



RESEARCH ARTICLE

Soil physico-chemical properties and enzyme activities in organic farmlands of Arunachal Pradesh

Lod Yama^{1,2}, Senggam Wakhet Singpho², Ashish Paul^{1*}, Karuna Shrivastava¹, Debajit Mahanta² & Om Prakash Tripathi³

¹Department of Forestry, North Eastern Regional Institute of Science and Technology (Deemed to be University), Nirjuli 791 109, Arunachal Pradesh, India

²DBT-Arunachal Pradesh State Council for Science & Technology, Centre of Excellence for Bioresources and Sustainable Development, Kimin 791 121, Arunachal Pradesh, India

³Department of Environmental Science, Mizoram University, Aizawl 796 004, Mizoram, India

*Correspondence email - ashishpaul1@gmail.com

Received: 01 June 2025; Accepted: 13 April 2026; Available online: Version 1.0: 01 October 2026

Cite this article: Lod Y, Senggam WS, Ashish P, Karuna S, Debajit M, Om PT. Soil physico-chemical properties and enzyme activities in organic farmlands of Arunachal Pradesh. Plant Science Today. 2026; 13(sp5): 1-10. <https://doi.org/10.14719/pst.9759>

Abstract

Soil fertility management through organic amendments plays an important role in improving soil quality and biological functioning in vegetable cultivation systems. The present study evaluated the effects of traditionally prepared farmyard manure (FYM), conventional vermicompost (C_v) and their combined application on soil physico-chemical properties and enzymatic activities in vegetable growing lands. Soil bulk density ranged from $0.81 \pm 0.34 \text{ g/cm}^3$ to $1.88 \pm 0.33 \text{ g/cm}^3$ among the sites and amendments. Soil moisture content ranged from 28.58 % to 64.06 % and water holding capacity varied from 42.53 % to 69.69 %. Soil texture varied from loam to sandy loam. Soil was acidic in nature and pH value ranged from 4.49 ± 0.29 to 7.27 ± 0.96 . Percentage of total organic carbon was recorded highest ($3.84 \pm 0.12 \%$) in C_v (Siro) and lowest in Dutta ($1.43 \pm 0.34 \%$). Percentage of organic matter followed similar trend to that of soil organic carbon. ABC exhibited highest ($0.28 \pm 0.02 \%$) total nitrogen content and lowest ($0.08 \pm 0.03 \%$) in Dutta. Similar trend was followed by total phosphorus and total potassium content in the respective sites respectively. Correlation coefficient analysis revealed significant interrelationships among various soil parameters and enzymatic activities. Soil bulk density and moisture content showed negative correlations with enzymatic activities, while water holding capacity exhibited positive correlations with nitrogen and enzymatic activities. Soil pH exhibited significant positive correlations with arylsulphatase ($r = 0.567, p < 0.05$), acid phosphatase ($r = 0.623, p < 0.01$) and dehydrogenase ($r = 0.599, p < 0.01$). A significant positive correlation was observed between soil organic carbon and organic matter ($r = 0.969, p < 0.001$). Organic carbon showed significant positive correlations with arylsulphatase ($r = 0.825, p < 0.001$), acid phosphatase ($r = 0.676, p < 0.01$), alkaline phosphatase ($r = 0.648, p < 0.01$) and dehydrogenase ($r = 0.706, p < 0.01$). Total nitrogen exhibited significant positive correlations with arylsulphatase ($r = 0.658, p < 0.01$), acid phosphatase ($r = 0.720, p < 0.001$) and dehydrogenase ($r = 0.624, p < 0.01$). Total phosphorus showed strong positive correlations with acid phosphatase ($r = 0.773, p < 0.001$), alkaline phosphatase ($r = 0.737, p < 0.001$) and dehydrogenase ($r = 0.738, p < 0.001$). In contrast, total potassium showed weak or no significant correlations with enzymatic activities. Strong inter enzyme correlations were observed between dehydrogenase and acid phosphatase ($r = 0.929, p < 0.001$), arylsulphatase ($r = 0.854, p < 0.001$) and alkaline phosphatase ($r = 0.854, p < 0.001$). This study is an indicative of synergistic effects of incorporation of conventional vermicompost in traditional soil management system for vegetable farmlands in maintaining soil nutrient and fertility. The results provide a transferable framework for improving soil strength and nutrient cycling in low input vegetable systems and promote the use of locally produced organic inputs that support both environmental sustainability and farm level economic sustainability.

Keywords: Apatani; biofertiliser; farmyard manure; organic amendments; traditional compost; vegetable farms

Introduction

Soil health refers to the capacity of soil to function as a living ecosystem that supports plant growth, regulates nutrient cycling and sustains environmental quality. Healthy soils host diverse microbial, plant and faunal communities that collectively contribute to agricultural productivity and ecosystem stability. Because, soil health directly influences crop yield, nutrient availability, water quality and long-term sustainability, its preservation is a global priority in modern agriculture. Soil quality is governed by a combination of physical, chemical and biological properties, all of

which play essential roles in supporting plant development and ecosystem services. Sustainable soil management practices, such as crop rotation, organic matter addition, reduced tillage and regular soil testing, are widely recognized for maintaining soil fertility and productivity. Among these, the application of organic amendments has received increasing attention due to their ability to improve soil structure, enhance nutrient status and stimulate biological activity. Soil enzymes, in particular, are sensitive indicators of soil biological functioning and are widely used to assess the impact of management practices on soil health.

Farmyard manure (FYM) is one of the most commonly used organic amendments worldwide and has been shown significantly influence soil enzyme activity by enhancing microbial populations and nutrient cycling. Several studies have reported increased activities of enzymes such as urease, invertase and phosphatase following FYM application, reflecting improved microbial functioning (1–4). Farmyard manures derived from poultry and swine excreta have also been reported to increase alkaline and acid phosphatase activity in soils (1). Long-term FYM application enhances microbial biomass, accelerates soil organic matter turnover and increases exoenzyme activity, resulting in faster nutrient cycling rates (5). Soil enzymes such as dehydrogenase, phosphatase and arylsulphatase play key roles in soil biochemical processes and nutrient transformations. Dehydrogenases are intracellular enzymes present in all living microbial cells and are closely associated with microbial oxidative metabolism, making them reliable indicators of overall soil biological activity (6, 7). Phosphatase enzymes regulate phosphorus mineralisation and availability, while arylsulphatase is involved in sulphur cycling and is strongly influenced by soil organic matter content (8, 9). Previous studies have demonstrated that organic fertilisers and residue amendments can significantly enhance these enzyme activities across different agricultural systems (10–13).

In the face of extensive research on organic amendments, most studies have focused on standardised or commercially prepared inputs, while traditional plant based farmyard manures prepared through indigenous knowledge systems remain poorly documented, particularly with respect to their effects on soil enzymatic activity and nutrient dynamics. Such indigenous practices represent low input, ecologically balanced soil management strategies and may offer globally relevant insights for sustainable agriculture. The *Apatani* farming system of Ziro Valley, Lower Subansiri district of Arunachal Pradesh, India provides one such example. Vegetable cultivation in this region is carried out on elevated lands surrounded by paddy fields, where soils are prone to nutrient loss through runoff and erosion. To replenish soil fertility, farmers prepare farmyard manure using locally available weeds biomass such as *Alopecurus aequalis*, *Azolla* sp., *Eichhornia crassipes*, *Lemna minor* (Duckweed), *Rotala rotundifolia* and *Spirodella* sp. (Duckweed), often combined with pig faeces. These organic inputs are prepared and applied following long established indigenous practices, with women playing a central role in their management. These locally available organic resources hold economic relevance as it lowers input costs and positively influence farm level profitability in resource constrained situations. Such systems represent highly integrated and sustainable farming traditions (14). This agriculture system represents a broader model of low input vegetable cultivation rather than a location specific case.

Despite comprehensive studies, scientific validation of traditional organic amendments, particularly in comparison with conventional vermicompost, remains limited. Therefore, the present study aimed to evaluate the effects of traditional plant based farmyard manure, conventional vermicompost and their combined application on soil physico-chemical properties and enzymatic activities in vegetable growing soils. The study hypothesized that the combined application of traditional and conventional organic amendments would exert synergistic effects on soil enzyme activities and nutrient cycling, thereby improving soil functional quality. A detailed examination of this hypothesis is both environmentally and economically significant, as its confirmation

would support the development of biologically effective and cost-efficient soil management practices tailored to small holder, low input vegetable farming systems.

