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RESEARCH ARTICLE

Sustainable finger millet cultivation: Leveraging organic nutrient sources for productivity and soil health

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Abstract

Organic farming plays a pivotal role in promoting sustainable agriculture by enhancing soil health, improving crop productivity and minimizing environmental impacts. Finger millet, a vital rainfed crop, often encounters significant yield limitations due to poor soil fertility and inadequate nutrient availability. To address these challenges, a field study was conducted during the *Kharif* seasons of 2022-23 and 2023-24 at the Research Institute on Organic Farming, University of Agricultural Sciences, Bangalore. The study aimed to evaluate the impact of various organic nutrient sources on growth, yield, nutrient uptake, availability and microbial status of finger millet. The experiment comprised seven organic nutrient treatments applied on a nitrogen equivalency basis, along with an absolute control and was laid out in a randomized complete block design with three replications. The findings revealed that the application of poultry manure at 100 % nitrogen equivalency significantly enhanced plant growth, yield attributes, nutrient dynamics, soil microbial activity and enzymatic functions. Vermicompost and deoiled cake treatments also demonstrated notable improvements in productivity and soil health. Conversely, the absolute control consistently recorded the lowest values across all parameters. This study highlights the effectiveness of organic nutrient management, particularly poultry manure, in sustainably enhancing finger millet productivity and soil health.

Keywords: available nutrients; enzymatic activities; microbial diversity; nutrient uptake; organic manures; productivity

Introduction

The growing global emphasis on sustainable agricultural practices has increased the focus on organic nutrient management as a solution to mitigate the negative impacts of conventional farming (1). Among the various crops benefiting from organic approaches, finger millet (*Eleusine coracana* L. Gaertn.) stands out for its adaptability and resilience (2). This hardy cereal, an herbaceous annual plant. It belongs to the family Poaceae, tribe Panicaceae and group Chloridae. This crop thrives in arid and semi-arid regions, particularly under rainfed conditions on marginal soils with low fertility and limited water availability (3). It's remarkable ability to withstand drought and erratic rainfall patterns makes it an essential crop for small and marginal farmers practicing low-input agriculture.

Finger millet's significance extends beyond its resilience, as it is a nutritional powerhouse that provides essential carbohydrates (65-70 %), proteins (7.30-9.20 %) and dietary fiber (18-20 %), along with minerals such as calcium (300-350 mg per 100 g), iron (6.40 mg per 100 g) and phosphorus (283 mg per 100 g). These attributes make it a key staple in the diets of many, contributing to food and nutritional security (4). Additionally, its bioactive compounds, including polyphenols and dietary fibers, offer health benefits such as anti-diabetic, antioxidant and anti-inflammatory properties, solidifying its reputation as a "super cereal". Finger millet also plays a vital role in rural livelihoods and ecological sustainability. It is used to prepare traditional dishes such as porridge and dumplings, as well as processed products like biscuits and malt. The straw serves as valuable livestock fodder and is utilized for thatching, enhancing its economic utility. Its low input requirements and adaptability make it an excellent choice for sustainable farming systems, particularly in resource-constrained areas (5).

Despite its advantages, the productivity of finger millet is often limited by poor soil fertility management. Conventional farming practices have exacerbated soil degradation and nutrient depletion, highlighting the need for sustainable alternatives (6). Organic nutrient sources, including farmyard manure, vermicompost, poultry manure, neem cake and liquid organic manures, provide an effective solution. These inputs enrich the soil with essential nutrients, enhance microbial activity and improve soil organic carbon levels, which are crucial for maintaining soil health and boosting crop productivity (7).

The need for sustainable agriculture has grown more urgent in the wake of challenges posed by the Green Revolution. While intensive chemical farming methods achieved remarkable productivity gains, they also led to long-term issues such as soil erosion, reduced fertility and environmental pollution (8). Organic farming presents a promising alternative, emphasizing the use of natural inputs to restore soil health and ensure ecological balance (9). Integrating organic manures into finger millet cultivation can address these concerns while enhancing the crop's productivity and nutritional quality (10). The present study seeks to explore the impact of various organic amendments on growth, yield, nutrient uptake and soil health in finger millet cultivation.

Materials and Methods

Details of location, soil and climate

Field experiments were conducted during the *Kharif* seasons of 2022-23 and 2023-24 at the Research Institute on Organic Farming (RIOF), University of Agricultural Sciences (UAS), Bangalore, Karnataka, India. The experimental site is situated at 13°09' North latitude, 77°57' East longitude and an altitude of 924 m above mean sea level. This location falls under the Eastern Dry Zone of Karnataka (Zone-5) and is classified as a semi-arid tropic according to the modified Troll's climatic classification recognized by ICRISAT (International Crops Research Institute for the Semi-Arid Tropics).

The soil at the experimental site is very deep, well-drained and has a red sandy clay loam texture. It belongs to the *Vijayapura* series, a dominant soil type of the Bengaluru plateau. Based on United states department of agriculture classification, these soils are categorized as fine, kaolinitic, isohyperthermic, typic kandiustalfs. Soil analysis results showed an average pH of 6.654, electrical conductivity (EC) of 0.252 dS m^{-1}, organic carbon (OC) content of 0.532 % and available nitrogen, phosphorus and potassium levels of 140.025, 11.005 and 90.530 kg ha^{-1}, respectively (Table 1). The finger millet variety KMR-316 was sown in August and harvested in December in both years. The actual meteorological data recorded during the crop-growing period from August to December of both study years is depicted in Fig. 1.

Details of tillage and treatments

The land was initially ploughed using a disc plough once after the harvest of the previous crop. This was followed by two harrowing operations to eliminate weeds and break up the clods. To create a fine seedbed, the soil was then smoothed using a wooden plank. Plots were laid out and levelled as per the experimental design. Furrows were made at a 30 cm width and each plot was surrounded by bunds measuring 20 cm in width and 10 cm in height.

Well decomposed farmyard manure (FYM) at a rate of 7.5 t ha^{-1} was applied to all plots, except the absolute control, two weeks prior to sowing and was thoroughly incorporated into the soil. The experiment was designed using a randomized complete block design (RCBD) with eight treatments, each replicated three times. At the time of sowing, organic inputs were applied according to the assigned treatments. The treatments included: Absolute control (T_1); 100 % nitrogen equivalent FYM (T_2); 100 % nitrogen equivalent vermicompost (T_3); 100 % nitrogen equivalent urban compost (T_4); 100 % nitrogen equivalent poultry manure (T_5); 100 % nitrogen equivalent deoiled cake (T_6); 100 % nitrogen equivalent biodigester liquid organic manure (T_7) and 100 % nitrogen equivalent integrated nutrient sources of 50 % FYM + 25 % vermicompost + 25 % biodigester liquid organic manure (T_8).

