



Effect of integrated nutrient management on yield, yield attributes and economics of maize (*Zea mays* L.) in the Vertisols of South India

Vinaykumar B B^{1*}, Patil S L², Patil C R³ & Shivakumar B G⁴

¹Department of Agronomy, College of Agriculture, University of Agricultural Sciences, Dharwad 580 005, Karnataka, India

²ICAR-Indian Institute of Pulses Research (IIPR), Regional Research Station, Dharwad 580 005, Karnataka, India

³Department of Agricultural Microbiology, College of Agriculture, University of Agricultural Sciences, Dharwad 580 005, Karnataka, India

⁴ICAR-Indian Grassland and Fodder Research Institute (IGFRI), Southern Regional Research Station (SRRS), Dharwad 580 005, Karnataka, India

*Correspondence: Vinaykumar B B, slpatil1001@gmail.com

Abstract

A field experiment was conducted during rainy season of 2024 at ICAR-Indian Institute of Pulses Research, Regional Research Station, Dharwad, India to study the effect of integrated nutrient management on yield and economics of maize (*Zea mays* L.). Maize cultivar DKC 9133 was sown in the experiment with 8 treatments and was replicated thrice in a randomised complete block design (RCBD). Significantly higher grain yield (8006 kg ha⁻¹), straw yield (7044 kg ha⁻¹), biological yield (15050 kg ha⁻¹) and water use efficiency (26.90 kg ha⁻¹ mm⁻¹) were recorded with application of 100 % recommended rate of fertiliser + rhizosphere microbial consortia seed treatment at 8 mL kg⁻¹ of seed + zinc sulphate (ZnSO₄) and ferrous sulphate (FeSO₄) at 25 kg ha⁻¹ + farmyard manure at 2.0 t ha⁻¹ i.e. T₈ treatment. Higher grain yield in T₈ treatment is attributed to greater cob weight (157 g plant⁻¹), grain weight cob⁻¹ (133.6 g), cob length (16.7 cm) and cob girth (14.8 cm). Correlation analysis revealed that grain yield of maize was positively correlated with straw yield, harvest index, water use efficiency (WUE), grains cob⁻¹, cob weight, grain weight cob⁻¹, 100-grain weight, cob length and cob girth. From the point of economics; farmers with low input availability advised to apply 75 % recommended rate of macro and micronutrient fertiliser with rhizosphere consortium whereas the farmers who wants to realise higher returns with improved and sustainable crop productivity are advised to adopt 100 % recommended rate of macro and micronutrient fertiliser with rhizosphere consortium in rainfed conditions in the transitional zone of northern Karnataka, India.

Keywords: correlation; economics; integrated nutrient management; maize; water use efficiency; yield; yield attributes

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1. Introduction

Maize (*Zea mays* L.) is a staple crop of global significance, contributing substantially to the food security, animal feed and industrial applications (1). Globally, maize is cultivated on approximately 206.3 million hectares (Mha), with a total production of 1210.2 million tonnes (Mt) and an average productivity of 5.87 t ha⁻¹. In India, maize is cultivated over an area of 10.74 Mha, with a production of 38.09 Mt and the productivity is 3.54 t ha⁻¹ (2). Beyond its role as a food crop, maize also serves as a critical raw material in the manufacture of starch, ethanol and biofuels, making it economically important for both smallholder and commercial agricultural systems (3).

Among the cereals, maize crop has higher potential and its productivity is constrained by several limiting factors, among which nutrient deficiency is one

of the most critical in the northern parts of Karnataka and whole India/World in general. Maize has inherently high nutrient demands for nitrogen, phosphorus, potassium and micronutrients like zinc and iron. This necessitates the implementation of comprehensive nutrient management strategies to ensure both sustainable and optimal crop production especially in the present scenario of escalation and less availability of chemical fertilisers. Dependence on the chemical fertilisers alone is inadequate and environmentally unsustainable, often leading to soil health deterioration, nutrient imbalances and reduced fertiliser use efficiency. In the present context, integrated nutrient management (INM) has emerged as a promising approach to enhance soil fertility, improve crop productivity and increase nutrient use efficiency in maize (4–6).

