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NUTRIENT CONTENTS AND UPTAKE BY GARLIC (*Allium sativum* L.) AS INFLUENCED BY THE APPLICATION OF INORGANIC FERTILIZERS AND BIOFORMUALTIONS

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ABSTRACT

Field experiments were carried out to assess the impact of various bioformulations in presence of different levels of inorganic fertilizers on plant nutrient (NPK) availability and uptake by garlic during *rabi* seasons (2022-2023 and 2023-2024) at the Medicinal and Aromatic Plant Research Station, SKLTGHU, Rajendranagar, Hyderabad (India). The study was conducted in a contrast factorial randomized block design with ten treatments including control, each replicated three times. The results demonstrated higher nitrogen (2.14%), and phosphorus (0.59%) contents in plant and greater N & P uptake (98.62 and 27.42 kg ha^{-1}) in treatment 50% N + 100% P + 50% K + *Azotobacter* @ 5 kg ha^{-1} + potassium solubilizing bacteria @ 6 kg ha^{-1} + *Trichoderma viride* @ 10 mL L^{-1} + sesame oil @ 0.5% over other treatments. The highest available N, P and K (166.85, 38.31 and 137.22 kg ha^{-1}) in soil, highest potassium content (1.85%) and uptake (82.99 kg ha^{-1}) in plant was found in treatment (50% N + 50% P + 100% K + *Azotobacter* @ 5 kg ha^{-1} + phosphorus solubilizing bacteria @ 5 kg ha^{-1} + *Trichoderma viride* @ 10 mL L^{-1} + neem oil @ 0.5%). The study revealed that there is a need to assess different combinations of nutrient sources, botanicals and bioagents on physiological and nutritional behaviour of garlic.

Keywords: *Bacillus subtilis*, bioformualtions, garlic, neem oil, nutrient uptake, pongamia oil, sesame oil, *Trichoderma viride*

INTRODUCTION

Garlic (*Allium sativum* L), a monocotyledonous bulbous plant of relatively short vegetation season (90-140 days from sprouting to harvest), is grown in tropical to temperate regions all over the world. It is a member of Amaryllidaceae (Alliaceae) family and originates from Central Asia (Parreno *et al.*, 2023)**.** It is one of the most widely grown bulbous crop in the world and the 2nd most widely cultivated *Allium* species after onion. In India, garlic is cultivated on area of 3.83 lakh ha with a total production of 32.14 lakh tonnes in 2023-24 (Spice Board, 2023-2024).

Garlic requires balanced nutrient supply for optimal growth. Integrated nutrient management involving chemical nutrients and biofertilizers is an eco-friendly approach to achieve optimum yield without affecting the soil physicochemical conditions. Balanced use of fertilizers is vital for vegetative growth and high quality yields especially on arable soils (Chintala *et al.*, 2012). The availability of nitrogen and phosphorus is crucial for plant growth and development as these are indispensable components of nucleic acid, enzymes, etc. The adequate N supply to the plant is essential to enhance carbohydrate metabolism. This, in turn, increases bulb weight and total yield. Phosphorus regulates a number of physiological processes but its non-availability is a major concern as P-availability is controlled by soil conditions (Vilar *et al.*, 2010). Low P availability decreases garlic bulb quality and yield, as well as root and leaf development (Stone *et al.*, 2001). Potassium is essential for plant metabolism including photosynthesis, photosynthetic translocation, catalyst activation, and disease and pest resistance (Dorais *et al.*, 2001). In addition to NPK, sulphur is involved in many physiological functions vital for plant growth. However, garlic, being a shallow-rooted crop, often faces challenges in nutrient uptake, especially when nutrients leach beyond the root zone and render them unavailable to the plants (Thangasamy, 2016). To address this issue, the application of fertilizer nutrients in reduced amount directly in the root zone or via microbial inoculation has shown promise in enhancing the nutrient use efficiency (Shahwar *et al.*, 2023).

