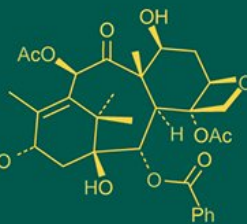
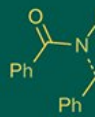


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Khushboo Tiwari
School of Sciences, MATS
University, Raipur,
Chhattisgarh, India

Ashish Saraf
School of Sciences, MATS
University, Raipur,
Chhattisgarh, India

Bhagyashree Deshpande
School of Sciences, MATS
University, Raipur,
Chhattisgarh, India

Corresponding Author:
Bhagyashree Deshpande
School of Sciences, MATS
University, Raipur,
Chhattisgarh, India

Synergistic effects of integrated nutrient management on growth and yield of horticultural and oilseed crops under controlled pot conditions

Khushboo Tiwari, Ashish Saraf and Bhagyashree Deshpande

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Abstract

Integrated Nutrient Management (INM) thru organic, microbial and inorganic nutrient sources is a sustainable way for increasing the crop productivity. The present investigation was conducted to know the effect of vermicompost (VC), Azospirillum (AZO), vesicular-arbuscular mycorrhiza (VAM) and recommended NPK fertiliser on growth and yield of tomato, chilli and mustard under pot culture. Nine nutrient treatments were evaluated for growth, biomass and yield parameters. The maximum plant growth, biomass accumulation and yield was observed in all the crops under combined treatment T₉ (AZO + VAM + VC + NPK) which was significantly higher than individual nutrient application and control. Principal Component Analysis explained 65.3% of the total variation and clearly separated integrated treatments from single-input treatments. Correlation analysis revealed strong positive correlations between the growth, biomass and yield traits. The results showed that the use of vermicompost, biofertilizers and balanced mineral fertilisers improved nutrient-use efficiency and crop productivity and is an effective and environmentally sustainable nutrient management strategy.

Keywords: Integrated nutrient management, Vermicompost, Azospirillum, Vesicular-arbuscular mycorrhiza (VAM), Biofertilizers, Tomato (*Solanum lycopersicum*), Chilli (*Capsicum annuum*), Mustard (*Brassica juncea*), Crop productivity, Sustainable agriculture

1. Introduction

The global agriculture is faced with the dual challenge of increasing productivity of crops and ensuring environmental sustainability. The world population is expected to exceed 9.7 billion by 2050. This equates to intensification of agricultural production and a great dependence on synthetic fertilisers. Chemical fertilisers have increased crop production significantly but their over-application and misuse have caused soil degradation, decreased soil organic matter, loss of microbial diversity, greenhouse gas emissions, eutrophication and contamination of groundwater (Tilman *et al.*, 2002) [39]. Such concerns have resulted in sustainable nutrient management practices that enhance crop production and soil health (FAO, 2017) [13].

Tomato (*Solanum lycopersicum* L.), Chilli (*Capsicum annuum* L.) and Mustard (*Brassica juncea* L.) are crop of high economic value with high nutritional and industrial value. Tomato is a good source of lycopene, β -carotene, vitamin C and other antioxidant compounds. The chilli is appreciated for its capsaicinoids and phenolic compounds with pharmaceutical and nutraceutical properties (Materska and Perucka, 2005) [24]. Mustard is one of the important oilseed crops of India, important for production of edible oil and provides glucosinolates and essential fatty acids. These crops are important but their productivity in many regions is lower than their genetic potential due to nutrient imbalance, declining soil fertility and poor management of organic matter (Vitousek *et al.*, 2009) [42].

The integrated nutrient management (INM) system consisting of organic manures, biofertilizers and balanced inorganic fertilisers has been found to be an effective approach to increase nutrient-use efficiency, sustain soil fertility and improve crop productivity (Vanlauwe *et al.*, 2010) [40]. Organic amendments like FYM and vermicompost improve soil structure, water holding capacity, microbial activities and nutrient availability. Vermicompost is produced by bio-degradation of organic residues by earthworms and is

particularly rich in plant available nutrients, humic substances and natural plant growth regulators which promote healthy plant growth.

Biofertilizers also complement the organic amendments by facilitating the uptake of nutrients thru biological processes. Nitrogen fixing bacteria such as *Azospirillum* spp. by producing phytohormones increase the availability of nitrogen and stimulate root growth, whereas vesicular-arbuscular mycorrhizal (VAM) fungi enhance the uptake of phosphorus, water absorption and tolerance to environmental stresses. Other helpful microorganisms such as phosphate-solubilizing bacteria, *Trichoderma* spp. and *Pseudomonas fluorescens* enhance nutrient mobilisation, inhibit soil-borne pathogens and stimulate overall plant growth thru various interactions in the rhizosphere (Bashan & De-Bashan, 2010; Weller, 1997) [4, 45]. Therefore, the present investigation was undertaken to study the effect of integrated organic and microbial nutrient management on growth and productivity of tomato, chilli and mustard under controlled pot condition. This study evaluated the individual and combined effects of vermicompost, *Azospirillum*, vesicular-arbuscular mycorrhiza (VAM) and recommended NPK fertiliser on the plant growth, root characteristics, biomass accumulation and yield parameters.

2. Materials and Methods

2.1 Experimental Site and Plant Materials

The present investigation was conducted under controlled environmental conditions in a pot experiment to study the effect of integrated organic and microbial nutrient management on three economically important crops viz., tomato (*Solanum lycopersicum* L.), chilli (*Capsicum annuum* L.) and Indian mustard (*Brassica juncea* L.). Certified seeds of all the three crops were procured from Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh, India. The experiments were conducted using uniform and healthy seeds.