The INM has emerged as a holistic and sustainable approach that synergistically combines organic and inorganic nutrient sources to increase the crop productivity and maintain soil health and environmental quality. This includes the judicious and balanced use of farmyard manure (FYM), vermicompost, biofertilisers and chemical fertilisers to improve nutrient availability, increase soil organic matter and stimulate beneficial microbial activity in the rhizosphere. Earlier studies have demonstrated that INM significantly improves maize growth, yield and yield attributes and grain quality when compared to the application of either organic or inorganic inputs alone (7–8).

The results of recent investigations indicated the potential of rhizosphere microbial consortia as seed treatment for increasing the nutrient uptake efficiency and promoting crop growth and yields in maize. The beneficial microorganisms like arbuscular mycorrhizal fungi and phosphate-solubilising bacteria, establish symbiotic associations with maize roots, thereby improving nitrogen fixation, phosphorus solubilisation and overall mobilisation of nutrients from native soil reserves (9–11). In addition, the foliar application of micronutrients such as zinc and iron has gained prominence as an effective strategy to correct micronutrient deficiencies, particularly in alkaline soils where their availability is inherently low (12–14). The integration of biological and micronutrient-based precision nutrient tools contributes to a greater extent in optimising maize productivity and sustaining soil health (8, 10).

Application of FYM has demonstrated substantial benefits in improving soil physical, chemical and biological properties, thereby contributing to sustainable maize productivity. As a slow-release nutrient source, FYM improves the soil organic carbon content, microbial biomass and nutrient cycling efficiency. The incorporation of well-decomposed organic matter supplies essential plant nutrients, improves soil structure, water-holding capacity and cation exchange capacity thus creating a favourable environment for root growth and nutrient uptake (15, 16). The improvement in soil physical and chemical properties is more significant in organic matter deficit soils, where FYM plays a crucial role in restoring soil fertility and supporting long-term crop performance.

Development of effective and low-cost nutrient management strategies is vital for improving maize productivity, particularly under declining soil fertility and emerging micronutrient deficiencies. Micronutrients such as zinc and iron play a crucial role in enhancing crop growth and yield in hybrid maize, as they contribute to physiological and enzymatic processes that are essential for better crop growth and development (17). Additionally, biological interventions such as seed treatment with microbial consortia, though more commonly explored in crops like tomato, have indicated potential in improving seed germination, seedling vigour and nutrient uptake, suggesting promising applications in maize and maize-based cropping systems (18).

Understanding the associations between grain yield and interrelationships among yield components and biometrical traits is vital for effective selection strategies in crop improvement. Traits exhibiting strong and positive correlations with yield serve as indirect selection criteria. A higher magnitude of the correlation coefficient reflects a stronger relationship between traits (19, 20). In rainy/kharif season maize, besides genetic factors, climatic conditions and agronomic management practices significantly influence maize yields, particularly in the Vertisols of southern India. These targeted nutrient strategies, when integrated effectively, contribute to more resilient and productive maize cultivation, particularly during the rainy season when crops are exposed to monsoon-related stresses.

2. Materials and Methods

A field experiment was conducted at ICAR-Indian Institute of Pulses Research, Regional Research Station, Dharwad, India, during 2024 rainy (kharif) season. The experimental site is situated at latitude of 15° 49' N and a longitude of 74° 99' E in the northern transition zone-8 of Karnataka, India, with an average elevation of 678 m above mean sea level. The soil of the experimental site was a Vertisol with medium soil depth. The composite soil samples were collected from top 0–30 cm soil depth before the initiation of the experiment. Soil samples were air dried, powdered and allowed to pass through 2 mm sieve and were analysed for physical and chemical properties. The soil was neutral in pH (7.30), normal in salt content (0.42 dS m⁻¹), low in organic matter content (0.45 %) and available nitrogen (211 kg ha⁻¹), medium in available phosphorus (38 kg ha⁻¹), high in available potassium (340 kg ha⁻¹). The experimental site was deficient in available zinc of 0.51mg kg⁻¹ and available iron of 4.23 mg kg⁻¹. The gross plot size was 5.4 m × 6.0 m (32.4 m²), while the net plot size was 3.0 m × 5.2 m (15.6 m²). The spacing between rows was maintained at 60 cm and between plants at 20 cm. Fertilisers were applied as a basal application. The experiment was replicated thrice in a randomised complete block design (RCBD) with 8 treatments and the maize variety i.e. DKC 9133 was sown.

