



Deciphering Soil-plant-microbiome Interlinkages: A Correlative Exploration of Chickpea Yield Enhancement under Integrated Nutrient Paradigms

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ABSTRACT

Background: Chickpeas (*Cicer arietinum* L.), a key pulse crop in Indian agriculture, often suffer from sub-optimal yields, which are constrained by deteriorating soil health and inadequate nutrient practices. Integrated Nutrient Management (INM), which combines chemical fertilizers with organic manures and biofertilizers, offers a sustainable alternative.

Methods: Field experiments on chickpeas were conducted at Karunya Institute of Technology and Sciences, Coimbatore, Tamil Nadu. The twelve treatments consisted of different combinations of inorganic fertilizers, farmyard manure (FYM), vermicompost (both enriched and non-enriched with microbes) and nano-emulsion biofertilizers applied through seed coating and foliar spray. Observations were made on yield, crop nutrient uptake, post-harvest soil fertility, microbial biomass, enzymatic activity and microbial populations. Statistical analyses included correlation and regression.

Result: The integration of 100% RDF with microbially enriched vermicompost resulted in a higher grain yield and higher NPK uptake. Soil nutrient status was maximum under this treatment. Correlation analysis confirmed strong positive associations between soil microbial indicators and yield, highlighting the synergistic benefits of integrating inorganic fertilizers with microbially enriched organic manure.

Key words: Biofertilizers, Chickpea, Integrated nutrient management, Nutrient uptake, Soil fertility, Soil microbiology, Sustainable agriculture, Vermicompost.

INTRODUCTION

Chickpea (*Cicer arietinum* L.) is an important pulse crop for owing to its high-quality protein content and capacity for symbiotic nitrogen fixation, chickpea contributes both to human nutrition and soil fertility enhancement, earning recognition as the “king of pulses.” Its strong adaptation to semi-arid climates, suitability for rainfed agriculture and efficient use of residual soil moisture enable its successful cultivation in marginal and fragile agro-ecosystems (Sharma *et al.*, 2025). The crop also integrates well into diverse cropping sequences, supporting sustainable food production where external inputs are constrained. At the global level, chickpea occupies about 148.11 million ha, producing 180.95 million tonnes with a mean productivity of 1222 kg ha⁻¹ (DPD, 2022-23). India is the leading producer, contributing nearly 86% of global output, with 122.67 million tonnes harvested from 104.71 million ha at an average yield of 1172 kg ha⁻¹. In Tamil Nadu, chickpea productivity remains relatively low, where chickpea is cultivated on 4065 ha, producing 3767 tonnes with an average yield of 927 kg ha⁻¹, indicating substantial scope for improvement. Despite its inherent potential, chickpea yields in many regions are constrained by declining soil fertility, nutrient imbalances, reduced microbial activity and prolonged dependence on chemical fertilizers. Continuous cultivation without adequate organic amendments has resulted in soil structural degradation, micronutrient deficiencies and loss of beneficial microbial populations

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(Patel and Thanki, 2022). While inorganic fertilizers offer immediate yield responses, their excessive use disrupts soil biological stability and compromises long-term sustainability (Pahalvi *et al.*, 2021). Moreover, nutrient losses through leaching, volatilization and fixation reduce fertilizer use efficiency. Integrated Nutrient Management (INM), which combines chemical fertilizers with organic manures and biofertilizers, provides a balanced and sustainable alternative (Paramesh *et al.*, 2023).

Inputs such as farmyard manure and vermicompost improve soil physical condition and nutrient availability (Hazarika *et al.*, 2023), while microbial enrichment with *Rhizobium* and phosphate-solubilizing bacteria (PSB) enhances nitrogen fixation and phosphorus solubilization (Janati *et al.*, 2021). Emerging nano-emulsion biofertilizers further improve nutrient delivery efficiency through enhanced absorption and rhizosphere interaction (Yousefzadeh *et al.*, 2021; Behl *et al.*, 2024). In this context, the present study investigates the role of integrated nutrient strategies in improving chickpea productivity and soil biological health under irrigated conditions.

MATERIALS AND METHODS

A field experiment comprising two consecutive chickpea trials were conducted during the *rabi* season of 2023-2024, with Trial I from October to December 2023 and Trial II from January to March 2024. The experiment was carried out at the Instructional Farm of the School of Agricultural Sciences, Karunya Institute of Technology and Sciences, Coimbatore, Tamil Nadu. Twelve nutrient management treatments were evaluated using a randomized block design with three replications. The treatments consisted of graded levels of recommended dose of fertilizer (RDF) alone or in combination with farmyard manure, vermicompost, microbial-enriched organic inputs and nano-emulsion biofertilizer formulations. The microbial-enriched organic manures were inoculated with *Bacillus megatherium* var. *phosphaticum* and *Rhizobium leguminosarum* (10 L inoculum per 50 kg substrate, 5 L each). PSB was mass-multiplied on Nutrient Agar (NA) and *Rhizobium* on Yeast Extract Mannitol Agar (YEMA). The nano-emulsion biofertilizer was developed as an oil-in-water polymer-based formulation using castor oil, Tween-80 and stabilizing agents for producing nanosized particles. The mixture was ultrasonicated at 40% amplitude for 20 minutes, producing nanoparticles of 74.3 nm size, 4.11 PDI and 30 mV zeta potential and further fortified with beneficial microbial inoculants (Cathrine *et al.*, 2024). Chickpea variety NBeG-49 was sown using the ridge and furrow method at a spacing of 30 cm between ridges and 10 cm between plants, with seeds placed at a depth of 3-4 cm. Recommended nutrient doses of 25 kg N, 50 kg P_2O_5 and 20 kg K_2O ha⁻¹ were applied at 100, 75, or 50% levels as per treatment. Nitrogen was supplied in three split applications, while phosphorus and potassium were applied basally. The grain yield, nutrient uptake, post-harvest soil fertility and soil biological health were assessed. Soil microbial biomass carbon and nitrogen, enzymatic activities (dehydrogenase, acid phosphatase and fluorescein-diacetate hydrolysis) and microbial populations were quantified using standard analytical protocols. Collected data were statistically analysed following randomized block design procedures and treatment means were compared using the critical difference test at 5% significance (Fisher, 1953). Pearson's correlation and regression analyses were performed using SPSS to

examine relationships among yield, nutrient uptake, soil enzymes and microbial dynamics, providing integrated insights into agronomic and soil ecological responses.