Data collection and measurement

Growth parameters

Growth parameters were measured at 30, 60 and 90 days after sowing (DAS), as well as at harvest. Plant height was measured from the ground level to the base of the ear head on five randomly selected plants, with the mean height expressed in centimeters (cm). The number of leaves per plant was determined by counting the leaves on the same selected plants and the average was calculated. Similarly, leaf area was measured using a leaf area meter (Inc/LI-COR Ltd., Nebraska, USA) by separating the green leaves from the selected plants and the average area was expressed in cm^2 per plant. Tiller number per plant was also recorded and averaged.

Dry matter partitioning

Dry matter production was evaluated by collecting plant samples at harvest, which were then oven dried at 65 °C for 72 hr. After drying, the samples were weighed and the dry weight was recorded in grams (g). For dry matter partitioning, five plants were carefully uprooted from each treatment and

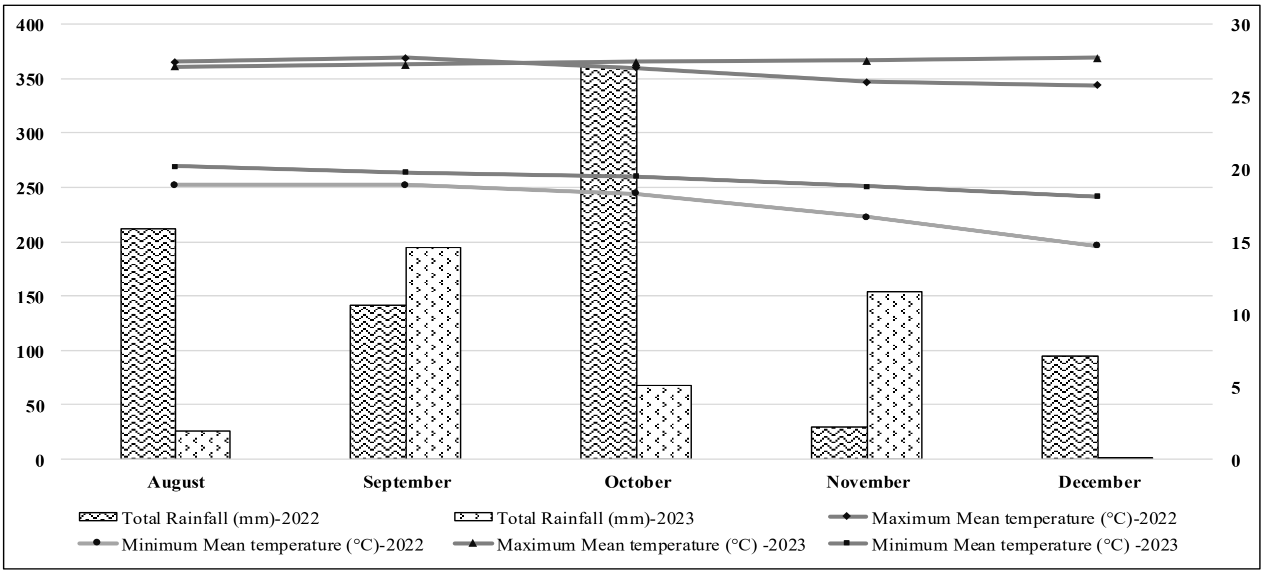


Fig. 1. Meteorological data for crop growing period (August to December) for the years 2022 and 2023.

replication. These plants were washed thoroughly and separated into different parts, such as leaf, stem and ear head using a knife. The samples were dried in a hot air oven at 65 °C until the weight remained constant after repeated weighing. The dry matter from each plant part (leaves, stems and ear heads) was directly measured in grams (g) to determine the total dry weight based on actual recorded values.

Yield attributes

At harvest, the number of productive tillers per plant was determined by counting the ear head bearing tillers from five randomly selected plants in the net plot and calculating the average. The number of fingers per ear head was recorded by counting the individual grain-bearing segments from five randomly selected and the average number was calculated. Ear length was measured from the base to the tip of five randomly selected ear heads and the average length was recorded in centimeters (cm). Finger length was assessed by measuring five randomly selected fingers from the ear heads, recording their length from base to tip and calculating the average finger length in centimeters (cm).

Yield

At harvest, test weight was determined by counting 1000 grains from the grain yield of five plants using a seed counter (Alphanumeric, Indosaw), which automatically stops after counting the set number and the weight was recorded as the 1000 grain weight in grams. Grain yield was measured by sun drying the harvested grain from each net plot for 4-6 days to reduce moisture to 10-12 %, which was confirmed by the oven-drying method. Followed by threshing, cleaning and weighing the grains. The yield was then computed on a hectare basis and expressed in kilograms per hectare. Straw yield was recorded by sun drying the straw from the net plot for 8-10 days and calculating the yield per hectare. Harvest index was calculated by using following formula.

$$\text{Harvest index} = \frac{\text{Economic yield}}{\text{Biological yield}} \quad \text{(Eqn. 1)}$$

Plant sampling, processing and analysis

For nutrient uptake analysis, plant samples were collected at the harvest stage. Two plants from each net plot were selected, tagged and separated into different envelopes for grain and straw, which were then appropriately labelled. The samples were dried in a hot air oven at 60 °C for 48 hr. After drying, each sample was ground separately using a Willy mill to pass through a 20 mm-mesh sieve. The resulting ground material was subjected to chemical analysis to determine the nutrient concentration in the grain and straw by following standard procedures (Table 2). Nutrient uptake was calculated by using following formula.

$$\text{Nutrient uptake (kg/ha)} = \frac{\text{Nutrient connection (\%) x Total dry nature (kg/ha)}}{100} \quad \text{(Eqn. 2)}$$

Soil sampling, processing and analysis

Soil samples were collected after harvest of finger millet from each treatment and replication, with a sampling depth of 0-30 cm, representing the effective root zone of the crop. Multiple sub-samples were taken using a soil auger in a zigzag pattern across the field to ensure representativeness. For rhizosphere soil, samples were collected by removing the root systems with adhering soil from finger millet, with loosely attached soil separated by gently shaking the roots, while tightly held rhizosphere soil was shaken over a plastic sheet. On the other hand, non-rhizospheric soil was collected from between the plant rows of crops. After collection, all soil samples were air-dried in the shade, ground using a wooden pestle and mortar, sieved through a 2 mm mesh and stored for further analysis. The sub-samples were mixed to form a composite sample, with debris carefully removed, before being air-dried, crushed and sieved again. The final processed samples were stored in clean, labelled bags for subsequent analysis of their physico-chemical properties using standard procedures as outlined in Table 3.