2.2 Soil Collection and Characterization

The surface soil (0-15 cm depth) was collected from an agricultural field of Raipur, Chhattisgarh, India. A composite sample was prepared by mixing soils from a number of sites so as to avoid bias to any one location. The collected soil was air dried in shade, gently crushed, passed thru 2mm sieve and stored under laboratory conditions till further use. The soil was described before the experiment. Electrical conductivity and soil pH were determined in a soil-water suspension (1:25) following the APHA (2017) [3] procedures. The organic carbon was estimated by the Walkley and Black wet oxidation method (Walkley and Black, 1934) [43]. Available nitrogen was determined by alkaline potassium permanganate method (Subbiah & Asija, 1956) [37], phosphorus by Olsen's sodium bicarbonate extraction method (Olsen *et al.*, 1954) [28] and potassium by neutral ammonium acetate extraction (Hanway & Heidel, 1952) [16]. Soil texture was determined by the Bouyoucos hydrometer method (Bouyoucos, 1962) [10] and cation exchange capacity (CEC) estimated by the ammonium acetate saturation method (Chapman, 1965) [11]. All analyses were performed using standard soil analytical procedures recommended for agricultural soil testing and laboratory quality assurance (Rakshit *et al.*, 2020; Mylavarapu *et al.*, 2023) [29, 26].

2.3 Preparation of Organic Nutrient Sources

2.3.1 Vermicompost

The biodegradable agricultural residues like wheat straw, vegetable waste, dried leaves, partially decomposed cattle dung were used for preparation of vermicompost. The raw materials were first subjected to an aerobic pre-decomposition period of about 20 days, so as to stabilise the substrate and to avoid the thermal shock that is usually associated to fresh organic matter. The matrix inoculated with pre-decomposed *Eisenia fetida*. Vermicomposting was carried out in brick lined beds maintaining moisture content in the range of 55 to 70% during the process. The compost was allowed to mature for about 60 days when it had dark brown granular appearance indicating vermicast maturity. Mature vermicompost was passed thru a 4 mm mesh before application (Yadav and Garg, 2013) [46].

2.3.2 Farmyard Manure

Farmyard manure well decomposed from cattle dung, urine soaked bedding material and farm residues were aerobically composted for about 90 days. The mature FYM was sieved thru 5-mm mesh to remove coarse debris and maintained under shaded condition till application (Ravindran *et al.*, 2020) [31].

2.4 Biofertilizers

The microbial inputs used in the study were liquid *Azospirillum* inoculum with a titer of about 10⁸ CFU mL⁻¹ and vesicular-arbuscular mycorrhiza inoculum comprising viable spores, colonised root fragments and hyphal networks. Prior to experimentation, the viability and quality of the two microbial inoculants were checked. The population of *Azospirillum* was estimated by Most Probable Number technique and the density of VAM spores was determined by wet sieving and decanting method. The VAM spores were also examined microscopically to confirm viability (Reddy and Singh, 2018) [32].

2.5 Experimental Design and Treatments

The experiment was arranged in a completely randomised design. A total of eighty one plastic pots (29 cm × 27 cm) were used, twenty seven pots per crop (nine treatments × three replicates) giving three replicate pots per treatment for each crop. Each pot had 4 kg of soil, 3 kg of vermicompost and 1 kg of sand as a normal growth medium. The soil mixture was solarised for 7 days before filling to reduce the native pathogen load. Nine nutrient management treatments for each crop were evaluated (Table 1). The same treatment combinations were continued independently for tomato, chilli and mustard during the whole period of study.

Table 1: Nutrient management treatments applied to tomato, chilli and mustard

Treatment	Description
T ₁	Soil (untreated control)
T ₂	Soil + Vermicompost (VC)
T ₃	Soil + Recommended NPK Fertilizer
T ₄	Soil + <i>Azospirillum</i> (AZO)
T ₅	Soil + Vesicular-Arbuscular Mycorrhiza (VAM)
T ₆	Soil + AZO + VAM
T ₇	Soil + AZO + VAM + VC
T ₈	Soil + AZO + VAM + NPK
T ₉	Soil + AZO + VAM + VC + NPK

2.6 Seed Treatment and Sowing

The seeds were washed and surface sterilised sequentially in 70% ethanol and 1% sodium hypochlorite solution. The seeds were washed several times with sterile distilled water to remove the residual chemicals and were biologically treated with suspension of *Trichoderma harzianum* & *Pseudomonas fluorescens*. Hydropriming was carried out for 4-6 h to enhance germination uniformity. The treated seeds were dried in shade and sown immediately.

2.7 Application of Organic, Microbial, and Chemical Inputs

Before sowing the growth medium was thoroughly mixed with vermicompost. *Azospirillum* was applied as root inoculant at transplanting time. VAM inoculum was applied just below the root zone for rapid colonisation. The chemical fertilisers like urea, Factamphos and muriate of potash were applied according to the recommended nutrient schedules of the respective crops. To avoid salt accumulation in the root zone, potassium fertiliser was applied in split doses, while nitrogen and phosphorus fertilisers were applied as basal doses.

2.8 Growth Parameters

The growth observation was recorded in regular intervals of crop growth cycle. Plant height was measured from soil surface to the apical meristem using measuring scale. At the end of the vegetative stage, the number of branches and leaves per plant was counted manually. At harvest time, the roots were carefully washed and measured. Total plant biomass was obtained by drying the plant samples in an oven at 70±2 °C to a constant weight and expressed on dry weight basis.

2.9 Yield Parameters

The yield performance was evaluated in terms of number of fruits per plant and fresh fruit yield. Average fruit yield per plant was calculated by determining total weight of fruits of each plant by digital balance. Seed yield was recorded at physiological maturity stage for mustard.

3. Results and Discussion

3.1 Effect of Seed Treatment on Germination and Seedling Vigour

Hydropriming, *Trichoderma harzianum* and *Pseudomonas fluorescens* significantly increased seed germination and seedling vigour in tomato, chilli and mustard as compared to untreated control. Of the treatments *P. fluorescens* gave the highest germination percentage and the lowest mean germination time (MGT), while untreated seeds performed the worst according to the ISTA standards. Tomato germination increased from 70 to 94% with MGT decreasing from 7.0 to 4.3 days. Chilli germination increased from 65 to 92% and MGT was reduced from 8.2 to 4.9 days. Mustard showed >95% germination and MGT reduced from 5.9 to 4.0 days. *P. fluorescens* improved Seedling Vigour Index (SVI) significantly by 2.17-, 2.35- and 1.75- fold in tomato, chilli and mustard respectively. The higher performance of *P. fluorescens* is attributed to the production of indole-3-acetic acid, siderophores, phosphate-solubilizing organic acids and antimicrobial metabolites that enhance the germination and early seedling growth. *T. harzianum* improved germination and root growth thru phytohormone production, suppression of pathogens and

induced resistance, while hydropriming gave moderate improvement. Results confirm that microbial seed treatments are an effective strategy for improving germination and early seedling vigour in tomato, chilli and mustard.