The treatment details are presented in Table 1. The 8 treatments comprised of combinations of organic, inorganic sources with microbial consortium. The treatment levels were selected based on the recommended nutrient management practices for maize. The FYM was applied at 1.0 and 2.0 t ha⁻¹ to evaluate the effect of different organic nutrient rates on crop growth, yield and soil health. Zinc sulphate (ZnSO₄) and ferrous sulphate (FeSO₄) were applied at 25 kg ha⁻¹ each based on the recommended rates for correcting zinc and iron deficiencies in maize- growing soils and to ensure adequate micronutrient availability throughout the crop growth period. The microbial consortium that is used in the experiment contains nitrogen fixer,



phosphorus solubiliser, potassium solubiliser, zinc, iron, silica mobiliser and plant growth promoting rhizosphere microorganisms. The maize seeds were treated with rhizosphere microbial consortia at 8 mL kg⁻¹ as per the recommendations of Organic Farming Research Institute, University of Agricultural Sciences, Dharwad, to enhance nutrient mobilisation, root growth and microbial activity in the rhizosphere. After through survey of fertiliser management in the maize cultivating farmers in the northern and central Karnataka we observed that farmers generally apply 75 % of the nitrogen, phosphorus and potassium and with 50 % of recommended rate of FYM application i.e. 1.0 t ha⁻¹ and hence this treatment was included as control with rhizosphere microbial consortia seed treatment at 8 mL kg⁻¹ and application of recommended rate of zinc and iron at 25 kg ha⁻¹ as T₁ to T₄ treatments. Whereas treatments T₅ to T₈ consisted of application of 2.0 t FYM ha⁻¹ with rhizosphere microbial consortia seed treatment at 8 mL kg⁻¹ and application of recommended rate of zinc and iron at 25 kg ha⁻¹. The total annual rainfall that fell during crop growth period was 714.4 mm. Excess rainfall during the experimental period especially from flowering to grain formation resulted in water logging and nutrient leaching resulting in marginal reduction in the crop yields than the expected. Three irrigations were applied to maize at critical stages of their growth. During the kharif season, fall armyworm (*Spodoptera frugiperda*) emerged as the major insect pest in maize. To manage it, Proclaim (Emamectin benzoate) was sprayed at the rate of 0.5 mL L⁻¹ of

water. Yield components were recorded at harvest of the crop by using standard procedure. Grain and straw yields from the net plot were harvested; sun dried, weighed and further converted to kg ha⁻¹. The water use efficiency (WUE) was worked out by dividing economic yield by evapo-transpiration i.e. water utilised (mm) from sowing up to harvest of maize crop and expressed in kg ha⁻¹ mm⁻¹.

Economics of maize was worked out with the cost invested in land preparation, cultural practices adopted from sowing till harvest including transport cost to market and existing costs during cultivation of maize and market rates of maize grain and straw at the harvest, inputs like seed, FYM, fertiliser and pesticides used in the cost of cultivation during rainy season of 2024. The benefit-cost (B : C) ratio was calculated by dividing gross returns by cost of cultivation.

Statistical analysis

The data collected from the experiment at different crop growth stages and at physiological maturity was subjected to statistical analysis (21). The level of significance used for 'F' and 't' tests was $p = 0.05$. The mean value of all factors and their interactions were separately subjected to Duncan's multiple range test (DMRT) using the corresponding error mean sum of squares and degrees of freedom. The correlation analysis was carried out by the method suggested in a previous study (22). Statistical analysis was carried out using Microsoft Excel and OPSTAT software.