Enumeration of soil microbial status

Microbial enumeration was performed by collecting soil samples from the 0-15 cm depth, followed by serial dilution for analysis. In this procedure, 1 g of soil was mixed with 100 mL of sterile water to create a dilution, which was subsequently

Table 1. Physico-chemical properties of the experimental site

Particulars	Values		Method of analysis	References
	2022	2023		
Physical properties				
Mechanical analysis				
Coarse sand (%)	34.96	35.68	Bouyoucos hydrometer	(11)
Fine sand (%)	29.01	28.82		
Silt (%)	6.41	6.76		
Clay (%)	29.62	28.74		
Textural class	**Red sandy loamy soil**			
Physico-chemical properties				
Soil pH	6.620	6.688	Digital pH meter DI 707	(12)
Electrical conductivity (dS m^{-1})	0.249	0.255	Digital EC meter	(12)
Chemical properties				
Organic carbon (%)	0.531	0.533	Wet digestion method	(13)
Available nitrogen (kg ha^{-1})	134.63	145.42	Alkaline permanganate method	(14)
Available phosphorus (kg ha^{-1})	10.45	11.56	Bray's No.1 method	(15)
Available potassium (kg ha^{-1})	86.63	94.43	Flame photometer	(16)
Exchangeable calcium (cmol p+ kg^{-1})	1.13	1.26	Complex ometric titration	(17)
Exchangeable magnesium (cmol p+ kg^{-1})	0.75	0.82	Complex ometric titration	(17)
Available sulphur (kg ha^{-1})	7.05	7.21	Turbidimetric method	(18)

Table 2. Methods employed for plant analysis

S. No.	Nutrient	Method	References
1	Total nitrogen (%)	Kelplus - analyzer distillation method	(14)
2	Total phosphorus (%)	Triple acid digestion and Vanadomolybdate phosphoric yellow color method	(16)
3	Total potassium (%)	Triple acid digestion and Flame photometry	(16)

Table 3. Methods employed for soil analysis

S. No.	Nutrient	Method	References
1	Available nitrogen (kg ha^{-1})	Alkaline permanganate method	(14)
2	Available phosphorus (kg ha^{-1})	Bray's no.1 method	(15)
3	Available potassium (kg ha^{-1})	Flame photometer	(16)
4	Exchangeable calcium (cmol p+ kg^{-1})	Complex ometric titration	(17)
5	Exchangeable magnesium (cmol p+ kg^{-1})	Complex ometric titration	(17)
6	Available sulphur (kg ha^{-1})	Turbidimetric method	(18)

plated on various agar media to isolate specific microbial groups. The traditional dilution plate method was employed, where the number of colonies formed on the agar plates was counted and then multiplied by the dilution factor to estimate microbial populations, expressed as colonies per gram of oven-dried soil. Different types of agar media were used for different microorganisms: Nutrient agar for bacteria, Martin's rose Bengal agar for fungi and Kuster's agar for actinomycetes. Soil dehydrogenase activity was measured using a standard procedure, while urease activity was assessed following a recognized protocol and phosphatase activity in the soil was determined according to an established method (19-21).

Statistical analysis

The statistical analysis of the data was conducted using Fisher's analysis of variance (ANOVA) method (22). The data were analyzed for individual years as well as for pooled years and a comparison of means was conducted using Duncan's multiple range test (DMRT). In cases where the F-test revealed significant differences, the critical difference (CD) was computed to compare the treatment means. If the F-test showed no significant differences, the results were labeled as NS (non-significant). All statistical tests were performed at a 5 % probability level and the findings were presented and discussed accordingly.

Results

Growth parameters

Pooled analysis over the years revealed significant differences in finger millet growth parameters at harvest under different organic nutrient treatments (Table 4). The application of 100 % nitrogen equivalent poultry manure (T_5) resulted in a higher plant height (103.73 cm), average number of leaves per plant (23.74), leaf area per plant (1007.51 cm^2) and average number of tillers per plant (5.63). Treatments with 100 % nitrogen equivalent vermicompost (T_3) and 100 % nitrogen equivalent deoiled cake (T_6) showed statistically comparable performance to T_5. In contrast, the absolute control (T_1) exhibited the lower growth parameters, with a plant height of 74.57 cm, 16.71 leaves per plant, 581.09 cm^2 leaf area per plant and 3.89 tillers per plant.

Dry matter partitioning

Pooled analysis of dry matter partitioning in finger millet at harvest showed that the treatment T_5 resulted in the highest values for leaf dry weight (11.74 g), stem dry weight (20.06 g), ear head dry weight (37.08 g) and total dry weight (67.33 g). Among these, the ear head contributed the most to the total dry matter accumulation, followed by the stem and leaf. Treatments T_3 and T_6 were statistically on par with T_5 (Table 4). Conversely, the treatment T_1, which did not receive any nutrient input, recorded the lowest values for leaf, stem, ear head and total dry weights (7.52, 11.86, 21.08 and 40.45 g, respectively).

Yield attributes

Application of 100 % nitrogen equivalent poultry manure (T_5) exhibited the best performance, with an average of 5.50 productive tillers per plant, 6.14 fingers per ear head, 9.19 cm ear length and 8.28 cm finger length. Similar results were observed from 100 % nitrogen equivalent vermicompost, which recorded an average of 5.17 productive tillers, 5.68 fingers per ear head, 8.80 cm ear length and 8.17 cm finger length and from 100 % nitrogen equivalent deoiled cake, which achieved mean of 5.07 productive tillers, 5.56 fingers per ear head, 8.60 cm ear length and 8.05 cm finger length (Table 5). On the other hand, T_1 resulted in the lower values. However, the test weight across all treatments remained unaffected by the nutrient inputs, with a narrow range of 3.54 to 3.71 g, which is primarily determined by the genetic characteristics of the finger millet variety.