3.2 Effect of Integrated Organic and Microbial Nutrient Management on Plant Height

The plant height, an important indicator of vegetative growth and nutrient use efficiency increased gradually with the combined application of vermicompost, *Azospirillum*, vesicular-arbuscular mycorrhiza (VAM) and the recommended NPK fertilisers. Maximum plant height was recorded in T₉ (Soil + *Azospirillum* + VAM + Vermicompost + NPK) and minimum in untreated control (T₁) among all the three crops. Same observations were made by Safarpour *et al.* (2018) [34] on integrated nutrient management. Tomato plant height increased from 90.20 cm (T₁) to 182.54 cm (T₉) which was 102.4% increase. The combined treatments (T₆-T₉) showed a consistent improvement over the individual nutrient application, suggesting a synergistic effect of biofertilizers and organic amendments. The plant height in Chilli increased from 30.43cm to 79.25cm (160.4%) which was maximum among the three crops. The improved answer reveals that PGPR and VAM have a positive interaction with the availability of nutrients to enhance vegetative growth. In mustard, the plant height increased from 81.48 cm to 172.67 cm, which is an increase of 111.9%. The growth was much higher when *Azospirillum*, VAM, vermicompost and NPK were used together than when used alone.

Mechanistic Interpretation

The significant increase in the height of plants under integrated nutrient management (INM) may be attributed to the synergistic effects of organic amendments, microbial inoculants and balanced mineral fertilisation. Vermicompost improves soil physical properties, water holding capacity, nutrient availability and microbial activity and provides humic substances and macro- and micronutrients that stimulate root growth and nutrient uptake (Lazcano & Domínguez, 2019) [21]. *Azospirillum* application enhances biological nitrogen fixation and yields plant growth promoting phytohormones such as auxins and gibberellins that stimulate cell division, stem elongation and overall vegetative growth (Fukami *et al.*, 2018) [15]. Similarly, vesicular-arbuscular mycorrhizal (VAM) fungi promote phosphorus uptake, water uptake and root growth thru an extensive hyphal network, thus enhancing nutrient-use efficiency and plant vigour (Begum *et al.*, 2019) [6].

The superior performance of combined treatment (T₉) revealed that the simultaneous application of vermicompost, microbial inoculants and recommended NPK fertiliser provided a balanced nutrient environment for continuous plant growth during the cropping period. The combined effect of adequate mineral nutrition and increased microbial activity in the rhizosphere likely enhanced chlorophyll synthesis, photosynthetic efficiency and biomass accumulation, resulting in significantly taller plants compared to plants treated with either organic or inorganic nutrient sources alone. Integrated nutrient management has been found similar synergistic effects on the vegetative growth in tomato, chilli and other vegetable crops. The integrated sources of nutrients in these crops are found to

improve nutrient-use efficiency and soil biological activity compared to sole fertiliser application (Mahanta *et al.*, 2021; Bhat *et al.*, 2022) ^[23, 8].

In present study maximum plant height for tomato, chilli and mustard was recorded in the treatment T₉ whereas minimum was observed in the control treatment (T₁). The gradual increase of plant height from T₁ to T₉ is due to the synergistic effects of organic amendments combined with beneficial microorganisms and the balanced mineral fertilisation. These results agree with previous reports that integrated nutrient management improves crop growth and productivity, soil fertility as well as sustainable agriculture by reducing dependence on chemical fertilizers (Agegnehu *et al.*, 2021; FAO, 2022) ^[2, 14].

3.3 Effect of Integrated Organic and Microbial Nutrient Management on Number of Leaves

Leaf production, an important indicator of canopy development and photosynthetic capacity, increased significantly with integrated nutrient management. The combined application of vermicompost, *Azospirillum*, VAM, and recommended NPK (T₉) produced the highest number of leaves in tomato, chilli, and mustard, while the untreated control (T₁) recorded the lowest values, consistent with previous reports (Selim, 2020) ^[35]. In tomato, leaf number increased from 12.26 to 21.47 leaves plant⁻¹ (75% increase). Chilli showed the greatest response, increasing from 9.80 to 17.49 leaves plant⁻¹ (78.5% increase), while mustard increased from 11.48 to 19.67 leaves plant⁻¹ (71.3% increase). Combined treatments (T₆-T₉) consistently outperformed individual applications, demonstrating the synergistic effects of biofertilizers, vermicompost, and NPK in promoting leaf initiation and canopy development across all three crops.

Cross-crop Comparative Analysis

The direct comparison between the three crops showed that the absolute leaf increment was highest in tomato (+9.21), followed by mustard (+8.19) and chilli (+7.69 leaves plant⁻¹), while the relative gain was highest in chilli (+78.5%), followed by tomato (+75%) and mustard (+71.3%). The convergence of the two independent scales to the same monotonic ranking and the finding that all three crops peak at T₉ and bottom at T₁ confirm that the integrated regime enhances leaf production irrespective of botanical family while sole-NPK fertilisation saturates earlier in leaf-N response and lacks the rhizospheric microscale N₂-fixation, humate-mediated micronutrient chelation and AMF hyphal-phosphorus scavenging that drive the integrated response (Kesavan & Swaminathan, 2007; Yadav *et al.*, 2025) ^[18, 47].