RESULTS AND DISCUSSION

Influence of nutrient uptake on yield

The combined use of 100% recommended fertilizer dose with microbe-enriched vermicompost (6 t ha⁻¹) significantly improved nutrient uptake in chickpea across both seasons. This treatment recorded the higher uptake of nitrogen, phosphorus and potassium (66.75, 192.25 and 51.37 kg ha⁻¹ in trial I; 96.52, 278.01 and 74.28 kg ha⁻¹ in trial II), closely followed by microbial-enriched FYM. Nano-emulsion biofertilizer integration also enhanced nutrient absorption, though to a slightly lesser extent (Table 1 and 2). These results confirm that the combination of mineral fertilizers with organic and biological inputs consistently enhances nutrient acquisition across seasons.

Nitrogen uptake

Nitrogen uptake had a strong and consistent association with grain yield across both experimental trials, reaffirming its pivotal role in chickpea productivity. Higher nitrogen acquisition substantially enhanced vegetative growth and efficient grain development, as reflected by the very high positive correlations observed in trial I ($r = 0.923^{**}$) and trial II ($r = 0.940^{**}$) (Fig 8a, 8b). Regression analysis further confirmed a pronounced linear relationship, with nitrogen uptake explaining nearly 85-88% of the variation in grain yield, indicating its dominant contribution to yield formation (Fig 1).

Treatments supplemented with microbe-enriched organic manures and biofertilizers recorded higher nitrogen uptake, likely due to improved soil physical properties, enhanced nutrient retention and greater root proliferation (Zhang *et al.*, 2023). These conditions promote chlorophyll synthesis, photosynthetic efficiency and effective translocation of assimilates to grain formation (Sodavadiya *et al.*, 2023). Additionally, organic inputs stimulate microbial-mediated nitrogen fixation and mineralization processes, improving nitrogen availability to crops (Solangi *et al.*, 2024). In contrast, reduced nitrogen uptake under sole inorganic or lower-input treatments constrained root activity, microbial functioning and ultimately low yield.

Phosphorus uptake

Phosphorus uptake emerged as a dominant determinant of grain yield across both seasons. A strong and positive association was recorded between phosphorus uptake and grain yield in Trial I ($r = 0.808^{**}$) and was further strengthened in Trial II ($r = 0.928^{**}$), indicating a season-stable yield response to enhanced phosphorus acquisition (Fig 8a, 8b). Regression analysis substantiated this relationship, with phosphorus uptake explaining 65.2% of yield variability in trial I ($R^2 = 0.652$) and a higher 86.2% in trial II ($R^2 = 0.862$), reflecting improved growing conditions (Fig 2).

Table 1: Influence of microbial enriched organic manures and nano-emulsion bio-fertilizer on yield, nutrient uptake, post-harvest soil nutrients and microbial status of chickpea cultivation on trial I.

Treatment	Grain yield (kg ha ⁻¹)	Stover yield (kg ha ⁻¹)	N-uptake (kg ha ⁻¹)	P-uptake (kg ha ⁻¹)	K-uptake (kg ha ⁻¹)	OC (%)	N (kg ha ⁻¹)	P (kg ha ⁻¹)	K (kg ha ⁻¹)	SMEN (µg g ⁻¹ soil)	SMBC (µg g ⁻¹ soil)	AP-nitrophenol (µg p-TPF g ⁻¹ soil)	DHG (µg fluorescein g ⁻¹ soil)	Bacteria (×10 ³ CFU g ⁻¹ soil)	PSB (×10 ³ CFU g ⁻¹ soil)
T ₁	659	1335	34.70	99.95	25.71	0.40	313.60	19.99	151.20	2.38	38.49	1.23	1.81	0.06	0.60
T ₂	667	1354	35.30	101.68	26.17	0.40	327.60	19.98	152.32	2.75	68.91	2.08	2.11	0.10	0.80
T ₃	676	1373	35.09	101.95	26.78	0.42	330.40	20.72	156.80	2.82	46.49	2.94	2.14	0.30	0.80
T ₄	1259	2498	65.22	187.85	50.19	0.70	478.80	36.06	292.00	4.78	164.40	10.52	5.74	1.26	1.61
T ₅	1276	2569	66.75	192.25	51.37	0.75	481.60	37.30	296.85	5.13	164.62	10.72	6.65	1.46	1.68
T ₆	1211	2412	62.90	181.15	48.40	0.55	448.00	25.31	181.85	4.59	140.10	9.33	4.51	1.18	1.49
T ₇	869	1689	44.41	127.90	34.17	0.70	464.80	30.80	289.75	3.43	75.71	4.94	3.09	0.45	1.07
T ₈	872	1883	47.83	138.63	35.58	0.70	476.00	35.28	290.95	3.43	110.87	7.24	3.12	0.47	1.07
T ₉	1197	2392	62.31	179.45	47.95	0.55	439.60	25.20	189.28	4.58	133.27	8.58	4.44	1.16	1.37
T ₁₀	839	1628	42.83	123.35	32.96	0.58	462.00	27.44	238.56	3.33	93.25	4.61	2.81	0.40	1.02
T ₁₁	851	1635	43.16	124.30	33.21	0.63	464.80	28.11	274.40	3.32	70.36	4.88	2.92	0.43	1.04
T ₁₂	1033	2133	54.97	159.05	41.77	0.50	421.20	22.84	178.55	4.01	131.35	8.52	3.80	0.80	1.22
Mean	950.75	1908.42	49.62	143.13	37.85	0.57	434.85	27.70	227.86	3.71	101.88	6.30	3.60	0.67	1.15
SE(d)	76.75	119.39	3.41	9.38	2.64	0.03	29.00	1.88	15.78	0.26	11.09	0.43	0.26	0.05	0.07
CD (5%)	159.17	247.60	7.07	19.45	5.48	0.07	60.13	3.89	32.72	0.53	22.99	0.88	0.53	0.10	0.14