Materials and Methods

Study site

Study sites were selected in the farmland of Ziro Valley, Lower Subansiri district of Arunachal Pradesh, India which lies at 1500 m asl between 27°33' N to 27°35' N latitude and 93°49' E to 93°50' E longitude. The district covers an area of 1961.20 km² which is 2.34 % of the state's geographical area. The forest cover of the district is 1763.27 km² which is 89.91 % of the total geographical area of the district (15). The Ziro Valley is popularly known as the Rice Bowl of Arunachal Pradesh (16). The valley is entirely inhabited by the *Apatani* tribe and have their unique culture, tradition and agricultural knowledges. In the present study, 14 vegetable gardens spread across 8 villages viz., Bamin Michi, Biirri, Dutta, Hari, Kalung, Reru, Siiro and Tajang were selected randomly (Fig. 1). Soil samples were collected from the respective farmlands and analyses were conducted using standard methodologies.

Methods

The soil samples were collected randomly from 0–15 cm depth in cold packs from selected croplands of all the listed villages using soil corer and kept at about 5 °C. The soil samples were mixed thoroughly and made composite. Separate soil samples were collected for the estimation of bulk density. The indigenous farmyard manure (FYM) and locally made vermicompost were collected from progressive farmers of Kalung and Siiro village respectively. The samples were shipped to the laboratory in cold packs and kept at approximately 5 °C until analysis. The experimental site was slightly elevated mixed vegetable farmland that had been under continuous vegetable cultivation for more than 4 years prior to soil sampling. It was surrounded by low lying paddy cum fish culture lands. Soil samples were collected randomly, avoiding areas under tree canopies, near field boundaries, irrigation channels and disturbed areas. Surface litter and plant residues were removed prior to sampling to ensure representative samples.

Fresh soil samples were used for the analysis of soil pH and moisture content. The remaining soil samples were air dried after removing all the pebbles, plant or animal debris, etc. Then, the soil samples were smashed and sieved through 2 mm sieve and kept for further analysis. Soil moisture content (SMC) was estimated following gravimetric method (17) and soil bulk density (BD) by soil core method (18). Soil texture was determined following Bouyoucos hydrometric method (19) and water holding capacity (WHC) was determined using standard laboratory soil-water retention procedures (20). Soil pH was determined using a digital pH meter by weight: volume into a ratio of 1:2.5 (17). Soil organic carbon (SOC) was determined following Walkley-Black dichromate oxidation rapid titration method (21) and soil organic matter (SOM) was calculated by multiplying the percent of SOC with Van Bemmelen factor 1.724, assuming that SOM comprises 58 % carbon (22). Soil total nitrogen (TN) was estimated following Kjeldahl digestion-distillation method with Kel Plus nitrogen analyser (22). Total phosphorus (TP) concentration was determined by molybdenum blue method using UV Spectrophotometer (Shimadzu, UV-1900I) (23) and total potassium (TK) by the neutral ammonium acetate method using Flame Photometer (22).

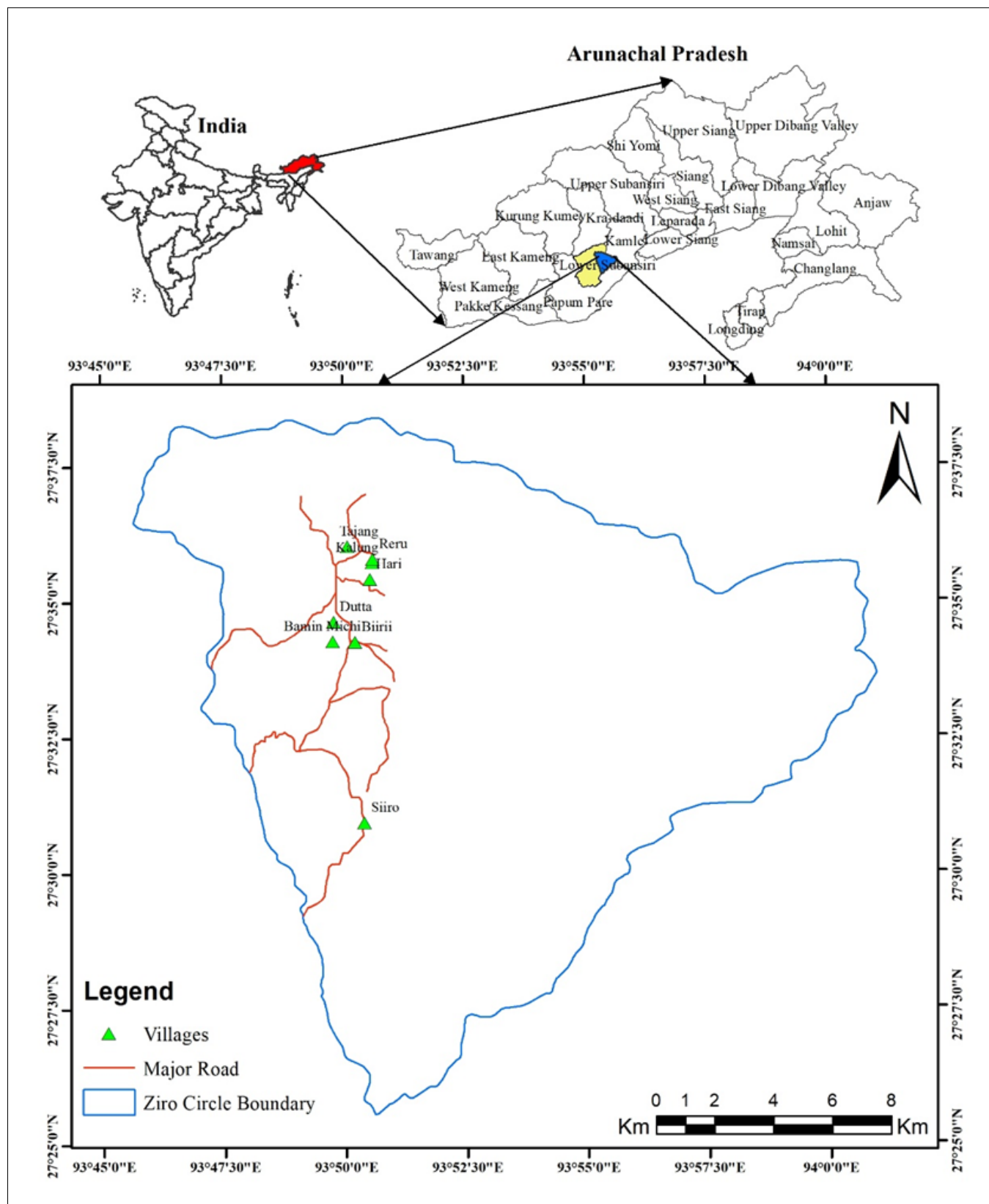


Fig. 1. Map showing the selected villages within the study area of the Ziro Valley, Lower Subansiri district, Arunachal Pradesh.

Dehydrogenase activity (DhA) was determined following standard procedure (24) by quantifying the reduced triphenyl tetrazolium formazan at 485 nm spectrophotometrically. Arylsulphatase (AsA) and phosphatase activities, including acid phosphatase (AcP) and alkaline phosphatase (AkP) were estimated using the p-nitrophenyl substrate colorimetric method and the p-nitrophenol released was measured spectrophotometrically at 400 nm and 410 nm respectively (25, 26). Soil enzymatic assays for arylsulphatase, dehydrogenases, acidic phosphatases and alkaline

phosphatase were quantified and analysed at DBT-APSCS & T Centre of Excellence for Bioresources and Sustainable Development, Kimin, Arunachal Pradesh. The data gathered was statistically analysed. The samples are listed below:

A. Soil composite (A)

Soil composites from vegetable farm sites at Kalung village free from any chemical or organic inputs were collected for soil enzymatic assays.

