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Zeolite as a component of INM in enhancing nutrient mineralization and enzyme activities in an Ultisol

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Abstract

In modern agricultural practices, there is a growing interest to optimize fertilizer usage to improve crop productivity and minimize environmental impact with special emphasis on soil carbon. In this study, the effect of slow-release fertilization characteristics of zeolites on soil carbon mineralization, enzyme activities and available NPK contents were investigated. A three month period incubation study at ambient temperature and constant soil moisture conditions was conducted in laterite soil with 27 treatments consisting of three commonly available organic manures (farm yard manure (FYM), vermi compost (VC), leaf manure (LM) and three different levels of near neutral zeolites, specifically the grade Zeolite 4A (@ 0, 1 and 2%, w/w) and fertilizer doses (@ 100% NPK, 75% NPK and 50% NPK corresponds to cassava crop with a recommended dose of 100:50:100 kg NPK per hectare). Addition of NPK fertilizers from 50% to 100% decreased the mean carbon mineralization activity and increasing levels of zeolites from 1% to 2% increased the carbon mineralization rates (3.39 as against 6.64 g CO_2 per kg soil). Among the organic manures, leaf manure had higher carbon mineralization rate (5.70 g CO_2 per kg soil). The NPK @ 50% and 2% zeolite treated soils under vermi compost showed maximum activity of soil dehydrogenases (up to 42.99 μg TPF g^{-1} 24 h^{-1}). Fertilizer and zeolite at 75% NPK and 1% doses respectively, registered the maximum acid phosphatase activity (1.258 μg pnp $g^{-1}h^{-1}$). NPK fertilizers additions from 50% to 100% increased the soil available nitrogen content (127.97 to 136.67 kg ha^{-1}). Maximum content of mean available K was found with 50% NPK and 1% zeolite treatments.

Keywords: Zeolites, Carbon mineralization, Soil dehydrogenases, Organic manures

Introduction

The sustainability of agricultural systems largely depends on the effective management of soil fertility, nutrient dynamics, and soil health. Conventional fertilizers, while vital for meeting the nutrient demands of crops, often lead to nutrient losses through leaching, volatilization, and runoff, causing environmental pollution and reduced nutrient use efficiency. Slow-release fertilizers (SRFs) offer a promising alternative by releasing nutrients gradually, aligning with crop uptake patterns, and minimizing losses. Use of slow-release fertilizers which deliver nutrients more gradually than commercial fertilizers is very crucial to boost nutrient use efficiency and minimize environmental effects. This slow release encourages improved nutrient delivery to the plants, which speeds up early germination, rapid development, and a high nutritional level .Among the diverse materials used in SRF formulations, zeolites, a class of naturally occurring aluminosilicates minerals, have garnered attention due to their exceptional ion-exchange capacity, porosity, and ability to adsorb and desorb nutrients

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besides water absorption and retention benefits.In this regard, the use of natural zeolites (crystalline hydrated aluminosilicates) and artificial zeolites (crystalline sodium aluminosilicates) is crucial not only to increase the fertilizer use efficiency of crops but also to combat the adverse effects of chemical fertilizer on agriculture ecosystems. Zeolites are naturally occurring, alkaline-hydrated alumina silicates with a wide range of applications in agriculture such as modifier of soil physical properties, enhancing water and nutrient retention and fertilizer use efficiency due to high cation exchange capacity and has a positive influence in carbon storage. Their high surface area, large porosity, ion exchange property, and high nutrients loading capacity make them important materials in agriculture as nutrient carriers and slow releaser. Zeolites, with or without surfactant modification, have a special porous structure that allows them to efficiently hold nutrients and water. In addition, zeolites emerge as potential soil ameliorating agents, possess superior nutrient and water capturing capacity, cation exchange potential, and better water capture from seepages (Ferretti et al. 2020, 2022; Galamini et al. 2020; Medoro et al. 2022, Jha and Singh, 2016; Sarkar and Naidu, 2015). Soil application of zeolites in combination with chemical fertilizers reduces nitrogen leaching and volatilization by slowing down the mineralization process and subsequent reduction in greenhouse gases (GHGs) emission. Zeolites have remarkable role in agriculture, medical and environmental protection fields (Ayesha et al. 2024). Zeolites are good fertilizers as well as functioning as chelating substances; they decrease the rapid release of nutrients from fertilizer to provide consistent availability of nutrients throughout the growth phases. Zeolite does not break down over time but remains in the soil to improve nutrient retention. Therefore, its addition to the soil may significantly reduce water and fertilizer costs by retaining beneficial nutrients in the root zone. The porous structure of natural zeolite helps keep the soil aerated and moist as well as active for a long time (Yasuda et al. 1998).