T₁ - 100% RDF, T₂ - 100% RDF + FYM @12.5 t ha⁻¹, T₃ - 100% RDF + Vermicompost @ 6 t ha⁻¹, T₄ - 100% RDF + Microbial enriched FYM @ 12.5 t ha⁻¹, T₅ - 100% RDF + Microbial enriched FYM @ 12.5 t ha⁻¹, T₆ - 100% RDF + Nano-emulsion biofertilizer (Seed treatment @ 10 ml/kg seeds + 2 foliar sprays @ 10 ml/l at 30 and 45 DAS), T₇ - 75% RDF + Microbial enriched FYM @ 12.5 t ha⁻¹, T₈ - 75% RDF + Microbial enriched FYM @ 12.5 t ha⁻¹, T₉ - 75% RDF + Nano-emulsion biofertilizer (Seed treatment @ 10 ml/kg seeds + 2 foliar sprays @ 10 ml/l at 30 and 45 DAS), T₁₀ - 50% RDF + Microbial enriched FYM @ 12.5 t ha⁻¹, T₁₁ - 50% RDF + Microbial enriched FYM @ 12.5 t ha⁻¹, T₁₂ - 50% RDF + Nano-emulsion biofertilizer (Seed treatment @ 10 ml/kg seeds + 2 foliar sprays @ 10 ml/l at 30 and 45 DAS).

Table 2: Influence of microbial enriched organic manures and nano-emulsion bio-fertilizer on yield, nutrient uptake, post-harvest soil nutrients and microbial status of chickpea cultivation on trial II.

Treatment	Grain yield (kg ha ⁻¹)	Stover yield (kg ha ⁻¹)	N-uptake (kg ha ⁻¹)	P-uptake (kg ha ⁻¹)	K-uptake (kg ha ⁻¹)	OC (%)	N (kg ha ⁻¹)	P (kg ha ⁻¹)	K (kg ha ⁻¹)	SMBN (µg g ⁻¹ soil)	SMBC (µg g ⁻¹ soil)	AP (µg p-nitrophenol g ⁻¹ soil)	DHG (µg TPF g ⁻¹ soil)	FDA fluorescein (µg g ⁻¹ soil)	Bacteria (×10 ³ CFU g ⁻¹ soil)	PSB (×10 ³ CFU g ⁻¹ soil)
T ₁	834	1834	52.12	150.12	40.11	0.40	394.80	19.92	170.85	2.96	51.49	1.93	2.01	2.76	0.08	1.00
T ₂	838	1886	53.19	153.20	40.93	0.42	394.80	21.42	173.90	3.04	55.91	2.24	2.04	3.38	0.12	1.00
T ₃	861	1928	54.48	156.92	41.93	0.42	397.60	21.49	174.80	3.50	59.49	2.78	2.41	2.61	0.42	1.00
T ₄	1514	3374	96.10	276.78	73.96	1.03	498.40	34.76	308.00	7.01	151.40	10.02	6.04	9.38	1.85	2.45
T ₅	1569	3406	96.52	278.01	74.28	1.05	498.40	39.86	311.36	7.61	153.10	10.03	6.35	9.46	2.17	2.52
T ₆	1484	3310	93.61	269.62	72.04	0.58	427.60	23.98	203.84	6.96	147.62	9.82	4.81	8.62	1.77	2.20
T ₇	1069	2354	66.81	192.42	51.41	0.78	492.80	31.96	287.76	4.80	88.71	5.64	3.11	4.43	0.66	1.50
T ₈	1079	2427	68.49	197.25	52.71	0.87	498.40	33.06	297.84	4.91	97.87	6.54	3.42	4.90	0.66	1.53
T ₉	1448	3243	91.63	263.90	70.51	0.55	427.00	23.08	179.90	6.88	146.27	9.22	4.14	7.59	1.68	1.98
T ₁₀	1046	2255	64.53	185.87	49.66	0.58	490.00	29.66	216.05	4.46	80.25	4.18	2.62	3.95	0.59	1.22
T ₁₁	1049	2352	66.39	191.22	51.09	0.63	492.80	30.29	288.85	4.65	83.36	5.31	2.79	4.26	0.59	1.50
T ₁₂	1261	2813	79.55	229.11	61.22	0.50	436.80	23.52	189.28	5.90	118.35	7.88	4.10	6.20	1.14	1.75
Mean	1171.01	2598.52	73.62	212.03	56.66	0.65	444.97	27.25	228.39	5.22	102.82	6.30	3.65	5.63	0.98	1.64
SE(d)	85.28	174.82	3.41	13.64	3.84	0.04	29.85	1.88	15.78	0.43	9.38	0.60	0.25	0.43	0.08	0.10
CD (5%)	176.86	362.56	7.07	28.30	7.96	0.09	61.90	3.91	32.19	0.88	19.45	1.24	0.51	0.88	0.16	0.21

T₁ - 100% RDF, T₂ - 100% RDF + FYM @ 12.5 t ha⁻¹, T₃ - 100% RDF + Vermicompost @ 6 t ha⁻¹, T₄ - 100% RDF + Microbial enriched FYM @ 12.5 t ha⁻¹, T₅ - 100% RDF + Microbial enriched vermicompost @ 6 t ha⁻¹, T₆ - 100% RDF + Nano-emulsion biofertilizer (Seed treatment @ 10 ml/kg seeds + 2 foliar sprays @ 10 ml/l at 30 and 45 DAS), T₇ - 75% RDF + Microbial enriched FYM @ 12.5 t ha⁻¹, T₈ - 75% RDF + Microbial enriched vermicompost @ 6 t ha⁻¹, T₉ - 75% RDF + Nano-emulsion biofertilizer (Seed treatment @ 10 ml/kg seeds + 2 foliar sprays @ 10 ml/l at 30 and 45 DAS), T₁₀ - 50% RDF + Microbial enriched FYM @ 12.5 t ha⁻¹, T₁₁ - 50% RDF + Microbial enriched vermicompost @ 6 t ha⁻¹, T₁₂ - 50% RDF + Nano-emulsion biofertilizer (Seed treatment @ 10 ml/kg seeds + 2 foliar sprays @ 10 ml/l at 30 and 45 DAS).

