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Response of maize yield, nutrient concentration and total uptake to integrated inorganic and biofertilizer applications in black soils

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Abstract

A field experiment entitled "Effect of inorganic and biofertilizers on yield, nutrient content and uptake of maize in black soils" was conducted at Agricultural College Farm, Bapatla, during *rabi*, 2025- 2026. The experiment was conducted in randomized block design (RBD) with ten treatments in three replications. The treatments consisted of T₁- absolute control; T₂- 50% RDF+PSB; T₃- 50% RDF+ PSB + VAM; T₄- 50% RDF + PSB + VAM + KRB; T₅- 75% RDF +PSB; T₆- 75% RDF + PSB + VAM; T₇- 75% RDF + PSB + VAM + KRB; T₈- 100% RDF +PSB; T₉- 100% + PSB + VAM and T₁₀- 100% + PSB + VAM + KRB. Among the treatments, the combined application of 100% RDF + PSB + VAM + KRB (T₁₀) produced the highest yield, as well as higher nutrient content and uptake. The performance of yield and macro nutrient content and uptake was statistically on par with T₉ (100% RDF + PSB + VAM) and T₇ (75% RDF + PSB + VAM + KRB), but micro nutrients were non significantly influenced by imposed treatments at both knee high and harvest stage of maize. The findings indicate that integrating biofertilizers with the recommended dose of inorganic fertilizers enhanced nutrient accumulation and nutrient uptake, resulting in improved crop performance.

Keywords: Maize, Black soils, inorganic fertilizers, biofertilizers, recommended dose of fertilizers (RDF)

Introduction

Maize (*Zea mays* L.) is an important cereal crop grown across a wide range of agro-climatic regions because of its high adaptability and productivity (Navya Sree *et al.*, 2026) ^[16]. Owing to its superior genetic yield potential, it is widely referred to as the "Queen of Cereals." Worldwide, maize is cultivated on approximately 190 million hectares in nearly 166 countries. In India, it ranks as the third most important cereal after rice and wheat and contributes nearly 9 per cent to the country's food grain basket. Besides serving as a staple food, maize is an important source of quality livestock feed and a valuable raw material for numerous industries. It is extensively used in the manufacture of starch, edible oil, protein products, sweeteners, alcoholic beverages, pharmaceuticals, cosmetics, textiles, paper, packaging materials, gums and several other industrial products (Diya Vincent *et al.*, 2025) ^[3]. Maize is successfully cultivated under both tropical and temperate conditions, and its productivity largely depends on the use of high-yielding hybrids supported by efficient nutrient management, particularly nitrogen fertilization (Kumar *et al.*, 2020) ^[9]. According to Chen, 2006 ^[2] reported that inoculation of beneficial microorganisms can reduce the dependence on chemical fertilizers by improving nutrient availability and uptake. Biofertilizers enhance soil fertility, promote plant growth and contribute to sustainable crop production by improving nutrient-use efficiency and maintaining soil health. Integrated application of inorganic fertilizers and biofertilizers has been reported to increase the concentration

and uptake of nutrient in both grain and stover of maize. The improved nutrient uptake is mainly attributed to better root development, enhanced microbial activity and increased nutrient availability in the rhizosphere. Biofertilizers contain beneficial microorganisms that facilitate nutrient solubilization, mobilization and biological transformations, thereby improving nutrient absorption by plants. Since nitrogen, phosphorus and potassium are essential macronutrients for crop growth and development, an adequate supply of these nutrients through integrated nutrient management helps achieve balanced nutrition, higher productivity and sustained soil fertility.

Biofertilizers such as phosphate-solubilizing bacteria (PSB), potassium-releasing bacteria (KRB) and vesicular arbuscular mycorrhiza (VAM) play an important role in improving nutrient availability in the soil. PSB converts insoluble phosphorus into forms that are readily available to plants, while KRB releases potassium from insoluble potassium-bearing minerals. VAM enhances the uptake of phosphorus and other essential nutrients through its extensive hyphal network. Together, these beneficial microorganisms improve nutrient availability and uptake by crops. A considerable proportion of the nitrogen and phosphorus applied through inorganic fertilizers becomes unavailable to plants because of fixation by iron and aluminium oxides present in the soil. This reduces fertilizer use efficiency and increases production costs. The rising cost of chemical fertilizers has further highlighted the need to improve nutrient-use efficiency by mobilizing fixed soil nutrients. Therefore,

integrating biofertilizers such as PSB, KRB and VAM with inorganic fertilizers is considered a sustainable strategy to enhance nutrient availability, improve crop productivity and reduce dependence on chemical fertilizers.

