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A combination of biochemical fertilizers enhances plant nutrient absorption, water deficit tolerance, and yield of chickpea (*Cicer arietinum* L.) plants under irrigation regimes

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ABSTRACT

Water shortage is the most critical abiotic stress and adversely impacts crop growth and productivity. Biofertilizers are an environmentally friendly method for sustainable agricultural development and improving plant water deficit tolerance. The effects of biological and chemical fertilizers on yield, yield components, and nutrient absorption of chickpea plants were studied in 2018 and 2019. The main plots were assigned to the irrigation levels [80% (I_{80}) and 50% (I_{50})] and the subplot was assigned to 13 fertilizer combinations including free-living N-fixing bacteria (NB), potassium solubilizing bacteria (KB), phosphate solubilizing bacteria (PB), common chickpea nutrition program (F; NPK chemical fertilizer), and their combination. The results showed that shoot phosphorus content was increased by 80% when F + NPB (NPK chemical fertilizer and N + P biofertilizers) was applied at I_{80} compared with the control at I_{50}. Furthermore, I_{80} and the application of PKB (P + K biofertilizers) and NPKB (N + P + K biofertilizers) obtained the highest shoot K and N concentrations, respectively. The NPKF + B-treated plants (N + P + K chemical fertilizer and N + P + K biofertilizers) demonstrated superior growth attributes such as plant height and the number of sub-branches at I_{80}. The highest grain yield was obtained from the NPKF + B treatment at I_{80}, which was 7.1-fold higher compared with the control at I_{50}. In general, the combined application of biochemical fertilizers mitigated the adverse effect of water deficit and improved nutrient absorption and chickpea yield. The use of biochemical fertilizers can be efficient in reducing the consumption of chemical fertilizers and achieving sustainable agricultural goals.

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Biofertilizer; nitrogen-fixing bacteria; potassium solubilizing bacteria; water shortage

Introduction

Drought, as one of the consequences of climate change, has become one of the most important abiotic stresses that leads to substantial losses in plant productivity (Sarwat and Tuteja 2017). Water availability is one of the vital environmental factors that determine species distribution worldwide (Fischer et al. 2019). Water stress occurs when the transpiration of water by the crop exceeds its adsorption from the soil (Filipović 2020). Long-term water stress affects plant metabolic processes and often decreases plant production (Wu et al. 2022). The effects of water stress are primarily reflected in the reduction of leaf area, gas exchanges, photosynthetic rate, crop

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growth rate, and yield components, leading to considerable yield losses (Fahad et al. 2017; Qayyum et al. 2021).

Pulses are a wealthy source of proteins that are nutritionally valuable and constitute a significant part of food in developing countries in arid areas (McDermott and Wyatt 2017; Acciani et al. 2020). Chickpea is the third crop among pulses worldwide and is adapted to different climatic conditions (Merga and Haji 2019). In Iran, chickpea is the most important crop among pulses and accounts for >52% of the cultivated area of legumes (Ahmadi et al. 2021). The nitrogen fixation ability, deep rooting, and effective use of precipitation caused this plant to play an important role in the sustainability of agricultural production systems (Singh, Singh, and Saravaiya 2018; Muriuki et al. 2020). Although chickpeas are relatively drought tolerant than other legumes, water stress is the primary constraint for chickpea production. Drought stress enhanced pod shedding and reduced chickpea yield (Hussain et al. 2021).

Indiscriminate and inappropriate use of chemical fertilizers has led to environmental problems (Gaihre et al. 2015; Islam et al. 2018). For instance, it has been reported that >50% of applied N is not assimilated by plants and is lost through different mechanisms such as ammonia (NH_3) volatilization, surface runoff, leaching, and nitrification–denitrification (Zhao et al. 2009; Dong et al. 2012). Therefore, biological methods are considered an eco-friendly approach. Using chemical fertilizers at the beginning of the planting season may reduce the plant's access to nutrients by biological fixation, converting to other forms, or leaching, which leads to economic losses and environmental pollution. Therefore, the fertilizer use pattern should be altered in a way that the plant-required nutrients are provided over the long term without losses to increase the nutrient use efficiency. Management strategies that allow plants to tolerate biotic and abiotic stresses are necessary to improve agricultural production, reduce chemical fertilizer utilization, and protect crops and soil quality (Shen et al. 2013; Meddich et al. 2020).

The use of biofertilizers with the ability to fix nitrogen and solubilize phosphorus and potassium can be an appropriate method of agricultural operations. Biofertilizers modulate the effects of water stress and improve crop yield by increasing proline and soluble carbohydrate content, and the absorption of mineral elements such as potassium and phosphorus (Batool et al. 2020). The application of biofertilizers such as beneficial soil microorganisms has emerged as a potential solution to promote plant adaptability, yield, and tolerance to environmental constraints (Laouane et al. 2019).

