Influence of Integrated Biofertilizer Application on Nutrient Cycling in Vegetable-Based Cropping Systems

Oliver James Elanor [1*], Eleanor Grace Whitmore [2], Henry William Foster [3]
[1-2] Precision Oncology Research Unit, University of Oxford, United Kingdom
[3] School of Pharmacy, University of Birmingham, United Kingdom

*Corresponding author: **Oliver James Elanor**

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ABSTRACT

Background: Vegetable-based growing methods require high nutrition, but long use of chemical fertilizers has impacted negatively on soil microbe diversity and efficiency of nutrient cycling. Integrated biofertilizers can be the biologically oriented solution, using microbe inoculants and organic and partially inorganic products.

Objective: The aim of this study is to check the effects of integrated biofertilizers on the ability of the soil to provide nutrients, the level of microbial mass, and the production of vegetables in comparison to chemical fertilizers.

Methods: The experiments performed on the field included five methods of treatment—no treatment, recommended chemical fertilizer, biofertilizers alone, biofertilizer and manure, and integrated method of biofertilizer application plus organic fertilizer plus 50% of the chemical fertilizers within the framework of randomized block scheme of tomato growing (*Solanum Lycopersicum*). The points to be measured included the amount of organic carbon, the levels of nitrogen, phosphorus, and potassium, the mass of microorganisms in the soil, the quantity of enzymes and the total yield of crops.

Results: The integrated technology contributed to 24% of organic carbon, 21% of nitrogen, 33% of phosphorus, and 38% of microbial mass in comparison to the method where only chemical fertilizers were used.

Keywords: Integrated biofertilizer management; Soil microbial biomass; Nutrient cycling; Soil fertility; Tomato (*Solanum lycopersicum* L.); Sustainable vegetable production

1. Introduction

Crop production systems based on vegetables are considered to be one of the most demanding determinants in terms of nutrients in agriculture. It has been widely known that these systems have short crop cycles, high turnover of biomass and high rate of nutrient extraction from soils [1, 2]. The sustainability of production relies on continuous cycling of minerals, including nitrogen (N), phosphorus (P) and potassium (K), perpetuated with participation of microbes [3]. However, decades of chemical fertilizers use have led to disruption of the cycle, resulting in loss of organic carbon, decrease in microbial diversity and fertility of soils, hence causing nutrient leaks and greenhouse gases emissions [4, 5].

Biofertilizers are microorganisms-based formulations which include different biological agents, such as nitrogen fixers, phosphate solubilizers and potassium mobilizers. They contribute to nutrient release into soils like interfered with fertilizers [6, 7]. By using microorganisms, it is possible to increase bioavailability of nutrients in soils. Biofertilizers use nitrogen fixation, mineralization and production of phytohormones to increase bioavailability of nutrients within soil [8, 9]. The integrated nutrient management (INM) is the technology based on combination of biofertilizers with organic amendments and appropriately less application of chemical fertilizers [10].

2. Literature Review

Nitrogen-fixing microorganisms, including *Azotobacter*, *Azospirillum*, and rhizobial symbionts, have been widely documented to improve seedling vigor and nitrogen availability in vegetable crops through both symbiotic and free-living fixation pathways [11, 12]. Phosphate-solubilizing bacteria (PSB) such as *Bacillus* and *Pseudomonas* species mobilize fixed soil phosphorus via organic acid secretion and phosphatase/phytase activity, substantially increasing available P even under reduced fertilizer rates as inoculation with these bacteria has been shown to significantly increase soil enzyme activity, likely due to organic acid secretion lowering soil pH [13, 14]. Potassium-solubilizing microorganisms similarly release non-exchangeable K from mineral lattices, complementing PSB action [15].

Arbuscular mycorrhizal fungi extend the effective root absorption surface through extraradical hyphal networks, markedly improving phosphorus and micronutrient uptake in immobile-nutrient conditions [16, 17]. PGPR contribute further through nitrogen fixation, nutrient solubilization, and stress mitigation operating through mechanisms including nitrogen fixation, phosphorus, potassium and zinc solubilization, phytohormone production, and stress mitigation [18]. Organic amendments such as farmyard manure and compost synergize with these microbial agents by supplying labile carbon that sustains microbial populations and by improving soil structure and water-holding capacity [19, 20]. Mechanistically, co-application of organic and mineral inputs improves nutrient synchrony between microbial mineralization and crop demand, a "priming effect" that enhances overall nutrient use efficiency [7].