The close linkage between phosphorus uptake and microbial indicators underscores the regulatory role of soil microorganisms in phosphorus dynamics. Microbial-enriched organic amendments enhance phosphatase activity and organic acid production, thereby promoting phosphorus solubilisation and mineralisation (Malhotra *et al.*, 2018). Phosphate-solubilising microbes further mobilise fixed phosphorus and reduce fixation through chelation, improving soil solution availability (Tian *et al.*, 2021). Given phosphorus' critical role in energy metabolism, root development, nodulation and assimilate translocation, improved uptake directly translated into higher grain yield (Aslam *et al.*, 2024).

Potassium uptake

Potassium uptake showed a strong and positive association with grain yield in both seasons, confirming its critical role in yield formation. In Trial I, grain yield exhibited a very high correlation with potassium uptake ($r = 0.919^{**}$), which was similarly evident in Trial II ($r = 0.928^{**}$), demonstrating that enhanced K absorption directly translated into higher productivity (Fig 8a, 8b). Regression analysis further supported this relationship, with potassium

uptake accounting for 84.4% and 86.2% of yield variability in Trial I and Trial II, respectively ($R^2 = 0.844$ and 0.862) (Fig 3).

Improved potassium uptake under integrated nutrient management was closely linked to increased soil microbial biomass carbon, highlighting the role of microorganisms in mobilizing non-exchangeable potassium fractions. Organic amendments and microbial inputs stimulate rhizospheric activity and organic acid release, thereby enhancing K solubilization (Hasanuzzaman *et al.*, 2018). Adequate potassium nutrition improves photosynthesis, stress tolerance and assimilate translocation, while synergistic N-P-K interactions further enhance nutrient-use efficiency and yield (Rawat *et al.*, 2021). In contrast, sole fertilizer application resulted in comparatively lower potassium uptake due to limited biological mobilization.

Influence of soil microbial status on post-harvest soil nutrition

The post-harvest soil nutrient status in chickpea was significantly influenced by treatments enhancing soil microbial activity. The combined application of 100% recommended dose of fertilizers (RDF) along with microbial-enriched vermicompost at 6 t ha^{-1} recorded the

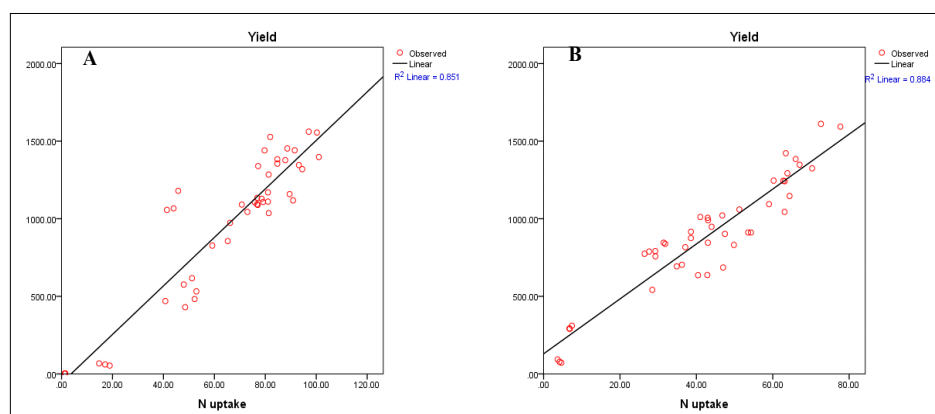


Fig 1: Relationship between nitrogen uptake and yield in trial I (A) and Trial II (B) under INM.

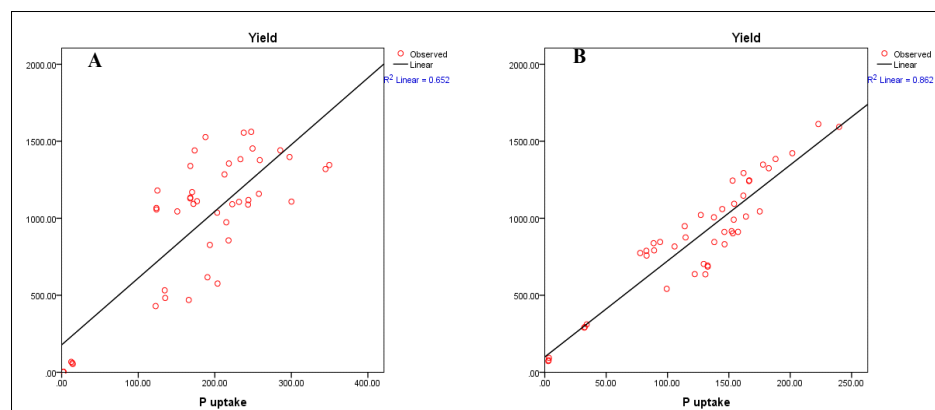


Fig 2: Relationship between phosphorus uptake and yield in trial I (A) and trial II (B) under INM.

highest nutrient status, with soil organic carbon (OC) of 0.75%, available nitrogen (481.6 kg ha^{-1}), phosphorus (37.3 kg ha^{-1}) and potassium ($296.85 \text{ kg ha}^{-1}$) in trial I and 0.75% OC, 498.4 kg ha^{-1} N, 39.86 kg ha^{-1} P and $311.36 \text{ kg ha}^{-1}$ K in trial II (Table 1 and 2). Comparable improvements in post-harvest soil fertility were also observed under microbial-enriched farmyard manure (FYM), indicating its effectiveness in sustaining nutrient availability. Additionally, the application of nano-emulsion biofertilizers resulted in a significant enhancement in soil nutrient status across both trials. These findings clearly demonstrate that treatments promoting active soil microbial populations enhance nutrient mineralization, improve nutrient cycling and ultimately maximize residual soil fertility.