Materials and Methods

A field experiment was carried out during *rabi*, 2025-2026 at Agricultural College Farm, Bapatla. Geographically located at an altitude of 5.49 m above mean sea level, 15 ° 92' North latitude, 80°48' East longitude and about 8 km away from Bay of Bengal. It is located in Krishna agro-climatic zone of Andhra Pradesh. The experiment was laid out in randomized block design (RBD) with ten treatments and replicated thrice. The experimental treatment details are as following T₁- absolute control; T₂- 50% RDF +PSB; T₃- 50% RDF+ PSB + VAM; T₄- 50% RDF + PSB + VAM + KRB; T₅- 75% RDF +PSB; T₆- 75% RDF + PSB + VAM; T₇- 75% RDF + PSB + VAM + KRB; T₈- 100% RDF +PSB; T₉- 100% + PSB + VAM and T₁₀- 100% + PSB + VAM + KRB. RDF for maize 280:85:80 kg ha⁻¹ N, P₂O₅ and K₂O through applied Urea, Single super phosphate and Muriate of potash and biofertilizers like VAM -12.5 kg ha⁻¹, PSB and KRB 1.25 litres ha⁻¹ through applied FYM. The maize hybrid PAC 751 was chosen for the study. Plant samples of maize was collected from five randomly selected plants at knee high stage and harvest. The samples were first dried in shade and then in hot air oven at 65 °C. The plant samples were ground in willey mill and stored in labeled brown paper bags for analysis. The grain samples were also processed and stored in similar fashion. Nitrogen content in plant samples was determined by micro Kjeldahl method. Di-acid extract was prepared as per the method outlined by Jackson. It was carried out using a 9:4 mixture of HNO₃: HClO₄. The pre digestion of sample was done by using 10ml of HNO₃ g⁻¹ sample. This di-acid extract was used to determine P, K and micro nutrient content in the plant and grain samples. Phosphorus in the diacid extract of plant samples was estimated by vanadomolybdo phosphoric yellow colour method using spectrophotometer at 420 nm wave length. Potassium in the diacid extract of plant samples was determined using flame photometer as per the method described by Jackson^[5]. Iron, manganese, copper and zinc in the diacid extract were determined using atomic absorption spectrophotometer as per the specifications mentioned by Lindsay and Norvell, 1978^[12]. The data on various parameters was statistically analysed by using Fisher's method of analysis of variance as suggested by Panse and Sukhatme, 1978^[18] for the randomized block design adopted in this study. Statistical significance was tested by applying F-test at 0.05 level of probability. Critical differences at 0.05 levels were worked out for the effects, which were significant.

From the chemical analytical data, uptake of the macro nutrients and micro nutrient at knee high stage and harvest of the maize crop was calculated and expressed by using the formulae.

$$\text{Macronutrient uptake (kg ha}^{-1}\text{)} = \frac{\text{Nutrient content (\%)} \times \text{dry weight in kg ha}^{-1}}{100}$$

$$\text{Micronutrient uptake (kg ha}^{-1}\text{)} = \frac{\text{Nutrient content (\%)} \times \text{dry weight in kg ha}^{-1}}{1000}$$

Results and Discussion

Yield (kg ha⁻¹)

Data pertaining to kernel and stover yield of the maize was assessed and the data was presented in Table1. The results indicated that the application of inorganic and biofertilizers showed a significant effect on kernel and stover yield.

Kernel yield (kg ha⁻¹)

The maximum kernel yield of 6553 kg ha⁻¹ was recorded significantly in treatment T₁₀ with the application of 100%RDF + PSB + VAM + KRB which was at par with treatments T₉ (100% RDF + PSB + VAM) (6128 kg ha⁻¹) and T₇ (75% RDF + PSB + VAM + KRB) (9010 kg ha⁻¹), which was significantly superior over the rest of the treatments. The lowest kernel yield was observed in the treatment T₁ (absolute Control) with 6884 kg ha⁻¹ which received no fertilizers during crop growth period. The combined application of inorganic and biofertilizers significantly enhanced Kernel yield of maize. The application of biofertilizers improved the fertilizer use efficiency by increasing the availability of nutrients through enhanced microbial activity in the rhizosphere. These microorganisms promote mineralization of organic matter and facilitate the gradual release of essential nutrients and make them readily available to plants throughout the crop growth period, in addition to this biofertilizers such as VAM improve the root growth which enables the crop to explore a larger volume of soil for nutrient and water uptake. This results in better plant vigour and higher productivity. Gundlur *et al.* (2015)^[4] and Tomar *et al.* (2017)^[20] reported that the combined application of inorganic and biofertilizers enhanced the grain yield, due to the efficient nutrient utilization and improved yield attributes, which collectively contributed to increased productivity. The higher availability of N, P, and K in the soil due to balanced nutrient management showed a significant positive effect, which is in agreement with the findings of Nayak *et al.* (2020)^[17].

Stover yield (kg ha⁻¹)

The highest stover yield of maize was recorded significantly in the treatment T₁₀(100%RDF + PSB + VAM + KRB) with 11662 kg ha⁻¹ which was found to be at par with treatments T₉ (100%RDF+ PSB + VAM) (8367kg ha⁻¹) and T₇(75% RDF + PSB + VAM + KRB) (8264 kg ha⁻¹), while the lowest stover yield of 8512 kg ha⁻¹ was observed in the treatment T₁(absolute control).The increased stover yield might be due to higher nitrogen availability to the crop through combined application of inorganic and biofertilizers, which promoted the vigorous vegetative growth among the biofertilizers, PSB plays an important role in increasing phosphorus availability in the soil, as it enhances phosphorus uptake and improves several physiological and biochemical processes, including photosynthesis, energy transfer, carbohydrate metabolism, starch synthesis and improving overall crop productivity. Similar findings were reported by Tomar *et al.* (2017)^[20].