B. Farmyard manure composite (B_{FYM})

Farmyard manure (FYM) was selected based on information collected through a questionnaire survey with the women farmers on their unique, organic and native farming system and the utility of plant resources for manure and mulching. The FYM was sourced from a progressive farmer Mrs. Kalung Diming which was prepared using pig manure and decomposed plant residues of *Alopecurus aequalis*, *Azolla* sp., *Eichhornia crassipes*, *Lemna minor*, *Rotala tundifolia* and *Spirodella* sp. The farmyard manure (B_{FYM}) used in the study was prepared following traditional farm practices. It consisted primarily of pig manure applied at approximately 160 kg acre⁻¹ year⁻¹ and plant-based biomass applied at approximately 240 kg acre⁻¹ year⁻¹, corresponding to a pig manure to plant biomass ratio of approximately 2:3 (w/w). In addition, fine soil collected from paddy fields was incorporated as a bulking and moisture retaining material during FYM preparation. As the FYM was prepared using customary methods, the paddy field soil was not added in a fixed or quantified proportion.

C. Vermicompost (C_{VC})

The conventional vermicompost sample was collected from a progressive farmer Mr. Takhe Tacha, Siiro village, who prepared vermicompost locally for commercial sale to neighbouring farmers. The vermicompost was produced using locally available organic wastes and cow dung as a substrate following routine farmer practice. Vermicompost was prepared using cow dung and plant-based biomass in an approximate ratio of 3:2 (w/w), following conventional vermicomposting practices. Bedding materials were added without fixed proportions. The vermicompost sample was included in the study for comparative analysis along with normal soil and farmyard manure (FYM).

D. Soil composite from plot AB

The newly tilled bed of 10' x 10' was treated with 10 kg of farmyard manure (B_{FYM}) at the Kalung vegetable farm site.

E. Soil composite from plot AC

The newly tilled bed of 10' x 10' was treated with 10 kg of vermicompost (C_{VC}) at Kalung vegetable farm site (A).

F. Soil composite from plot ABC

The newly tilled bed of 10' x 10' were treated with 5 kg of farmyard manure (B_{FYM}) and 5 kg of vermicompost (C_{VC}) at Kalung vegetable farm site (A).

The organic amendments evaluated in this study rely exclusively on locally available plant biomass and animal manure,

requiring no external chemical inputs or energy-intensive processing. Their preparation involves simple aerobic composting and vermicomposting processes that can be implemented at the farm level with minimal infrastructure. This low material and energy requirements indicate potential cost reductions through decreased reliance on synthetic fertilisers, making the approach economically feasible for small holder vegetable production systems.

Statistical analysis

One-way ANOVA was performed to assess the variation of soil parameters and enzymatic activities followed by Tukey's multiple comparison test was performed at the 95 % probability level. Pearson correlation coefficient analysis was carried out between soil properties and soil enzymatic activities across treatments. Significance of correlation coefficients were assessed at $p < 0.05$, $p < 0.01$ and $p < 0.001$ levels respectively. All statistical analyses were performed using Microsoft Excel and Origin 7.

Results

Soil physical properties

Soil bulk density ranged from 0.81 ± 0.34 g/cm³ to 1.88 ± 0.33 g/cm³. It was found to be highest (1.88 ± 0.33 g/cm³) in Bamin Michi and lowest (0.81 ± 0.34 g/cm³) in Kalung. Soil moisture content ranged from 28.58 ± 2.35 % to 64.06 ± 4.97 %. Maximum soil moisture content (64.06 ± 4.97 %) was recorded in Tajang followed by Hari (63.01 ± 5.21 %) and lowest (28.58 ± 2.35 %) in C_{VC} (Siuro) (Table 1). Water holding capacity varied from 42.53 ± 4.05 % to 69.69 ± 4.17 %. It was recorded maximum (69.69 ± 4.17 %) in C_{VC} (Siuro) followed by Hari (63.01 ± 5.21 %) and minimum in Siuro (42.53 ± 4.05 %). It was observed that the incorporation of FYM and C_{VC} helped in moisture retention capacity at sites ABC, AB and AC respectively. Soil particle size analysis indicated the texture varied among the sites i.e., loam (Biiri, Dutta, Tajang), sandy loam (Bamin Michi, Reru, Siuro), silt loam (Hari) and silt clay loam (Kalung) (Table 1).

Soil chemical properties

It was observed that soils were acidic in nature and the pH value ranged between 4.49 ± 0.29 to 7.27 ± 0.96 . Incorporation of farmyard manure and vermicompost into sites at AB, AC and ABC seemed to have an effect in alleviating their pH levels (Table 2). It was observed that vermicompost (C_{VC}) exhibited lowest (7.27 ± 0.96) pH followed by site ABC (6.64 ± 0.32), FYM (Reru) (5.59 ± 0.63), B_{FYM}(Kalung) (5.57 ± 0.30) and highest (4.49 ± 0.29) in Kalung (A) (Table 2). The percentage of total organic carbon content ranged from 1.43 ± 0.34 % to

Table 1. Soil physical properties of traditionally prepared vegetable farm soils of Ziro Valley, Lower Subansiri district, Arunachal Pradesh.

Sites/Soil parameters	Bulk density (g/cm ³)	Moisture content (%)	Water holding capacity (%)	Sand (%)	Silt (%)	Clay (%)	Texture
Bamin Michi	1.88±0.33a	48.00±2.57ab	50.27±2.66ab	56.00	32.00	12.00	Sandy loam
Biirii	1.21±0.44ac	57.60±4.28a	51.46±3.77ab	36.00	46.00	18.00	Loam
Dutta	0.93±0.19bc	51.17±2.57ab	54.20±3.63ab	52.00	34.00	14.00	Loam
Hari	0.91±0.12bc	63.01±5.21a	52.03±1.33ab	30.00	50.00	20.00	Silt loam
Kalung (A)	0.81±0.34c	51.76±3.84ab	52.41±2.13ab	20.00	48.00	32.00	Silt clay loam
Reru	1.19±0.22ac	61.18±3.77a	43.29±6.11b	56.00	36.00	8.00	Sandy loam
Siuro	1.80±0.41ab	56.58±0.87a	42.53±4.05b	68.00	26.00	6.00	Sandy loam
Tajang	1.17±0.39ac	64.06±4.97a	49.88±2.66ab	44.00	38.00	18.00	Loam
FYM (Reru)	-	51.78±7.12ab	45.31±3.54b	-	-	-	-
B _{FYM} (Kalung)	-	39.47±3.85ab	54.50±2.09ab	-	-	-	-
C _{VC} (Siuro)	-	28.58±2.35b	69.69±4.17a	-	-	-	-
AB	1.02±0.33ac	40.22±2.88ab	54.57±3.43ab	-	-	-	-
AC	1.08±0.14ac	46.95±1.87ab	61.69±2.67ab	-	-	-	-
ABC	1.11±0.34ac	41.54±2.08ab	60.07±3.11ab	-	-	-	-

*Within columns, means followed by the same letter are not significantly different ($p = 0.05$) using Tukey's multiple comparison test.

3.46 ± 0.64 %. The C_{VC} (Siro) recorded highest total organic carbon content (3.84 ± 0.12 %) followed by site ABC (3.46 ± 0.64 %) and lowest (1.43 ± 0.34 %) in Dutta. Where as, relatively similar organic carbon contents were observed in sites AB (3.39 ± 0.33 %) and AC (3.17 ± 0.28 %) respectively. The percentage of organic matter content followed a similar trend to that of soil organic carbon (Table 2).

The percentage of total nitrogen content varied among the sites, with the lowest (0.08 ± 0.03 %) value recorded in Dutta followed by Kalung (A) (0.15 ± 0.01 %), ABC (0.200 ± 0.03 %) and highest (0.28 ± 0.02 %) in C_{VC} (Siro). However, a decreasing trend was observed in the nitrogen content from sites AB (0.17 ± 0.06 %) and AC (0.16 ± 0.05 %). Among the organic amendments, vermicompost sample (C) resulted highest nitrogen content 0.28 ± 0.02 % followed by farmyard manure (FYM) from Kalung (B), which had a nitrogen content of 0.19 ± 0.04 % (Table 2). The percentage of total phosphorus content was observed lowest (0.52 ± 0.07 %) in Reru and highest (1.05 ± 0.07 %) in C_{VC} (Siro). It was observed that site ABC showed significant percentage of phosphorus content (0.79 ± 0.10 %) followed by AC (0.68 ± 0.07 %) and AB (0.64 ± 0.18 %) respectively. C_{VC} (Siro) exhibited highest (1.05 ± 0.07 %) percentage of phosphorous content followed by FYM from Kalung (B) (0.83 ± 0.08 %) (Table 2). Low percentage of total soil potassium content was observed amongst the sites. It was observed that vermicompost sample exhibited the highest percentage of potassium content (0.02 ± 0.04 %) followed by site ABC (0.01 ± 0.08 %), AB (0.01 ± 0.14 %) and AC (0.01 ± 0.05 %) respectively (Table 2).