Post-harvest soil organic carbon

In both trials, post-harvest soil organic carbon (SOC) showed a consistent positive association with microbial biomass and biological activity, indicating tight coupling between carbon availability and microbial functioning under integrated nutrient management (INM). In Trial I, SOC was significantly related to SMBC ($r = 0.621^{**}$ and 0.728^{**}), SMBN ($r = 0.677^{**}$ and 0.778^{**}), key soil enzymes and microbial populations, while these relationships were stronger in Trial II, as reflected by higher correlation coefficients, suggesting enhanced microbial control over soil carbon dynamics (Fig 8a, 8b).

Regression analysis further confirmed a significant linear dependence of SOC on SMBN, accounting for approximately 46-60% of SOC variability across trials (Fig 4), with SMBC also contributing significantly, though to a slightly lesser extent (Ashraf *et al.*, 2020). Enrichment with microbial-loaded manures accelerates residue decomposition, thereby augmenting OC turnover and soil biological functioning (Zhai *et al.*, 2024). Sustained organic inputs, root-derived carbon and microbial turnover under INM treatments likely explain the higher SOC stocks (Dhaliwal *et al.*, 2021). In contrast, lower SOC in control plots indicates rapid oxidation and weak carbon stabilisation, whereas elevated SOC improved soil structure and microbial habitat stability (Ahmad *et al.*, 2025).

Post-harvest soil nitrogen

Post-harvest soil nitrogen availability was primarily governed by microbial biomass size and its turnover dynamics. Soil N exhibited strong positive associations with microbial biomass nitrogen (SMBN; $r = 0.711^{**}$ and 0.695^{**}) and microbial biomass carbon (SMBC, $r = 0.618^{**}$ and 0.658^{**}) in both experiments, confirming microbial biomass as an active and readily exchangeable nitrogen reservoir (Fig 8a, 8b). Regression analysis further revealed that SMBN alone accounted for nearly half of the variability in residual soil nitrogen ($R^2 = 0.506$ and 0.483), whereas SMBC contributed comparatively less ($R^2 = 0.382$), indicating the dominant role of microbial N pools (Fig 5).

Significant relationships with dehydrogenase, FDA hydrolysis and acid phosphatase activities reflected enhanced organic substrate decomposition and N mineralisation (Solangi *et al.*, 2024). These associations can be attributed to nitrogen's essential role in microbial protein and nucleic acid synthesis (Imran *et al.*, 2024). Integrated nutrient management promoted microbial immobilisation, reduced N losses and synchronised nutrient release during biomass turnover. In contrast, nutrient-poor treatments recorded lower soil N due to restricted microbial activity (Uwituze *et al.*, 2022). Overall, enzyme-regulated microbial processes emerged as key drivers of post-harvest soil nitrogen regulation (Tang *et al.*, 2025).

Post-harvest soil phosphorus

Post-harvest soil phosphorus availability was largely governed by biological processes, particularly microbial biomass dynamics and enzyme-mediated mineralization. Strong positive correlations were observed between available phosphorus and acid phosphatase activity ($r = 0.798^{**}$ in trial I and 0.688^{**} in trial II), highlighting the critical role of phosphatase enzymes in mobilizing organically bound P (Fig 8a, 8b). Soil microbial biomass carbon and nitrogen also showed significant associations with available P, confirming their function as dynamic reservoirs facilitating phosphorus turnover. Regression

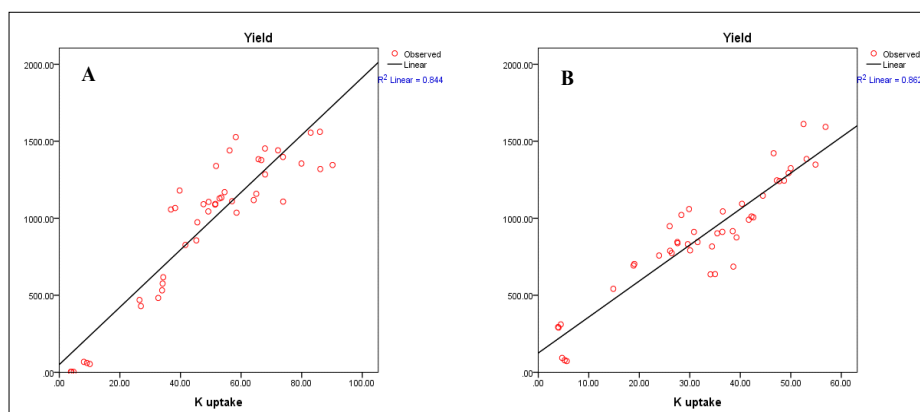


Fig 3: Relationship between potassium uptake and yield in trial I (A) and trial II (B) under INM.