Yield

The pooled year analysis of finger millet yields indicated remarkable differences among the treatments (Table 5). The treatment T_5 obtained a higher grain yield and straw yield of 3155 kg ha^{-1} and 4339 kg ha^{-1}, respectively. This was on par with T_3, recording grain and straw yield of 3085 kg ha^{-1} and 4230 kg ha^{-1}, while T_6 attained 2821 kg ha^{-1} and 3982 kg ha^{-1}, respectively. T_1 produced lower grain yields of 1903 kg ha^{-1} and straw yield of 3298 kg ha^{-1}. Notably, the harvest index across treatments showed no significant variation, ranging between 0.37 and 0.42.

Nutrient uptake

The nutrient uptake of finger millet at harvest is illustrated in Fig. 2. Among the treatments, T_5 recorded higher uptake across all parameters. Nitrogen uptake in grain was 33.86 and 37.43 kg ha^{-1} and in straw, it was 60.14 and 64.53 kg ha^{-1}. Phosphorus uptake in grain was 10.97 and 12.62 kg ha^{-1} and in straw, it was 13.17 and 14.02 kg ha^{-1}. Potassium uptake in grain was 18.42 and 21.32 kg ha^{-1}, while in straw, it was 57.68 and 62.43 kg ha^{-1} for 2022 and 2023, respectively. Treatments T_3 and T_6 performed on par with T_5. In contrast, the absolute control recorded the lower uptake of nitrogen, phosphorus and potassium in both grain and straw in both the years.

Table 4. Effect of various organic nutrient sources on growth parameters and dry matter partitioning of finger millet at harvest (pooled data of 2022 and 2023)

Treatment	Growth parameters				Dry matter partitioning			
	Plant height (cm)	Number of leaves/plant	Leaf area/ plant (cm^2)	Number of tillers/plant	Leaf dry weight (g)	Stem dry weight (g)	Ear head dry weight (g)	Total dry weight (g)
T_1	74.57^{d}	16.71^{c}	581.09^{e}	3.89^{c}	7.52^{d}	11.86^{e}	21.08^{d}	40.45^{e}
T_2	81.15^{cd}	17.46^{c}	671.46^{de}	4.14^{c}	8.34^{d}	13.22^{de}	23.54^{d}	44.07^{de}
T_3	103.36^{a}	22.77^{a}	976.59^{a}	5.35^{a}	10.66^{ab}	18.77^{a}	34.84^{ab}	64.04^{a}
T_4	90.12^{bc}	19.49^{bc}	755.14^{cd}	5.02^{ab}	9.83^{bc}	16.58^{bc}	31.13^{bc}	56.06^{bc}
T_5	103.73^{a}	23.74^{a}	1007.51^{a}	5.63^{a}	11.74^{a}	20.06^{a}	37.08^{a}	67.33^{a}
T_6	100.43^{ab}	21.85^{ab}	941.92^{ab}	5.21^{a}	10.54^{ab}	18.59^{ab}	33.49^{ab}	62.40^{ab}
T_7	86.78^{cd}	19.40^{bc}	839.42^{bc}	4.25^{c}	8.13^{d}	14.94^{cd}	23.79^{d}	46.85^{de}
T_8	90.24^{bc}	19.25^{bc}	708.31^{d}	4.42^{bc}	8.63^{cd}	15.63^{c}	28.19^{c}	51.25^{cd}

Note: The mean with different letters as superscripts are significant ($p < 0.05$). The mean with same letters or having common letter(s) are not significantly different.

Available nutrients

Nitrogen availability was higher with 100 % nitrogen equivalent poultry manure (T_5), recording 239.51 and 248.32 kg ha^{-1} in the rhizosphere and 235.14 and 243.11 kg ha^{-1} in the non-rhizosphere for 2022 and 2023, respectively, which was on par with 100 % nitrogen equivalent vermicompost and deoiled cake. Similarly, phosphorus availability in T_5 was 33.14 and 36.67 kg ha^{-1} in the rhizosphere and 35.28 and 38.07 kg ha-^{1}in the non-rhizosphere and potassium availability reached 172.79 and 183.15 kg ha^{-1}in the rhizosphere and 165.86 and 178.94 kg ha^{-1} in the non-rhizosphere, with T_3 and T_6 exhibiting comparable results. For calcium and magnesium availability, T_2 recorded the higher values of 4.56 and 4.78 cmol (p-) $kg^{-1}$for calcium and 1.88 and 2.01 cmol (p-) kg^{-1} for magnesium in the rhizosphere during 2022 and 2023, respectively, also on par with T_5 and T_3. Sulphur availability was higher under T_5, with 14.47 and 16.14 mg kg^{-1} in the rhizosphere and 16.93 and 17.26 mg kg^{-1} in the non-rhizosphere for the two years, closely followed by T_3 and T_6. In contrast, the absolute control (T_1) consistently recorded the minimal soil nutrient availability across all parameters during both years (Fig. 3).

Microbial status

The microbial counts and enzymatic activities of the soil at crop harvest were profoundly influenced by the application of various organic nutrient sources during 2022 and 2023 as depicted in Fig. 4. Among the treatments, T_5 recorded higher values across all microbial and enzymatic parameters. The bacterial count was 36.45 and 39.63 × 10^6 CFU g^{-1} of soil, the fungal count was 23.02 and 24.24 × 10^4 CFU g^{-1} of soil and actinomycetes count reached 25.58 and 26.87 × 10^3 CFU g^{-1} of soil in 2022 and 2023, respectively. Similarly, enzymatic activities under T_5 were also superior, with dehydrogenase activity at 56.68 and 60.47 µg TPF formed g^{-1} of soil day^{-1}, urease activity at 9.42 and 10.52 µg NH_4-N formed g^{-1} of soil hr^{-1} and phosphatase activity at 31.12 and 34.30 µg PNP formed g^{-1} of soil hr^{-1}during the two years. Treatments T_3 and T_6 performed on par with T_5 in all parameters. Conversely, the absolute control recorded lower microbial counts and enzymatic activities in both years.