Table 1. Grain yield, straw yield, biological yield, harvest index and water use efficiency of maize as influenced by integrated nutrient management practices

Treatments	Grain yield (kg ha ⁻¹)	Straw yield (kg ha ⁻¹)	Biological yield (kg ha ⁻¹)	Harvest index (%)	WUE (kg ha.mm ⁻¹)
T ₁ : FP -75 % RRF + FYM at 1.0 t ha ⁻¹	5882 ^d	5832 ^b	11713 ^d	50.2 ^a	19.76 ^d
T ₂ : FP + <i>Rhizosphere</i> microbial consortia seed treatment at 8 mL kg ⁻¹ of seed + FYM at 1.0 t ha ⁻¹	6271 ^{cd}	6094 ^b	12365 ^{cd}	50.7 ^a	21.07 ^{cd}
T ₃ : FP + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 1.0 t ha ⁻¹	6519 ^{cd}	6455 ^{ab}	12974 ^{cd}	50.2 ^a	21.90 ^{cd}
T ₄ : FP + <i>Rhizosphere</i> microbial consortia seed treatment at 8 mL kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 1.0 t ha ⁻¹	7073 ^{a-c}	6448 ^{ab}	13521 ^{bc}	52.3 ^a	23.77 ^{a-c}
T ₅ : RRF + FYM at 2.0 t ha ⁻¹	6980 ^{bc}	6548 ^{ab}	13528 ^{bc}	51.6 ^a	23.45 ^{bc}
T ₆ : RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 mL kg ⁻¹ of seed + FYM at 2.0 t ha ⁻¹	7780 ^{ab}	6944 ^a	14724 ^{ab}	52.8 ^a	26.14 ^{ab}
T ₇ : RRF + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 2.0 t ha ⁻¹	7836 ^{ab}	6936 ^a	14772 ^{ab}	53.0 ^a	26.33 ^{ab}
T ₈ : RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 mL kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 2.0 t ha ⁻¹	8006 ^a	7044 ^a	15050 ^a	53.2 ^a	26.90 ^a
S.Em. ±	297	219	429	1.1	1.00
LSD at 5 %	900	664	1300	3.3	3.02

FP: farmers practice- 75 % Recommended rate of fertiliser (75 : 37.5 : 37.5 N : P : K kg ha⁻¹) and farmyard manure (FYM) at 1.0 t ha⁻¹ every year for maize; RRF: recommended rate of fertiliser (100 : 50 : 50 N : P : K kg ha⁻¹) and farmyard manure at 2.0 t ha⁻¹ every year for maize; WUE: water use efficiency. Means followed by the same letter (s) within a column are not significantly differed by DMRT ($p = 0.05$).



3. Results and Discussion

Application of recommended rate of fertilisers (RRF) + rhizosphere microbial consortia seed treatment at 8 mL kg⁻¹ of seed + ZnSO₄ and FeSO₄ at 25 kg ha⁻¹ + FYM at 2.0 t ha⁻¹ (T₈) recorded significantly higher maize grain yield of 8006 kg ha⁻¹, straw yield of 7044 kg ha⁻¹ and biological yield of 15050 kg ha⁻¹ and were at par with the yields recorded in the treatment with application of RRF + ZnSO₄ and FeSO₄ at 25 kg ha⁻¹ + FYM at 2.0 t ha⁻¹ i.e. 7836, 6936, 14772 kg ha⁻¹, respectively. Significantly lower maize grain; straw and biological yields were recorded with application of farmers' practice (FP)- 75 % RRF + FYM at 1.0 t ha⁻¹ (T₁) i.e., 5882, 5832 and 11713 kg ha⁻¹, respectively (Table 1). The grain, straw and biological yields in T₈ treatment were greater by 36, 21 and 28 %, respectively over farmers practice (FP) of nutrient management i.e., T₁.