Mechanistic Interpretation

The direct comparison between the three crops showed that the absolute leaf increment was highest in tomato (+9.21), followed by mustard (+8.19) and chilli (+7.69 leaves plant⁻¹), while the relative gain was highest in chilli (+78.5%), followed by tomato (+75%) and mustard (+71.3%). The convergence of the two independent scales to the same monotonic ranking and the finding that all three crops peak at T₉ and bottom at T₁ confirm that the integrated regime enhances leaf production irrespective of botanical family while sole-NPK fertilisation saturates earlier in leaf-N response and lacks the rhizospheric microscale N₂-

fixation, humate-mediated micronutrient chelation and AMF hyphal-phosphorus scavenging that drive the integrated response (Sinha *et al.*, 2019; Hungria *et al.*, 2022). VAM also enhanced the uptake of phosphorus and micronutrients by extending its hyphal network, which led to increased photosynthesis and biomass accumulation (Chen *et al.*, 2018; Zhang *et al.*, 2022) ^[12, 48]. The combined treatment was consistently better than the individual treatments, implying that nutrient synchrony is important. Organic amendments supplied slow-release nutrients and improved soil health. Mineral fertilisers met immediate crop requirements. Microbial inoculants increased nutrient-use efficiency. These together resulted in improved vegetative growth and canopy development. The progressive increase in height of plants from T₁ to T₉ in tomato, chilli and mustard confirms earlier results that integrated nutrient management improves plant growth, soil fertility and nutrient-use efficiency and reduces dependence on synthetic fertilizers (Niu *et al.*, 2021; Adesemoye *et al.*, 2023) ^[27, 1].

3.4 Effect of Integrated Organic and Microbial Nutrient Management on Number of Branches

Branch development increased significantly under integrated nutrient management, indicating improved vegetative growth and canopy architecture. The highest number of branches was recorded in T₉ (Soil + *Azospirillum* + VAM + Vermicompost + NPK) across all three crops, while the lowest was observed in the control (T₁). In tomato, branch number increased from 4.60 to 7.99 branches plant⁻¹ (73.7% increase). Chilli increased from 5.60 to 8.79 branches plant⁻¹ (57.0% increase), whereas mustard showed the greatest response, increasing from 2.99 to 8.67 branches plant⁻¹ (190% increase). The enhanced branching under T₉ can be attributed to the complementary effects of vermicompost, *Azospirillum*, VAM, and NPK. Vermicompost improved soil fertility and nutrient availability, *Azospirillum* enhanced nitrogen fixation and phytohormone production, while VAM increased phosphorus uptake and root efficiency, collectively promoting lateral shoot development and biomass accumulation (Bernados *et al.*, 2024) ^[7]. The superior performance of integrated nutrient management over individual treatments agrees with earlier studies showing that combining organic, biological, and mineral nutrient sources improves nutrient-use efficiency, canopy development, and crop productivity (Bhat *et al.*, 2023) ^[9].

Cross-crop comparative synthesis

Maximum response of mustard was observed under integrated nutrient management with highest absolute (5.68 branches plant⁻¹) and relative (190.0%) increase in branch number followed by tomato (3.39 branches plant⁻¹; 73.7%) and chilli (3.19 branches plant⁻¹; 57.0%). The consistent higher performance of treatment T₉ and the lowest performance under the control treatment (T₁) in all the crops suggest that the combined application of vermicompost, microbial inoculants and recommended NPK fertiliser effectively enhanced the vegetative development irrespective of the crop species. These results indicated that integrated nutrient management enhanced branching mainly thru enhancement in nutrient availability, nutrient use efficiency and increase in biological activity in the rhizosphere, which enhance canopy development and

provides greater potential for reproductive growth in diverse cropping systems.

Mechanistic Interpretation

The enhanced branching associated with the integrated nutrient management could be due to the synergistic effects of organic amendments, beneficial microorganisms and balanced mineral fertilisation in the enhancement of plant nutrition and physiological activity. Vermicompost is a rich source of readily available nutrients, humic substances and beneficial microorganisms which improve the physical properties of the soil, promote root development and nutrient availability in the growing season [citation needed: the Meghvansi reference in the source manuscript did not cover this topic]. The increase in biological activity of the soil creates conditions favourable for continued vegetative growth and increased canopy development.

Azospirillum inoculation also results in increased branch formation by associative biological nitrogen fixation also due to increased availability of nitrogen and production of plant growth promoting substances such as indole-3-acetic acid, gibberellins and cytokinins. These phytohormones stimulate cell division, lateral bud outgrowth and shoot formation thus increasing branching and improving vegetative vigour (Hungria *et al.*, 2022). Vesicular-arbuscular mycorrhizal (VAM) fungi also increase the effective surface of roots for water and micronutrient absorption and facilitate phosphorus absorption via the development of external hyphal networks. Improved phosphorus nutrition supports energy metabolism, photosynthesis and biomass production and thus promotes the lateral branch initiation and growth (Kumar *et al.*, 2022) [20].

The combination of vermicompost, microbial inoculants and recommended NPK fertiliser resulted in balanced nutrient supply which improved the nutrient-use efficiency and activated the rhizosphere microbial activity. This integrated approach probably improved the synthesis of chlorophyll, production of assimilates and partitioning of photosynthates toward vegetative growth leading to more branch development than individual nutrient sources alone. More branching leads to more canopy expansion and more sites for flowering, which translates to better reproductive performance and increased crop productivity. The present findings are in conformity with the recent reports which demonstrated that integrated nutrient management significantly improved the vegetative growth, canopy architecture and yield by improving the soil fertility, microbial diversity and availability of nutrients. Similar improvement in branching and plant vigour in tomato, chilli and mustard has been reported with the use of organic manures, biofertilizers and balanced chemical fertilisers in combination (Rivitra *et al.*, 2021) [33]. The results also suggest that integrated nutrient management is a sustainable approach for maximising crop growth and minimising the application of synthetic fertilisers.

3.5 Effect of Integrated Organic and Microbial Nutrient Management on Root Length

Root growth, an important index of plant health and nutrient uptake, was much more enhanced with the integrated nutrient management. In all the three crops highest root length was noted in T₉ (Soil + Azospirillum + VAM + Vermicompost + NPK). Lowest root length was found in

control (T₁). In tomato, root length increased from 54.60 cm to 99.22 cm (an increase of 81.7%). Chilli roots increased from 15.60 to 22.79 cm (46.1%) and mustard from 104.99 to 158.67 cm (51.1%). The combined treatments were consistently better than the individual nutrient applications, indicating synergistic effects of organic, biological and mineral nutrient sources. The enhanced root growth is due to the improved soil structure and nutrient availability from vermicompost, nitrogen fixation and phytohormone production by Azospirillum and increased phosphorus and water uptake thru VAM hyphal networks. Together, these components created a favourable rhizosphere, improving root development, nutrient acquisition, and plant growth. These findings are consistent with the earlier studies reporting that integrated nutrient management improve root characteristics, nutrient-use efficiency and crop productivity in vegetable and oilseed crops (Tadesse *et al.*, 2018) [38].