Ultisols, characterized by their low fertility, high acidity, and poor nutrient-holding capacity, are particularly responsive to interventions aimed at improving soil nutrient availability and health. Incorporating zeolite-based fertilizers into these soils could address nutrient deficiencies while influencing key soil biological and biochemical processes. Carbon in agricultural soils are the major sink as well as source of carbon dioxide emission from/to the atmosphere thereby play a significant role in impacting climate change especially in view of temperature rise. Increased temperature may lead to more rapid breakdown of soil organic matter and even small increases in temperature may prompt large releases of C from soils (Conant et al. 2008). Modelling studies and data-based predictions indicated a C release of 11.1 to 33.8 Pg C from soil organic matter (SOM) for a one-degree centigrade increase in global mean annual temperature. Native carbon is stored in soil as soil organic matter is protected in micro aggregates, fungal hyphae etc. The added carbon especially easily decomposable fraction (labile C) is subjected to loss and needs to be properly conserved (sequestered). Considering the multiple benefits of zeolites as slow release fertilizer actions and carbon conservation, this study was undertaken to find out its effect in tropical laterite soils. The study aims to evaluate the characteristics of zeolite-based slow-release fertilizers and their impact on soil carbon mineralization; estimate the changes in soil quality in different treatments involving different types of organic manures, zeolites and NPK fertilizer doses and assessing the relationship in soil variables with the C mineralization in Ultisols

Materials and Methods

Soil sampling and preparation

Bulk soil samples were collected from the surface layer (0-15 cm) of an Ultisol from a field at Block I of the institute farm of ICAR-Central Tuber Crops Research Institute (CTCRI). The collected soil was air-dried, sieved (<2 mm), and thoroughly mixed to ensure homogeneity. Initial soil properties, including pH, available nitrogen (N), phosphorus (P), and potassium (K), were analyzed using standard methods. The treatments consisted of three types of organic manures (Farmyard manure, vermicompost, and leaf manure). These were composted materials and prepared from dried leaf wastes and available as dark brown coarse powder which were sieved with 2 mm sieve and used for the study each @ 12 t ha^{-1}, three levels of zeolite 4A (0%, 1% and 2% w/w), and three fertilizer doses (100%, 75% and 50% of the recommended dose of NPK for cassava corresponding to 100:50:100 kg of NPK. Thus, a total of 27 treatments were replicated twice in a completely randomized design, consisting of all possible combinations of organic manure types, zeolite levels, and fertilizer doses.

Incubation Study

An incubation study was conducted with the above treatments involving organic manures, zeolites and fertilizers in 500 g of soil kept in incubation containers and maintained at 50% water-holding capacity (WHC) and at ambient temperature throughout the study period of 90 days. Carbon mineralization was assessed using the Alkali Trap Method (Anderson, 1982) by trapping evolved CO_2 in NaOH and quantifying it via titration with HCl. Soil dehydrogenase activity was measured using the TTC Reduction Method (Casida et al. 1964), where formazan produced was extracted with methanol and quantified spectrophotometrically at 485 nm. Acid phosphatase activity was determined using the p-nitrophenyl phosphate method (Tabatabai and Bremner, 1969), measuring p-nitrophenol released spectrophotometrically at 410 nm. Soil pH was analyzed in a 1:2.5 soil water suspension using a pH meter, while available NPK were determined using the micro diffusion method for nitrogen, the Olsen method for phosphorus (initial soil), and flame photometry for potassium. Observations for carbon mineralization at monthly intervals, enzyme activities, soil pH and nutrient availability were estimated during the incubation period. Results were interpreted to evaluate the impact of organic manures, zeolite levels, and fertilizer doses on soil health indicators.