The higher maize grain yield is attributed to greater values of the yield components i.e., grain weight cob⁻¹ (133.6 g), cob length (16.7 cm), grain rows cob⁻¹ (14.2), grains cob⁻¹ (452) and test weight (29.6 g) recorded in T₈ treatment (Table 1). Increase in the values of yield components was to an extent of 27 % for the grains weight cob⁻¹, 10.6 % for the cob length, 7.6 % for grain rows cob⁻¹, 23 % for grains cob⁻¹ and 11.2 % for 100 grain weight in T₈ treatment compared to the application of FP-75 % RRF + FYM at 1.0 t ha⁻¹ (T₁). Application of RRF + rhizosphere microbial consortia seed treatment at 8 mL kg⁻¹ of seed + ZnSO₄ and FeSO₄ at 25 kg ha⁻¹ + FYM at 2.0 t ha⁻¹ recorded significantly higher yield attributes compared to the other integrated nutrient management practices and was attributed to the higher total dry matter production and its accumulation in leaves, stem and reproductive parts (23). In addition, the growth parameters i.e. plant height, number of leaves, leaf area, leaf area index and total dry matter production also contributed to the grain yield at physiological maturity (24–26).

The increase in the values of yield and yield attributing characters is a result of better soil physical and chemical properties with greater availability of macro, micronutrients in the soil and higher microbial population and dehydrogenase activity in soil with T₈ treatment. The higher yield in T₈ treatment is also attributed to greater uptake of water and nutrients that might have resulted in greater water use efficiency. The integration of FYM improved soil organic matter and microbial diversity, while the micronutrients activated higher enzyme activation and grain development. Significantly 36 % higher WUE of 26.90 kg ha⁻¹ mm⁻¹ was recorded in T₈ treatment over T₁ treatment, thus reflecting the ability of plants to

produce more biomass and grain per unit quantity of water used (Table 1).

The higher yield and yield attributes recorded under T₈ treatment, it is attributed to the improvement in soil health parameters. The combined application of recommended fertilisers, FYM, microbial consortia and micronutrients enhanced soil organic matter content, microbial activity, nutrient cycling and nutrient availability throughout the crop growth period. The FYM application at higher rates as a source of organic carbon promoted the proliferation of beneficial soil microorganisms, which improved soil aggregation, aeration, water-holding capacity and nutrient retention. The rhizosphere microbial consortia further enhanced nutrient mobilisation through biological processes such as nutrient solubilisation, mineralisation and improved root-soil interactions. These synergistic effects produced better root growth, higher nutrient uptake and sustained nutrient supply, ultimately resulted in enhanced crop productivity (7–8, 27).

Furthermore, the integration of organic and biological nutrient sources with inorganic fertilisers has considerable potential to reduce dependency on chemical fertilisers over the time. Continuous reliance on chemical fertilisers alone often leads to nutrient imbalances, deterioration of soil physical properties and thus declining fertiliser use efficiency. Increasing cost of fertilisers and their shortage in the present situation calls for inclusion of FYM and microbial consortia that improves nutrient-use efficiency by minimising nutrient losses through leaching and fixation while enhancing nutrient availability from native soil reserves. This integrated approach sustains the maize productivity and contributes to environmental sustainability by reducing the requirement of chemical fertilisers. Therefore, INM represents a viable strategy for maintaining soil fertility, improving resource-use efficiency and achieving sustainable maize production in the Vertisols of south India.

Higher WUE is attributed to better root development as depicted in the greater values of root length, root spread and root weight, leaf area and enhanced physiological efficiency with integrated nutrient supply (Table 1). Integrated nutrient management enhanced maize yields and WUE through better root development and physiological efficiency (27). Higher yield attributes also suggest improved reproductive development and effective source-sink relationships. The synergistic effect of integrated nutrient sources ensured continuous nutrient supply during critical reproductive stages of maize thereby enhanced the grain setting and its filling thus producing higher values of yield attributes i.e., grain rows cob⁻¹ and 100-grain weight (28, 29) (Table 2).