Cross-crop comparative synthesis

Root development responses were different for three crops under integrated nutrient management. The highest absolute increase in root length was shown by mustard (53.68 cm) followed by tomato (44.62 cm) and chilli (7.19 cm). Tomato showed maximum relative improvement over control (81.7%) followed by mustard (51.1%) and chilli (46.1%). These differences suggest that the inherent root system architecture of the crops influenced their response, with crops having relatively smaller or less developed root systems showing a greater proportional improvement with increased nutrient availability. However, treatment T₉ always produced the longest roots in all the three crops. Thus, the combination of vermicompost, Azospirillum, VAM and recommended NPK fertiliser provided the most favourable conditions for root development. It was observed that T₉ was consistently superior over different crop species under study indicating the efficacy of integrated nutrient management for the enhancement of below ground growth and nutrient acquisition with diverse cropping systems.

Mechanistic Interpretation

The improved root development under integrated nutrient management might be attributed to synergistic effects of organic amendments, beneficial micro-organisms and balanced mineral fertilisation on soil quality and rhizosphere function. Vermicompost improves soil structure by increasing aggregate stability, porosity, water holding capacity and microbial activity, decreasing resistance to root penetration and providing conditions for continuous root growth (Hussain *et al.*, 2022). Further, better soil physical properties lead to better diffusion of nutrients and more availability of moisture for development of a large root system. The inoculation with Azospirillum promotes root elongation by associative nitrogen fixation and by production of plant growth promoting substances, mainly indole-3-acetic acid (IAA), which enhances root initiation, lateral root formation and root hair development (Hungria *et al.*, 2022). Similarly, arbuscular mycorrhizal fungi (VAM) increase the effective absorptive surface of roots thru extensive hyphal networks, thereby improving the acquisition of relatively immobile nutrients such as phosphorus and micronutrients, as well as increasing water uptake and nutrient-use efficiency [citation needed: the Ilahy reference in the source manuscript does not address this subject and the year does not match the reference list]. The recommended NPK fertiliser gives well-balanced

mineral nutrients also contributing to these biological processes by preventing nutrient deficiencies and keeping root growth throughout the crop cycle.

3.6 Effect of Integrated Organic and Microbial Nutrient Management on Dry Biomass Accumulation

Shoot and root dry biomass (Figure 4) showed the same progressive pattern as for vegetative growth with maximum biomass accumulation in T₉ (Azospirillum + VAM + Vermicompost + Recommended NPK) and minimum in T₁ (untreated control) in all the three crops (mean $\pm$ SE, n = 3 replicate pots per treatment). In tomato, shoot dry biomass increased from 2.65 kg plant⁻¹ in T₁ to 4.12 kg plant⁻¹ in T₉ (55.5% increase), whereas root dry biomass increased from 0.25 to 0.99 kg plant⁻¹ (296.0% increase). The biomass of Chilli shoot increased from 1.71 to 2.23 kg plant⁻¹ (30.4% increase) and root biomass from 0.26 to 0.55 kg plant⁻¹ (111.5% increase). Mustard shoot biomass increased from 1.41 to 1.99 kg plant⁻¹ (41.1% increase) and root biomass from 0.33 to 0.88 kg plant⁻¹ (166.7% increase) from T₁ to T₉. The relative gain in root biomass was proportionately larger than the relative gain in shoot biomass in all three crops. Thus, the integrated treatments stimulated below-

ground allocation of photosynthate more strongly than the above-ground allocation.

3.7 Effect of Integrated Organic and Microbial Nutrient Management on Yield Attributes

Yield attributes (number of fruits or seeds per plant, Figure 5; yield per plant, Figure 6) were highest under T₉ and lowest under T₁ in all three crops (mean SE, n = 3), in line with the growth and biomass responses. In tomato, the number of fruits per plant increased from 7.45 in T₁ to 13.35 in T₉ (79.2% increase) and fresh fruit yield per plant increased from 87.45 g to 153.35 g (75.4% increase). In chilli, fruits per plant increased from 11.40 to 26.77 (134.8% increase) and mean fruit weight from 0.50 g to 4.77 g. Mustard showed an increase in number of seeds per pod from 11.98 to 21.65 (80.7%) and seed yield per pod from 5.98 g to 11.85 g (98.2%). The consistent out-performance of T₉ for the number of reproductive units, individual fruit/seed weight and total yield per plant across all three crops confirms that the integrated nutrient regime translated the gains in vegetative growth and biomass accumulation into a corresponding gain in final yield, directly supporting the "Yield" component of the study title.

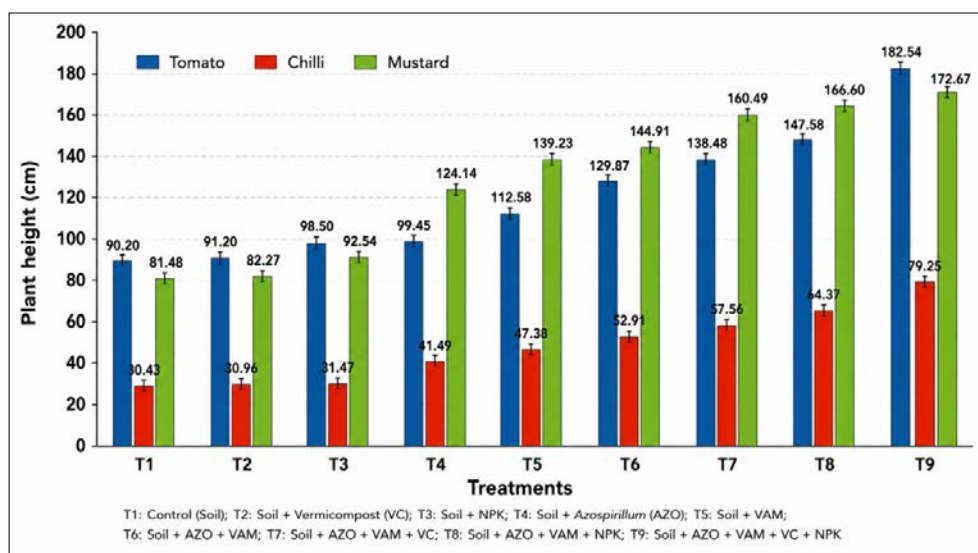


Fig 1: Shows the effect of nine nutrient management treatments on plant height of tomato, chilli, and mustard