Nutrient Content

Nitrogen content (%)

In the present study, the nitrogen content was assessed during knee high and harvest stages and the data pertaining to nitrogen content presented in the Table 2 The results indicated that the application of inorganic and biofertilizers

showed a significant difference on nitrogen content at both knee high and harvest stage. The application of 100% RDF + PSB + VAM + KRB in treatment T₁₀ recorded significantly the highest nitrogen content of 2.59% which was found to be at par with the treatments T₉ (100% RDF+ PSB + VAM) (2.53%) and T₇ (75% RDF + PSB + VAM + KRB) (2.47%). These treatments were found to be significantly superior over the rest of the treatments. The minimum nitrogen content of 1.76% was observed in the treatment T₁ (absolute control) at knee high stage of the crop. The highest nitrogen content was recorded significantly in kernel and stover in the treatment T₁₀ (100%RDF + PSB + VAM + KRB) (1.96% and 0.92%) which was found to be at par with the T₉ (100%RDF+ PSB + VAM) (1.91% and 0.86%) and T₇(75% RDF + PSB + VAM + KRB) (1.83% and 0.81%) treatments in kernel and stover respectively and the lowest nitrogen content was observed in treatment T₁ (absolute control) with 1.35% and 0.41%. Significantly higher nitrogen content was observed in the treatments having combined application of biofertilizers with inorganic fertilizers as compared to control treatment. It might due to combined application inorganic fertilizers and biofertilizers which supplied nutrients readily during the early stages of crop growth, whereas nutrients from organic sources became available gradually through microbial decomposition and mineralization. This continuous release of nutrients throughout the crop growth period ensured a sustained nutrient supply, resulting in better nutrient uptake and improved crop performance. The results obtained in the present study are consistent with the observations of Khatana *et al.* (2021) [7]. According to the combined application of chemical fertilizers (100% NPK) and biofertilizers might improve soil fertility and crop productivity. The enhanced performance is attributed to the synergistic effect of integrated nutrient sources, where inorganic fertilizers provided essential nutrients, particularly nitrogen, while biofertilizers enhanced nutrient availability and use efficiency, resulting in improved crop growth and productivity.

Phosphorus content (%)

In the present study, the phosphorus content was assessed during knee high stage and harvest and the data pertaining to phosphorus content presented in the Table 2. The results indicated that the application of inorganic and biofertilizers showed a significant difference on content of phosphorus at both knee high and harvest stages. The highest phosphorus content was recorded significantly in the treatment T₁₀ (100%RDF + PSB + VAM + KRB) with 0.62% which was found to be at par with the T₉ (100%RDF+ PSB + VAM) (0.57%) and T₇ (75% RDF + PSB + VAM + KRB) (0.53%) treatments. These treatments were found to be significantly superior over the rest of the treatments. The lowest phosphorus content of 0.23% was observed in the treatment T₁ (absolute control) at knee high stage. The highest content of phosphorus in kernel and stover was recorded significantly in the treatment T₁₀ (100%RDF + PSB + VAM + KRB) with 0.41% and 0.26% which was found to be at par with the treatments T₉ (100%RDF+ PSB + VAM) (0.37% and 0.23%) and T₇ (75% RDF + PSB + VAM + KRB) (0.33%, 0.21%) and lowest phosphorus content was observed in treatment T₁ (absolute control) with 0.17% and 0.06% respectively. Significantly higher P content was observed in the treatments

having combined application of biofertilizers with inorganic fertilizers as compared to control treatment. The phosphorus content in maize straw gradually declined from the knee-high stage to harvest, whereas the P concentration in grain was higher than in straw at harvest. This might be due to the movement of phosphorus from vegetative plant parts to the kernels during the grain-filling period. The application of inorganic fertilizers along with phosphate-solubilizing biofertilizers increased the availability of phosphorus in the soil through enhanced solubilization of native and applied phosphorus. This improved phosphorus availability promoted greater absorption by the root system, resulting in higher phosphorus concentration in the plant. Furthermore, the combined use of inorganic fertilizers with biofertilizers such as VAM and PSB created a favourable rhizosphere environment, which enhanced phosphorus uptake and accumulation in both straw and grain. Phosphate-solubilizing microorganisms increase phosphorus availability by converting insoluble phosphate compounds into forms that can be readily absorbed by plants through the secretion of organic acids and phosphatase enzymes. The enhanced microbial activity in the rhizosphere promotes phosphorus solubilization and mineralization, resulting in improved phosphorus availability and uptake by the crop reported by Marlina *et al.* (2017) [13].

Potassium content (%)

In the present study, the content of potassium was assessed at knee high stage and harvest the data pertaining to content of potassium was presented in the Table 2. The results indicated that the application of inorganic and biofertilizers showed a significant difference on content of potassium at both knee high and harvest stages. The potassium content was recorded significantly the highest in the treatment T₁₀(100%RDF + PSB + VAM + KRB) with 2.84% and it was found to be at par with the T₉ (100%RDF+ PSB + VAM) (2.76%) and T₇(75% RDF + PSB + VAM + KRB) (2.71%) at knee high stage. The lowest potassium content of 2.11% was observed in the treatment T₁ (Control). The highest potassium content in kernel and stover was recorded significantly in the treatment T₁₀(100%RDF + PSB + VAM + KRB) with 0.56% and 2.37% which was found to be at par with the T₉(100%RDF+ PSB + VAM) (0.53%, 2.35%) and T₇(75% RDF + PSB + VAM + KRB) (0.48%, 2.31%), while the lowest potassium content was observed in treatment T₁(Control) (0.19% and 1.69%). Significantly higher potassium content was observed in the treatments having combined application of biofertilizers with inorganic fertilizers as compared to control treatment. The highest potassium content was recorded at the knee-high stage in all treatments, after which it decreased as the crop advanced through its growth stages. This decline might be due to the dilution effect resulting from increased drymatter accumulation and the translocation of potassium from vegetative tissues to developing plant parts during the crop growth period. Potassium content in the grain was less compared the straw, indicates that a larger proportion of the absorbed potassium was retained in the vegetative tissues. The combined application of biofertilizers and recommended inorganic fertilizers improved potassium availability in the soil, which resulted in greater potassium uptake by maize. The enhanced availability of potassium under integrated

nutrient management may be attributed to improved nutrient mobilization in the rhizosphere and better root development, enabling the crop to absorb potassium more efficiently throughout its growth period. The integrated use of inorganic and biofertilizers along with organic sources improved microbial activity in the soil, which facilitated the release of potassium from its non-exchangeable sites into the soil solution. The increased availability of potassium enhanced its uptake by maize and contributed to better crop growth. Similar observations were reported by Gundlur *et al.* (2015) [4].