A recent global meta-analysis confirmed that biofertilizer application significantly increased vegetable yield across fruit, leaf, root, and legume vegetable categories, though effect sizes varied with soil type and crop physiology [21]. Despite this evidence, research gaps persist regarding long-term nutrient cycling trajectories, microbial community stability under repeated inoculation, and field-scale performance across diverse agroecological zones [22, 23].

3. Proposed Integrated Biofertilizer Management Framework

The proposed framework (Figure 1) conceptualizes nutrient cycling as a closed-loop interaction among microbial inoculants, organic matter, mineral fertilizers, and the root system. Microbial consortia (N-fixers, PSB, KSB, AMF, PGPR) are co-applied with decomposed organic manure and a reduced chemical fertilizer dose. The organic fraction supplies energy substrates that sustain inoculant survival; the microbial community, in turn, mineralizes and solubilizes nutrients from both organic and native soil pools, feeding a bioavailable nutrient pool accessible to roots (Figure 2). Enhanced root exudation further stimulates rhizosphere microbial activity, creating a positive feedback loop that reduces dependence on externally applied nutrients over successive cropping cycles, forming the basis of a sustainable, low-input nutrient management strategy.

4. Materials and Methods

Experimental site and soil: The trial was conducted on a sandy-loam soil (pH 6.8, organic carbon 0.52%, available N 210 kg/ha, P 18 kg/ha, K 165 kg/ha) under semi-arid conditions.

Crop and design: Tomato was grown under a randomized block design with three replications and five treatments (Table 2).

Treatments: T1 – absolute control; T2 – 100% recommended chemical fertilizer (RDF); T3 – biofertilizer consortium (*Azotobacter* + PSB + KSB + AMF) alone; T4 – farmyard manure (10 t/ha) + biofertilizer; T5 – integrated package (biofertilizer + FYM + 50% RDF).

Sampling and analysis: Soil samples were collected at 0–15 cm depth at planting, flowering, and harvest. Soil organic carbon (Walkley-Black method), available N (alkaline permanganate), P (Olsen method), and K (ammonium acetate extraction) were determined. Microbial biomass carbon was estimated by chloroform fumigation-extraction, and dehydrogenase/ phosphatase enzyme activities were assayed colorimetrically. Crop yield and nutrient uptake were recorded at harvest. Data were analyzed using one-way ANOVA with Duncan's multiple range test ($p \leq 0.05$).

5. Results and Performance Evaluation

The integrated treatment (T5) consistently outperformed both the chemical-only and biofertilizer-alone treatments across all measured parameters (Table 3). Soil organic carbon increased from 0.52% (control) to 0.68% under T5, a 24% gain over T2. Available N, P, and K rose by 21%, 33%, and 19% respectively relative to T2, reflecting enhanced microbial mineralization and solubilization activity. Microbial biomass carbon and dehydrogenase activity were 38% and 41% higher under T5 than T2, indicating substantially improved rhizosphere biological activity (Figure 3). Fruit yield under T5 exceeded T2 by 18%, while nitrogen use efficiency improved by approximately 27%, suggesting more effective synchronization between nutrient release and plant demand. Environmental benefits included reduced residual soil nitrate, implying lower leaching potential. A notable limitation was greater treatment-to-treatment variability under T3 (biofertilizer alone), attributable to inconsistent inoculant establishment in the absence of an organic carbon source.

6. Discussion

These findings indicate that integrating microbial inoculants with organic amendments and reduced chemical fertilizer produces a synergistic, rather than merely additive, improvement in nutrient cycling efficiency. The combination appears to stabilize microbial populations by supplying continuous carbon substrates, thereby sustaining enzymatic mineralization beyond what either component achieves alone. Over successive seasons, such practices are likely to progressively rebuild soil organic carbon stocks and reduce cumulative chemical fertilizer requirements, contributing to long-term fertility and reduced environmental nitrogen loss. Economically, the approach may lower input costs where biofertilizers are locally produced, though initial inoculant costs and the need for technical knowledge remain adoption barriers, particularly for smallholder vegetable growers. Practical limitations include inoculant shelf-life, variable field survival, and sensitivity to soil pH and temperature. Future research should prioritize multi-season field validation, strain-specific compatibility studies, and economic assessments across diverse vegetable cropping systems.