Table 2. Yield attributes of maize as influenced by integrated nutrient management practices

Treatments	Yield attributes						
	Grain rows cob ⁻¹	Grains cob ⁻¹	Cob weight (g)	Grain weight cob ⁻¹ (g)	100-grain weight (g)	Cob length (cm)	Cob girth (cm)
T1: FP -75 % RRF + FYM at 1.0 t ha ⁻¹	13.2 ^d	367 ^e	128.33 ^e	105.0 ^e	26.63 ^c	15.1 ^c	14.1 ^a
T2: FP + <i>Rhizosphere</i> microbial consortia seed treatment at 8 mL kg ⁻¹ of seed + FYM at 1.0 t ha ⁻¹	13.4 ^{cd}	404 ^d	132.67 ^{de}	110.3 ^{de}	27.30 ^{bc}	15.4 ^c	14.4 ^a
T3: FP + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 1.0 t ha ⁻¹	13.5 ^{b-d}	410 ^d	134.67 ^{c-e}	112.0 ^d	27.33 ^{bc}	15.7 ^{bc}	14.4 ^a
T4: FP + <i>Rhizosphere</i> microbial consortia seed treatment at 8 mL kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 1.0 t ha ⁻¹	13.8 ^{a-c}	418 ^c	136.33 ^{c-e}	119.0 ^c	28.50 ^{ab}	15.6 ^{bc}	14.5 ^a
T5: RRF + FYM at 2.0 t ha ⁻¹	13.8 ^{a-c}	424 ^c	139.67 ^{b-d}	123.6 ^{bc}	29.10 ^a	15.6 ^{bc}	14.5 ^a
T6: RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 mL kg ⁻¹ of seed + FYM at 2.0 t ha ⁻¹	13.9 ^{a-c}	432 ^b	143.00 ^{bc}	126.0 ^b	29.20 ^a	16.1 ^{ab}	14.5 ^a
T7: RRF + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 2.0 t ha ⁻¹	14.0 ^{ab}	433 ^b	147.67 ^b	127.0 ^b	29.30 ^a	16.4 ^a	14.6 ^a
T8: RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 mL kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 2.0 t ha ⁻¹	14.2 ^a	452 ^a	157.00 ^a	133.6 ^a	29.60 ^a	16.7 ^a	14.8 ^a
S.Em. ±	0.17	2.0	3.05	8.7	0.45	0.19	0.33
LSD at 5 %	0.52	6.1	9.25	26.2	1.37	0.58	1.01

FP: farmers practice- 75 % Recommended rate of fertiliser (75 : 37.5 : 37.5 N : P : K kg ha⁻¹) and farmyard manure (FYM) at 1.0 t ha⁻¹ every year for maize; RRF: recommended rate of fertiliser (100 : 50 : 50 N : P : K kg ha⁻¹) and farmyard manure at 2.0 t ha⁻¹ every year for maize; WUE: water use efficiency. Means followed by the same letter (s) within a column are not significantly differed by DMRT ($p = 0.05$).

Grain yield was significantly and positively correlated with yield components and physiological traits, suggesting a strong and correlation influence of yield parameters on the yield. The grain yield was positively and perfectly correlated with WUE i.e. $r = 1.000^{**}$ thus indicating that the treatments enhancing WUE simultaneously increased the grain yield. Grain yield was highly correlated with straw yield ($r = 0.976^{**}$), harvest index ($r = 0.961^{**}$), grain weight cob⁻¹ ($r = 0.967^{**}$), cob length ($r = 0.940^{**}$) and 100-grain weight ($r = 0.950^{**}$) (Table 3). This clearly indicates that higher the biomass production, greater will be its efficiency in translocation of dry matter to the grain during reproductive stages i.e. from grain formation to the grain filling stages. This highlights the contribution of sink size and grain filling efficiency. The role of integrated nutrient inputs in improving biomass allocation, cob structure and water-use efficiency,

leading to enhanced maize grain yield (30, 31). The seed index, representing the weight of 100 seeds, is a key yield component and was highly and significantly correlated with all yield-attributing traits (Table 2 and 3). A strong positive association between seed index and grain yield components in maize (32–35).