Iron content (mg kg⁻¹)

The results revealed that, different levels of fertilizers and biofertilizer treatments applied to maize has a non-significant influence on iron content. Irrespective of the growth stages of maize application of 100% RDF + PSB + VAM + KRB (T₁₀) (113, 46.5 and 64.7 mg kg⁻¹) recorded numerically higher iron content at knee high and harvest (stover and grain) stages of maize crop growth, respectively. The lowest iron content was recorded with the treatment T₁ (83.3, 31.1 and 41.2 mg kg⁻¹). The slight increase in iron (Fe) content at all crop growth stages might due to the combined application of biofertilizers and inorganic fertilizers. However, the integrated use of inorganic fertilizers along with biofertilizers did not exert a significant influence on the iron content of maize. Irrespective of the year of study, the Fe content gradually declined from the knee-high stage to the harvest stage, indicating a reduction in iron concentration as the crop advanced through its growth.

Manganese content (mg kg⁻¹)

The results revealed that, different levels of fertilizers and biofertilizer treatments applied to maize has a non-significant influence on manganese content. Irrespective of the growth stages of maize application of 100% RDF + PSB + VAM + KRB (T₁₀) (58.3, 16.1 and 30.0 mg kg⁻¹) recorded numerically higher manganese content at knee high and harvest (stover and grain) stages of maize crop growth, respectively. The lowest manganese content was recorded with the treatment T₁ (36.7, 10.3 and 20.4 mg kg⁻¹). The results of the present study revealed that the integrated application of biofertilizers and inorganic fertilizers recorded numerically higher manganese (Mn) content compared to the control treatment. However, the combined application of biofertilizers with inorganic fertilizers did not exert a significant influence on Mn content. Irrespective of the year of study, the Mn content in maize straw decreased progressively from the knee-high stage to harvest, which may be attributed to the dilution effect associated with increased biomass production. Furthermore, the considerable variation in Mn concentration between straw and grain could be due to the limited translocation of Mn from the vegetative parts to the developing grains.

Copper content (mg kg⁻¹)

The results revealed that, different levels of fertilizers and biofertilizer treatments applied to maize has a non-significant influence on copper content (Table 3). Irrespective of the growth stages of maize application of 100% RDF + PSB + VAM + KRB (T₁₀) (16.5, 10.5 and 13.2 mg kg⁻¹) recorded numerically higher copper content at knee

high and harvest (kernel and stover) stages of maize crop growth, respectively. The lowest copper content was recorded with the treatment T₁ (11.1, 7.33 and 9.50 mg kg⁻¹). The findings of the present investigation indicated that the integrated application of biofertilizers and inorganic fertilizers resulted in a numerically higher copper (Cu) content than the control treatment. However, the combined application of inorganic fertilizers and biofertilizers did not exert a statistically significant effect on copper content. Irrespective of the treatments, copper concentration declined as the crop progressed from the knee-high stage to harvest. At harvest, the copper content was higher in the stover than in the grain across all the treatments, indicating greater accumulation of Cu in the vegetative parts of the maize crop.

Zinc content (mg kg⁻¹)

The results revealed that, different levels of fertilizers and biofertilizer treatments applied to maize has a non-significant influence on zinc content (Table 3). Irrespective of the growth stages of maize application of 100% RDF + PSB + VAM + KRB (T₁₀) (38.4, 33.2 and 36.0 mg kg⁻¹) recorded numerically higher zinc content at knee high and harvest (kernel and stover) stages of maize crop growth, respectively. The lowest zinc content was recorded with the treatment T₁ (30.7, 22.5 and 24.3 mg kg⁻¹). The combined application of inorganic fertilizers and biofertilizers resulted in a slight increase in zinc concentration, which may be attributed to the formation of zinc-organic complexes that enhanced zinc availability and facilitated its uptake by maize plants. However, the differences among the treatments were statistically non-significant. Across the crop growth stages, zinc concentration gradually declined from the knee-high stage to tasseling, which could be attributed to the dilution effect associated with increased biomass production. Furthermore, the zinc concentration was lower in the grain than in the stover. The reduction in zinc concentration with crop advancement may be due to its greater utilization in the synthesis of growth-regulating substances and its involvement in reproductive development and grain formation.