Soil enzyme activities

Enzyme activity for soils from the 6 soil mixtures were analysed and are presented in Table 3 and Fig. 2. Soil mixture from site A (Kalung) with no treatment showed least activity against arylsulphatase enzyme (20.10 ± 4.02) and highest activity against acid phosphatase enzyme (34.47 ± 7.53). The activity for dehydrogenase enzyme was

slightly higher (31.53 ± 13.37) whereas a prominent low (22.25 ± 7.22) activity was observed for alkaline phosphatase enzyme (Fig. 2, Table 3). The traditional organic farm input (B_{FYM}) showed least activity against alkaline phosphatase enzyme (36.87 ± 5.19) and highest activity against acid phosphatase enzyme (96.05 ± 10.76). Dehydrogenase enzyme also exhibited slightly higher activity (64.99 ± 7.23) whereas for arylsulphatase enzyme the activity was comparatively lower (47.78 ± 11.69). The sample from commercial vermicompost (C_{VC}) showed least activity against alkaline phosphatase enzyme (67.23 ± 11.36) and highest activity was exhibited against acid phosphatase enzyme (172.20 ± 27.26). Activity for dehydrogenase enzyme was found higher (127.79 ± 18.17) whereas the activity for arylsulphatase enzyme was comparatively lower (77.65 ± 15.46) (Fig. 2, Table 3).

Soil mixture of site AB treated with traditional farm input (B_{FYM}) showed least activity against alkaline phosphatase enzyme (30.67 ± 7.19) and highest activity against acid phosphatase enzyme (76.71 ± 8.36). Activity for arylsulphatase enzyme the activity was comparatively lower (40.07 ± 7.80) and dehydrogenase enzyme activity was slightly higher (62.93 ± 8.75). Soil mixture of site AC treated with commercial vermicompost (C_{VC}) showed least activity against alkaline phosphatase enzyme (33.80 ± 5.25) followed by arylsulphatase enzyme (46.03 ± 7.58) and dehydrogenase enzyme (67.66 ± 3.89) (Fig. 2, Table 3). The highest activity was exhibited against acid phosphatase enzyme (77.18 ± 15.75). Soil mixture of site ABC treated with both traditional farm input (B_{FYM}) and locally sourced commercial vermicompost (C_{VC}) showed least activity against alkaline phosphatase enzyme (52.39 ± 8.76) and highest activity against acid phosphatase enzyme (134.40 ± 25.98). Sample ABC showed increased activity for both dehydrogenase enzyme (115.47 ± 3.76) and arylsulphatase enzyme (62.43 ± 12.03) (Fig. 2, Table 3).

Table 2. Soil chemical properties of traditionally prepared vegetable farm soils of Ziro Valley, Lower Subansiri district, Arunachal Pradesh.

Sites/Soil parameters	pH	OC (%)	OM (%)	N (%)	P (%)	K (%)
Bamin Michi	5.14±0.48ab	1.81±0.48cd	3.12±0.08cd	0.13±0.2b	0.58±0.02ce	0.01±0.01bc
Biiiri	4.79±0.28ab	2.94±0.05b	5.07±0.08b	0.11±0.03b	0.63±0.02be	0.01±0.14bc
Dutta	5.06±0.05ab	1.43±0.34d	2.47±0.59d	0.08±0.03b	0.53±0.03de	0.01±0.02bc
Hari	5.30±0.12ab	1.62±0.16d	2.79±0.27d	0.14±0.04ab	0.62±0.03be	0.01±0.03bc
Kalung (A)	4.49±1.06b	2.02±0.34cd	3.48±0.58cd	0.15±0.01ab	0.61±0.10be	0.01±0.03bc
Reru	5.42±0.48ab	2.69±0.08bc	4.64±0.4bc	0.11±0.04b	0.52±0.07e	0.01±0.01bc
Siio	5.06±0.15ab	1.76±0.76d	3.04±0.13d	0.09±0.05b	0.57±0.03ce	0.01±0.07c
Tajang	4.52±0.29ab	1.45±0.21d	2.50±0.36d	0.09±0.02b	0.65±0.09be	0.01±0.13bc
FYM (Reru)	5.59±0.63ab	2.96±0.42ab	5.10±0.72ab	0.19±0.05ab	0.76±0.08bcd	0.01±0.02bc
B _{FYM} (Kalung)	5.57±0.44ab	2.99±0.44ab	5.16±0.75ab	0.19±0.04ab	0.83±0.08ab	0.01±0.07bc
C _{VC} (Siro)	7.27±0.96a	3.84±0.12a	6.62±0.21a	0.28±0.02a	1.05±0.07a	0.02±0.04a
AB	5.09±0.30ab	3.39±0.33ab	5.85±0.57ab	0.17±0.06ab	0.64±0.18be	0.01±0.14ac
AC	5.24±0.44ab	3.17±0.28ab	5.46±0.49ab	0.16±0.05ab	0.68±0.07be	0.01±0.05bc
ABC	6.64±0.32ab	3.46±0.64ab	5.96±1.09ab	0.20±0.03ab	0.79±0.10bc	0.01±0.08ab

*Within columns, means followed by the same letter are not significantly different (p = 0.05) using Tukey's multiple comparison test.

Table 3. Variations in enzymatic activity across the soil mixtures in vegetable farm soils of Ziro Valley, Lower Subansiri district, Arunachal Pradesh.

Samples	Dehydrogenase (µg TPF g ⁻¹ soil 24 h ⁻¹)	Arylsulphatase (µg p-nitrophenol g ⁻¹ soil h ⁻¹)	Acid phosphatase (µg p-nitrophenol g ⁻¹ soil h ⁻¹)	Alkaline phosphatase (µg p-nitrophenol g ⁻¹ soil h ⁻¹)
A	31.53±13.37c	20.10±4.02c	34.47±7.53d	22.25±7.22c
B _{FYM}	64.99±7.23b	47.78±11.69bc	96.05±10.76bc	36.87±5.19bc
C _{VC}	127.79±18.17a	77.65±15.46a	172.20±27.26a	67.23±11.36a
AB	62.93±8.75b	40.07±7.80bc	76.71±8.36cd	30.67±7.19c
AC	67.66±3.89b	46.03±7.58bc	77.18±15.75cd	33.80±5.25bc
ABC	115.47±3.76a	62.43±12.03ab	134.40±25.98ab	52.39±8.76ab

*Within columns, means followed by the same letter are not significantly different (p = 0.05) using Tukey's multiple comparison test.

