water suspension using a pH meter, following the method described by [8].

Cation Exchange Capacity (CEC): CEC of the soil was determined using the ammonium acetate or sodium oxalate extraction method as described by [7].

Results and Discussion

Yield per Plant (g plant^{-1})

The results presented in Table (3) demonstrate the effect of soil amendments, nitrogen levels (nano and conventional), and their interaction on yield per plant of potato. Statistical analysis revealed significant differences among all amendment treatments. Biochar derived from date palm residues (A_4) recorded the highest mean yield per plant (885.46 g plant^{-1}), significantly outperforming the non-amended control (A_0), which produced the lowest mean value (673.20 g plant^{-1}). This represents an increase of 31.53% over the control treatment.

The positive response associated with biochar application may be attributed to its role in improving soil structure, increasing cation exchange capacity, and enhancing nutrient retention, particularly under silty loam soils characterized by moderate salinity and relatively low organic matter content. Biochar's porous structure likely contributed to improved root development and nutrient availability, which ultimately translated into greater assimilate production and tuber filling.

Table 3. Effect of some soil amendments and levels of nano and conventional nitrogen on yield per plant (g plant^{-1})

Mean (N)	A_4 (Biochar)	A_3 (Organic residues)	A_2 (Perlite)	A_1 (Zeolite)	A_0 (Control)	Nitrogen Levels
606.32	628.70	641.30	582.00	604.30	575.30	N_0 (Control)
845.88	1020.70	840.70	764.00	895.70	708.30	N_1 (100% Urea)
702.20	694.30	764.00	646.00	739.70	667.00	N_2 (50% Urea)
946.52	1179.30	972.30	805.00	1034.30	741.70	N_3 (100% Nano-N)
760.60	904.30	806.00	621.70	797.30	673.70	N_4 (50% Nano-N)
	885.46	804.86	683.74	814.26	673.20	Mean (A)
N*A		A		N		LSD 0.05
112.96		50.52		50.52		

Regarding nitrogen treatments, significant differences were also observed among the various nitrogen levels. The treatment N_3 (100% nano-nitrogen) achieved the highest mean yield per plant (946.52 g plant^{-1}), compared with the control treatment (N_0),

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which recorded the lowest mean value (606.32 g plant^{-1}). This corresponds to an increase of 56.11%. The superior performance of nano-nitrogen may be explained by its enhanced nutrient-use efficiency, controlled release behaviour, and reduced nitrogen losses, which together improve nitrogen availability during critical growth stages, particularly canopy development and tuber initiation.

The interaction between soil amendments and nitrogen treatments was statistically significant. The combined treatment of biochar with 100% nano-nitrogen (A_4 N_3) recorded the highest yield per plant (1179.30 g plant^{-1}), compared with the absolute control (A_0 N_0), which produced 575.30 g plant^{-1}. This represents an increase of 104.99%.

Yield per Experimental Unit

The results presented in Table (4) illustrate the effect of soil amendments, nano and conventional nitrogen levels, and their interaction on yield per experimental unit of potato. The analysis revealed significant differences among all types of soil amendments. The biochar treatment (A_4) recorded the highest mean yield per experimental unit, reaching 21,251.2 kg, compared with the control treatment (A_0), which produced the lowest mean value of 16,156.8 kg, representing an increase of 31.53%.

The results further indicated significant differences among the nitrogen levels. The treatment N_3 (100% nano-nitrogen) achieved the highest mean yield per experimental unit (22,716.8 kg), whereas the control treatment (N_0) recorded the lowest mean value (14,552.0 kg), with a percentage increase of 56.11%.

A significant interaction effect between soil amendments and nitrogen levels was also observed. The combined treatment of biochar with 100% nano-chelated nitrogen (A_4 N_3) recorded the highest yield per experimental unit, reaching 28,304.0 kg, compared with the control treatment (A_0 N_0), which produced 13,808.0 kg, representing an increase of 104.98%.

Table 4. Effect of some soil amendments, formulas and levels of nitrogen on the yield of the experimental unit (kg)

Mean (N)	A_4 (Biochar)	A_3 (Organic residues)	A_2 (Perlite)	A_1 (Zeolite)	A_0 (Control)	Nitrogen Levels
14552.0	15088.0	15392.0	13968.0	14504.0	13808.0	N_0 (Control)
20300.8	24496.0	20176.0	18336.0	21496.0	17000.0	N_1 (100% Urea)
16852.8	16664.0	18336.0	15504.0	17752.0	16008.0	N_2 (50% Urea)
22716.8	28304.0	23336.0	19320.0	24824.0	17800.0	N_3 (100% Nano-N)
18254.4	21704.0	19344.0	14920.0	19136.0	16168.0	N_4 (50% Nano-N)