Nutrient Uptake

Nitrogen uptake (kg ha⁻¹)

Data pertaining to nitrogen uptake by maize crop at knee high stage and harvest is presented in table 4. The treatments showed significant effect on N uptake at both the stages of crop growth. At knee high stage significantly the highest nitrogen uptake of 48.7 kg ha⁻¹ by maize was recorded with the application of 100% RDF + PSB + VAM + KRB in the treatment T₁₀ and it was at par with treatments T₉ (100% RDF + PSB + VAM) (43.6 kg ha⁻¹) and T₇ (75% RDF + PSB + VAM + KRB) (42.7 kg ha⁻¹). Significantly lowest nitrogen uptake of 18.8 kg ha⁻¹ was recorded in the control treatment (T₁), where no nutrient sources were applied. The poor nitrogen uptake in the control treatment may be attributed to inadequate nutrient availability, which restricted plant growth and drymatter production. At harvest, significantly the highest nitrogen uptake of 128 and 79 kg ha⁻¹ was recorded in both the kernel and stover with the application of 100% RDF + PSB + VAM + KRB) the treatment T₁₀ and it was found to be at par with the treatments T₉ (100% RDF + PSB + VAM) (117 & 71.9 kg ha⁻¹) and T₇ (75% RDF + PSB

+ VAM + KRB) (110&67 kg ha⁻¹), while significantly lowest nitrogen uptake was observed in treatment T₁(absolute control) (52.4 & 22.5 kg ha⁻¹) in both the kernel and stover. Irrespective of the treatment, nitrogen uptake increased progressively with the advancement of crop growth from the knee-high stage to harvest. The highest uptake was recorded at harvest, because continuous nutrient absorption throughout the crop growth period, which led to higher quantity of nitrogen accumulated in both grain and straw. The increase in nitrogen uptake with crop age is mainly associated with greater drymatter production and increased nutrient demand during the reproductive phase of the crop. The higher nitrogen uptake observed under integrated nutrient management practices might be due to the combined effect of inorganic fertilizers and biofertilizers which helps in improving nitrogen availability throughout the crop growth period. Adequate nutrient supply improves the root growth which increases nutrient absorption and enhanced biomass production, it results in higher nitrogen accumulation in plant tissues. Similar observations were reported by Chaudhary *et al.* (2020)^[1].

Phosphorus uptake (kg ha⁻¹)

Data pertaining to P uptake by maize crop at knee high and harvest stages are presented in table 4. The treatment shows the significant effect on P uptake at both the stages of crop growth. The highest phosphorus uptake of 11.6 kg ha⁻¹ was recorded significantly highest in maize with the application of 100% RDF + PSB + VAM + KRB in the treatment T₁₀ which was at par with treatments T₉ (100% RDF + PSB + VAM) (9.82 kg ha⁻¹) and T₇ (75% RDF + PSB + VAM + KRB) (9.15 kg ha⁻¹) at knee high stage. The lowest phosphorus uptake of 2.51 kg ha⁻¹ was recorded in the treatment T₁ (absolute control), where no nutrient sources were applied. Among the treatments the highest phosphorous uptake of 26.8 and 22.6 kg ha⁻¹ was recorded in both the kernel and stover with the application of 100%RDF + PSB + VAM + KRB in the treatment T₁₀which was found to be at par with the treatments T₉ (100%RDF+ PSB + VAM) (22.4 & 193 kg ha⁻¹) and T₇ (75% RDF + PSB + VAM + KRB) (19.8 & 17.5 kg ha⁻¹), while significantly lowest P uptake was observed in treatment T₁ (absolute control) (6.63 & 3.32 kg ha⁻¹) in both the kernel and stover. The combined application of inorganic fertilizers with biofertilizers such as phosphate-solubilizing bacteria (PSB) and vesicular-arbuscular mycorrhiza (VAM), enhanced phosphorus availability by converting insoluble forms of phosphorus into plant-available forms and improving its uptake through better root growth and increased root surface area. This resulted in higher phosphorus accumulation in the plant. In contrast, the lowest phosphorus uptake recorded in the control was mainly due to limited phosphorus availability, which restricted root development, reduced plant growth and ultimately limited phosphorus absorption by the crop. The increased phosphorus uptake might be due to greater phosphorus availability in the soil and improved root growth by PSB, which facilitated enhanced availability of phosphorus and better nutrient absorption. Similar findings were reported by Jat *et al.* (2018)^[6].

Potassium uptake (kg ha⁻¹)

The data presented in table 4 showed that potassium uptake by maize was significantly influenced by the different

nutrient management practices. Potassium uptake increased with the application of inorganic fertilizers in combination with biofertilizers compared to the control at all stages of crop growth. Among all the treatments the highest potassium uptake was 53.2 kg ha⁻¹ recorded with the application of 100% RDF + PSB + VAM + KRB in the treatment T₁₀which was at par with treatments T₉ (100% RDF + PSB + VAM) (47.9 kg ha⁻¹) and T₇ (75% RDF + PSB + VAM + KRB) (46.6 kg ha⁻¹) at knee high stage. The lowest potassium uptake of 22.4 kg ha⁻¹ was recorded in the treatment T₁ (absolute control), where no nutrient sources were applied. The highest potassium uptake of 36.6 and 205 kg ha⁻¹ was recorded in both the kernel and stover with the application of 100%RDF + PSB + VAM + KRB in the treatment T₁₀ which was found to be at par with the treatments T₉ (100%RDF+ PSB + VAM)(32.4 & 196 kg ha⁻¹) and T₇ (75% RDF + PSB + VAM + KRB) (28.8 & 190 kg ha⁻¹), and the minimum potassium uptake was observed in treatment T₁(absolute control) (7.42 & 93.1 kg ha⁻¹) in both the kernel and stover. The combined application of inorganic fertilizers with PSB, VAM and KRB enhanced root growth and increased the efficiency of nutrient absorption. In particular, potassium-releasing bacteria (KRB) helped solubilize potassium from unavailable soil minerals into plant available forms, while VAM improved the effective root surface area for nutrient absorption reported by Lasya *et al.* (2018)^[11]. The enhanced potassium uptake may be attributed to the synergistic effect of PSB and KRB on root development. The release of organic acids by the fungus increases the availability of native soil potassium by solubilizing K-bearing minerals, thereby improving potassium uptake by plants. Improved soil physical properties may have further facilitated nutrient absorption and contributed to higher potassium uptake. Bio-inoculant application enhances root growth and increases potassium availability in the rhizosphere through potassium solubilization, thereby improving potassium uptake by plants.