Discussions

Growth parameters

The superior growth parameters of finger millet under poultry manure can be attributed to its rich nitrogen and organic matter content, ensuring sustained nutrient release. This promoted cell division and elongation, leading to taller plants (23, 24). Vermicompost and deoiled cake also supported notable plant height due to their nutrient richness and soil-enhancing properties. The increased number of leaves per plant with poultry manure application is likely due to enhanced nutrient uptake, stimulating cell proliferation and higher leaf production (25). Similarly, poultry manure significantly expanded leaf area due to its high nitrogen content, which supports chlorophyll synthesis and vegetative growth (26). Vermicompost and deoiled cake also enhanced leaf area by providing essential nutrients, beneficial microorganisms and growth regulators. The number of tillers per plant increased with poultry manure, driven by improved nitrogen uptake, protein synthesis and root development, facilitating nutrient absorption (27). In contrast, absolute control showed inferior growth due to inadequate nutrient supply, highlighting the critical role of organic amendments in enhancing finger millet growth.

Dry matter partitioning

The enhanced dry matter partitioning in finger millet with poultry manure application is attributed to its nutrient rich composition and continuous release, which enhance photosynthetic activity and biomass translocation, particularly to the ear head. High nitrogen levels promote chlorophyll synthesis and carbohydrate

Table 5. Effect of various organic nutrient sources on yield attributes and yield of finger millet (pooled data of 2022 and 2023)

Treatment	Number of productive tillers/plant	Number of fingers/ear head	Ear length (cm)	Finger length (cm)	Test weight (g)	Grain yield (kg/ha)	Straw yield (kg/ha)	Harvest index
T_1	3.81^{d}	4.19^{d}	7.21^{c}	6.63^{d}	3.54^{a}	1903^{e}	3298^{c}	0.37^{a}
T_2	4.01^{d}	4.35^{cd}	7.79^{bc}	6.85^{d}	3.56^{a}	2301^{d}	3402^{c}	0.40^{a}
T_3	5.17^{ab}	5.68^{a}	8.80^{ab}	8.17^{ab}	3.69^{a}	3085^{ab}	4230^{ab}	0.42^{a}
T_4	4.85^{bc}	4.98^{bc}	8.07^{abc}	7.15^{bcd}	3.61^{a}	2778^{bc}	3814^{bc}	0.42^{a}
T_5	5.50^{a}	6.14^{a}	9.19^{a}	8.28^{a}	3.71^{a}	3155^{a}	4339^{a}	0.42^{a}
T_6	5.07^{ab}	5.56^{ab}	8.60^{ab}	8.05^{abc}	3.65^{a}	2821^{abc}	3982^{ab}	0.42^{a}
T_7	4.12^{d}	4.62^{cd}	7.98^{bc}	7.13^{cd}	3.58^{a}	2425^{d}	3707^{bc}	0.40^{a}
T_8	4.30^{cd}	4.93^{bc}	7.91^{bc}	7.16^{bcd}	3.60^{a}	2525^{cd}	3776^{bc}	0.40^{a}

Note: The mean with different letters as superscripts are significant ($p < 0.05$). The mean with same letters or having common letter(s) are not significantly different.