Statistical analysis

Data were subjected to ANOVA and least significant difference (LSD) tests at a 5% probability level to evaluate treatment effects and student's t-test analysis was used to assess relationships between soil properties, enzyme activities, and carbon mineralization using the WASP 2.0 statistical software (ICAR-CCARI, Goa).

Results and Discussion

Initial soil, manure and zeolite properties

The soil used for the study was characterized as a sandy clay loam texture, with sand, silt, and clay fractions of 60%, 15%, and 25%, respectively. The pH of the soil was moderately acidic, indicating that it is likely to pose challenges for nutrient availability, particularly for macronutrients like phosphorus. Soil organic carbon (SOC) content was measured as 0.76%, reflecting a high organic matter status typical of tropical soils under continuous cropping. The available nitrogen, phosphorus, and potassium levels were 124, 56.2 and 436.4 kg ha^{-1}, respectively. While potassium was present at a high level, low levels of nitrogen and very high phosphorus were potentially limiting plant growth if not supplemented adequately.

The bulk density of soil was recorded as 1.54 Mg m^{-3}, indicative of a moderately compact soil, which may affect root penetration and water movement. The water holding capacity (WHC) was 36%, and the porosity (Po) was 38%, showing reasonable soil aeration and moisture retention capacity, though these characteristics could still be limiting for certain crops during periods of water stress. These baseline properties provided the foundation for evaluating the impact of the applied treatments on carbon mineralization, enzyme activities, and nutrient availability during the incubation study.

The pH values of the organic manures used in the study were slightly acidic to near neutral, reflecting their suitability for application in moderately acidic soils like the Ultisol under investigation. Farmyard manure (FYM) had a pH of 6.69, which was the highest among the three manures, indicating its potential to buffer soil acidity effectively. Vermicompost (VC) exhibited a similar pH of 6.67, suggesting that it can also contribute to mitigating soil acidity while providing essential nutrients. Leaf manure (LM) had a relatively lower pH of 6.34, indicating a slightly higher acidic nature compared to FYM and VC. Despite its lower pH, LM is expected to improve soil organic carbon content and microbial activity upon decomposition. Like-wise, the zeolite powder used in the study showed a loam texture, bulk density of 1.13 Mg m^{-3}, cation exchange capacity (CEC) of 186 cmol(p+) kg^{-1} and pH of 7.4. The NPK contents (%) of the three organic manures *viz.* FYM, VC and LM were found to be 0.7-0.35-0.5, 1.1-0.6-1.0 and 0.5-0.27-0.80, respectively.

These initial pH values highlight the varying acid-neutralizing capacities of the organic amendments, which are crucial for managing soil acidity and enhancing nutrient availability during the incubation study. The application of these organic manures, along with zeolite, was anticipated to create a more favorable pH environment for nutrient release and microbial activity, supporting improved soil health and productivity.

Table 1. Influence of treatments on carbon mineralization capacity (g CO_2 per kg soil)

Treatment	Soil+FYM	Soil+VC	Soil+LM
Mean (Manure level)	5.24	5.51	5.70
Fertilizer level			
50%	4.77	4.93	6.09
75%	6.03	6.01	6.56
100%	4.95	5.57	4.45
Zeolite level			
0%	3.14	3.19	3.85
1%	6.58	6.49	6.22
2%	6.03	6.84	7.04

CD (p = 0.05)
Manure/Fertilizer/Zeolite level (Main effect) = 0.092
Manure/Fertilizer/Zeolite level (Interaction) = 1.594

Carbon pools

The study evaluated the total carbon (TC) and different carbon fractions, including very labile carbon (VLC), labile carbon (LC), less labile carbon (LL), and recalcitrant carbon (RC), in the soil and the organic amendments used and the details are presented in Fig. 1. The native soil exhibited a total carbon content (TC) of 1.47%, with VLC, LC, LL, and RC fractions contributing 0.35%, 0.25%, 0.096%, and 0.77%, respectively. The dominance of recalcitrant carbon indicates a significant portion of stable carbon in the soil, which is resistant