Iron uptake (g ha⁻¹)

The data was presented in table 5 and it shows that significantly higher Fe uptake was recorded in the treatment T₁₀ that received 100% RDF + PSB + VAM + KRB (213,305 and 561 g ha⁻¹) and it was on par with the treatments T₉ and T₇ at knee high and harvest (kernel and stover) stages of maize the lowest iron uptake was recorded with the treatment (T₁) control (87.6, 120 and 227g ha⁻¹). The increased uptake of cationic micronutrients following the integrated application of biofertilizers, organic manures, and inorganic fertilizers may be attributed to enhanced mineralization and the release of organic acids during decomposition. These organic acids facilitate the solubilization of otherwise unavailable micronutrient compounds in the soil, thereby improving their availability to plants. In addition, naturally occurring chelating substances released during organic matter decomposition form stable complexes with micronutrient cations, protecting them from fixation, precipitation, oxidation, and leaching losses. This enhances the availability and subsequent uptake of micronutrients by maize plants. Similar observations were reported by Gogoi *et al.*, who noted improved micronutrient uptake under integrated nutrient management practices. Furthermore, the application of biofertilizers significantly enhanced the uptake of both macro- and micronutrients by improving nutrient

solubilization, root growth, and microbial activity in the rhizosphere. These findings are in agreement with the results of Mohammadi *et al.*, 2020^[14]; who reported that biofertilizers increase nutrient availability and promote greater nutrient uptake by crops.

Manganese uptake (g ha⁻¹)

Among all the treatments, the highest Mn uptake in plant was recorded in the treatment T₁₀ i.e., 100% RDF + PSB + VAM + KRB (109, 106 and 260 g ha⁻¹) and it was on par with the treatments T₉ and T₇ at knee high and harvest (kernel and stover) stages of maize (Table 5). The lowest manganese uptake was recorded with the treatment T₁ (38.7, 40.6 and 112 g ha⁻¹). The combined application of inorganic fertilizers and biofertilizers might have enhanced the availability of manganese (Mn) in the soil, resulting in greater Mn uptake by maize plants. The improved uptake can be attributed to the beneficial effects of biofertilizers in increasing nutrient solubilization, stimulating microbial activity, and promoting root growth, thereby improving nutrient acquisition. Moreover, Mn uptake increased progressively with the advancement of crop growth stages. The substantially higher dry matter accumulation, grain and stover yields, and Mn concentration observed at harvest contributed to significantly greater Mn uptake during the later stages of crop growth.

Copper uptake (g ha⁻¹)

The results revealed that Cu uptake at different stages of maize was significantly influenced by different treatments imposed during both the years study (Table 5). The highest Cu uptake by the plant was recorded in the treatment i.e., 100% RDF + PSB + VAM + KRB (31.3, 69.3 and 115 g ha⁻¹) and it was on par with the treatments T₉ and T₇ at knee high and harvest (kernel and stover) stages of maize (Table 3.12). The lowest manganese uptake was recorded with the treatment T₁ (11.7, 28.6 and 52.5 g ha⁻¹). The combined application of inorganic fertilizers and biofertilizers might have enhanced the availability of copper (Cu) in the soil, thereby increasing its uptake by maize plants. Copper uptake gradually increased from the vegetative stage to harvest, indicating greater nutrient absorption with crop growth. Adequate Cu availability during the vegetative phase plays an important role in chlorophyll synthesis, which is essential for photosynthesis, and promotes vigorous leaf, stem, and root development. Improved root growth further enhances the absorption and assimilation of micronutrients. In addition, the increased uptake of Cu may be attributed to the complexing action of biofertilizers and organic substances,

which helps prevent the precipitation and fixation of copper in the soil, thereby maintaining it in a soluble and plant-available form throughout the crop growth period.

Zinc Uptake (g ha⁻¹)

The results of the present study indicated that the combined application of inorganic fertilizers and biofertilizers enhanced zinc uptake by maize at different growth stages. Among the treatments, 100% RDF + PSB + VAM + KRB (T₁₀) recorded the highest zinc uptake of 72.3, 217 and 312 g ha⁻¹ at knee-high and harvest (Kernel and stover) stages and was statistically on par with T₉ (100% RDF + PSB + VAM) and T₇ (75% RDF + PSB + VAM + KRB). The lowest zinc uptake was observed under the absolute control (T₁) with 32.4, 87 and 134 g ha⁻¹ (Table 5). The higher zinc uptake under integrated nutrient management may be attributed to improved nutrient availability in the rhizosphere due to the synergistic effect of inorganic fertilizers and biofertilizers. The release of nutrients into the soil solution and enhanced microbial activity could have increased the availability of zinc by mobilizing it from the soil exchange complex, thereby facilitating greater root absorption. Furthermore, the improved uptake of major nutrients (N, P, and K), enhanced photosynthetic activity, and increased dry matter production promoted the accumulation and translocation of zinc from vegetative tissues to reproductive organs, resulting in higher zinc uptake at harvest. These findings are in agreement with the observations reported by Kumar *et al.*, 2020^[8]; who also reported that integrated nutrient management significantly improved micronutrient uptake in maize.