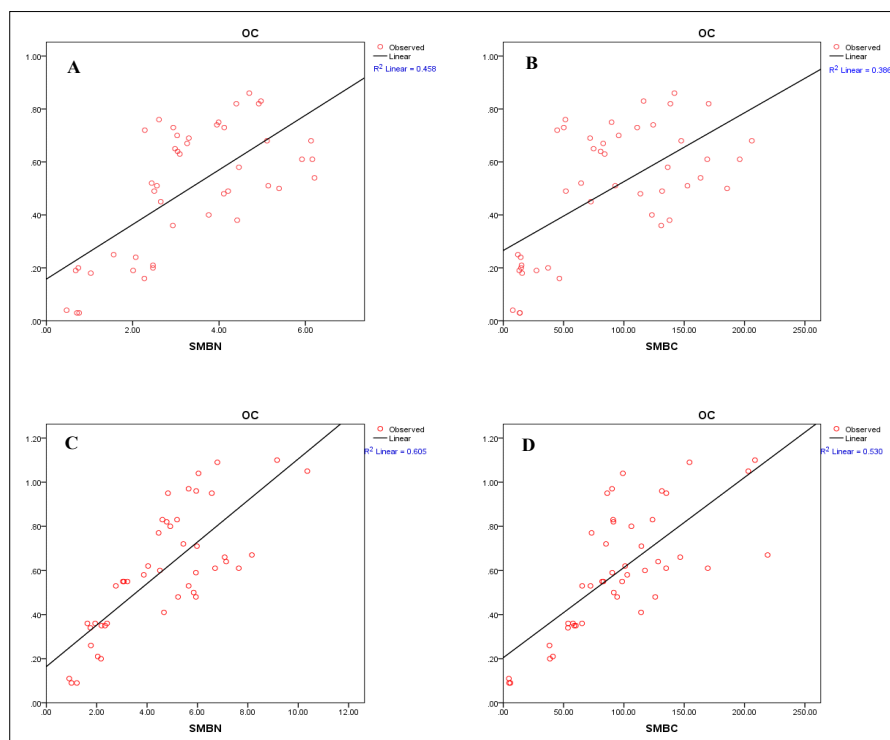


Fig 4: Relationship between soil microbial biomass nitrogen-organic carbon and soil microbial biomass carbon-organic carbon in trial I (A, B) and trial II (C, D) under INM.

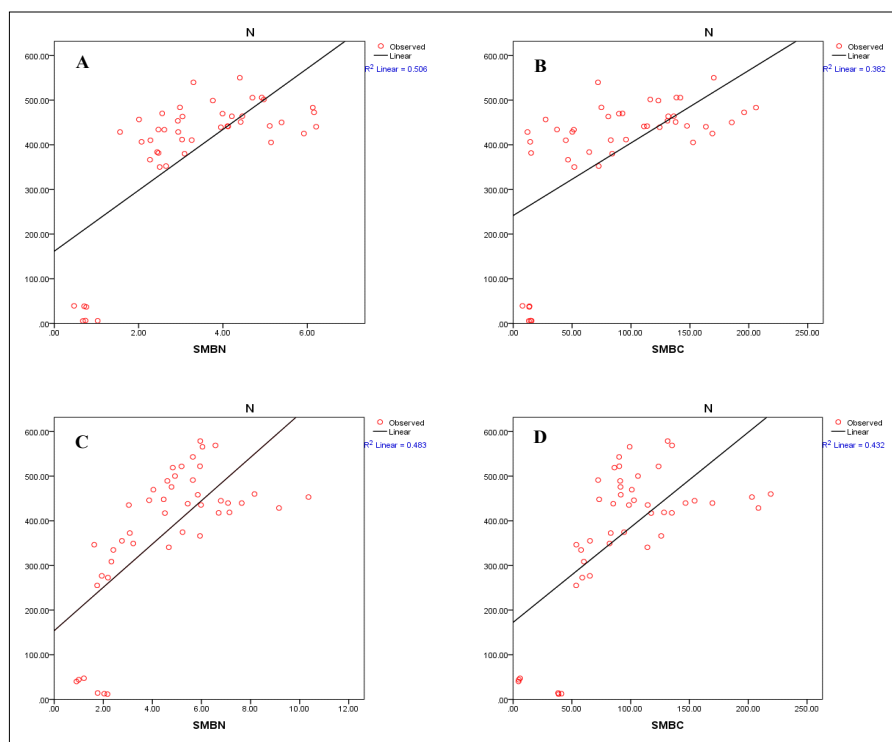


Fig 5: Relationship between soil microbial biomass nitrogen-post-harvest available nitrogen and soil microbial biomass carbon-post-harvest available nitrogen in trial I (A, B) and trial II (C, D) under INM.

analysis further demonstrated that SMBN accounted for 64% and 48% of the variability in available P across trials, while SMBC contributed 56% (Fig 6).

Phosphorus-solubilizing bacteria emerged as a dominant biological regulator, with high explanatory power ($R^2 = 0.777$ and 0.598). Phosphorus plays a pivotal role in microbial functioning, particularly through its association with acid phosphatase, which hydrolyses organic P into plant-available forms (Tian *et al.*, 2021; Solangi *et al.*, 2024). The close linkage between dehydrogenase and FDA activities reinforces the sustained influence of microbial metabolism on P release (Sardans and Penuelas, 2021). Enhanced nutrient management practices consistently improved microbial abundance, enzymatic activity and phosphorus solubilization efficiency (Shrivastava *et al.*, 2018; Ibrahim *et al.*, 2022).

Post-harvest soil potassium

Post-harvest soil potassium availability was strongly governed by microbial biomass and enzymatic activity, highlighting the central role of biological regulation of K dynamics under integrated nutrient management (INM). Available K exhibited significant positive associations with soil microbial biomass carbon (SMBC) ($r = 0.594^{**}$ and 0.518^{**}), indicating enhanced microbial-mediated mobilization of non-exchangeable potassium pools. Strong correlations with dehydrogenase ($r = 0.772^{**}$ and 0.661^{**}) and fluorescein diacetate hydrolysis ($r = 0.731^{**}$ and 0.547^{**}) suggest that intensified microbial respiration and enzymatic turnover promote mineral K release (Fig 8a, 8b).

Acid phosphatase activity also showed consistent relationships ($r=0.640^{**}$ - 0.501^{**}), reflecting coordinated enzyme-microbe interactions. Regression analysis