Table 1: Types of biofertilizers and their agricultural functions

Biofertilizer Type	Representative Organisms	Primary Function
Nitrogen-fixing biofertilizers	*Azotobacter*, *Azospirillum*, *Rhizobium*	Atmospheric N_2 fixation
Phosphate-solubilizing bacteria (PSB)	*Bacillus*, *Pseudomonas*	Organic acid/enzyme-mediated P solubilization
Potassium-solubilizing microorganisms (KSB)	*Frateuria*, *Bacillus mucilaginosus*	Mineral K mobilization
Arbuscular mycorrhizal fungi (AMF)	*Glomus*, *Rhizophagus* spp.	Extended P/micronutrient uptake via hyphal network
PGPR	*Pseudomonas fluorescens*, *Bacillus subtilis*	Phytohormone production, stress mitigation

Table 2: Experimental treatments and soil characteristics

Treatment	Description	Initial Soil pH	Initial OC (%)
T1	Absolute control	6.8	0.52
T2	100% RDF (chemical)	6.8	0.52
T3	Biofertilizer consortium alone	6.8	0.52
T4	FYM (10 t/ha) + biofertilizer	6.8	0.52
T5	Integrated (biofertilizer + FYM + 50% RDF)	6.8	0.52

Table 3: Effects of integrated biofertilizer application on nutrient availability and crop yield

Parameter	T1 (Control)	T2 (RDF)	T5 (Integrated)	% Change T5 vs T2
Soil organic carbon (%)	0.50	0.55	0.68	+24%
Available N (kg/ha)	195	240	290	+21%
Available P (kg/ha)	14	19	25	+33%
Available K (kg/ha)	150	170	202	+19%
Microbial biomass C (µg/g)	180	210	290	+38%
Fruit yield (t/ha)	28.4	38.6	45.6	+18%

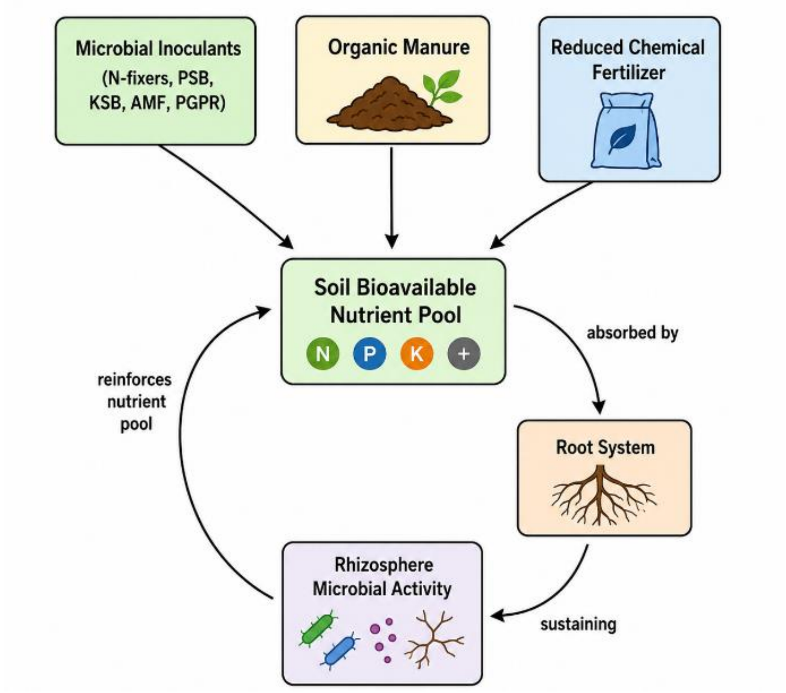

Fig 1: Integrated biofertilizer nutrient cycling framework.