The use of biofertilizers improves plant nutrient availability and uptake, thus lowers the chemical fertilizer requirement amid environmental concerns. *Azotobacter chroococcum* is a soil-dwelling, free-living N_2-fixing bacteria. Furthermore, phosphorus-solubilizing bacteria (PSB) play a crucial role in converting fixed or unavailable nutrients to readily available forms (Wang *et al.*, 2024; Xu *et al.*, 2024). Nutrient uptake rates vary with plant growth stages. N demand is the highest during seedling production and vegetative growth phase (Padhan *et al.*, 2023; Abou Fayssal *et al.*, 2024). The biological agents like *Trichoderma viride* can efficiently reduce the plant pathogenic population by triggering the plant defense mechanisms. The use of bioagents has gained worldwide acceptability as an alternative to conventional pesticides, frequently applied for pest/disease management (Benitez *et al.*, 2004; O'Brien, 2017). Some *Pseudomonas* species have the ability to produce phenazines and siderophores which improve the availability of iron and other growth promoting substances to the plant. Besides, the use of bioagents improves systemic resistance (Pierson and Pierson, 2010). Some *Bacillus* species like *B. subtilis* are efficient phosphorus solubilizers as well as promote plant growth through release of plant hormones (Gyaneshwar *et al*., 2002). The yield and quality traits of onion was enhanced by the combined use of half dose of chemical fertilizers (N, P and K) along with biofertilizers (Vikram Pal *et al.*, 2025). Arunachalam *et al.* (2024) suggested that combining 100% RDF with *S. indica* or PSB can enhance onion productivity and nutrient use efficiency of onion. Saini *et al.* (2024) reported that the combined application of 75% recommended dose of NPK, 40 kg S ha^{-1}, *B. subtilis* and farm yard manure resulted in improved availability of soil nutrients for onion. The present study was aimed to evaluate the effect of three different types/levels of biofertilizers in conjunction with various bioformulations (bioinoculants and botanical extracts) on plant nutrient (NPK) availability and uptake in garlic.

MATERIALS AND METHODS

Soil and climatic characteristics of experimental site

The field experiments were conducted at Medicinal and Aromatic Plant Research Station, Sri Konda Laxman Telangana Horticultural University, Rajendranagar, Hyderabad (India) [latitude, 17°.19’ N, longitude, 79°.23’ E; altitude 542.6 m masl]. The experimental site is situated in semi-arid tropical zone with average maximum temperature during crop period 2022-23 and 2023-24 recorded as 33.5 and 36.3°C, respectively, and minimum average temperature as 13.7 and 16°C, respectively. The average maximum relative humidity during crop period 2022-23 and 2023-24 was 92.0 and 92.0% with average minimum relative humidity of 35.0 and 29.0%, respectively. The soil was sandy loam in texture, poor in water holding capacity, and acidic in nature (pH, 5.53). In both years, the composite soil samples from the entire experimental plots were collected randomly and analysed for various soil characteristics before planting the cloves in field. Standard protocols were followed to analyse the soil pH (Jackson, 1973), electrical conductivity (Jackson, 1973), organic carbon (Walkley and Black, 1934), available nitrogen (Subbiah and Asija, 1956), available phosphorus (Bray and Kurtz, 1945) and available potassium (Jackson, 1973). The soil was low in organic carbon (0.2 g kg^{-1}), available N (124.33 kg ha^{-1}), available phosphorus (24.9 kg ha^{-1}) and medium in available K (107.06 kg ha^{-1}).

Experimental design and layout

The experimental area for present study was divided into 3 blocks, and each block subdivided into ten plots. The standard package of practices was followed during the entire crop period [ICAR-DOGR (Directorate of Onion and Garlic Research)]. Raised beds of 2.0 m x 3.0 m size were prepared. Recommended dose of well decomposed FYM @ 20 t ha^{-1} was applied before last ploughing and mixed well in the soil. The FYM contained 0.5% N, 0.25% P_2O_5, and 0.5% K_2O. The soil nutrient status was assessed before applying the fertilizers using standard methods as above. The recommended doses of fertilizers (RDF) for garlic is 100 kg N, 60 kg P_2O_5, and 50 kg K_2O ha^{-1}. One-third nitrogen, as per treatments, was applied as basal dose at planting time and the remaining two-third N was applied in two equal splits 30 and 45 days after planting. RDF were applied in the form of urea, single superphosphate, muriate of potash. Garlic cloves were planted at a spacing of 10 x 15 cm. The experiment comprised of 10 treatments and each treatment was replicated three times in a contrast factorial randomized block design (Teja *et al.,* 2024) with three levels of inorganic nutrients (N_1, N_2 and N_3) in main plots [1) N_1: 100% N + 50% P + 50% K + phosphorus solubilizing bacteria (PSB @ 5 kg ha^{-1} + potassium solubilizing bacteria (KSB) @ 6 kg ha^{-1}; 2) N_2: 50% N + 100% P + 50% K + *Azotobactor* @ 5 kg ha^{-1} + KSB @ 6 kg ha^{-1}; and 3) N_3: 50% N + 50% P + 100% K + *Azotobactor* @ 5 kg ha^{-1} + PSB @ 5 kg ha^{-1}] and three levels (B_1, B_2 and B_3) in subplot [1) B_1: *Trichoderma viride* @ 10 mL L^{-1} + neem oil @ 0.5%; 2) B_2: *Pseudomonas fluorescens* @ 10 mL L^{-1} + pongamia oil @ 0.5% and; 3) B_3: *Bacillus subtilis* @ 10 mL L^{-1} + sesame oil @ 1%]. Also, a control treatment (100% RDF + imidacloprid 17.8 SL @ 0.3 mL L^{-1}) was maintained for comparison. The combination treatment details are as under:

N_1B_1: 100% N + 50% P + 50% K + PSB 5 kg ha^{-1} + KSB 6 kg ha^{-1} + *T. viride* 10 mL L^{-1} + neem oil 0.5%;
N_1B_2: 100% N + 50% P + 50% K + PSB 5 kg ha^{-1} + KSB 6 kg ha^{-1} + *P. fluorescens* 10 mL L^{-1} + pongamia oil 0.5%;
N_1B_3: 100% N + 50% P + 50% K + PSB 5 kg ha^{-1} + KSB 6 kg ha^{-1} + *B. subtilis* 10 mL L^{-1} + sesame oil 1%;
N_2B_1: 50% N + 100% P + 50% K + *Azotobacter* 5 kg ha^{-1} + KSB 6 kg ha^{-1} + *T. viride* 10 mL L^{-1} + neem oil 0.5%;
N_2B_2: 50% N + 100% P + 50% K + *Azotobacter* 5 kg ha^{-1} + KSB 6 kg ha^{-1} + *P. fluorescens* 10 mL L^{-1} + pongamia oil 0.5%;
N_2B_3: 50% N + 100% P + 50% K + *Azotobacter* 5 kg ha^{-1} + KSB 6 kg ha^{-1} + *P. fluorescens* 10 mL L^{-1} + pongamia oil 1%;
N_3B_1: 50% N + 50% P + 100% K + *Azotobacter* 5 kg ha^{-1} + PSB 5 kg ha^{-1} + *T. viride* 10 mL L^{-1} + neem oil 0.5%;
N_3B_2: 50% N + 50% P + 100% K + *Azotobacter* 5 kg ha^{-1} + PSB 5 kg ha^{-1} + *P. fluorescens* 10 mL L^{-1} + pongamia oil 0.5%;
N_2B_3: 50% N + 100% P + 100% K + *Azotobacter* 5 kg ha^{-1} + PSB 5 kg ha^{-1} + *B. subtilis* 10 mL L^{-1} + sesame oil 1%;
Control: 100% RDF + imidacloprid @ 3 mL L^{-1}

The required quantities of bioformulations were applied as soil drench as well as foliar application to the plots. The biofertilizers *viz*., *Azotobacter*, PSB and KSB were applied in powder form while bioinoculants *viz*., *Trichoderma*, *Pseudomonas* and *Bacillus* were applied in liquid form. These bioorganic materials were collected from Department of Plant Pathology, Professor Jayashankar Telangana Agricultural University. The biofertilizers were applied before last ploughing and well mixed in soil. Neem oil was extracted from neem seeds and kernels while pongamia and sesame oils were extracted from pongamia and sesame seeds and applied as foliar spray. The bioformulations *viz*., biocontrol agents and botanical oils were applied as soil drench as well as repeated at 30 day's interval till bulb forming stage. Hand weeding was done 45 to 60 days after planting for weed management and irrigation was applied based on soil moisture content as and when required during the experimental period in all the plots.

Observations

The soil samples were collected at harvest from all the treatments by digging V shaped cut at a depth of 0−20 cm. These soil samples were processed and sieved using a 2 mm sieve and stored in cloth bag till soil analysis. The available soil N was estimated using alkaline $KMnO_4$ method (Subbiah and Asija, 1956), which is based on the extraction of inorganic and readily oxidizable nitrogen from organic compounds. The available soil P_2O_5 was determined by Olsen's method (Olsen *et al*., 1954). Available soil K_2O was determined with neutral normal NH_4OAc and K estimated from the extract by using a flame photometer (SYSTRONICS CL361) as suggested by Jackson (1973). Whole plant samples were collected from each treatment at harvest and thoroughly rinsed with distilled water. The samples were chopped into pieces, and air-dried. The samples were oven-dried at 58°C until a constant weight was attained. Also, the leaf and bulb samples were ground, passed through a 2.0 mm sieve, and used for plant nutrient analysis. Total N was analysed by using micro-Kjeldahl's method (Piper, 1966). To estimate total P, 0.5 g plant samples were digested using di-acid. The digest was filtered through Whatman filter paper No. 40 and used for P estimation. For potassium estimation the samples were digested in tri-acid and K content assessed as per Piper (1966). The plant nutrient uptake was computed by multiplying the estimated per cent nutrient concentration in plant with dry plant yield.