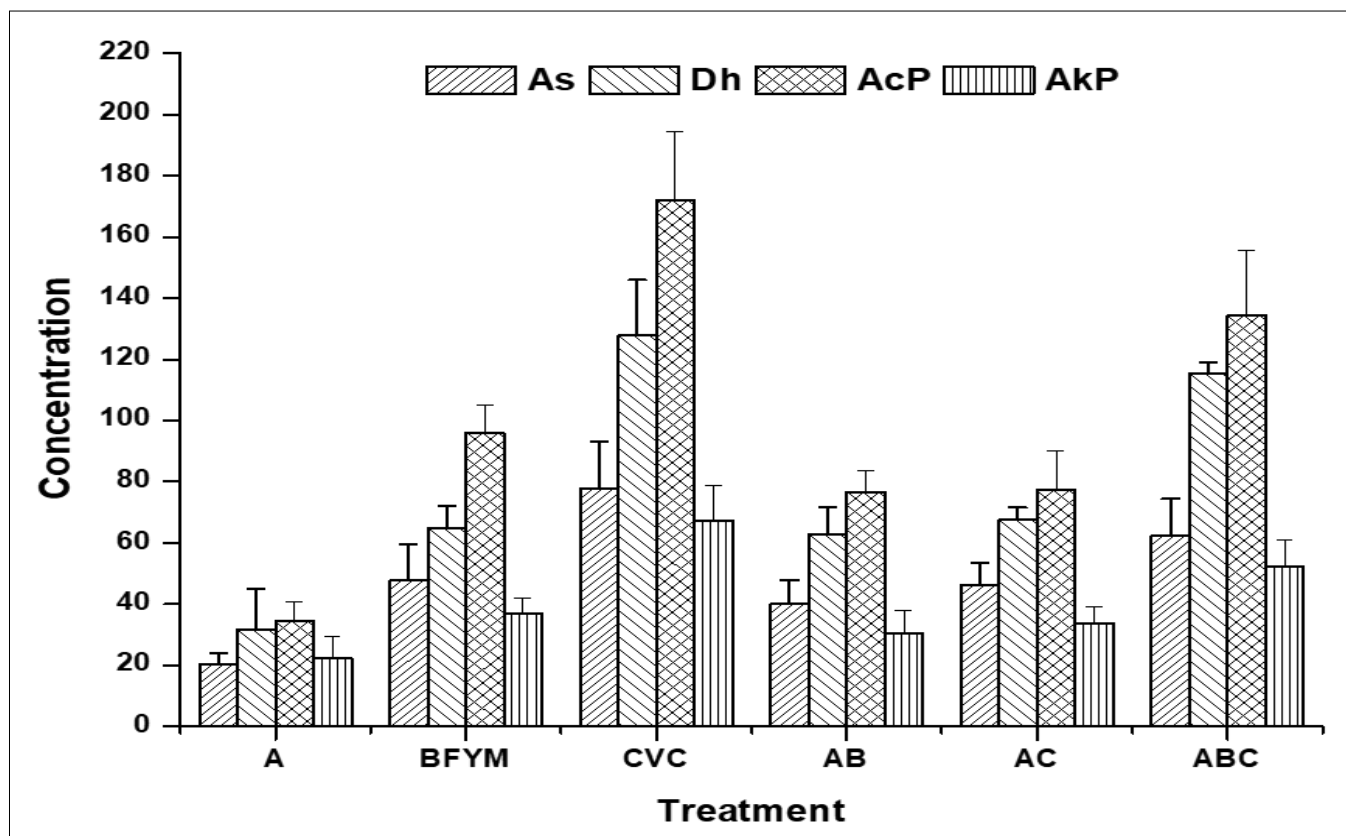


Fig. 2. Soil enzymatic activity across different soil mixtures of Ziro Valley, Lower Subansiri district, Arunachal Pradesh.

Pearson's correlation coefficient analysis between the soil physico-chemical properties and enzymatic activities

The Pearson's correlation coefficient analysis revealed significant interrelationships among various soil parameters and enzymatic activities. Soil bulk density showed negative correlations with enzymatic activities, whereas water holding capacity showed positive correlations with nitrogen and enzymatic activities. Further, soil moisture content exhibited significant negative correlations with dehydrogenase, arylsulphatase and phosphatase activities (Table 4). Soil pH exhibited significant positive correlations with arylsulphatase ($r = 0.567$, $p < 0.05$), acid phosphatase ($r = 0.623$, $p < 0.01$) and dehydrogenase ($r = 0.599$, $p < 0.01$). A significant positive correlation was observed between soil organic carbon and organic matter ($r = 0.969$, $p < 0.001$). Soil organic carbon and organic matter exhibited significant positive correlations with all enzymatic activities. Organic carbon showed significant positive correlations with arylsulphatase ($r = 0.825$, $p < 0.001$), acid phosphatase ($r = 0.676$, $p < 0.01$), alkaline phosphatase ($r = 0.648$, $p < 0.01$) and dehydrogenase ($r = 0.706$, $p < 0.01$) (Table 4). Total nitrogen exhibited significant positive correlations with arylsulphatase ($r = 0.658$, $p < 0.01$), acid phosphatase ($r = 0.720$, $p < 0.001$) and dehydrogenase ($r = 0.624$, $p < 0.01$). Total phosphorus showed strong positive correlations with acid phosphatase ($r = 0.773$, $p < 0.001$), alkaline phosphatase ($r = 0.737$, $p < 0.001$) and dehydrogenase ($r = 0.738$, $p < 0.001$). In contrast, total potassium showed weak or no significant correlations with enzymatic activities. Strong inter enzyme correlations were observed between dehydrogenase and acid phosphatase ($r = 0.929$, $p < 0.001$), arylsulphatase ($r = 0.854$, $p < 0.001$) and alkaline phosphatase ($r = 0.854$, $p < 0.001$), indicate coordinated microbial activity across the treatments (Table 4).

Discussion

The low input vegetable farm systems in the present study have been following a continuous mixed cropped pattern over the years, which may affect the observed soil properties. These types of farming methods include the application of regular organic amendments that can alter nutrient content of the soil, pH and organic carbon content. Vegetable crops like beans, chilli, cucumber, lettuce, maize and soybean are frequently cultivated by local farmers in the study sites. The soil physico-chemical properties and enzymatic activities observed in the present study may be influenced by the prior cropping pattern of continuous mixed vegetable cultivation (27). The elevated nature of the vegetable farms in contrast to the surrounding paddy cum fish culture fields promotes aerobic soil conditions, which favours microbial reproduction and enzyme linked nutrient cycling. Although crop yield was not evaluated in this study, the observed soil biological responses suggest that the existing cropping and land use system has improved soil functional quality.

Soil bulk density, moisture content and water holding capacity varied among the soil composites. The soil texture has been found to vary from sandy loam to silt clay. According to one report, the bulk density of croplands with minimum tillage was found to be 1.27 g/cm^3 that is consistent with our findings where elevated vegetable croplands are tilled with minimal tools like daon and wooden hoes (28). The higher bulk density values for sandy textured soils may be attributed to their smaller particle size and higher compaction. Water retention capacity for soil mixtures amended with B_{FYM} and C_{VC} increased compared to soil mixtures with no organic treatments. The incorporation of organic amendment has found to be beneficial in uplifting the water retention capacity of the vegetable farmland and reduce moisture loss (29). Significant variations were found in the chemical characteristics and soil

Table 4. Pearson's correlation coefficient between soil physico-chemical properties and enzymatic activities of Ziro Valley, Lower Subansiri district, Arunachal Pradesh.

Parameters	BD (g/cm ³)	WHC (%)	SMC (%)	N (%)	P (%)	K (%)	OC (%)	OM (%)	pH	As ($\mu\text{g PNP g}^{-1}\text{ soil h}^{-1}$)	Dh ($\mu\text{g TPF g}^{-1}\text{ soil 24 h}^{-1}$)	AcP ($\mu\text{g PNP g}^{-1}\text{ soil h}^{-1}$)	AkP ($\mu\text{g PNP g}^{-1}\text{ soil h}^{-1}$)
BD (g/cm ³)	1												
WHC (%)	0.048	1											
SMC (%)	-0.189	-0.610**	1										
N (%)	-0.290	0.695**	-0.555*	1									
P (%)	-0.177	0.393	-0.580*	0.425	1								
K (%)	0.078	0.371	-0.088	0.562*	0.066	1							
OC (%)	-0.033	0.38	-0.587*	0.477*	0.602**	0.348	1						
OM (%)	0.007	0.465	-0.594**	0.507*	0.562*	0.35	0.969***	1					
pH	0.055	0.454	-0.351	0.472*	0.610**	0.560*	0.588*	0.611**	1				
As ($\mu\text{g PNP g}^{-1}\text{ soil h}^{-1}$)	-0.221	0.465	-0.607**	0.658**	0.683**	0.361	0.825***	0.843***	0.567*	1			
Dh ($\mu\text{g TPF g}^{-1}\text{ soil 24 h}^{-1}$)	0.050	0.626**	-0.757***	0.624**	0.738***	0.334	0.706**	0.721***	0.599**	0.854***	1		
AcP ($\mu\text{g PNP g}^{-1}\text{ soil h}^{-1}$)	-0.083	0.579*	-0.692**	0.720***	0.773***	0.372	0.676**	0.657**	0.623**	0.830***	0.929***	1	
AkP ($\mu\text{g PNP g}^{-1}\text{ soil h}^{-1}$)	-0.230	0.358	-0.624**	0.538*	0.737***	0.129	0.648**	0.626**	0.438	0.878***	0.854***	0.854***	1