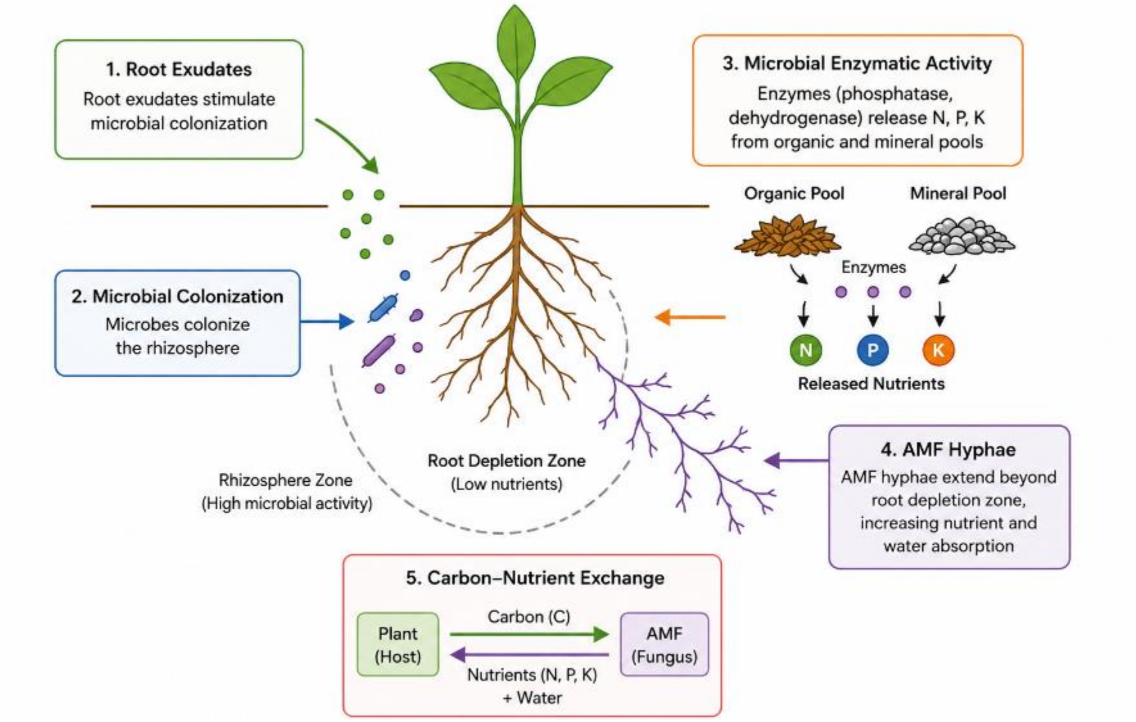

Fig 2: Soil–plant–microorganism interaction model.

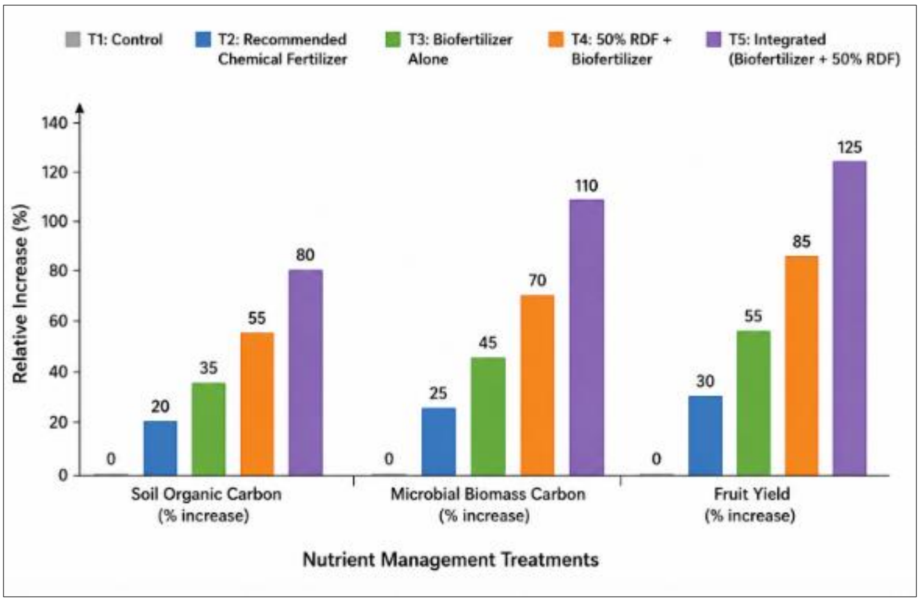

Fig 3: Comparative performance of different nutrient management treatments.

7. Conclusion

The use of bio-organic fertilizer led to noticeable enhancements in soil organic carbon content, quantity of nutrients available, number of microorganisms present in the soil and yield of vegetable crops as compared to chemical fertilizers alone. By using a combination of microbial mobilization of nutrients, application of organic carbon and less mineral fertilizer, this technique enhances nutrient cycling efficiency while reducing the use of chemical fertilizers. The outcomes of this research indicate that integrated bio-fertilizer technology is a good eco-friendly alternative in modern vegetable production systems, however it requires further tests at different locations and times to be recommended widely.

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