Statistical analyses

The mean data on various parameters obtained from consecutive two years were statistically analysed by analysis of variance (Gomez and Gomez, 1983). Least significant difference (LSD) values at $p_{0.05}$ were used to determine the significance of difference between treatment means.

RESULTS AND DISCUSSION

Nutrient content in soil

The available nutrient content in soil showed significant difference among soil nutrients and bioformulations (Table 1), while their interactions were non-significant. However, significant difference was found between control and interaction. The application of different levels of RDF along with microbial inoculations revealed significant increase in total N, P and K contents in soil as compared to the treatments involving 100% RDF without any microbial inoculation in both the years (Table 1). Based on two years pooled data, the highest available N (166.85 kg ha^{-1}), P (38.31 kg ha^{-1}) and K (133.20 kg ha^{-1}) was observed in the treatment receiving 50% N + 50% P + 100% K+ *Azotobacter* @ 5 kg ha^{-1} + PSB @ 5 kg ha^{-1} along with *Trichoderma viride* @10 mL L^{-1} + neem oil @ 0.5%. This treatment showed highest N, P and K content in soil, depicting an increase of 9.69% for N, 24.99% for P and 14.47% for K as compared to the 100% RDF treatment. The highest mean total N, P and K in soil was observed in the year 2022-2023 as compared to 2023-2024. The available N, P and K was notably high in the treatments inoculated with either PSB or KSB as compared to the inorganic fertilizer treatments. *Azotobactor* and PSB have the ability to convert both organic and inorganic P into soluble forms, thereby enhance their availability in soil (Kalayu, 2019; Rawat *et al.*, 2021) by secreting extracellular enzymes, mineralizing substrates, and producing mineral-dissolving complexes/ compounds (Sharma *et al.*, 2013; Silva *et al.*, 2023). Additionally, PSB activity in rhizosphere influences the production and availability of hormones like auxins, cytokinins, and gibberellins (Kenneth *et al.*, 2019; Raza *et al.*, 2019). The increase in available N, P and K contents in soil could possibly be due to the beneficial role of *Azotobactor*, PSB and KSB in arresting N, P and K fixation and retaining it in available form for extended period. These results are in agreement with findings of Nainwal *et al.* (2015).

Plant nutrient contents

The data pertaining to plant nutrient content showed significant difference among soil nutrients and bioformulations, while their interactions were non-significant (Table 2). However, significant difference was found between control and interaction. The application of different levels of RDF in combination with microbial inoculations significantly increased the total NPK concentration in plant as compared to the treatments involving 100% RDF without microbial inoculation in both the years (Table 3). Based on two years pooled data, the highest concentration of N (2.14%) and P (0.59%) was observed in the treatment receiving 50%N +100% P + 50% K + *Azotobacter* @ 5 kg ha^{-1} + KSB @ 6 kg ha^{-1} along with *Trichoderma viride* @ 10 mL L^{-1} + neem oil @ 0.5%. However, the highest K concentration (1.85%) was observed in the treatment receiving 50% N + 50% P + 100% K + *Azotobacter*

Table 1: Influence of soil nutrients and bioformulation application on soil NPK content