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	885.46	804.86	683.74	814.26	673.20	Mean (A)
N*A		A		N		LSD 0.05
2710.9		1212.4		1212.4		

The results presented in Tables (3) and (4) clearly show the superiority of biochar in both yield per plant and yield per experimental unit. This superiority can be attributed to the fundamental role of biochar in several biogeochemical processes within the soil. Biochar is characterized by a high negative surface charge and a large specific surface area (Table 2), which enhances its capacity to adsorb nutrients onto its particle surfaces. These properties enable biochar to create oxidized surfaces capable of attracting and retaining cations more effectively, thereby improving nutrient availability to plants [9].

The superior performance of nano-nitrogen can be attributed to the distinctive characteristics of nano-fertilizers. Compared with conventional fertilizers, nano-nitrogen formulations decompose more slowly, which delays the nitrification process and the transformation of ammonium into nitrite and subsequently nitrate. In addition, nano-fertilizers possess unique chemical and physical properties that enhance nutrient availability and improve the synchronization between nutrient release and root demand. This results in more efficient nutrient utilization compared with traditional mineral fertilizers. Furthermore, the higher concentration applied in treatment N_3 resulted in greater yield compared with N_4 [10].

Soil Nitrogen Concentration (mg N kg^{-1} soil)

The results presented in Table (5) demonstrate the effect of soil amendments, nano and conventional nitrogen levels, and their interaction on soil nitrogen concentration under potato cultivation. Significant differences were observed among all types of soil amendments. The treatment involving the addition of date palm organic residues (A_3) recorded the highest mean soil nitrogen concentration (97.67 mg N kg^{-1} soil), compared with the control treatment (A_0), which showed the lowest mean value (66.13 mg N kg^{-1} soil), representing an increase of 47.69%.

Table 5. Effect of some soil amendments, formulations and levels of nitrogen on the concentration of nitrogen in the soil (mg N kg^{-1} soil)

Mean (N)	A_4 (Biochar)	A_3 (Organic residues)	A_2 (Perlite)	A_1 (Zeolite)	A_0 (Control)	Nitrogen Levels
28.60	29.33	39.33	27.67	27.33	19.33	N_0 (Control)
103.27	112.67	120.33	94.67	99.67	89.00	N_1 (100% Urea)
79.53	91.33	89.33	76.67	87.33	53.00	N_2 (50% Urea)

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119.33	125.00	128.67	116.67	126.67	99.67	N_3 (100% Nano-N)
96.27	107.00	110.67	97.33	96.67	69.67	N_4 (50% Nano-N)
	93.07	97.67	82.60	87.53	66.13	Mean (A)
N*A		A		N		LSD 0.05
5.935		2.654		2.654		

The superiority of the organic residue treatment can be attributed to its role in improving soil aeration, enhancing soil water-holding capacity, and increasing the availability of N, P, and K through mineralization of organic matter and subsequent nutrient release. In addition, the formation of organo-mineral complexes may reduce nutrient fixation and protect nitrogen from leaching through adsorption onto particle surfaces [11].

The results further indicated significant differences among the nitrogen levels. Treatment N_3 (100% nano-nitrogen) achieved the highest mean soil nitrogen concentration (119.33 mg N kg^{-1} soil), whereas the control treatment (N_0) recorded the lowest mean value (28.60 mg N kg^{-1} soil), with a percentage increase of 317.24%. The increased nitrogen availability from the nano source may be attributed to the slow-release characteristics of nano-fertilizers and their unique chemical and physical properties, which enhance nutrient availability and improve synchronization with plant root demand compared with conventional fertilizers, particularly through ion exchange processes [12].

A significant interaction effect between soil amendments and nitrogen levels was also observed. The combined treatment of date palm organic residues with 100% nano-chelated nitrogen ($A_3 N_3$) recorded the highest soil nitrogen concentration (128.67 mg N kg^{-1} soil), compared with the control treatment ($A_0 N_0$), which showed 19.33 mg N kg^{-1} soil, representing an increase of 565.65%.

Soil Reaction (pH)

The results presented in Table (5) indicate a significant effect of soil amendments, nano and conventional nitrogen levels, and their interaction on soil pH under potato cultivation. Significant differences were observed among all amendment treatments. The biochar treatment (A_4) recorded the lowest mean soil pH (7.67), compared with the control treatment (A_0), which showed the highest mean value (7.95), representing a decrease of 3.52%.