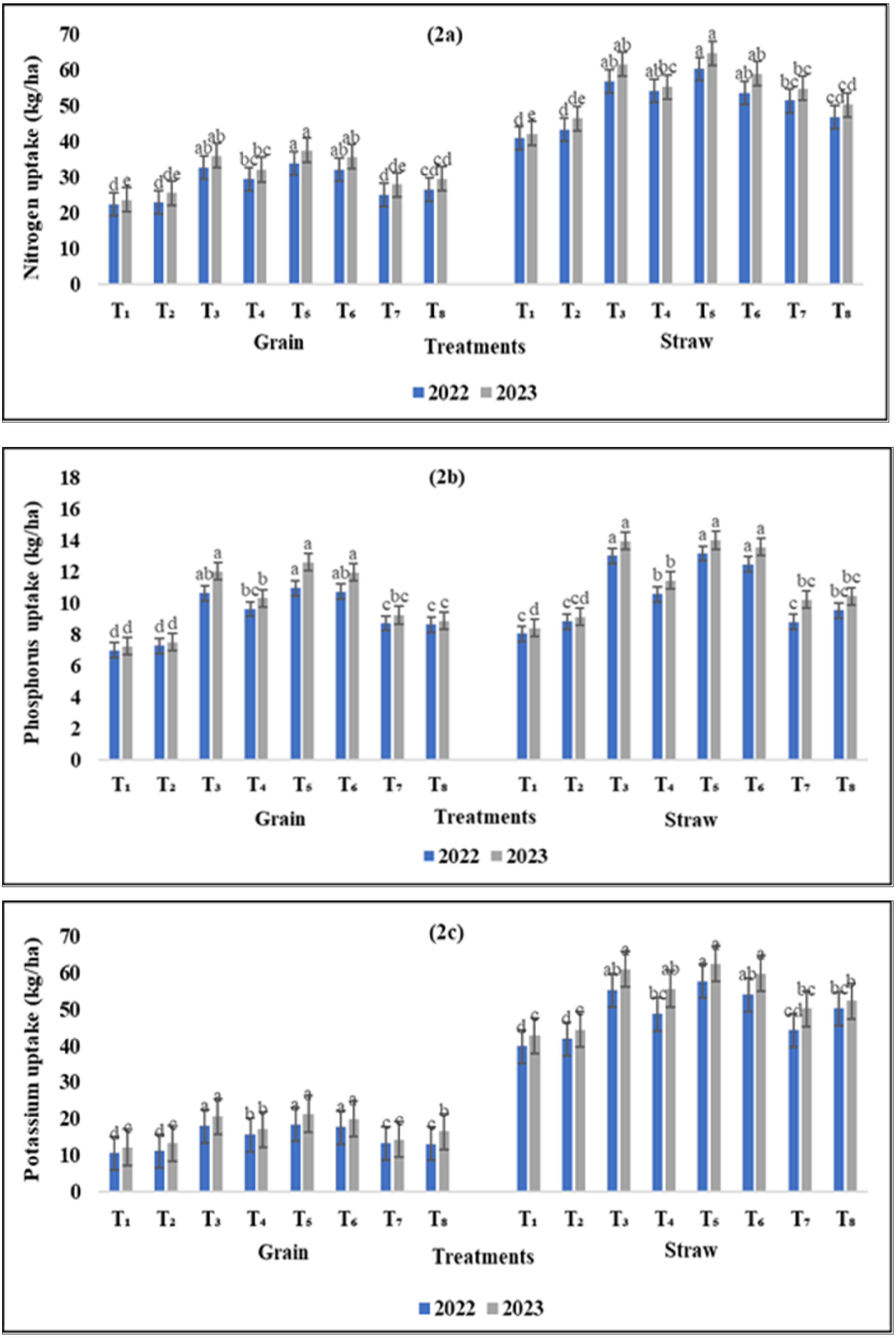
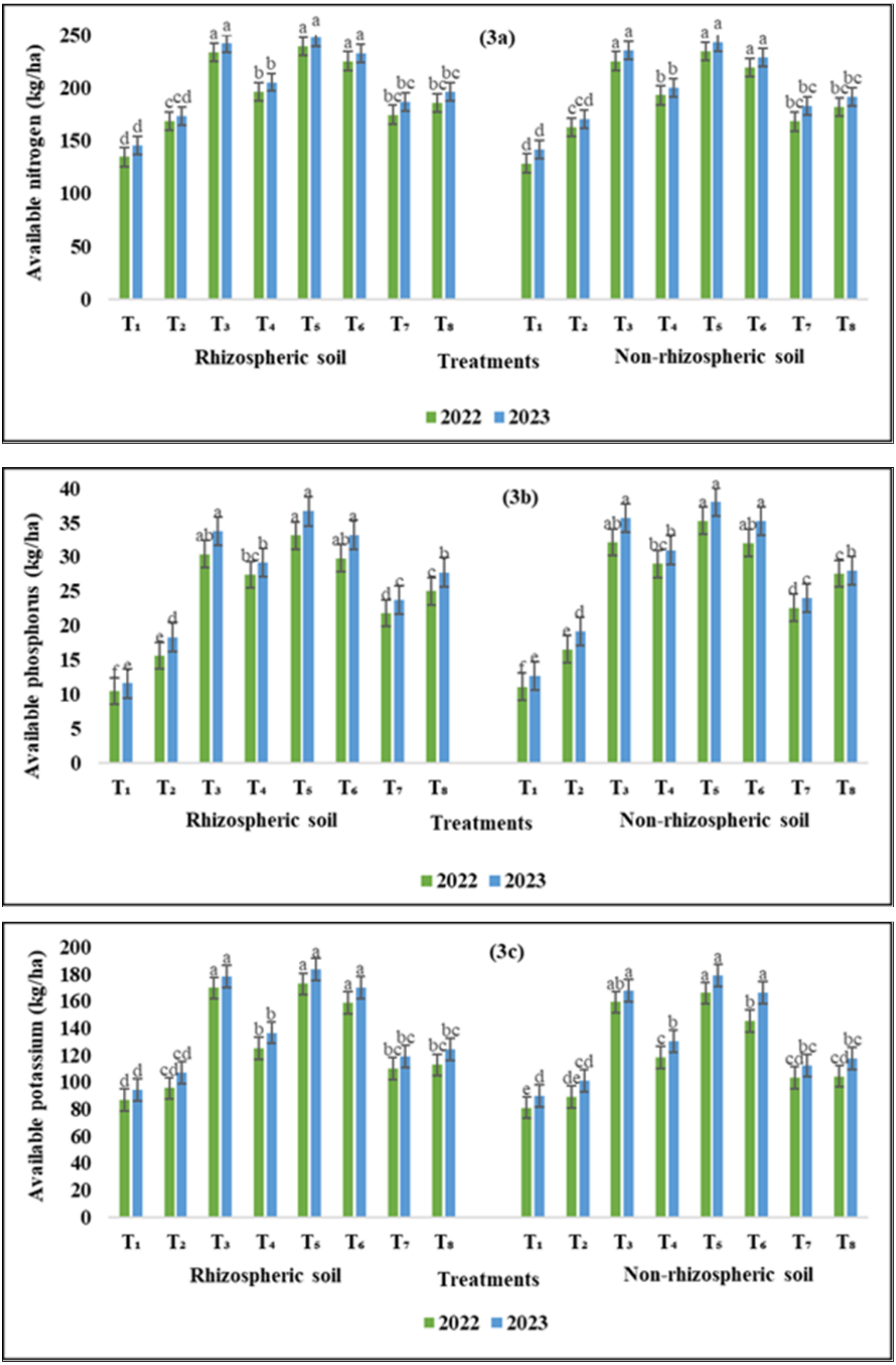


Fig. 2. Effect of various organic nutrient sources on grain and straw nutrient uptake of finger millet at harvest during 2022 and 2023. 2a: nitrogen uptake, 2b: phosphorus uptake and 2c: potassium uptake.


(3a)
Available nitrogen (kg/ha)
0
50
100
150
200
250
T1 T2 T3 T4 T5 T6 T7 T8
Rhizospheric soil
Treatments
Non-rhizospheric soil
2022 2023
(3b)
Available phosphorus (kg/ha)
0
5
10
15
20
25
30
35
40
T1 T2 T3 T4 T5 T6 T7 T8
Rhizospheric soil
Treatments
Non-rhizospheric soil
2022 2023
(3c)
Available potassium (kg/ha)
0
20
40
60
80
100
120
140
160
180
200
T1 T2 T3 T4 T5 T6 T7 T8
Rhizospheric soil
Treatments
Non-rhizospheric soil
2022 2023