Treat-ments	Available nitrogen (kg ha^{-1})			Available phosphorus (kg ha^{-1})			Available potassium (kg ha^{-1})		
	2022-2023	2023-2024	Overall mean	2022-2023	2023-2024	Overall mean	2022-2023	2023-2024	Overall mean
				Soil nutrients (N)					
N_1	157.57^{b}	154.46^{b}	156.01^{b}	34.33^{b}	28.94^{b}	31.6^{b}	121.93^{b}	116.0^{b}	118.9^{b}
N_2	151.52^{c}	150.62^{c}	151.07^{c}	31.82^{c}	27.93^{c}	29.8^{c}	114.58^{c}	109.2^{c}	111.9^{c}
N_3	165.57^{a}	162.59^{a}	164.08^{a}	39.27^{a}	34.34^{a}	36.8^{a}	132.32^{a}	128.8^{a}	130.6^{a}
S.Em$\pm$	0.37	0.38	0.26	0.13	0.14	0.10	0.35	0.32	0.19
$CD_{0.05}$	1.13	1.15	0.79	0.40	0.44	0.32	1.05	0.96	0.59
				Bio-formulations (B)					
B_1	160.39^{a}	158.34^{a}	159.37^{a}	36.65^{a}	32.25^{a}	34.4^{a}	125.82^{a}	120.9^{a}	123.3^{a}
B_2	155.57^{c}	153.4^{c}	154.48^{c}	33.34^{c}	29.13^{c}	31.2^{c}	119.65^{c}	115.4^{c}	117.5^{c}
B_3	158.69^{b}	155.93^{b}	157.31^{b}	35.43b	29.84^{b}	32.6^{b}	123.36^{b}	117.6^{b}	120.5^{b}
SEm$\pm$	0.37	0.38	0.26	0.13	0.14	0.10	0.35	0.32	0.19
$CD_{0.05}$	1.18	1.75	0.91	0.49	0.44	0.32	1.55	0.98	0.99
				Interaction (N x B)					
N_1B_1	158.45^{d}	157.21^{d}	157.83^{d}	36.13^{b}	32.09^{b}	34.11^{b}	124.5^{d}	119.9^{d}	122.2^{d}
N_1B_2	155.12^{e}	152.3^{ef}	153.7^{e}	32.21^{de}	28.56^{c}	30.39^{c}	119.4^{f}	113.4^{ef}	116.4^{f}
N_1B_3	159.14^{d}	153.91^{e}	156.53^{d}	34.64^{c}	26.18^{d}	30.41^{c}	121.7^{e}	114.6^{e}	118.2^{e}
N_2B_1	154.48^{e}	152.4^{ef}	153.42^{e}	32.99^{d}	28.87^{c}	30.93^{c}	117.4^{gh}	112.0^{f}	114.7^{g}
N_2B_2	148.95^{g}	148.45^{g}	148.7^{g}	30.77^{f}	26.56^{d}	28.67^{d}	110.54^{i}	106.2^{h}	108.4^{i}
N_2B_3	151.13^{f}	151.04^{f}	151.09^{f}	31.7^{ef}	28.36^{c}	30.03^{c}	115.76^{h}	109.4^{g}	112.6^{h}
N_3B_1	168.25^{a}	165.45^{a}	166.85^{a}	40.83^{a}	35.78^{a}	38.31^{a}	135.45^{a}	130.9^{a}	133.2^{a}
N_3B_2	162.64^{c}	159.48^{c}	161.06^{c}	37.03^{b}	32.27^{b}	34.65^{b}	128.98^{c}	126.5^{c}	127.7^{c}
N_3B_3	165.81^{b}	162.85^{b}	164.33^{b}	39.95^{a}	34.98^{a}	37.47^{a}	132.54^{b}	128.8^{b}	130.7^{b}
SEm$\pm$	1.13	1.15	0.79	0.40	0.44	0.32	1.05	0.96	0.59
$CD_{0.05}$	ns	ns	ns	ns	ns	ns	ns	ns	ns
Control	150.5^{fg}	153.67^{e}	152.1^{ef}	36.13^{b}	28.63^{c}	30.65^{c}	118.69^{fg}	114.03^{e}	116.36^{f}
SEm$\pm$	1.13	1.15	0.79	0.40	0.44	0.32	1.05	0.96	0.59
$CD_{0.05}$	4.34	4.44	3.04	1.56	1.69	1.24	4.06	3.71	2.28

N_1 = 100% N + 50% P + 50% K + PSB @ 5 kg ha^{-1} + KSB @ 6 kg ha^{-1}; N_2 = 50% N + 100% P + 50% K + *Azotobacter* @ 5 kg ha^{-1} + KSB @ 6 kg ha^{-1}; N_3 = 50% N + 50% P + 100% K + *Azotobacter* @ 5 kg ha^{-1} + PSB @ 5 kg ha^{-1}; B_1 = *Trichoderma viride* @ 10 mL L^{-1} + neem oil @ 0.5%; B_2 = *Pseudomonas fluorescens* @ 10 mL L^{-1} + pongamia oil @ 0.5%; B_3 = *Bacillus subtilis* @ 10 mL L^{-1} + sesame oil @ 1%; Control = 100% RDF + imidacloprid @ 3 mL L^{-1}.