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Table 6. Effect of some soil amendments and formulations and levels of nano and conventional nitrogen on soil pH

Mean (N)	A_4 (Biochar)	A_3 (Organic residues)	A_2 (Perlite)	A_1 (Zeolite)	A_0 (Control)	Nitrogen Levels
7.95	7.63	7.97	8.00	8.07	8.10	N_0 (Control)
7.73	7.47	7.43	8.00	7.93	7.83	N_1 (100% Urea)
7.83	7.90	7.63	7.80	7.87	7.93	N_2 (50% Urea)
7.85	7.67	7.73	8.00	7.83	8.00	N_3 (100% Nano-N)
7.88	7.70	8.17	7.87	7.77	7.90	N_4 (50% Nano-N)
	7.67	7.79	7.93	7.89	7.95	Mean (A)
N*A		A		N		LSD 0.05
0.303		0.136		0.136		

This reduction in soil pH may be attributed to the decomposition of biochar as an organic source, which leads to the release of CO_2 and organic acids that contribute to lowering soil pH [13].

The results also revealed significant differences among nitrogen treatments. Treatment N_1 recorded the lowest mean soil pH (7.73), whereas the control treatment (N_0) showed the highest mean value (7.95), representing a decrease of 2.77%. This reduction can be explained by the effect of nitrogen fertilization on soil reaction. Nitrogen fertilizers, particularly those containing ammonium, tend to increase soil acidity. This occurs through chemical and biological transformations in the soil, where ammonium is converted to nitrate by soil bacteria, releasing hydrogen ions and consequently increasing soil acidity [14].

Furthermore, the interaction between soil amendments and nitrogen levels was statistically significant. The combined treatment of biochar with 100% conventional nitrogen ($A_4 N_1$) recorded the lowest soil pH value (7.47), compared with the control treatment ($A_0 N_0$), which showed a value of 8.10, representing a decrease of 7.78%.

Cation Exchange Capacity (CEC)

The statistical analysis presented in Table (7) showed the effect of soil amendments, nano and conventional nitrogen levels, and their interaction on cation exchange capacity (CEC) in soil cultivated with potato. Significant differences were observed among all soil amendment treatments. The zeolite treatment (A_1) recorded the highest mean CEC value (27.29 cmol kg^{-1} soil), compared with the control treatment (A_0), which showed the lowest mean value (16.43 cmol kg^{-1} soil), representing an increase of 66.09%.

Table 7. Effect of some soil amendments and formulations and levels of nano and conventional nitrogen on the cation exchange capacity (cmol kg^{-1} soil)

Mean (N)	A_4 (Biochar)	A_3 (Organic residues)	A_2 (Perlite)	A_1 (Zeolite)	A_0 (Control)	Nitrogen Levels
21.08	22.87	21.88	16.89	27.54	16.22	N_0 (Control)
21.24	22.89	20.34	18.80	27.65	16.53	N_1 (100% Urea)
21.93	24.88	23.59	16.74	27.51	16.93	N_2 (50% Urea)
21.61	24.94	22.66	16.94	27.29	16.24	N_3 (100% Nano-N)
21.56	23.60	22.67	18.80	26.46	16.26	N_4 (50% Nano-N)
	23.83	22.23	17.63	27.29	16.43	Mean (A)
N*A		A		N		LSD 0.05
1.612		0.721		N.S		

The increase in CEC can be attributed to the inherent properties of zeolite, which possesses a high cation exchange capacity due to its distinctive silicate framework structure. This structure contains open cavities in the form of channels occupied by water molecules and exchangeable cations such as sodium and calcium. These cations are largely exchangeable, contributing to the high CEC of zeolite-amended soils [15].

The results further indicated that there were no significant differences among the nano and conventional nitrogen levels, when supported by soil amendments, in their effect on CEC.

However, a significant interaction effect between soil amendments and nitrogen levels was observed. The combined treatment of zeolite with 100% conventional nitrogen ($A_1 N_1$) recorded the highest CEC value (27.65 cmol kg^{-1} soil), compared with the control treatment, which showed the lowest mean value (16.22 cmol kg^{-1} soil), representing an increase of 70.47%.

Conclusion

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The results indicate that biochar had a significant effect on increasing both the yield per plant and the yield per experimental unit, demonstrating its effectiveness in improving plant growth and productivity. Zeolite, on the other hand, excelled in cation exchange capacity, indicating its high capacity for nutrient retention and soil fertility improvement. Palm kernel residues also demonstrated superiority in increasing soil nitrogen concentration, reflecting their role in enhancing soil nutrient content. Furthermore, 100% concentration nano-nitrogen achieved a clear advantage in both the yield per plant and the yield per experimental unit, as well as in soil nitrogen concentration, confirming its high efficacy in improving growth and productivity and increasing soil nitrogen levels.

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