*, ** and *** denote significance at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively. As: Arylsulphatase; AcP: Acid phosphatase; AkP: Alkaline phosphatase; BD: Bulk density; Dh: Dehydrogenase; K: Potassium; N: Nitrogen; P: Phosphorus; PNP: p-nitrophenol; OC: Organic carbon; OM: Organic matter; SMC: Soil moisture content; TPF: Triphenyl formazan; WHC: Water holding capacity

nutrient contents throughout the research area. The study indicated that the combination of traditionally prepared farmyard manure (B_{FYM}) and commercial vermicompost (C_{VC}) helped the soil in maintaining higher organic carbon content, organic matter content, nitrogen, phosphorus and potassium contents compared to other soil sample types. The soil samples except for C_{VC} , all were acidic in nature, but it was observed that samples with amendments of organic matter showed comparative alleviation in their pH values. Comparative analysis of soil organic matter in reference to soil sets for enzymatic analysis with respect to soil from A that was not treated with any amendment showed 71 % higher at site ABC, 68 % higher at AB and 56 % higher at site AC. Site ABC with amendments in combination of B_{FYM} and C_{VC} also showed 36 %, 29 % and 42 % increase in total nitrogen, available phosphorus and potassium in comparison to soil from A respectively. The findings are similar to another study (30) where tea-based compost in combination with vermicompost were observed to induce incremental effects on soil chemical properties including soil organic matter content, total nitrogen, total phosphorous and total potassium. The study also highlights a similar decreasing trend in pH and soil bulk density.

Reports are on the importance of vermicompost and other traditional organic amendments in compensating the soil organic loss due to deep tillage as well as alleviating the overall soil organic matter content (31). The incorporation of traditional vermicompost prepared from water hyacinth along with conventional vermicompost amendments was found to augment the concentration of total phosphorous and exchangeable potassium in soils which is in accordance with the earlier findings (32). Similarly, reports are also the positive improvement in C/N ratio, phosphorus and potassium content in soils treated with organic amendments over control soils (33). Studies reveal that various farming practices can have an impact on the amount of nitrogen that accumulates in soil profiles (34, 35) and can be said to be true for the unique age-old agricultural practises employed by the farmers of Ziro Valley specific to vegetable farming. Furthermore, the kind of planting areas such as upland or paddy fields can affect the nitrogen content and spatial variations of the soil. According to a study on cotton cultivation high phosphorus concentration in farming soil improves soil nutrients, enzymatic activity and crop biomass, all of which eventually increase crop output (36). Increased in nutrient availability of soil indicated a high organic carbon concentration in farmed soils as confirmed by the findings of various authors in their studies (37–41).

The levels of arylsulphatase (AsA), dehydrogenase (DhA) and phosphatases (AcP, AkP) in six soil composites were measured enzymatically. The sample with the lowest enzyme activity across all samples was observed at site A, where neither FYM nor VC was added. All enzymatic activities showed similar trends where AC showed higher activity than AB. The results of incorporating both B_{FYM} and C_{VC} on Kalung (A) combined showed a considerable increase in enzymatic activity, with C_{VC} composite exhibiting the highest activity for all enzymes, followed by ABC. The overall findings showed that adding organic inputs like B_{FYM} and C_{VC} significantly increases enzymatic activity (42). Aryl sulphatase activity (AsA) revealed an upward trend in soil samples from plot A to ABC, pointing to the impacts of higher organic inputs at site A (Kalung). While ABC showed higher activity than B_{FYM} , B_{FYM} demonstrated higher activity than the soil composites AB and AC. The maximum arylsulphatase activity was shown by C_{VC} composites. The results indicated a significant and positive correlation ($r = 0.8979$) with soil organic matter content and it corroborates with the earlier works (43, 44).

A similar trend was observed for dehydrogenase activity (DhA) across all soil samples. A simple linear regression analysis for organic matter vs DhA indicated a significant relationship between them as well as a positive correlation between organic matter content and DhA. It was reported that dehydrogenase activity was higher in soils amended with vermicompost and farmyard manures as compared to soils treated with mineral fertilisers and unamended soils respectively (45, 46). Similarly, reports are also on the use of vermicompost amendments tend to increase dehydrogenase activity and acid phosphatase activity but reduced the activity of alkaline phosphatase activity (33). Acid phosphatase activity (AcP) was significantly higher for soil treated both farmyard manure and vermicompost (ABC, AB and AC) compared to those with no inputs (A). AcP also showed a significant linear correlation with organic matter content ($r = 0.8557$) indicating an increase in phosphorous mineralisation with higher organic inputs. Similarly, alkaline phosphatase activity (AkP) showed insignificant linear correlation with soil organic matter contents ($r = 0.8004$). Several studies have reported that higher soil phosphatase activity is associated with higher soil organic carbon content (47, 48). Correlation analysis validates the observed influence of soil physico-chemical properties on enzymatic activities under organic amendment treatments in other similar studies. Soil organic carbon displayed strong positive linkages with all 3 enzymes investigated, indicating its role in supporting microbial activity (49, 50). A close relationship was observed between phosphorus and phosphatase activity, reflecting increased microbial functioning in phosphorus mineralisation. Phosphorus and nitrogen exhibited strong positive relationships with dehydrogenase and phosphatase activities, indicating improved nutrient transformation in amended soils (51). Strong inter enzyme correlations amongst the soil enzyme activities indicate coordinated microbial functioning and integrated cycling of carbon, sulphur and phosphorus (52). Soil pH and enzymatic activities have showed positive correlation, indicating favourable conditions for enzyme stability. Enzyme activities correlated with potassium yielded weak associations, implying a weak role in the regulation of microbial activity. Soil physical properties also influenced enzymatic activity. Bulk density has correlated negatively with enzymes, suggesting that reduced soil compaction improves microbial functioning through better aeration (53). The strong positive correlations between soil organic carbon, nutrient availability and enzymatic activities highlight the role of organic matter inputs in enhancing soil biological quality. Present results suggest that maintaining balanced soil moisture conditions is crucial for efficient microbial-mediated nutrient cycling in vegetable cultivation systems. The results of the present study are indicative and aligned with their findings. According to the results, adding organic inputs like plant based green manure and conventional vermicompost increases the enzymatic activity of the soil significantly (54–56). The absence of crop productivity data is a limitation of the present study and future investigations integrating soil biological indicators with crop performance under similar cropping systems are warranted.

Conclusion

The present study demonstrates that the application of traditional plant based farmyard manure and conventional vermicompost significantly improved soil physico-chemical properties and enzymatic activities in the vegetable growing soil of Ziro Valley,

Lower Subansiri district of Arunachal Pradesh. The combined application of both amendments resulted in the most pronounced improvement in organic matter, total nutrient concentrations and the activities of dehydrogenase, arylsulphatase and phosphatase enzymes, indicating a synergistic influence on soil biological functioning and nutrient cycling. These findings confirm the effectiveness of integrating indigenous organic inputs with vermicompost as a sustainable soil fertility management strategy for vegetable farmlands. The study also provides baseline information on the nutrient and biochemical status of soil, contributing to the scientific validation of traditional soil management practices. This study reliance on locally available resources and low energy processes, serves as an environmentally and economically sustainable soil fertility mechanism, as it reduces dependence on commercial inputs. The results have broader implications for low input and ecologically resilient vegetable production systems in comparable agroecological regions. Further investigation on long term field performance and crop productivity responses would strengthen the understanding of the agronomic benefits of such integrated organic amendment practices.

Acknowledgements

The authors are grateful to the local *Apatani* community, especially the women farmers, for their invaluable support and cooperation throughout the entire study period. We are also thankful to the Scientist-in-Charge, Govind Ballabh Pant National Institute of Himalayan Environment, North East Regional Centre, Itanagar, Arunachal Pradesh, for providing laboratory facilities to carry out soil analysis. The authors sincerely acknowledge the Director, DBT-APSCS & T Centre of Excellence for Bioresources and Sustainable Development, Kimin, Arunachal Pradesh, for laboratory facilities and logistical support that enabled the successful completion of this research. We also express our sincere gratitude to the Director, NERIST and the Head, Department of Forestry, for providing laboratory facilities for this research work. The authors are thankful to Dr. Biswajit Das, System Manager, GIS Lab, LRI-OUAT, College of Agriculture, OUAT, Bhubaneswar, Odisha, for his assistance in preparing the study area map. We further acknowledge the technical staff of GBPNIE and CBRSD, Kimin, for their help and support during the analytical work.