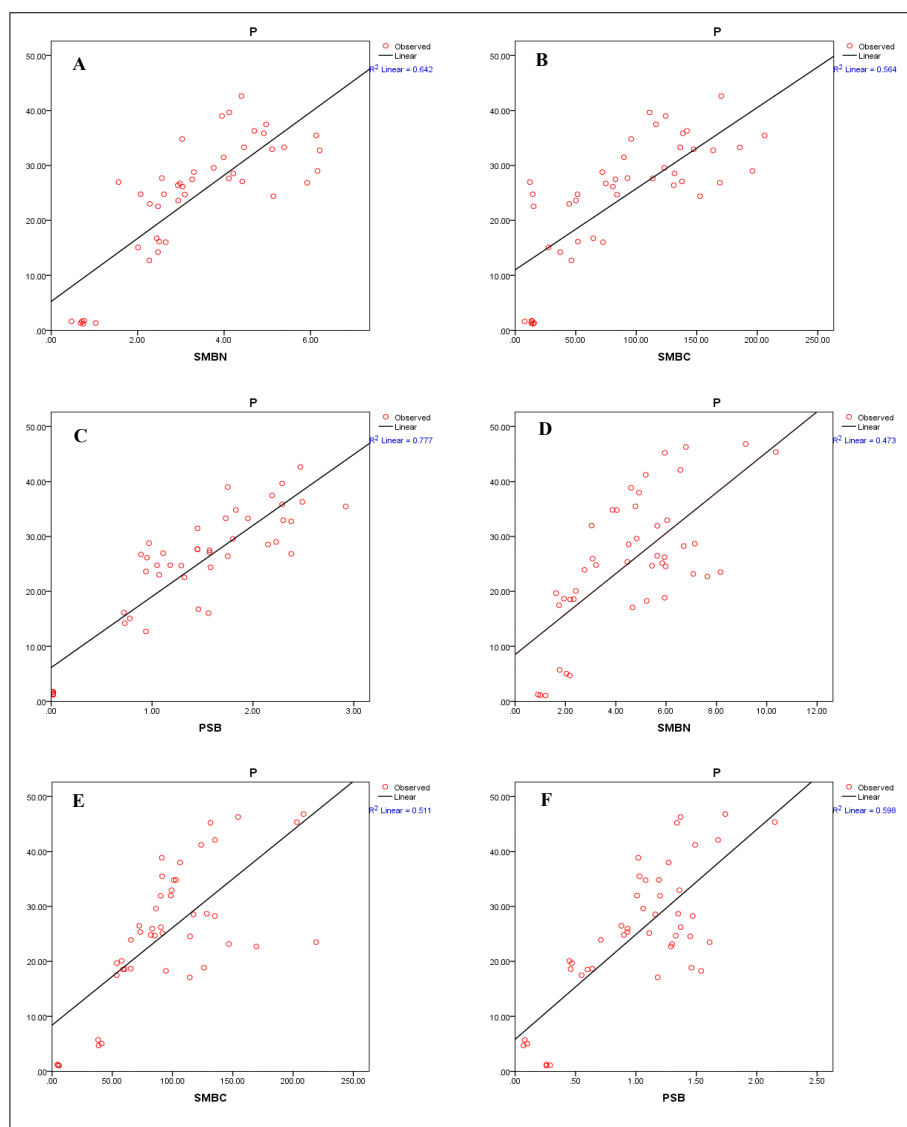


Fig 6: Relationship between soil microbial biomass nitrogen, soil microbial biomass carbon, soil microbial biomass carbon and PSB-Post-harvest available phosphorus in trial I (A, B, C) and trial II (D, E, F) under INM.

confirmed significant linear dependence of available K on dehydrogenase activity ($R^2 = 0.437$ and 0.596) across trials (Fig 7). The strong positive associations of available K with microbial biomass carbon (MBC) and dehydrogenase activity highlight its critical role in microbial energy metabolism and intracellular redox balance (Ashraf *et al.*,

2020). Adequate K availability is known to enhance microbial protein synthesis and extracellular polysaccharide production, which in turn facilitates biofilm formation and improves soil aggregation (Daunoras *et al.*, 2024). Sustained INM likely enhances mineral weathering through microbial organic acid production while maintaining

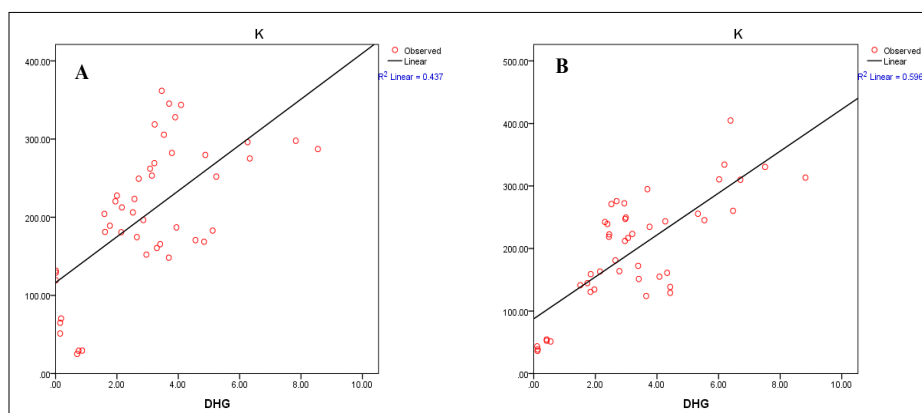


Fig 7: Relationship between dehydrogenase activity-post-harvest available potassium in trial I (A) and trial II (B) under INM.