@ 5 kg ha^{-1} + PSB @ 5 kg ha^{-1} along with *T. viride* @ 10 mL L^{-1} + neem oil @ 0.5%. The treatment led to the highest N and P content in plant depicting an increase of 15.5% for N, 20.5% for P and 4.5% for K as compared to the 100% RDF alone. The highest mean total NPK concentration in plants was observed in the year 2023-2024. NPK concentration in plant was notably higher in treatments inoculated with *Azotobacter* and PSB as compared to those treated with mineral fertilizers alone (Table 2). Increase in N, P and K contents in garlic plants may be attributed to application of mineral fertilizers in conjunction with biofertilizers which enhanced their concentrations in root zone (El-Zohery, 2003). This increased NPK might be due to improved availability and uptake by plant through efficient absorption of nutrients by root. Additionally, free-living N_2-fixing bacteria like *Azotobacter chroococcum* can secrete growth-promoting substances including auxins, gibberellic acid and cytokinins, which might improve plant growth and root biomass by enhancing root hairs, which promoted nutrient absorption (Mohsen *et al*., 2017).

Nutrient uptake

The data on nutrient uptake revealed significant difference among soil nutrients and bioformulations, while their interactions were non-significant. However, there was statistically significant difference

Table 2: Influence of soil nutrients and bioformulations on NPK contents in garlic plants

Treat-ments	Nitrogen content (%)			Phosphorus content (%)			Potassium content (%)		
	2022-2023	2023-2024	Overall mean	2022-2023	2023-2024	Overall mean	2022-2023	2023-2024	Overall mean
				Soil nutrients (N)					
N_1	1.86b	1.91b	1.88b	0.42b	0.46b	0.44b	1.53c	1.58c	1.55c
N_2	2.06a	2.11a	2.09a	0.53a	0.57a	0.55a	1.60b	1.63b	1.62b
N_3	1.79c	1.85c	1.82c	0.32c	0.37c	0.35c	1.77a	1.88a	1.83a
SEm$\pm$	0.004	0.004	0.003	0.003	0.004	0.003	0.005	0.005	0.004
$CD_{0.05}$	0.01	0.01	0.01	0.008	0.01	0.01	0.01	0.01	0.01
				Bio-formulations (B)					
B_1	1.94a	1.99a	1.96a	0.45a	0.49a	0.47a	1.65a	1.72a	1.69a
B_2	1.87c	1.93c	1.90c	0.39c	0.44c	0.42c	1.60c	1.67c	1.63c
B_3	1.90b	1.96b	1.93b	0.42b	0.46b	0.44b	1.64ab	1.70ab	1.60ab
SEm$\pm$	0.004	0.004	0.003	0.003	0.004	0.003	0.005	0.005	0.004
$CD_{0.05}$	0.01	0.01	0.01	0.008	0.01	0.01	0.01	0.01	0.01
				Interaction (N x B)					
N_1B_1	1.90^{bcd}	1.93^{bc}	1.92^{bcd}	0.46^{abcd}	0.49^{abc}	0.48^{abc}	1.55^{bcd}	1.60^{c}	1.58^{c}
N_1B_2	1.83^{d}	1.89^{bc}	1.86^{cd}	0.38^{bcd}	0.43^{abc}	0.41^{abc}	1.51^{d}	1.55^{c}	1.53^{c}
N_1B_3	1.85^{cd}	1.91^{bc}	1.88^{cd}	0.41^{abcd}	0.46^{abc}	0.44^{abc}	1.53^{cd}	1.58^{c}	1.56^{c}
N_2B_1	2.10^{a}	2.17^{a}	2.14^{a}	0.56^{a}	0.61^{a}	0.59^{a}	1.62^{abc}	1.66^{bc}	1.64^{bc}
N_2B_2	2.02^{abc}	2.04^{ab}	2.03^{abc}	0.50^{abc}	0.54^{abc}	0.52^{abc}	1.57^{bcd}	1.59^{c}	1.58^{c}
N_2B_3	2.07^{ab}	2.11^{a}	2.09^{ab}	0.52^{ab}	0.56^{ab}	0.54^{ab}	1.61^{abc}	1.64^{bc}	1.63^{bc}
N_3B_1	1.80^{d}	1.87^{bc}	1.84^{cd}	0.34^{cd}	0.38^{bc}	0.36^{bc}	1.8^{a}	1.9^{a}	1.85^{a}
N_3B_2	1.78^{d}	1.84^{c}	1.81^{d}	0.30^{d}	0.36^{c}	0.33^{c}	1.72^{abc}	1.86^{a}	1.79^{ab}
N_3B_3	1.79^{d}	1.85^{bc}	1.82^{d}	0.32^{d}	0.38^{bc}	0.35^{bc}	1.79^{a}	1.89^{a}	1.84^{a}
SEm$\pm$	0.01	0.01	0.01	0.008	0.01	0.01	0.01	0.01	0.01
$CD_{0.05}$	ns	ns	ns	ns	ns	ns	ns	ns	ns
Control	1.85^{cd}	1.86^{bc}	1.86^{cd}	0.46^{abcd}	0.52^{abc}	0.49^{abc}	1.73^{ab}	1.81^{ab}	1.77^{ab}
SEm$\pm$	0.01	0.01	0.01	0.008	0.01	0.01	0.01	0.01	0.01
$CD_{0.05}$	0.04	0.05	0.03	0.03	0.04	0.03	0.05	0.05	0.04