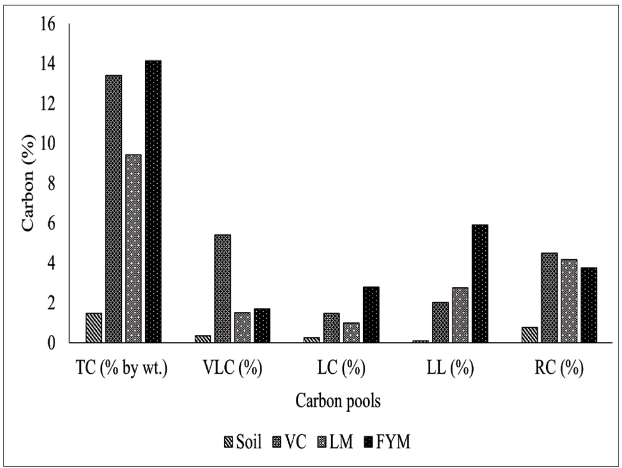

Fig.1. Different Carbon pools in incubated soil and materials used in incubation

to decomposition and essential for long-term carbon storage. However, the low labile fractions highlight limited readily decomposable organic carbon in the soil.

Among the organic amendments, farmyard manure had the highest TC at 14.13%, followed by vermicompost (13.39%) and leaf manure (9.42%). The carbon fraction distribution revealed significant variations. Vermicompost exhibited the highest VLC (5.4%), suggesting its potential for rapid carbon mineralization and immediate microbial energy supply. Farmyard manure showed a higher proportion of LC (2.79%) and LL (5.90%), indicating moderate decomposition potential and a sustained release of nutrients. Leaf manure, with a lower VLC (1.5%) and relatively higher LL (2.76%) and RC (4.17%), reflected its potential for both medium-term and long-term carbon stabilization in soil.

These results highlight the differential roles of organic amendments in contributing to the soil carbon pool. Vermicompost provides a quick carbon and energy source for microbial activity, whereas Farmyard manure and leaf waste contribute to both immediate and long-term carbon sequestration. Integrating these amendments with soil can balance carbon turnover and sequestration, fostering improved soil health and fertility.

Carbon mineralization

The effects of different combinations of organic manures, fertilizer levels, and zeolite levels on different soil properties were evaluated, with results highlighting significant interactions and main effects (Table 1). The mean values for treatments with different organic manures showed that soil amended with leaf manure (LM) recorded the highest average value of carbon mineralisation rate (5.70 g CO_2 per kg soil), followed by vermicompost (VC) at 5.51, and Farmyard manure (FYM) at 5.24. This indicates that LM had the most pronounced impact, possibly due to its higher proportion of less labile and recalcitrant carbon contributing to sustained soil health improvements.

The effect of fertilizer levels was consistent across manure types. At 50% of the recommended dose of NPK fertilizer, treatments with LM exhibited the highest value (6.09 g CO_2 per kg soil), followed by VC (4.93) and FYM (4.77). At 75% of the recommended dose, LM treatments again showed the highest impact (6.56), reflecting their enhanced ability to sustain nutrient availability under reduced fertilizer inputs. Conversely, at 50% of the recommended dose, the values were generally lower, with LM (4.45) showing the least decline compared to other manures, indicating their superior nutrient buffering capacity. The addition of zeolite showed a clear positive effect, with increasing zeolite levels enhancing soil properties across all treatments. At 2% zeolite, treatments with LM recorded the highest value (7.04 g CO_2 per kg soil), followed by VC (6.84) and FYM (6.03). Even at 1% zeolite, significant improvements were observed, with LM showing a value of 6.22. The control (0% zeolite) exhibited the lowest values across treatments, underscoring the beneficial impact of zeolite on soil nutrient retention and availability.

The critical difference values at a 5% probability level revealed significant effects for the main treatments and their interactions. The main effect of manure, fertilizer, and zeolite levels was significant (CD = 0.092), indicating that these factors individually influenced soil properties. Additionally, their interactions showed a substantial impact (CD = 1.594), highlighting the importance of integrated approaches in soil management.