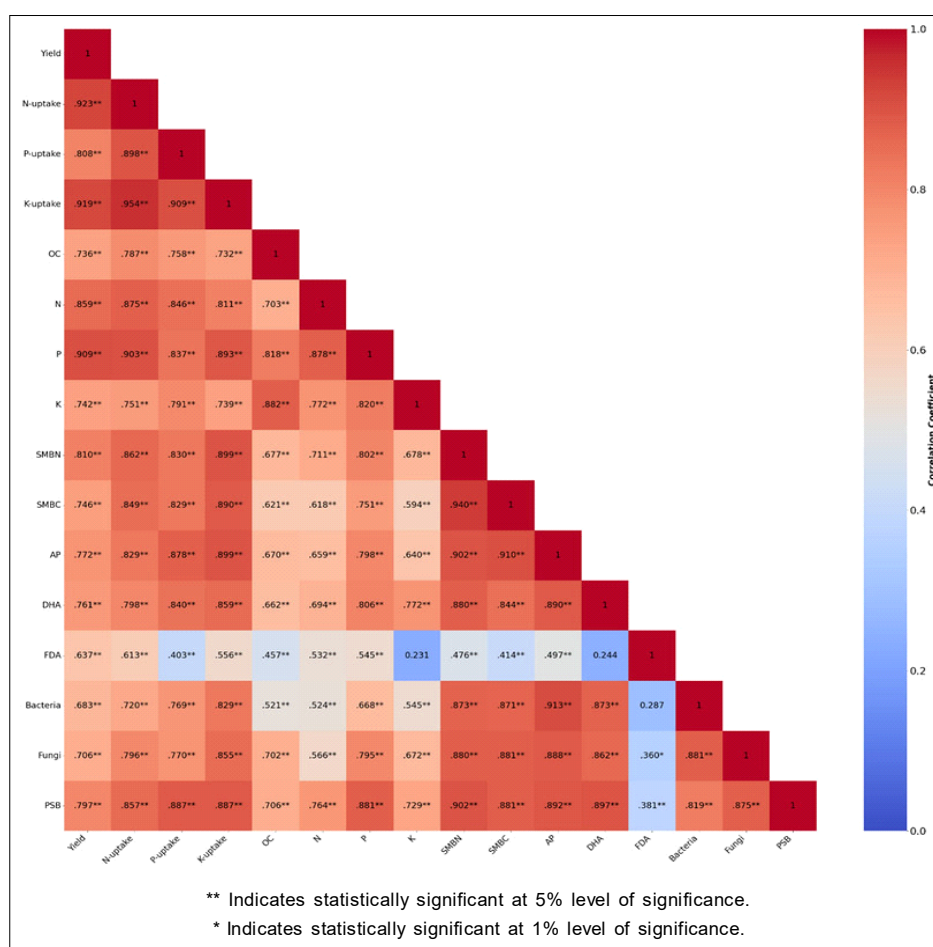


Fig 8a: Correlation matrix of yield, nutrient uptake, soil parameters and microbial biomarkers in trial i of chickpea cultivation.

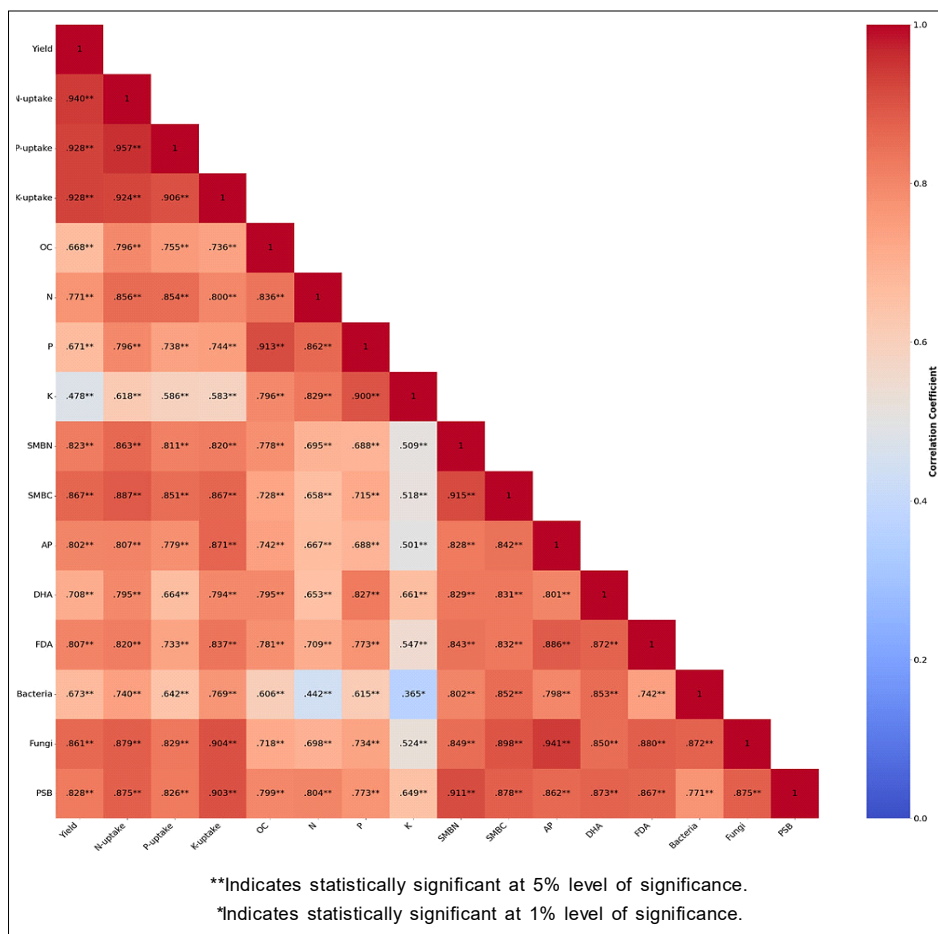


Fig 8b: Correlation matrix of yield, nutrient uptake, soil parameters and microbial biomarkers in the second trial of chickpea cultivation.

microbial stability, unlike poorly integrated treatments where biological K mobilization remained limited (Sardans and Penuelas, 2021; Wei *et al.*, 2024).

CONCLUSION

The study clearly demonstrates that integrated nutrient management (INM) plays a crucial role in improving chickpea productivity and sustaining soil biological functioning under irrigated conditions. Combining microbe-enriched organic sources (Farmyard manure and vermicompost) with nano-emulsion biofertilizers and graded levels of inorganic fertilizers significantly enhanced crop growth, yield attributes and soil fertility. Further, the application of the full recommended fertilizer dose along with microbial-enriched vermicompost at 6 t ha⁻¹ proved to be the most effective strategy. Statistical analyses further indicated that increased nutrient uptake and yield were strongly associated with improved soil microbial activity under INM practices. The results highlight that enhanced microbial dynamics play a pivotal role in regulating nutrient availability and crop performance. Overall, the findings emphasize that INM not only boosts chickpea yield but also supports long-term soil health, making it a

viable and sustainable approach for pulse-based production systems aimed at resource conservation and environmental sustainability.

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Informed consent/ethical approval

All experimental procedures involving animals were conducted in accordance with approved ethical standards. The study protocols were reviewed and approved by the Institutional Animal Ethics Committee (IAEC)/University

Animal Care Committee and all animal handling procedures complied with established guidelines for the care and use of laboratory animals.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. Furthermore, no funding or sponsorship influenced the study design, data collection, analysis, decision to publish, or preparation of the manuscript.

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