Number of grain rows cob⁻¹ indicated strong positive correlation with number of grains cob⁻¹ ($r = 0.958^{**}$), grain weight cob⁻¹ ($r = 0.982^{**}$) and cob girth ($r = 0.936^{**}$). Even the number of grains cob⁻¹ was also positively correlated with cob length ($r = 0.901^{**}$) and cob girth ($r = 0.954^{**}$) (Table 3). This indicates that cob dimensions directly related to grain number and grain weight per cob. Grain weight cob⁻¹ was positively and highly correlated with 100 grain weight ($r = 0.983^{**}$) and thus suggests that both grain size and number contribute to heavier cobs (36, 37).

Table 3. Estimate of correlation coefficient among grain yield, yield components, water use efficiency (WUE) of rainy season maize as influenced by integrated nutrient management practices

	Grain yield (kg ha ⁻¹)	Straw yield (kg ha ⁻¹)	Harvest index	WUE (kg ha ⁻¹ mm ⁻¹)	Grain rows cob ⁻¹	Grains cob ⁻¹	Cob weight (g)	Grain weight cob ⁻¹ (g)	100-grain weight (g)	Cob length (cm)	Cob girth (cm)
Grain yield (kg ha ⁻¹)	1.000										
Straw yield (kg ha ⁻¹)	0.976**	1.000									
Harvest index	0.961**	0.879**	1.000								
WUE (kg ha ⁻¹ mm ⁻¹)	1.000**	0.976**	0.961**	1.000							
Grain rows cob ⁻¹	0.966**	0.943**	0.931**	0.966**	1.000						
Grains cob ⁻¹	0.926**	0.945**	0.848**	0.926**	0.958**	1.000					
Cob weight (g)	0.923**	0.912**	0.862**	0.923**	0.951**	0.908**	1.000				
Grain weight cob ⁻¹ (g)	0.967**	0.948**	0.928**	0.967**	0.982**	0.948**	0.949**	1.000			
100-grain weight (g)	0.950**	0.921**	0.932**	0.950**	0.954**	0.923**	0.879**	0.983**	1.000		
Cob length (cm)	0.940**	0.941**	0.860**	0.940**	0.926**	0.901**	0.969**	0.906**	0.831*	1.000	
Cob girth (cm)	0.866**	0.856**	0.821*	0.866**	0.936**	0.954**	0.926**	0.897**	0.838**	0.907**	1.000

*, significant at 5 %, **: significant at 1 %.

Significantly higher gross and net returns of ₹212469 ha⁻¹ and ₹137239 ha⁻¹ were recorded in RRF + rhizosphere microbial consortia seed treatment at 8 mL kg⁻¹ of seed + ZnSO₄ and FeSO₄ at 25 kg ha⁻¹ + FYM at 2.0 t ha⁻¹ (T₈) compared to other treatments, wherein the synergistic interactions among RRF, microbial inoculation, FYM and micronutrients facilitated improved nutrient uptake and augmented crop productivity (Table 4). The net returns in (T₈) were on par with T₆ i.e. ₹134726 ha⁻¹ and T₇ i.e., ₹133560 ha⁻¹. The greater gross and net returns in T₈ treatment compared to other treatments are attributed to higher grain and straw yields. The B : C ratio a critical measure of economic viability. The T₄ treatment produced greater B : C of 2.99 and was on par with other treatments except T₁ (2.70) and T₅ (2.66) treatments. The economic evaluation demonstrates that integrated nutrient management practices especially low cost biological and micronutrient inputs are financially viable and the additional expenditure invested on these inputs justified by the higher maize production. Earlier researchers recorded similar economic advantages of combining fertilisers with organic manures, beneficial microorganisms and micronutrients that produced higher net returns and improved B : C ratio under integrated nutrient management systems compared to conventional fertiliser practices (38–40).

4. Conclusion

This study emphasises the significant role of integrated nutrient management (INM) in optimising and sustaining the productivity and water use efficiency of maize (*Zea mays*) cultivated in the Vertisols of the southern India. Integrated application

of 100 % RRF + rhizosphere microbial consortia seed treatment at 8 mL kg⁻¹ seed + ZnSO₄ and FeSO₄ at 25 kg ha⁻¹ each + FYM at 2.0 t ha⁻¹ produced the higher grain yield of 8006 kg ha⁻¹, straw yield of 7044 kg ha⁻¹, water use efficiency of 26.90 kg ha⁻¹ mm⁻¹ with and greater values of yield attributes. The synergistic effect of balanced chemical fertilisers, organic inputs, beneficial microbes and micronutrients contributed for improved nutrient uptake, root development and source-sink dynamics.