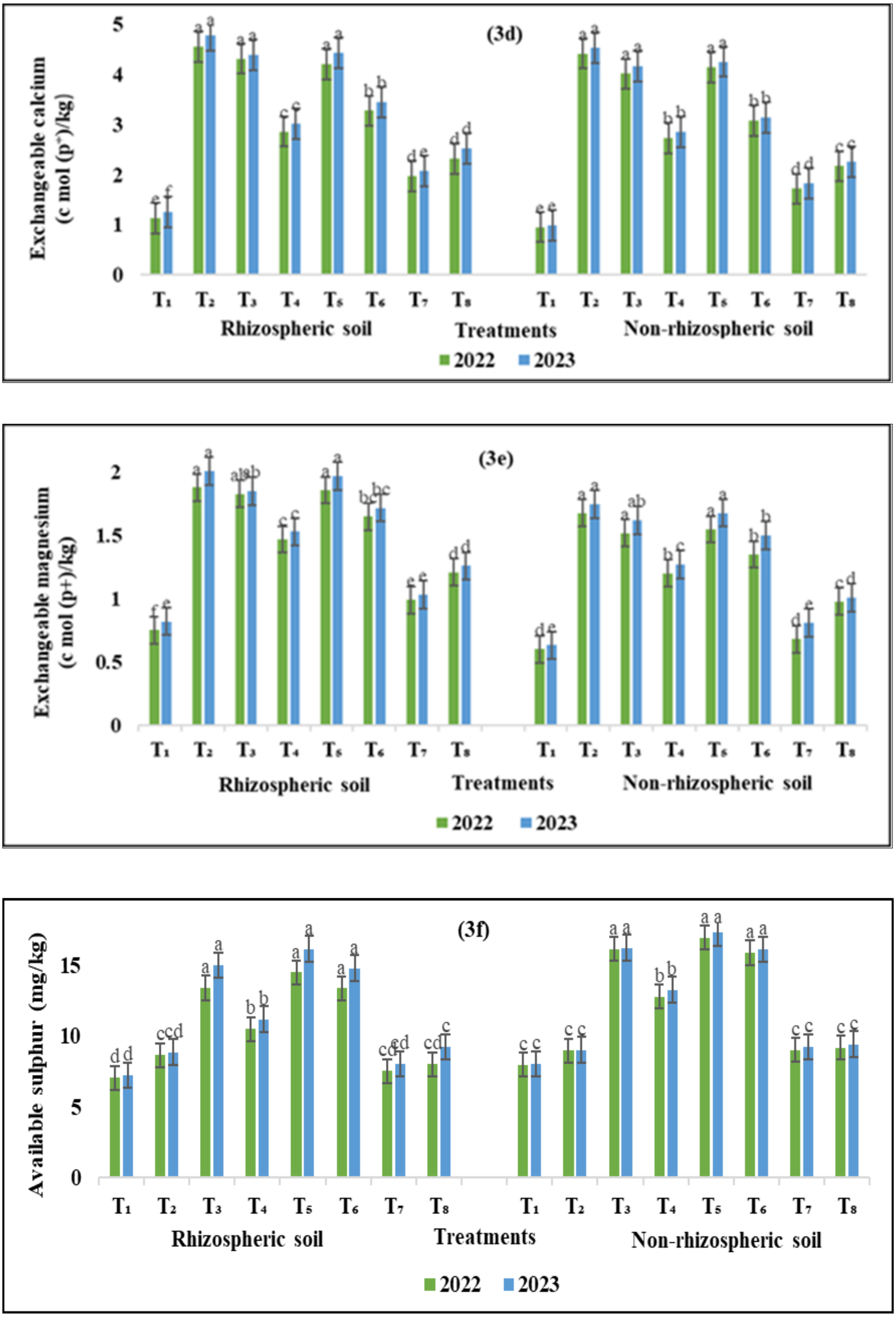


Fig. 3. Effect of various organic nutrient sources on available nutrients in rhizosphere and non-rhizospheric soil at harvest during 2022 and 2023. 3a: available nitrogen, 3b: available phosphorus, 3c: available potassium, 3d: exchangeable calcium, 3e: exchangeable magnesium and 3f: available sulphur.

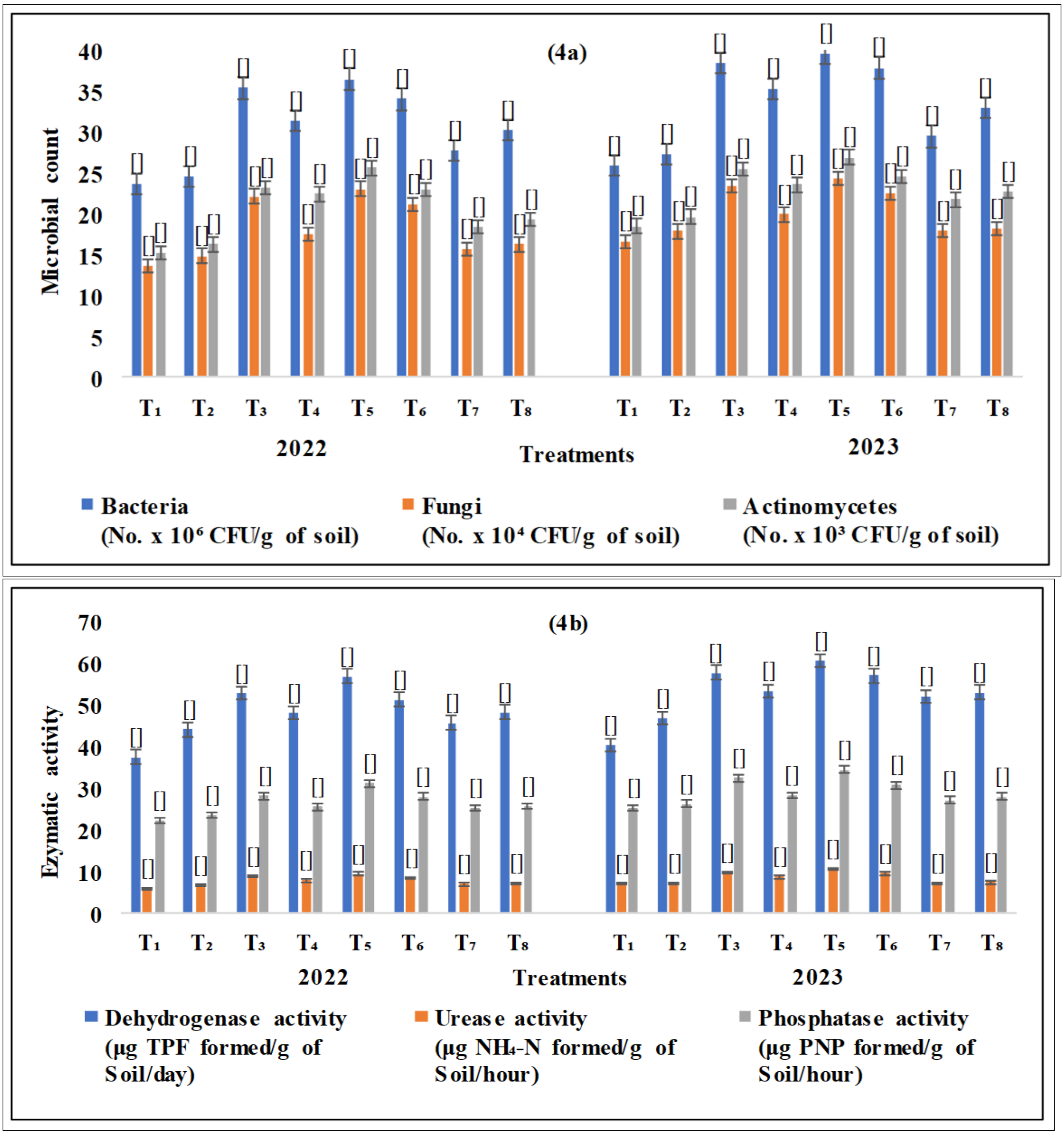


Fig. 4. Effect of various organic nutrient sources on microbial status in soil at crop harvest during 2022 and 2023. 4a: microbial count and 4b: enzymatic activity.