Authors' contributions

LY performed data collection, conceptualisation, methodology, analysis and writing of original draft. SWS carried out data collection, conceptualisation, methodology and writing. AP made conceptualisation, methodology, writing, review and editing. KS made conceptualisation, methodology, review and editing. DM performed conceptualisation, methodology, review and editing. OPT did conceptualisation, methodology, review and editing. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare that they do not have any conflict of interest to declare.

Ethical issues: None

References

1. Afangide AI, Ekpe II, Okoli NH, Egboka NT. Dynamics of phosphatase enzyme and microbial properties in a degraded ultisol amended with animal manures. *J Clean WAS*. 2020;4(1):21–7. <https://doi.org/10.26480/jcleanwas.01.2020.21.27>
2. Antonious GF, Turley ET, Dawood MH. Monitoring soil enzymes activity before and after animal manure application. *Agriculture*. 2020;10(5):166. <https://doi.org/10.3390/agriculture10050166>
3. Ma Q, Wen Y, Wang D, Sun X, Hill PW, Macdonald A, et al. Farmyard manure applications stimulate soil carbon and nitrogen cycling by boosting microbial biomass rather than changing its community composition. *Soil Biol Biochem*. 2020;144:107760. <https://doi.org/10.1016/j.soilbio.2020.107760>
4. Wang L, Xiong X. Long-term organic manure application alters urease activity and ureolytic microflora structure in agricultural soils. *Agronomy*. 2022;12(12):3018. <https://doi.org/10.3390/agronomy12123018>
5. Balakrishnan V, Venkatesan K, Ravindran KC. The influence of halophytic compost, farmyard manure and phosphobacteria on soil microflora and enzyme activities. *Plant Soil Environ*. 2007;53(4):186–92. <https://doi.org/10.17221/2311-PSE>
6. Moeskops B, Sukristiyonubowo, Buchan D, Sleutel S, Herawaty L, Husen E, et al. Soil microbial communities and activities under intensive organic and conventional vegetable farming in West Java, Indonesia. *Appl Soil Ecol*. 2010;45(2):112–20. <https://doi.org/10.1016/j.apsoil.2010.03.005>
7. Gu T, Jia R, Unsal T, Xu D. Toward a better understanding of microbiologically influenced corrosion caused by sulfate reducing bacteria. *J Mater Sci Technol*. 2019;35(4):631–6. <https://doi.org/10.1016/j.jmst.2018.10.026>
8. Zhang N, He XD, Gao YB, Li YH, Wang HT, Ma D, et al. Pedogenic carbonate and soil dehydrogenase activity in response to soil organic matter in *Artemisia ordosica* community. *Pedosphere*. 2010;20(2):229–35. [https://doi.org/10.1016/S1002-0160\(10\)60010-0](https://doi.org/10.1016/S1002-0160(10)60010-0)
9. Kalembasa S, Godlewska A. Total sulfur and its fractions as well as activity of arylsulfatase in soil depending on waste organic materials and liming. *Environ Prot Eng*. 2010;36(1):5–11.
10. Kim JW, Hong YK, Kim HS, Oh EJ, Park YH, Kim SC. Assessment of soil enzyme activities in TPH-contaminated soil after soil washing and landfarming application. *Korean J Soil Sci Fert*. 2022;55(1):13–9. <https://doi.org/10.7745/KJSSF.2022.55.1.013>
11. Igalavithana AD, Lee SS, Niazi NK, Lee YH, Kim KH, Park JH, et al. Assessment of soil health in urban agriculture: soil enzymes and microbial properties. *Sustainability*. 2017;9(2):310. <https://doi.org/10.3390/su9020310>
12. Sharma S, Sharma N, Gupta N, Angmo P, Siddiqui MH, Rahman MA. Impact of chemically diverse organic residue amendment on soil enzymatic activities in a sandy loam soil. *Agronomy*. 2023;13(7):1719. <https://doi.org/10.3390/agronomy13071719>
13. Zhang X, Dong W, Dai X, Schaeffer S, Yang F, Radosevich M, et al. Responses of absolute and specific soil enzyme activities to long-term additions of organic and mineral fertilizer. *Sci Total Environ*. 2015;536:59–67. <https://doi.org/10.1016/j.scitotenv.2015.07.043>
14. Chaudhuri KN, Chaudhuri S. The art of 'organic' living: Lessons from Apatani women in Ziro Valley of Arunachal Pradesh in Northeast India. In: Ghosh KK, Mandal P, Neogi S, editors. *Back to Basics: A Multidisciplinary Approach to Organic Living and Waste Management*. Vol. 3. Kolkata (India): Jogamaya Devi College Interdisciplinary; 2022. p. 75–90.
15. Forest Survey of India. *India State of Forest Report 2023*. Vol. II. Dehradun (India): Ministry of Environment, Forest and Climate Change, Government of India; 2023. p. 17.
16. Dollo M, Samal PK, Sundriyal RC, Kumar K. Environmentally sustainable traditional natural resource management and conservation in Ziro Valley, Arunachal Himalaya, India. *J Am Sci*. 2009;5(5):41–52.
17. Anderson JM, Ingram JSI. *Tropical soil biology and fertility: A handbook of methods*. 2nd ed. Wallingford (UK): CAB International; 1993. p. 368
18. Blake GR. Bulk density. In: Black CA, editor. *Methods of soil analysis. Part 1. Physical and mineralogical properties, including statistics of measurement and sampling*. Madison (WI): American Society of Agronomy; 1965. p. 374–90. <https://doi.org/10.2134/agronmonogr9.1.c30>
19. Bouyoucos GJ. The hydrometer method improved for making particle size analyses of soils. *Agron J*. 1962;54(5):464–5. <https://doi.org/10.2134/agronj1962.00021962005400050028x>
20. Piper CS. *Soil and plant analysis: A laboratory manual of methods for the examination of soils and the determination of the inorganic constituents of plants*. Adelaide (Australia): Hassell Press, University of Adelaide; 1942. p. 368
21. Walkley A, Black IA. An examination of the Degtjareff method for determining organic matter and a proposed modification of the chromic acid titration method. *Soil Sci*. 1934;37(1):29–38. <https://doi.org/10.1097/00010694-193401000-00003>
22. Allen SE, Grimshaw HM, Parkinson JA, Quarmby C. *Chemical analysis of ecological materials*. Oxford (UK): Blackwell Scientific Publications; 1974. p. 576
23. Bray RH, Kurtz LT. Determination of total, organic and available forms of phosphorus in soils. *Soil Sci*. 1945;59(1):39–46. <https://doi.org/10.1097/00010694-194501000-00006>
24. Alef K, Nannipieri P, editors. *Methods in applied soil microbiology and biochemistry*. London: Academic Press; 1995. p. 576
25. Acosta-Martínez V, Tabatabai MA. Enzyme activities in a limed agricultural soil. *Biol Fertil Soils*. 2000;31(1):85–91. <https://doi.org/10.1007/s003740050628>
26. Eivazi F, Tabatabai MA. Phosphatases in soils. *Soil Biol Biochem*. 1977;9(3):167–72. [https://doi.org/10.1016/0038-0717\(77\)90070-0](https://doi.org/10.1016/0038-0717(77)90070-0)
27. Singh SR, Yadav PPS, Singh A, Kumar S. Transition of cropping systems influences nutrient stability, microbial diversity and soil quality in the upper Indo-Gangetic plains of India. *J Soil Sci Plant Nutr*. 2026. <https://doi.org/10.1007/s42729-026-03011-3>
28. Bhuyan SI, Chakma B, Laskar I. Degradation of soil physical properties due to modernization of tillage techniques: A recent man-made crisis to agro-ecology in North East India. *Proc Int Acad Ecol Environ Sci*. 2022;12(3):113–9.
29. Lal R. Soil organic matter and water retention. *Agron J*. 2020;112(5):3265–77. <https://doi.org/10.1002/agj2.20282>
30. El-Shaieny AH, Farrag HM, Bakar AAA, Abdelrasheed KG. Combined use of compost, compost tea and vermicompost tea improves soil properties and growth, yield and quality of *Allium cepa* L. *Not Bot Horti Agrobot Cluj-Napoca*. 2022;50(1):12565. <https://doi.org/10.15835/nbha50112565>
31. Ding Z, Kheir AMS, Ali OAM, Hafez EM, ElShamey EA, Zhou Z, et al. A vermicompost and deep tillage system to improve saline-sodic soil quality and wheat productivity. *J Environ Manage*. 2021;277:111388. <https://doi.org/10.1016/j.jenvman.2020.111388>
32. Das D, Kumar A, Banik P, Swain DK. Comparative evaluation of changes in soil biochemical properties after application of traditional and enriched vermicompost. *Environ Technol Innov*. 2022;28:102956. <https://doi.org/10.1016/j.eti.2022.102956>
33. Przemieniecki SW, Zapłowska A, Skwiercz A, Damszel M, Telesiński A, Sierota Z, et al. An evaluation of selected chemical, biochemical and biological parameters of soil enriched with vermicompost. *Environ Sci Pollut Res Int*. 2021;28(7):8117–27. <https://doi.org/10.1007/s11356-020-10981-z>