Grain yield in rainy season maize is closely associated with water use efficiency (WUE), harvest index and yield-attributing traits, particularly cob morphology and grain weight plant⁻¹. The INM practices significantly improved physiological and structural traits thus resulting in higher productivity. The findings of this study indicate the importance of integrated nutrient management strategies that combine organic and inorganic nutrient sources along with microbial consortium to enhance maize performance in resource-limited environments. The farmers with low input availability can apply 75 % recommended rate of macro and micronutrient fertiliser with rhizosphere consortium whereas the farmers who are interested in higher returns with improved and sustainable soil and crop productivity can adopt 100 % recommended rate of macro and micronutrient fertiliser with rhizosphere consortium. Future breeding and management programs should focus on optimising WUE, cob traits and nutrient use efficiency to sustainably increase maize productivity. Thus, the integrated nutrient management approach is recommended for sustainable yield enhancement and efficient resource use in maize cultivation under rainfed Vertisols in the South India.



Table 4. Economics of maize as influenced by integrated nutrient management

Treatments	Economics			
	Cost of Cultivation (₹ ha ⁻¹)	Gross returns (₹ ha ⁻¹)	Net returns (₹ ha ⁻¹)	B : C ratio
T ₁ : FP- 75 % RRF + FYM at 1.0 t ha ⁻¹	57008 ^e	154230 ^d	97223 ^d	2.70 ^b
T ₂ : FP + <i>Rhizosphere</i> microbial consortia seed treatment at 8 mL kg ⁻¹ of seed + FYM at 1.0 t ha ⁻¹	58487 ^e	167439 ^{cd}	108952 ^{cd}	2.86 ^{ab}
T ₃ : FP + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 1.0 t ha ⁻¹	61567 ^d	174264 ^{cd}	112697 ^{b-d}	2.83 ^{ab}
T ₄ : FP + <i>Rhizosphere</i> microbial consortia seed treatment at 8 mL kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 1.0 t ha ⁻¹	62949 ^d	188099 ^{a-c}	125150 ^{a-c}	2.99 ^a
T ₅ : RRF + FYM at 2.0 t ha ⁻¹	69793 ^c	185962 ^{bc}	116169 ^{a-d}	2.66 ^b
T ₆ : RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 mL kg ⁻¹ of seed + FYM at 2.0 t ha ⁻¹	71928 ^b	206654 ^{ab}	134726 ^{ab}	2.87 ^{ab}
T ₇ : RRF + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 2.0 t ha ⁻¹	74471 ^a	208031 ^{ab}	133560 ^{ab}	2.79 ^{ab}
T ₈ : RRF + <i>Rhizosphere</i> microbial consortia seed treatment at 8 mL kg ⁻¹ of seed + ZnSO ₄ and FeSO ₄ at 25 kg ha ⁻¹ + FYM at 2.0 t ha ⁻¹	75230 ^a	212469 ^a	137239 ^a	2.82 ^{ab}
S.Em. ±	692	7904	7247	0.08
LSD at 5 %	2100	23972	21978	0.24

FP: farmers practice -75 % Recommended rate of fertiliser (75 : 37.5 : 37.5 N : P : K kg ha⁻¹) and farmyard manure (FYM) at 1.0 t ha⁻¹ every year for maize; RRF: recommended rate of fertiliser (100 : 50 : 50 N : P : K kg ha⁻¹) and farmyard manure at 2.0 t ha⁻¹ every year for maize; WUE: water use efficiency. Means followed by the same letter (s) within a column are not significantly differed by DMRT ($p = 0.05$).

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Authors' contributions

VBB and PSL contributed to conceptualisation and literature collection. PSL contributed to supervision and visualisation. VBB, PSL, PCR and SBG contributed to writing original draft. PSL, PCR and SBG contributed to writing review and editing. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

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