N_1 = 100% N + 50% P + 50% K + PSB @ 5 kg ha^{-1} + KSB @ 6 kg ha^{-1}; N_2 = 50% N + 100% P + 50% K + *Azotobacter* @ 5 kg ha^{-1} + KSB @ 6 kg ha^{-1}; N_3 = 50% N + 50% P + 100% K + *Azotobacter* @ 5 kg ha^{-1} + PSB @ 5 kg ha^{-1}; B_1 = *Trichoderma viride* @ 10 mL L^{-1} + neem oil @ 0.5%; B_2 = *Pseudomonas fluorescens* @ 10 mL L^{-1} + pongamia oil @ 0.5%; B_3 = *Bacillus subtilis* @ 10 mL L^{-1} + sesame oil @ 1%; Control = 100% RDF + imidacloprid @ 3 mL L^{-1}.

while their interactions were non-significant. However, there was statistically significant difference between control and interaction combination. The application of different levels of RDF in combination with microbial inoculations significantly increased the total N, P and K uptake as compared to treatments involving 100% RDF without microbial inoculation in both the years (Table 3). Based on two years pooled data, the highest uptake of N (96.59 kg ha^{-1}) and P (27.47 kg ha^{-1}) was observed in the treatment receiving 50% N + 100% P + 50% K + *Azotobacter* @ 5 kg ha^{-1} + KSB @ 6 kg ha^{-1} along with *T. viride* @ 10 mL L^{-1} + neem oil @ 0.5%. However, highest K uptake (82.99 kg ha^{-1}) was noted in the treatment receiving 50% N + 50% P + 100% K + *Azotobacter* @ 5 kg ha^{-1} + PSB @ 5 kg ha^{-1} along with *T. viride* @ 10 mL L^{-1} + neem oil @ 0.5%. The application led to the highest N and P uptake, showing an increase of N by 6.59%, P by 53.89% and K by 16.59% as compared to 100% RDF treatment. In terms of yearly variations, the highest mean N uptake was recorded in the year 2022-2023, whereas the highest mean total P and K uptake was observed in 2023-2024. N, P and K recovery efficiency was notably higher in treatments inoculated with *Azotobacter* and PSB as compared to those treated with mineral fertilizers alone (Table 3). Furthermore, nutrient uptake efficiencies in these treatments exceeded with those observed in treatments receiving mineral fertilizers in combination with bioinoculation. The application of *Azotobactor* and KSB with 50% N and K along with 100% P led to notable increases in various plant growth parameters, this increase is potentially attributable to the enhanced uptake of N, P and K. The higher nitrogen uptake and its content in plant may be due to the biofertilizers which played important role in solubilizing the unavailable forms of inorganic nutrients to available form. Girigowda *et al*. (2005) opined that the highest NPK uptake by onion was due to the biofertilizers made these nutrients available. Our results are also supported by Shaheen *et al*. (2007), Arif *et al*. (2016) and Mulatu *et al*. (2017).

Table 3: Influence of soil nutrients and bioformulations on N, P and K uptake by garlic plant