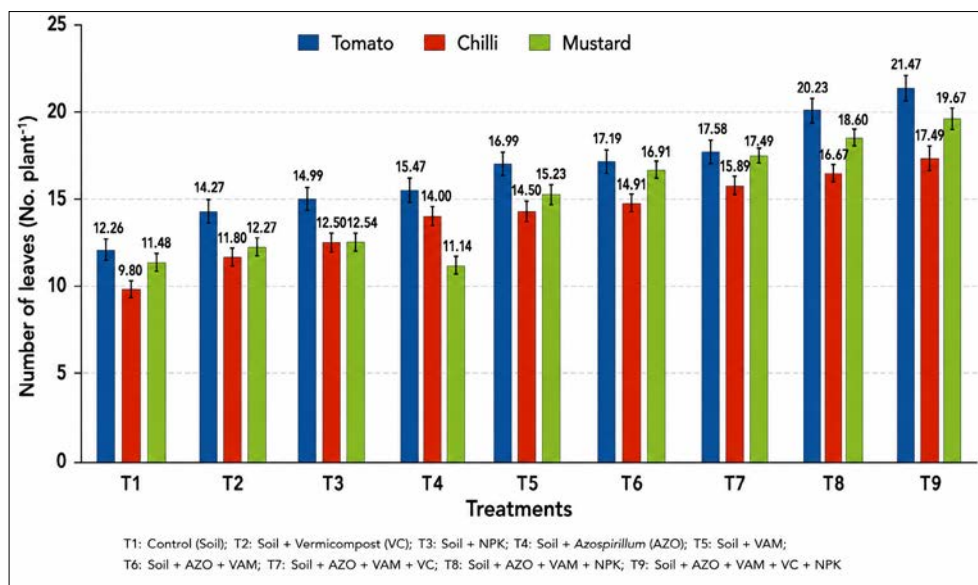


Fig 2: Presents the number of leaves per plant under the nine nutrient management treatments

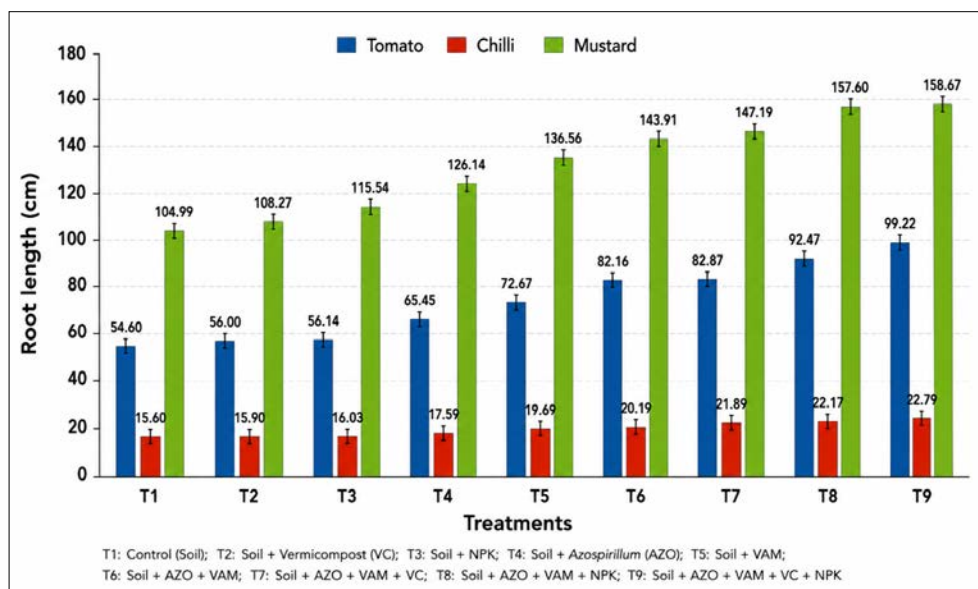


Fig 3: Illustrates the effect of nutrient management on root length in tomato, chilli, and mustard

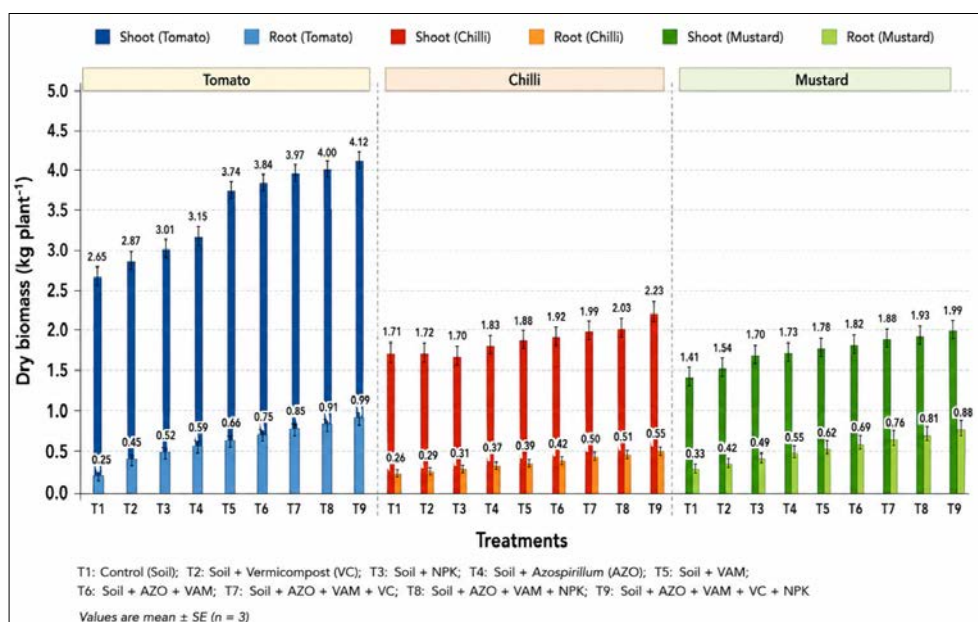


Fig 4: Shows shoot and root dry biomass accumulation in tomato, chilli, and mustard under the nine nutrient treatments