34. Gao H, Xu L. Study of nitrate-nitrogen leaching characteristics in the agricultural extensively planted farmland. In: 2011 International Conference on Remote Sensing, Environment and Transportation Engineering (RSETE); 2011; Nanjing, China. New York: IEEE; 2011. p. 2527–30. <https://doi.org/10.1109/RSETE.2011.5964828>
35. Watros A, Lipińska H, Lipiński W, Tkaczyk P, Krzyszcak J, Baranowski P. Mineral nitrogen content in the 60–90 cm layer of grassland soils relative to other fodder crops, way of managing agricultural lands and farming intensity. *Acta Agroph.* 2018;25(3):343–57. <https://doi.org/10.31545/aagr/97185>
36. Iqbal B, Khan I, Javed Q, Alabbosh KF, Inamullah I, Zhou Z, et al. The high phosphorus incorporation promotes the soil enzymatic activity, nutritional status and biomass of the crop. *Pol J Environ Stud.* 2023;32(3):2125–39. <https://doi.org/10.15244/pjoes/158765>
37. Gardi C, Visioli G, Conti FD, Scotti M, Menta C, Bodini A. High nature value farmland: Assessment of soil organic carbon in Europe. *Front Environ Sci.* 2016;4:47. <https://doi.org/10.3389/fenvs.2016.00047>
38. Colombi T, Walder F, Büchi L, Sommer M, Liu K, Six J, et al. On-farm study reveals positive relationship between gas transport capacity and organic carbon content in arable soil. *SOIL.* 2019;5(1):91–105. <https://doi.org/10.5194/soil-5-91-2019>
39. Zhang L, Li Z, Zhang S, Xia S, Zou H, Huang Y. Characteristics and driving mechanism of soil organic carbon content in farmland of Beijing Plain: Implication for the fate of engineered polymers in soil. *Adv Polym Technol.* 2019;2019:4837658. <https://doi.org/10.1155/2019/4837658>
40. Wei F, Liu J, Xia LH, Xu ZW, Long XC. Spatial prediction method of farmland soil organic matter in Weibei dryland of Shaanxi Province. *Huan Jing Ke Xue.* 2022;43(2):1097–107.
41. Han C, Li W, Li M, Guo Y, Li M, Wu H. Investigating the vertical distribution of dissolved organic matter in 5-m soil profiles in farmland and typical woodland on the southern Loess Plateau. *Environ Res.* 2023;219:115017. <https://doi.org/10.1016/j.envres.2022.115017>
42. Serrano-Grijalva L, van der Putten WH, Ochoa-Hueso R, Margenot AJ, van Rijssel SQ, Koorneef GJ, et al. Soil extracellular enzyme activity increases during the transition from conventional to organic farming. *Agric Ecosyst Environ.* 2024;375:109202. <https://doi.org/10.1016/j.agee.2024.109202>
43. Lori M, Symnacczik S, Mäder P, De Deyn G, Gattinger A. Organic farming enhances soil microbial abundance and activity: A meta-analysis and meta-regression. *PLoS One.* 2017;12(7):e0180442. <https://doi.org/10.1371/journal.pone.0180442>
44. Carneiro RG, de Figueiredo CC, Malaquias JV, Mendes IC. A soil health assessment tool for vegetable cropping systems in tropical soils based on beta-glucosidase, arylsulfatase and soil organic carbon. *Appl Soil Ecol.* 2024;198:105394. <https://doi.org/10.1016/j.apsoil.2024.105394>
45. Tejada M, Hernandez MT, Garcia C. Soil restoration using composted plant residues: Effects on soil properties. *Soil Tillage Res.* 2009;102(1):109–17. <https://doi.org/10.1016/j.still.2008.08.004>
46. Marinari S, Masciandaro G, Ceccanti B, Grego S. Influence of organic and mineral fertilisers on soil biological and physical properties. *Bioresour Technol.* 2000;72(1):9–17. [https://doi.org/10.1016/S0960-8524\(99\)00094-2](https://doi.org/10.1016/S0960-8524(99)00094-2)
47. Dodor DE, Tabatabai MA. Effect of cropping systems on phosphatases in soils. *J Plant Nutr Soil Sci.* 2003;166(1):7–13. <https://doi.org/10.1002/jpln.200390016>
48. Williams G, Miller R, Deng S. Dynamic relationships between microbial community, enzyme activity and soil properties across global ecosystems. *Appl Soil Ecol.* 2025;206:105843. <https://doi.org/10.1016/j.apsoil.2024.105843>
49. Chang EH, Chung RS, Tsai YH. Effect of different application rates of organic fertilizer on soil enzyme activity and microbial population. *Soil Sci Plant Nutr.* 2007;53(2):132–40. <https://doi.org/10.1111/j.1747-0765.2007.00122.x>
50. Zhu Y, Zhang H, Wang Q, Zhu W, Kang Y. Soil extracellular enzyme activity linkage with soil organic carbon under conservation tillage: A global meta-analysis. *Eur J Agron.* 2024;155:127135. <https://doi.org/10.1016/j.eja.2024.127135>
51. Parham JA, Deng SP, Raun WR, Johnson GV. Long-term cattle manure application in soil: I. Effect on soil phosphorus levels, microbial biomass C and dehydrogenase and phosphatase activities. *Biol Fertil Soils.* 2002;35(5):328–37.
52. Nannipieri P, Trasar-Cepeda C, Dick RP. Soil enzyme activity: A brief history and biochemistry as a basis for appropriate interpretations and meta-analysis. *Biol Fertil Soils.* 2018;54(1):11–19. <https://doi.org/10.1007/s00374-017-1245-6>
53. Sainju UM, Liptzin D, Dangi SM. Enzyme activities as soil health indicators in relation to soil characteristics and crop production. *Agrosyst Geosci Environ.* 2022;5(3):e20297. <https://doi.org/10.1002/agg2.20297>
54. Saleem A, Ur Rahim H, Khan U, Irfan M, Akbar WA, Akbar Z, et al. Organic materials amendments can improve NPK availability and maize growth by reducing heavy metals stress in calcareous soil. *Int J Environ Sci Technol.* 2024;21(3):2533–46. <https://doi.org/10.1007/s13762-023-05135-w>
55. Das D, Abhishek K, Banik P, Swain DK. Comparative evaluation of changes in soil biochemical properties after application of traditional and enriched vermicompost. *Environ Technol Innov.* 2022;28:102956. <https://doi.org/10.1016/j.eti.2022.102956>
56. Sidhu AS, Walia SS, Rani N, Aulakh CS, Pandove G, Kumar N. From soil health to economic benefits: The role of organic and natural farming in sustainable agriculture. *J Soil Sci Plant Nutr.* 2026. <https://doi.org/10.1007/s42729-026-03063-5>

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonpublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc. See https://horizonpublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.