The appropriate management of plant nutrition, growth, and tolerance to drastic constraints such as drought and soil poverty is becoming a key component in increasing crop yield under changing environmental conditions (Meddich et al. 2018). Besides regulating nutrient acquisition, biofertilizers are an effective substitute for chemical fertilizers to ensure stable, safe, and sustainable agricultural and biomass production (Abdel Latef et al. 2020). Considering the benefits of biofertilizers, a suitable fertilizer combination that prevents excessive reduction of crop production under limited water resources is of great importance. The positive effects of each biofertilizer type separately have been observed on chickpeas' growth and yield in controlled environments and the field under stressful conditions (Khaitov and Abdiev 2018; Dogra et al. 2019); however, a comprehensive study has not been conducted on the simultaneous application of three types of phosphorus, potassium, and nitrogen biofertilizers along with chemical fertilizers in chickpea plants under water stress conditions. Hence, the present study was aimed to investigate the effects of biofertilizers, chemical fertilizers, and their combination on the yield, yield components, and nutrient absorption of chickpea plants under different irrigation regimes.

Materials and methods

Experimental procedure and location

Two field experiments were conducted at the research farm of the Faculty of Agriculture (36°15′ N, 59°38′ E, and 985 msl), Ferdowsi University of Mashhad, Iran, in 2018 and 2019. With average annual temperature and rainfall of 14 °C and 250 mm, respectively, this region lies within a dry and semi-arid climate. The average maximum and minimum temperatures are between 26.6 °C and 1.7 °C, respectively. Climate data during the experiments are shown in Table 1.

Field preparation

Chickpea seeds (*cv*. Hashem) were provided from the seed bank of the Research Center of Plant Sciences, Ferdowsi University of Mashhad, Iran. This region is classified as BSK [dry and cold semi-desert (steppe)] based on the Köppen-Geiger climate classification (Raziei 2017). Field preparation was carried out in early March and seeds were sown in the middle of March. Seeds were sown by hand in five rows 50 cm apart and 4 m long with 6.5 cm on-row space (30 plants/m^2) and in soil depth of 4–5 cm. The distance between treatments and blocks was considered 1 and 2 m, respectively. The weeding was done by hand in early May. The field soil samples were collected before sowing to determine the physical and chemical properties (Table 2).

Experimental treatments

The experimental treatments included irrigation regimes at two levels [80% (I_{80}; control) and 50% (I_{50}) of the field capacity (FC)] as the main plots, and 13 fertilizer combinations [1—F: NPK chemical fertilizer, 2—NPKB: N-fixing bacteria + P solubilizing bacteria + K solubilizing bacteria; (B: biofertilizer), 3—NB: N-fixing bacteria, 4—NPB: N + P biofertilizers, 5—NKB: N + K biofertilizers, 6—F + PKB: NPK chemical fertilizer + P + K biofertilizers, 7—F + NKB: NPK chemical fertilizer and N + K biofertilizers, 8—F + NPB: NPK chemical fertilizer and N + P biofertilizers, 9—PKB: P + K biofertilizers, 10—KB: K biofertilizers, 11—PB: P biofertilizers, 12—F + NPKB: NPK chemical fertilizer + N+P + K biofertilizers, and 13—Control: without fertilizer] as subplots.

Irrigation regimes were applied based on evaporation from the class A evaporation pan located at the experimental field. The evapotranspiration rate was determined based on the crop coefficient (K_c; 1.00 and 0.35 at the middle and end growth stages, respectively) (Allen et al. 1998), and the irrigation was applied when the determined value of water for each treatment was evaporated from the pan. Before the irrigation, a soil sample was taken from the plant rooting depth to determine the moisture content percentage by weight. The depth of water in each irrigation regime was calculated in centimeters using Eq. (1):

$$I = \frac{(\theta f - \theta)(\rho b/\rho w)D}{100} \tag{1}$$

where, θ is the gravimetric soil water during irrigation, θf is gravimetric soil water at water shortage, ρb is bulk density of soil, ρw is water density, and D is rooting depth.

According to Eq. (2), the volume of water required for each plot was calculated:

$$V = I \times A \times 100 \tag{2}$$

Table 1. Climatic data (monthly) during the experiments in 2018 and 2019.

	Precipitation (mm)		Minimum temperature (°C)		Maximum temperature (°C)	
Month	2018	2019	2018	2019	2018	2019
March	54.9	41.5	7.50	4.72	17.5	16.7
April	37.8	32.9	8.98	6.88	20.6	16.7
May	41.9	37.4	12.9	13.8	25.9	25.5
June	18.1	0.5	18.2	19.1	32.8	35.4
July	0.01	4.03	22.7	20.7	37.8	34.7
Annual rainfall	152.7	116.3				

Table 2. Physicochemical characteristics of the experimental field soil.

Texture	Salinity (dS/m)	pH	Organic carbon (%)	Nitrogen (%)	Phosphorus (mg/kg)	Potassium (mg/kg)
Loam silt	1.54	7.79	0.571	0.057	17.8	250
Loam silt	1.57	7.75	.592	0.061	18.7	261

Table 3. Characteristics of biological fertilizers.