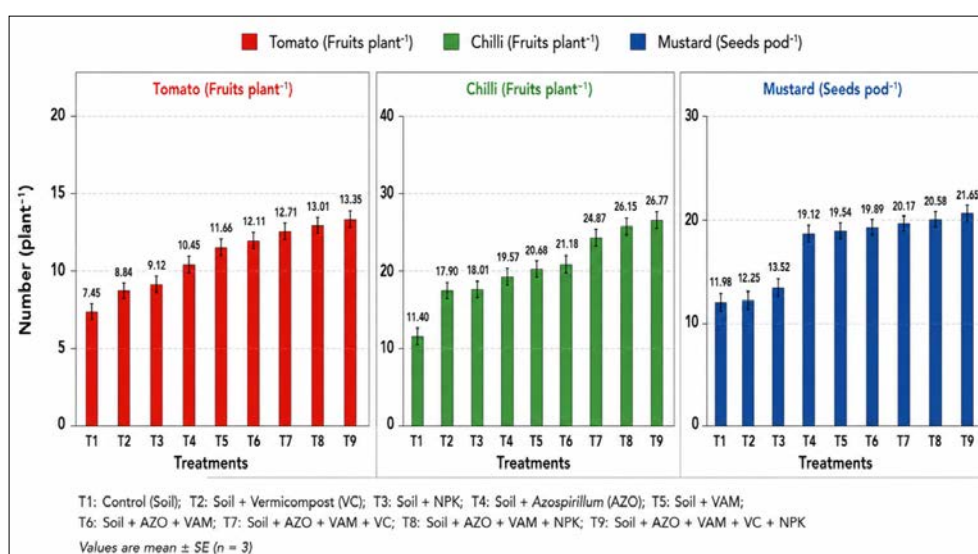


Fig 5: Presents yield attributes expressed as fruits plant⁻¹ for tomato and chilli and seeds pod⁻¹ for mustard

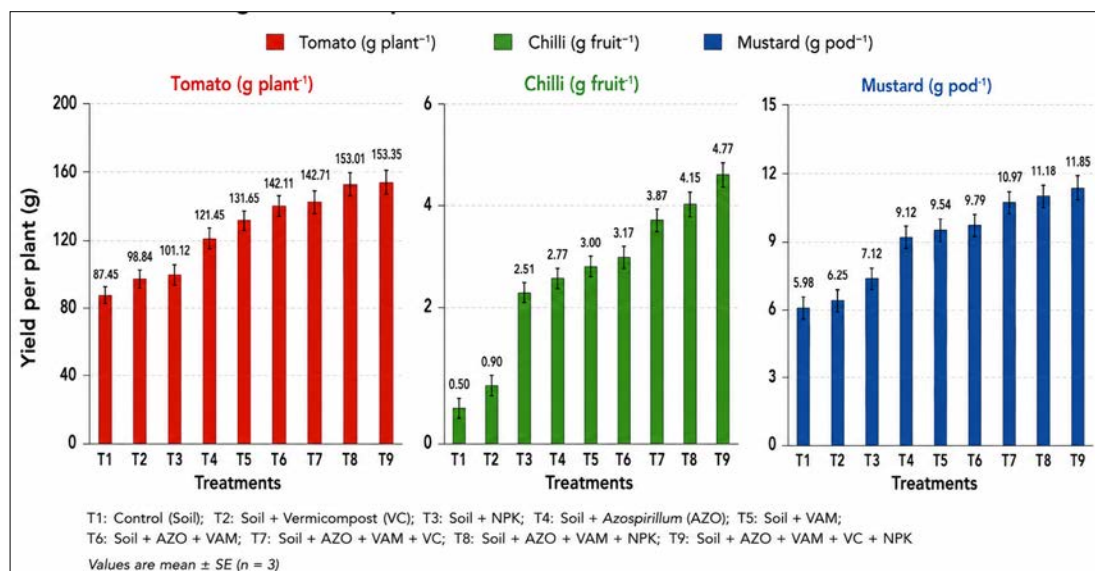


Fig 6: Shows yield per plant for tomato, chilli, and mustard under the nine nutrient management treatments