The results demonstrate the synergistic effects of organic manures, balanced fertilizer applications, and zeolite amendments in improving soil properties. Leaf manure consistently showed superior performance across treatments, particularly when combined with higher zeolite levels and reduced fertilizer inputs. These findings emphasize the potential of combining organic amendments with zeolite to enhance nutrient use efficiency and soil health under sustainable agricultural practices

Soil dehydrogenase activity

The soil dehydrogenase activity (DHA), a key indicator of microbial activity and soil health, was significantly influenced by organic manures, fertilizer levels, and zeolite application (Table 2). The mean dehydrogenase activity varied across manure types, with vermicompost (VC) showing the highest activity (21.01 μg TPF g^{-1} soil 24 h^{-1}), followed by Farm yard manure (FYM) at 17.62 μg TPF g^{-1} soil 24 $h^{-1}$and leaf manure (LM) at 17.32 μg TPF g^{-1} soil 24 h^{-1}. The higher activity with VC can be attributed to its higher labile carbon content and nutrient availability, which support microbial growth and enzymatic activity.

Table 2. Influence of treatments on dehydrogenase activity (μg TPF g^{-1} soil 24 h^{-1})

Treatment	Soil+ FYM	Soil+ VC	Soil+ LM
Mean (Manure level)	17.62	21.01	17.32
Fertilizer level			
50%	27.35	13.49	17.46
75%	10.36	15.09	13.42
100%	15.14	34.45	21.09
Zeolite level			
0%	13.01	14.02	13.79
1%	12.27	13.66	16.51
2%	27.57	35.35	21.67
CD (P= 0.05)			

Manure/ Fertilizer/ Zeolite level (Main effect) = 1.21
Manure/ Fertilizer/ Zeolite level (Interaction) = 2.09

Fertilizer levels showed significant variation in DHA. At 50% fertilizer dose, soil with FYM exhibited the highest activity (27.35 μg TPF g^{-1} soil 24 h^{-1}), indicating the synergistic effect of organic manure and reduced fertilizer application. At 75% fertilizer dose, treatments with LM recorded (34.45 μg TPF g^{-1} soil 24 h^{-1}), highlighting its ability to sustain microbial activity even at moderate fertilizer inputs. Conversely, at 100% fertilizer dose, VC treatments exhibited the highest activity 34.45 μg TPF g^{-1} soil 24 h^{-1}, reflecting its balanced nutrient release that supports microbial activity under high nutrient availability.

Zeolite application significantly enhanced DHA across all treatments. The highest activity was observed at 2% zeolite with VC (35.35 μg TPF g^{-1} soil 24 h^{-1}), followed by FYM (27.57 μg TPF g^{-1} soil 24 h^{-1}) and LM (21.67 μg TPF g^{-1} soil 24 h^{-1}). The enhanced activity at higher zeolite levels can be attributed to improved nutrient retention, moisture availability, and microbial habitat due to the high cation exchange capacity and porous structure of zeolite. The main effects of manure, fertilizer, and zeolite levels were statistically significant, indicating that each factor independently influenced DHA. Furthermore, their interactions were highly significant, emphasizing the combined impact of these treatments on soil microbial activity. The observed trends in dehydrogenase activity highlight the critical role of organic amendments, fertilizer levels, and zeolite in modulating soil microbial activity. Vermicompost consistently supported higher DHA due to its rich nutrient content and labile organic carbon, which are readily available to soil microbes. The lower activity observed with leaf manure is likely due to its higher proportion of less labile carbon, which decomposes very slowly (Ramesh et al., 2010; Sangeetha and Baskar, 2016).

Fertilizer levels influenced DHA, with reduced doses (50% and 75% NPK) showing higher activity in specific treatments. This suggests that reduced chemical inputs, combined with organic amendments, create a favorable environment for microbial proliferation and enzyme activity by avoiding the inhibitory effects of excessive fertilizer. Zeolite application further enhanced DHA, particularly at 2% levels, by improving soil physical and chemical conditions, such as moisture retention and nutrient availability. The combination of zeolite with organic manures, particularly vermicompost, demonstrated the greatest synergistic effect, enhancing microbial activity and enzymatic functions (Sangeetha and Baskar, 2016).

Overall, the study highlights the importance of integrated soil fertility management, combining organic manures, optimized fertilizer inputs, and soil conditioners like zeolite to promote soil microbial activity, enzymatic processes, and long-term soil health. These findings support sustainable agricultural practices aimed at enhancing productivity while maintaining ecological balance.