production, while phosphorus facilitates ATP-driven active transport of assimilates and potassium supports phloem loading and cell expansion. These mechanisms lead to an efficient allocation of biomass to leaves, stems and ear heads (28).

Yield attributes and yield

The application of poultry manure resulted in a higher number of productive tillers per plant by enhancing root growth, leaf area and photosynthetic efficiency (29). This, in turn, supported greater nutrient uptake and biomass production, leading to an increased number of fingers per ear head and longer ear and finger lengths. Poultry manure's rich nutrient profile, including nitrogen and phosphorus, provided a sustained supply of nutrients crucial for cell division and elongation (30). Yield attributes in turn reflect significantly higher grain and straw yields with the application of poultry manure. The enhanced nutrient availability during flowering, panicle initiation and grain filling boosted carbohydrate synthesis and photosynthate translocation, leading to superior grain weight and biomass accumulation. Vermicompost and deoiled cake followed closely, demonstrating the effectiveness of sustained nutrient release in supporting physiological processes like chlorophyll synthesis and root development. Absolute control, by contrast, lacked the necessary nutrient inputs, limiting growth, yield attributes and grain production. Test weight showed no significant differences across treatments, indicating consistent genetic potential in grain development.

Nutrient uptake

The application of poultry manure resulted in a higher uptake of nitrogen, phosphorus and potassium in both grain and straw. This can be attributed to the high nitrogen content in poultry manure, providing an immediately available source of nitrogen, crucial for vegetative growth, protein synthesis and plant vigor (31). Additionally, poultry manure promotes the formation of humic acids, which enhance phosphorus availability by forming water soluble chelates, reducing soil fixation and facilitating phosphorus uptake (28). Phosphorus, vital for energy transfer, root development and flowering, was thus efficiently utilized. The rich potassium content in poultry manure further supported plant growth by regulating water balance, activating enzymes and enhancing disease resistance, with its gradual nutrient release ensuring a consistent supply throughout the growth cycle (32). The comparable nutrient uptake observed with vermicompost and deoiled cake is due to their balanced nutrient profiles and gradual release. In contrast, the absolute control recorded a lower uptake due to insufficient nutrient availability, limiting plant growth and root development.

Available nutrients

The variations in nutrient availability between rhizosphere and non-rhizosphere soils after crop harvest can be attributed to the distinct dynamics of the rhizosphere and nutrient release patterns. Poultry manure, rich in decomposable organic matter, promotes nitrogen mineralization, ensuring a steady supply and reducing leaching losses (33, 34). In the rhizosphere, enhanced microbial activity and root turnover further contribute to nitrogen retention. Poultry manure's dual phosphorus composition provides both immediate and long-term phosphorus availability. However, phosphorus availability is lower in the rhizosphere due to intense root uptake and microbial immobilization (35-37). Potassium availability is higher in the rhizosphere, facilitated by organic acids, root exudates and enhanced cation exchange capacity (34). The application of farmyard manure also increases calcium and magnesium availability through enhanced soil adsorption and mass flow mechanisms (38). Magnesium enrichment in the rhizosphere is primarily attributed to mass flow processes (39). Sulphur availability was higher in non-rhizosphere soil due to previous crop (groundnut) uptake, but it was gradually enriched over time through the decomposition of poultry manure (40).

Microbial status

The application of poultry manures significantly increased bacterial, fungal and actinomycetes populations due to its rich nutrient content and organic matter. Poultry manure creates an optimal environment for microbial growth by improving soil structure and promoting bacterial colonization (41, 42). Fungal populations thrived due to the nutrient-rich organic matter, which supported fungal hyphae and mycelium development, enhanced soil moisture retention and provided substrates such as decomposed plant residues and composted manure that promote fungal growth (43). Actinomycetes populations also higher, benefiting from the diverse organic substrates and the improved soil structure and moisture retention provided by the manure (44). This highlights poultry manure's role in enhancing the growth of diverse soil microbial populations.

Soil enzymatic activities also varied with treatment, reflecting the impact of organic nutrient sources on microbial processes. Poultry manure increased dehydrogenase activity, promoting microbial growth and oxidative degradation of organic matter (45, 46). Phosphatase activity was enhanced due to the nutrient-rich organic matter, supporting phosphorus mineralization (47, 48). Urease activity, critical for nitrogen mineralization, was significantly higher with poultry manure, promoting the breakdown of urea into ammonia and carbon dioxide (45, 49). Overall, poultry manure is better performed than other organic amendments in supporting microbial activity and enzymatic processes.

Conclusion

The study underscores the potential of organic nutrient management in enhancing finger millet productivity and soil health. Among the treatments, poultry manure proved most effective, significantly improving growth and yield attributes. Vermicompost and deoiled cake also contributed positively. Overall, the use of organic inputs enhanced nutrient dynamics and soil microbial activity, supporting sustainable and eco-friendly cultivation practices. These findings can guide farmers and agricultural policymakers in adopting organic nutrient sources to reduce chemical fertilizer dependency, improve soil fertility and promote climate-resilient agriculture. Future research may focus on optimizing organic input combinations for different agro-climatic zones to maximize productivity while preserving ecosystem health.

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Authors' contributions

SA conceptualized the idea, conducted the experiment and contributed to writing, reviewing, editing and drafting the manuscript. BB contributed to conceptualize the idea, the literature search, manuscript review, resource acquisition and supervised the experiment. VNGV, SNS and DG reviewed and drafted the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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