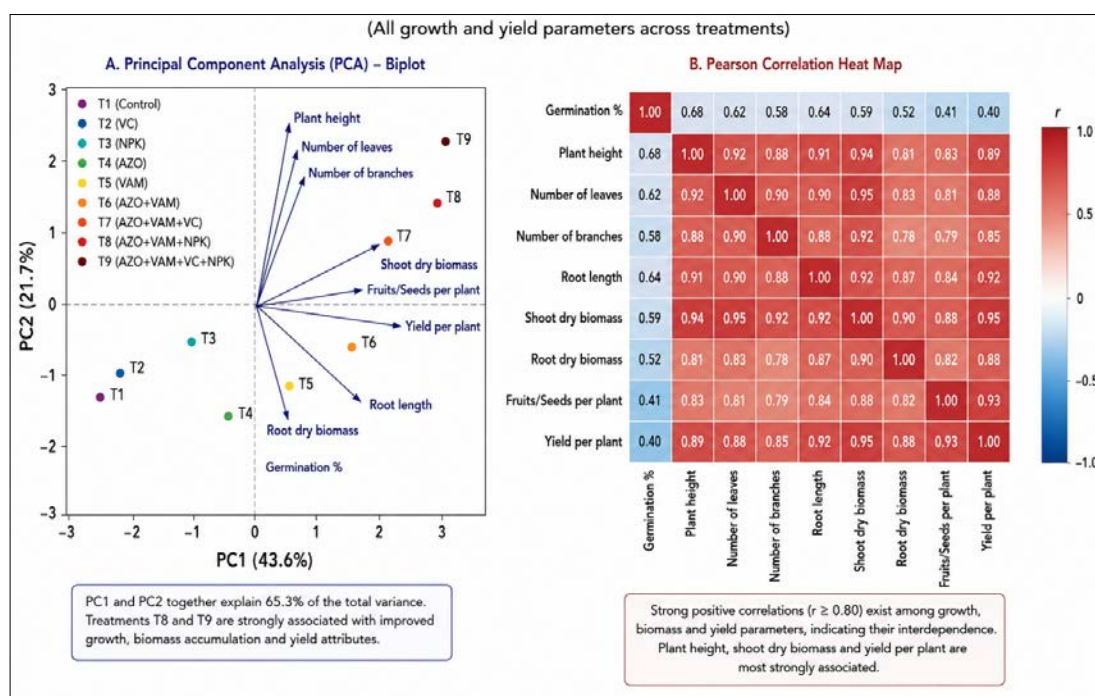


Fig 7: Combines principal component analysis (PCA) with a Pearson correlation heat map for growth and yield parameters across treatments

Figure 7 shows the multivariate analysis of the impact of different nutrient management treatments on the growth and yield characteristics of the experimental plants. Figure combines two complementary analyses: (A) a Principal Component Analysis (PCA) biplot and (B) a Pearson's correlation heat map. Both representations depict the relationships among treatments and measured plant parameters.

Principal Component Analysis (PCA) Biplot (Panel A). The PCA biplot explains the variation in the nine treatments (T1-T9) with all the growth and yield parameters recorded. The first two principal components (PC1 and PC2) explained 65.3% of the total variability, with 43.6% and 21.7% of total variance explained by PC1 and PC2 respectively. This suggests that the first two components are adequate to represent the overall response of plants to different nutrient management treatments.

The distribution of treatments along the principal components showed a clear separation of low-input and integrated nutrient management treatments. The control treatment (T₁) and treatments supplemented with individual nutrients (T₂-T₆) are grouped on the negative side of PC1 indicating relatively lower growth and productivity. On the other hand, the integrated treatments T₇, T₈ and especially T₉ are located on the positive side of PC1, indicating a better overall plant performance.

Among all treatments, T₉ (AZO + VAM + VC + NPK) is at the extreme positive position showing the highest association with increased plant growth and yield. T₈ (AZO + VAM + NPK) also shows a strong positive performance but still slightly lower than T₉. The proximity of these treatments to the vectors representing plant height, number of leaves, number of branches, shoot dry biomass, fruits/seeds per plant and yield per plant indicates that these

parameters contributed most strongly to their superior performance.

The direction and length of the vectors give information about the contribution of single variables. The long vectors of plant height, number of leaves, shoot dry biomass, fruits/seeds per plant and yield per plant indicated that these traits were the main contributors to variability among treatments. Conversely, germination percentage, root dry biomass and root length had a relatively small contribution to treatment discrimination, but contributed to development of plants in general.

Correlation Heat Map (Panel B)

The Pearson correlation heat map shows relationships between all the growth and yield parameters measured. Nearly all variables showed positive correlations, indicating that increases in one growth trait were typically associated with increases in other plant characteristics. Several important variables were very strongly positively correlated ($r \geq 0.90$). Plant height had strong positive correlation with number of leaves ($r=0.92$), number of branches ($r=0.88$), root length ($r=0.91$), shoot dry biomass ($r=0.94$), root dry biomass ($r=0.81$), fruits/seeds per plant ($r=0.83$) and yield per plant ($r=0.89$). Similarly, shoot dry weight was strongly correlated with root dry weight ($r = 0.90$), fruits/seeds per plant ($r = 0.88$), and yield per plant ($r = 0.95$), suggesting that biomass accumulation is closely related to reproductive performance.

The highest positive correlation in this dataset was between fruits/seeds per plant and yield per plant ($r = 0.93$), which is indicative of a direct positive contribution of increased reproductive development to the increase of the final yield. Root length was also highly positively correlated with shoot biomass ($r=0.92$), root biomass ($r=0.97$) and yield per plant ($r=0.92$) highlighting the importance of a well-developed root system in supporting nutrient uptake and crop productivity.

Germination percentage was positively correlated with all measured traits ($r = 0.40-0.68$) but relatively weakly compared with the other variables, suggesting that early seedling establishment contributed to subsequent plant performance but was less influential than vegetative growth and biomass accumulation.

The integrated nutrient management treatments especially T₉ (AZO + VAM + VC + NPK) gave the best overall response as evidenced by combined PCA and correlation analyses which improved the plant growth, biomass accumulation and yield simultaneously. The strong positive correlations between growth, biomass and yield parameters also suggest that the enhanced vegetative growth obtained through integrated nutrient management ultimately led to increased reproductive success and higher crop productivity. These multivariate analyses provide strong statistical evidence in favour of superiority of integrated nutrient management over individual nutrient application.

4. Conclusion

The present study revealed that integrated nutrient management (INM) significantly improved plant growth, biomass production, root development and yield under controlled pot conditions. Among the nine treatments, the combined application of *Azospirillum*, vesicular-arbuscular mycorrhiza (VAM), vermicompost and recommended NPK fertilizer (T₉) has resulted in the highest growth and yield of

all the experimental crops consistently. The enhanced performance of T₉ highlights the synergistic interaction of organic amendments, beneficial microorganisms and balanced mineral fertilization in improving nutrient availability and nutrient-use efficiency. Further, Principal Component Analysis and correlation analysis depicted the superiority of integrated nutrient management and revealed the strong positive relationships among vegetative growth, biomass production and yield attributes. The findings suggest that the combination of vermicompost, bio-fertilizers and mineral fertilizers can serve as a sustainable and efficient alternative to the sole use of chemical fertilizers, enhancing crop productivity and soil health. Long term studies under different agroclimatic conditions and further field based studies are suggested to confirm these findings and to assess their practical applicability for sustainable agricultural production.

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