Table 1: Effect of inorganic and biofertilizers on kernel yield (kg ha⁻¹) and stover yield (kg ha⁻¹) of maize

Treatments	Yield (kg ha ⁻¹)	
	Kernel	Stover
T ₁ : Control	6884	8512
T ₂ : 50% RDF + PSB	7145	9012
T ₃ : 50% RDF + PSB + VAM	7650	9590
T ₄ : 50% RDF + PSB + VAM + KRB	8016	10016
T ₅ : 75% RDF + PSB	8362	10338
T ₆ : 75% RDF + PSB + VAM	8789	10813
T ₇ : 75% RDF + PSB + VAM + KRB	9010	11264
T ₈ : 100% RDF + PSB	8931	10929
T ₉ : 100% RDF + PSB + VAM	9128	11367
T ₁₀ : 100% RDF + PSB + VAM + KRB	9553	11662
SEm (±)	326	395
CD (0.05%)	978	1185
CV (%)	10.4	9.3

Table 2: Effect of inorganic and biofertilizers on nitrogen, phosphorus, and potassium content (%) at knee high and harvest stages of maize

Treatments	Nitrogen content (%)			Phosphorus content (%)			Potassium content (%)		
	Knee high	Harvest		Knee high	Harvest		Knee high	Harvest	
		Kernel	Stover		Kernel	Stover		Kernel	Stover
T ₁ : CONTROL	1.76	1.35	0.41	0.23	0.17	0.06	2.11	0.19	1.69
T ₂ : 50% RDF + PSB	1.84	1.42	0.49	0.29	0.21	0.09	2.18	0.23	1.78
T ₃ : 50% RDF + PSB + VAM	1.97	1.49	0.53	0.34	0.22	0.11	2.29	0.29	1.89
T ₄ : 50% RDF + PSB + VAM + KRB	2.06	1.53	0.57	0.39	0.24	0.13	2.36	0.31	1.97
T ₅ : 75% RDF + PSB	2.11	1.64	0.65	0.41	0.26	0.16	2.41	0.38	2.08
T ₆ : 75% RDF + PSB + VAM	2.31	1.71	0.73	0.45	0.29	0.17	2.53	0.42	2.17
T ₇ : 75% RDF + PSB + VAM + KRB	2.47	1.83	0.81	0.53	0.33	0.21	2.71	0.48	2.31
T ₈ : 100% RDF + PSB	2.36	1.78	0.78	0.51	0.31	0.19	2.65	0.45	2.23
T ₉ : 100% RDF + PSB + VAM	2.53	1.91	0.86	0.57	0.37	0.23	2.76	0.53	2.35
T ₁₀ : 100% RDF + PSB + VAM + KRB	2.59	1.96	0.92	0.62	0.41	0.26	2.84	0.56	2.37
S.Em (±)	0.07	0.06	0.04	0.04	0.04	0.02	0.09	0.03	0.08
CD (0.05%)	0.21	0.18	0.12	0.12	0.12	0.06	0.27	0.09	0.24
CV (%)	6.0	7.8	8.6	8.1	7.3	9.8	5.8	11.8	7.2

Table 3: Effect of inorganic and biofertilizers on iron, manganese, copper and zinc content (mg kg⁻¹) at knee high and harvest stages of maize

Treatments	Iron content (mg kg ⁻¹)			Manganese content (mg kg ⁻¹)			Copper content (mg kg ⁻¹)			Zinc content (mg kg ⁻¹)		
	Knee high	Harvest		Knee high	Harvest		Knee high	Harvest		Knee high	Harvest	
		Kernel	Stover		Kernel	Stover		Kernel	Stover		Kernel	Stover
T ₁ : CONTROL	83.3	31.1	41.2	36.7	10.3	20.44	11.1	7.33	9.50	30.7	22.5	24.3
T ₂ : 50% RDF + PSB	89.5	31.8	42.0	37.1	11.1	21.1	12.6	7.90	9.76	31.4	25.3	27.9
T ₃ : 50% RDF + PSB + VAM	91.4	33.3	45.3	38.4	11.7	23.5	12.8	8.26	9.85	33.0	27.2	29.0
T ₄ : 50% RDF + PSB + VAM + KRB	95.1	35.1	48.0	41.6	12.7	23.7	13.7	8.61	9.97	33.8	27.9	29.8
T ₅ : 75% RDF + PSB	97.0	37.1	50.0	42.3	13.6	24.0	14.3	9.15	10.3	34.0	29.0	31.0
T ₆ : 75% RDF + PSB + VAM	102	39.2	52.1	45.8	13.7	25.2	14.5	9.29	11.0	34.9	29.9	31.6
T ₇ : 75% RDF + PSB + VAM + KRB	108	45.1	56.6	50.9	15.6	27.1	15.8	10.1	12.4	36.5	31.5	33.3
T ₈ : 100% RDF + PSB	105	43.0	54.6	48.8	15.2	26.0	15.3	9.34	11.3	35.3	30.2	32.4
T ₉ : 100% RDF + PSB + VAM	110	46.0	60.1	52.7	15.9	28.4	16.0	10.3	13.0	37.7	32.1	34.6
T ₁₀ : 100% RDF + PSB + VAM + KRB	113	46.5	64.7	58.3	16.1	30.0	16.5	10.5	13.2	38.4	33.2	36.0
S.Em (±)	6.5	3.8	4.9	4.68	1.34	1.99	1.10	0.72	0.95	2.45	2.10	2.30
CD (0.05%)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	9.3	7.2	6.7	7.9	9.0	6.7	9.3	10.6	9.8	7.2	8.6	10.8