Treat-ments	Nitrogen uptake (kg ha^{-1})			Phosphorus uptake (kg ha^{-1})			Potassium uptake (kg ha^{-1})		
	2022-2023	2023-2024	Overall mean	2022-2023	2023-2024	Overall mean	2022-2023	2023-2024	Overall mean
				Soil nutrients (N)					
N_1	83.1b	83.87b	83.49b	18.6b	20.13b	19.4b	68.4c	69.6c	69.0c
N_2	95.4a	96.8a	96.12a	24.4a	26.58a	25.49a	74b	75.9b	74.9b
N_3	79.0c	78.78c	78.92c	14.2c	15.76c	14.97c	79.61a	80.2a	79.9a
SEm±	0.29	0.41	0.32	0.12	0.21	0.16	0.36	0.39	0.30
$CD_{0.05}$	0.89	1.25	0.98	0.17	0.65	0.50	0.10	0.19	0.89
				Bio-formulations (B)					
B_1	88.20^{a}	89.14^{a}	88.69^{a}	20.70^{a}	22.46^{a}	21.59^{a}	76.14^{a}	77.50^{a}	76.80^{a}
B_2	83.30^{c}	83.30^{c}	83.31^{c}	17.10^{c}	19.28^{c}	18.45^{c}	71.65^{c}	72.40^{c}	72.00^{c}
B_3	86.10^{b}	87.01^{b}	86.53^{b}	18.90^{b}	20.74^{b}	19.82^{b}	74.22^{b}	75.80^{b}	75.00^{b}
SEm±	0.29	0.41	0.32	0.12	0.21	0.16	0.36	0.39	0.30
$CD_{0.05}$	0.89	1.25	0.98	0.17	0.65	0.50	0.10	0.19	0.89
				Interaction (N x B)					
N_1B_1	86.02^{d}	83.12^{e}	84.57^{d}	20.79^{d}	22.11^{c}	21.45^{c}	70.06^{f}	71.88^{f}	70.97^{d}
N_1B_2	80.70^{f}	86.53^{d}	83.62^{de}	16.87^{f}	18.22^{e}	17.55^{e}	66.69^{h}	67.46^{h}	67.08^{f}
N_1B_3	82.63^{e}	81.23^{e}	81.93^{e}	18.36^{e}	20.06^{d}	19.21^{d}	68.45^{g}	69.67^{g}	69.06^{e}
N_2B_1	97.73^{a}	95.45^{b}	96.59^{a}	26.17^{a}	28.77^{a}	27.47^{a}	75.22^{d}	77.90^{c}	76.56^{c}
N_2B_2	92.47^{b}	99.50^{a}	95.99^{ab}	22.97^{c}	24.93^{b}	23.95^{b}	72.01^{e}	73.18^{e}	72.60^{d}
N_2B_3	96.14^{a}	93.17^{c}	94.66^{b}	24.05^{b}	26.05^{b}	25.05^{b}	74.77^{d}	76.69^{d}	75.73^{c}
N_3B_1	80.99^{f}	79.05^{f}	80.02^{f}	15.23^{g}	16.49^{f}	15.86^{f}	83.14^{a}	82.83^{a}	82.99^{a}
N_3B_2	76.77^{g}	81.39^{e}	79.08^{fg}	13.01^{i}	14.69^{g}	13.85^{g}	76.24^{c}	76.66^{d}	76.45^{c}
N_3B_3	79.40^{f}	75.50^{g}	77.45^{g}	14.30^{h}	16.10^{fg}	15.20^{fg}	79.44^{b}	81.15^{b}	80.30^{b}
SEm±	0.89	1.25	0.98	0.17	0.65	0.50	0.10	0.19	0.89
$CD_{0.05}$	ns	ns	ns	ns	ns	ns	ns	ns	ns
Control	89.52^{c}	92.45^{c}	90.99^{c}	17.49^{f}	18.21^{e}	17.85^{e}	69.55^{f}	72.81^{e}	71.18^{d}
SEm±	0.89	1.25	0.98	0.17	0.65	0.50	0.10	0.19	0.89
$CD_{0.05}$	3.42	4.81	3.77	1.45	2.52	1.91	4.24	4.57	3.44

N_1 = 100% N + 50% P + 50% K + PSB @ 5 kg ha^{-1} + KSB @ 6 kg ha^{-1}; N_2 = 50% N + 100% P + 50% K + *Azotobacter* @ 5 kg ha^{-1} + KSB @ 6 kg ha^{-1}; N_3 = 50% N + 50% P + 100% K + *Azotobacter* @ 5 kg ha^{-1} + PSB @ 5 kg ha^{-1}; B_1 = *Trichoderma viride* @ 10 mL L^{-1} + neem oil @ 0.5%; B_2 = *Pseudomonas fluorescens* @ 10 mL L^{-1} + pongamia oil @ 0.5%; B_3 = *Bacillus subtilis* @ 10 mL L^{-1} + sesame oil @ 1%; Control = 100% RDF + imidacloprid @ 3 mL L^{-1}.

Conclusions: The study revealed that the use of inorganic fertilizers in combination with biofertilizers has remarkably influenced soil-plant system in terms of enhanced nutrient mineralization/ solubilisation/fixation resulting in higher nutrient release which, in turn, increased of nutrient uptake by the crop.

Competing interests: The authors declare that they have no conflict of interest in the publication.

Author's contributions: SR: carried out field experiment, sample collection, data recording, drafting research paper. JC: Designed and supervised the research; helped in manuscript preparation. PP: contributed in data analysis, manuscript writing, and MS: Edited the manuscript; BN: Analyzed soil and plant samples; VS: Performed data analysis; supervised field experiment. All authors read and approved the final manuscript.

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