Influence of soil-manure-zeolite mixtures on soil phosphatase activity and available nutrients

Influence of organic manures particularly FYM, fertilizer levels, and zeolite application on soil phosphatase activity, available phosphorus and potassium content is given in Table 3. The activity of soil phosphatase, an enzyme critical for phosphorus mineralization, varied significantly with fertilizer and zeolite levels. Across fertilizer treatments, the highest phosphatase activity (1.035 μg pnp $g^{-1}h^{-1}$) was observed at 75% fertilizer level, while the lowest activity (0.452 μg pnp g^{-1} h^{-1}) occurred at 50% fertilizer level. The average phosphatases activity across all treatments was 0.787 μg pnp $g^{-1}h^{-1}$. Zeolite application further enhanced phosphatase activity, with 2% zeolite recording the highest activity (1.188 μg pnp $g^{-1}h^{-1}$), significantly higher than the control (0.442 μg pnp $g^{-1}h^{-1}$).

Table 3. Influence of treatments on soil phosphatase enzyme activity and available nutrients in soil mixed with zeolite and Farmyard manure

Treatment	Soil phosphatase (μg pnp $g^{-1}h^{-1}$)	Available N (kg ha^{-1})	Available P (kg ha^{-1})	Available K (kg ha^{-1})
Fertilizer level				
50%	0.452	142.2	62.4	477
75%	1.035	121	71.6	544.3
100%	0.875	151.1	79.4	539.8
Average	0.787	138	71.1	520.4
Zeolite level				
0%	0.442	105.1	61.8	506.3
1%	0.732	136.7	70.8	511.7
2%	1.188	172.4	80.7	543.1

Average	0.787	138	71.1	520.4
CD (p = 0.05)	Main effect	Interaction effect		
Soil phosphatase	0.04	0.07		
Available N	13.31	23.05		
Available P	8.6	12.6		
Available K	38.69	67.01		

Soil pH and available nutrients

The pH of soils after the end of the incubation study varied from 6.41 to 6.68 and the differences among the different treatments were found to be significant.

Available nitrogen levels were influenced by both fertilizer and zeolite levels (Table 3). The highest nitrogen content (151.1 kg ha^{-1}) was observed at 100% fertilizer level, while the lowest (121.0 kg ha^{-1}) occurred at 75% fertilizer level. The average nitrogen content across all treatments was 138.0 kg ha^{-1}. Zeolite application significantly increased nitrogen availability, with 2% zeolite recording the highest value (172.4 kg ha^{-1}), compared to 105.1 kg ha^{-1} in the control. The available phosphorus values were found to be significantly higher over control and the influence of maximum zeolite levels was found to increase the available P content (80.7 against 61.8 kg ha^{-1}). As compared to the initial soil NPK values, an increase of 10-39 %, 10-44 % and 9-25% increase in values of NPK respectively, was observed due to different treatment combinations involving fertilizer and zeolite treatments. Available potassium was highest at 75% fertilizer level (544.3 kg ha^{-1}), followed by 100% fertilizer level (539.8 kg ha^{-1}), and lowest at 50% fertilizer level (477.0 kg it should come together average potassium content across treatments was 520.4 kg ha^{-1}. Zeolite application improved potassium availability, with 2% zeolite showing the highest value (543.1 kg ha^{-1}), significantly higher than the control (506.3 kg ha^{-1}). The main effect and interaction effects of fertilizer and zeolite levels were significant for all parameters.