Table 4: Effect of inorganic and biofertilizers on nitrogen, phosphorus, and potassium uptake (kg ha⁻¹) at knee high and harvest stages of maize

Treatments	Nitrogen uptake (kg ha ⁻¹)			Phosphorus uptake (kg ha ⁻¹)			Potassium uptake (kg ha ⁻¹)		
	Knee high	Harvest		Knee high	Harvest		Knee high	Harvest	
		Kernel	Stover		Kernel	Stover		Kernel	Stover
T ₁ : CONTROL	18.8	52.4	22.5	2.51	6.6	3.30	22.4	7.42	93.0
T ₂ : 50% RDF + PSB	21.6	58.8	29.5	3.43	8.7	5.41	25.6	9.49	107
T ₃ : 50% RDF + PSB + VAM	24.7	69.5	34.8	4.26	10.4	7.33	28.5	13.5	124
T ₄ : 50% RDF + PSB + VAM + KRB	27.7	76.8	39.9	5.21	12.0	9.12	31.6	15.5	138
T ₅ : 75% RDF + PSB	31.4	87.9	47.6	6.06	13.9	11.7	35.7	20.5	152
T ₆ : 75% RDF + PSB + VAM	36.7	98.9	57.0	7.26	16.7	13.2	40.5	24.6	169
T ₇ : 75% RDF + PSB + VAM + KRB	42.7	109	66.8	9.15	19.8	17.5	46.6	28.8	190
T ₈ : 100% RDF + PSB	39.3	105	61.9	8.58	18.4	15.1	43.9	26.7	176
T ₉ : 100% RDF + PSB + VAM	43.6	117	71.9	9.82	22.4	19.3	47.9	32.4	196
T ₁₀ : 100% RDF + PSB + VAM + KRB	48.7	128	79.8	11.6	26.8	22.6	53.2	36.6	205
S.Em (±)	1.55	6.37	4.41	1.07	2.46	1.93	2.31	1.96	8.01
CD (0.05%)	4.6	19.1	13.2	3.21	7.4	5.8	6.9	5.8	24
CV (%)	8.0	7.4	8.2	9.1	8.5	8.2	10.6	10.7	8.9

Table 5: Effect of inorganic and biofertilizers on iron, manganese, copper and zinc uptake (g ha⁻¹) at knee high and harvest stages of maize

Treatments	Iron uptake (g ha ⁻¹)			Manganese uptake (g ha ⁻¹)			Copper uptake (g ha ⁻¹)			Zinc uptake (g ha ⁻¹)		
	Knee high	Harvest		Knee high	Harvest		Knee high	Harvest		Knee high	Harvest	
		Kernel	Stover		Kernel	Stover		Kernel	Stover		Kernel	Stover
T ₁ : Control	87.6	120	227	38.7	40.6	112	11.7	28.6	52.5	32.4	87	134
T ₂ : 50% RDF + PSB	104	132	252	43.1	46.1	126	14.5	32.7	58.7	36.6	104	167
T ₃ : 50% RDF + PSB + VAM	114	155	298	47.9	47.9	155	16.2	38.9	64.6	41.2	126	191
T ₄ : 50% RDF + PSB + VAM + KRB	126	176	336	55.4	54.0	166	18.2	43.1	69.2	45.0	140	209
T ₅ : 75% RDF + PSB	143	199	367	67.4	64.7	176	21.1	49.8	75.4	50.2	155	227
T ₆ : 75% RDF + PSB + VAM	163	227	407	72.8	73.2	197	23.0	53.5	86.1	55.4	173	247
T ₇ : 75% RDF + PSB + VAM + KRB	187	271	468	87.7	94.5	223	27.0	60.9	103	62.3	189	275
T ₈ : 100% RDF + PSB	174	255	433	80.3	90.6	206	25.4	55.7	89.8	58.2	179	257
T ₉ : 100% RDF + PSB + VAM	192	282	503	91.4	97.4	238	27.5	63.2	109	65.4	197	289
T ₁₀ : 100% RDF + PSB + VAM + KRB	213	305	561	109	106	260	31.3	69.3	115	72.3	217	312
S.Em (±)	9.02	11.8	31.3	7.47	4.29	12.5	1.67	3.06	4.47	3.39	9.48	12.6
CD (0.05%)	27.0	35.4	94.0	22.1	12.7	37.1	5.0	9.2	13.4	10.1	28	38
CV (%)	8.7	9.6	9.0	9.3	8.4	10.1	8.1	10.7	9.3	11.0	9.0	9.3

Conclusion

The combined application of biofertilizers and inorganic fertilizers significantly improved nutrient content, nutrient uptake, growth, and yield of maize at different stages of crop development. The integrated use of these nutrient sources, together with the split application of inorganic fertilizers,

ensured a balanced and continuous supply of nutrients throughout the crop growth period, thereby enhancing the nutritional status of the plants. The synergistic interaction between biofertilizers and inorganic fertilizers promoted better root development, increased nutrient availability, and improved nutrient absorption, resulting in higher nutrient

content and uptake. The enhanced nutrient acquisition also contributed to increased dry matter accumulation, improved photosynthetic efficiency, and better translocation of assimilates from source to sink, ultimately leading to higher grain and stover yields. Thus, the integrated nutrient management approach improved crop productivity by increasing both biomass production and nutrient use efficiency.

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