The results highlight the significant effect of fertilizer and zeolite on soil enzymatic activity and nutrient availability. Enhanced phosphatase activity at 75% fertilizer level suggests that moderate fertilizer application, combined with organic amendments, creates optimal conditions for microbial activity and enzyme production. The addition of zeolite, particularly at 2%, further boosted enzyme activity, likely due to its role in improving nutrient retention and microbial habitat. The nitrogen availability increased with fertilizer level, reaching a peak at 100% NPK, reflecting the direct contribution of fertilizers to the soil nitrogen pool. Zeolite application enhanced nitrogen retention, with the highest levels observed at 2% zeolite. This improvement can be attributed to zeolite's high cation exchange capacity, reducing nitrogen losses through leaching and volatilization (Ramesh et al. 2010; Sangeetha and Baskar, 2016). Potassium availability was highest at 75% fertilizer level, indicating efficient nutrient uptake and cycling at moderate fertilizer rates. Zeolite further improved potassium availability, particularly at 2%, due to its ability to absorb and slowly release potassium ions. The findings demonstrate the potential of integrating moderate fertilizer applications with zeolite amendments to enhance soil enzyme activity and nutrient availability. This integrated approach supports sustainable nutrient management, reducing dependence on high fertilizer inputs while maintaining soil health and productivity.

Testing the significance of means

The student's t-test carried out in paired soil variables, revealed significant relationships (Table 4). The results highlight the intricate interactions between soil properties and their combined influence on soil health. A significant positive relationship was observed, indicating that higher soil pH levels favor microbial activity and enzymatic processes as reflected in increased DHA and phosphatase due to zeolite additions. The significant correlation between DHA and pH indicates that maintaining near-neutral pH levels fosters microbial activity, leading to enhanced enzymatic processes and nutrient cycling. This is consistent with the observation that phosphatase activity also increases with higher pH levels, promoting phosphorus availability.

Table 4. Test of significance between soil parameters

Soil Variables	T value	Significance at 5%
DHA and pH	2.976	Significant
DHA and available N	2.736	Significant
Phosphatase and pH	2.214	Significant
Phosphatase and available P	2.412	Significant
CO_2 mineralization and pH	7.318	Significant
CO_2 mineralization and available N	4.767	Significant
pH and available N	5.951	Significant

The relationship between DHA and available nitrogen was also significant, suggesting that enhanced microbial activity contributes to nitrogen mineralization, improving nitrogen availability. The significant relationships highlight the influence of soil pH and available phosphorus on phosphatase enzyme activity, which facilitates phosphorus mineralization. The strongest relationship was observed between CO_2 mineralization and pH, indicating that microbial respiration and carbon turnover are highly responsive to changes in soil acidity. Similarly, the significant relationship between CO_2 mineralization and available nitrogen suggests that nitrogen dynamics are closely linked to carbon mineralization processes in the soil. The strong relationship between CO_2 mineralization, pH, and nitrogen highlights the interconnectedness of carbon and nitrogen cycles. Improved microbial respiration at favorable pH levels supports organic matter decomposition and nitrogen mineralization, enhancing soil fertility. The significant correlation between pH and available nitrogen reflects the critical role of pH in nutrient solubility and microbial-mediated processes. Acidic soils may inhibit microbial activity and nutrient availability, emphasizing the importance of soil amendments, such as zeolites and organic manures, to regulate pH (Thirunavukkarasu and Subramanian, 2014). Overall, the findings emphasize the need for integrated soil management strategies that consider the interactions between soil pH, microbial activity, and nutrient dynamics to optimize soil fertility and sustainability.

Conclusion

The study provides significant insights into the role of organic manures, fertilizers, and zeolites in enhancing certain key soil parameters and nutrient dynamics, particularly under controlled conditions. Among the tested organic manures, leaf manure demonstrated the highest carbon mineralization rate (5.70 g CO_2 per kg soil), indicating its superior biodegradability and capacity to release carbon and associated nutrients into the soil. This highlights the potential of leaf manure which is otherwise a potential waste product exists and can act as a sustainable organic input to improve soil organic carbon pools and microbial activity. The high cation exchange capacity (CEC) of zeolites likely contributed to nutrient retention and slow release, reducing nutrient losses and improving fertilizer use efficiency. The findings of this study lay a foundation for the development of an organo-zeolite product tailored to optimize soil quality and productivity. Such a product, when used strategically, could significantly enhance the yield and sustainability of tuber crops, addressing the dual challenges of soil degradation and nutrient use efficiency. The integration of 1% zeolite with 50% NPK fertilizer proved to be the most effective treatment for promoting soil microbiological activity especially with FYM. This combination resulted in optimal carbon dioxide mineralization rates, indicating efficient microbial respiration, along with enhanced availability of major soil nutrients, including nitrogen, phosphorus, and potassium.

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