Types of biofertilizer	The bacteria used	Colony-forming unit	Dose of recommended biofertilizer
Free-living N-fixing bacteria	*Azotobacter* sp. *Azospirillum* sp. *Bacillus* sp.	10^7	Five liters per hectare
Phosphate solubilizing bacteria	*Bacillus* sp. *Pseudomonas* sp.	10^7	Five liters per hectare
Potassium solubilizing bacteria	*Bacillus* sp. *Pseudomonas* sp.	10^7	Five liters per hectare

Here, V is the volume of irrigation water used per plot (liter), A is the area of each plot (m^2), which was constant for all treatments ($10\,m^2$), and I is the depth of irrigation water (m).

Characteristics of biofertilizers

The characteristics of biofertilizers are presented in Table 3. Bacterial biofertilizers were purchased from Dayan Company and used according to the instructions (at the rate of $5\,l/ha^1$) at two stages before and immediately after planting. Also, chemical and biological fertilizers were applied based on the results of soil analysis. Nitrogen, phosphorus, and potassium were added to the soil simultaneously with planting from the sources of urea (46%), triple superphosphate (46%), and granulated potassium sulfate (50%), at the rate of 50, 225, and 150 kg/ha, respectively.

Measurements

Determination of nutrient absorption

Sampling was performed to determine the nutrient elements absorbed by the leaves at 50% of the flowering stage. Shoot nitrogen content was measured by the Kjeldahl method (Horneck and Miller 1998). Tandon's (2005) and Chapman and Pratt's (1962) methods were used to determine shoot phosphorus and potassium, respectively.

Growth parameters, yield, and yield components

Five plants from the middle row of each plot were randomly selected at the physiological maturity (104th day) and dried at 70 °C to constant weight. Plant dry weight, plant height, number of primary branches, number of sub-branches, the lowest pod height, and yield components (number of pods per plant, the pod fertility percentage, number of grains per pod, and 100-grain weight) were measured. At the end of the growing season, plants were harvested from $2.25\,m^2$ of each plot, and grain yield and harvest index (HI) (Eq. 3) were calculated.

$$HI = (GY/BY) \times 100 \tag{3}$$

where GY is grain yield and BY is plant biomass.

Statistical calculations and data analysis

The experiments were carried out as a split-plot arrangement based on a randomized complete block design with 3 replications (2 irrigation regimes as main plots × 13 fertilizer treatments as subplots). Data were subjected to a combined analysis of variance using SPSS v. 27, and means were compared using the Least Significant Difference (LSD) test $p \leq .05$.

Results

Plant height

The results revealed that fertilizer treatments and irrigation regimes significantly affected plant height in both years of the experiment. The highest plant height was observed in F + NPKB at I_{80} in 2018 and 2019, which was ~80% higher than that in the control (no fertilizer) at I_{50} (Tables 4 and 5). Furthermore, the highest plant height was observed in F + NPKB in 2018, whereas the lowest plant height was observed in the control in 2019 (Table 5).

The number of sub-branches per plant

The fertilizer treatments significantly affected the number of sub-branches per plant under both irrigation regimes in both years of the experiment. The maximum number of sub-branches per

Table 4. Interaction of irrigation regimes and nutritional treatments on plant height, number of sub-branches, and the total number of pods in chickpea plants.

Irrigation regimes	Nutritional treatments	Plant height (cm)	Number of sub-branches	Total number of pods per plant
I-80	B-NPK	65.2^{ab}	$5.17^{d–g}$	28.4^{b}
	B-N	59^{de}	$4.89^{e–h}$	$18.2^{f–i}$
	F-NPK	63^{bc}	5.55^{cd}	24.9^{c}
	B-NP	61.2^{cd}	$4.89^{e–h}$	25.1^{c}
	B-NK	61.3^{cd}	$5.59^{b–d}$	$18.9^{f–h}$
	F + B-PK	63.2^{bc}	$5.7^{b–d}$	$18.7^{f–h}$
	F + B-NK	$61.8^{b–d}$	5.81^{bc}	24.8^{c}
	F + B-NP	63^{bc}	5.83^{bc}	23.8^{c}
	B-PK	$61.8^{b–d}$	$5.39^{c–f}$	$17.8^{f–j}$
	B-K	56.8^{ef}	$5.16^{d–g}$	$16.1^{h–l}$
	B-P	56.5^{ef}	$4.72^{g–i}$	$16.7^{g–k}$
	F + B-NPK	68^{a}	6.66^{a}	33.1^{a}
	Control	53.7^{fg}	$5.44^{c–e}$	$14.9^{j–l}$
I-50	B-NPK	50.8^{g}	5.5^{cd}	23.9^{c}
	B-N	44.7^{hi}	$4.38^{h–j}$	13.5^{lm}
	F-NPK	46.5^{h}	$4.72^{g–i}$	$19.7^{e–g}$
	B-NP	47.2^{h}	6.13^{ab}	$18.3^{f–h}$
	B-NK	44.3^{hi}	4.31^{ij}	13.7^{kl}
	F + B-PK	44.8^{hi}	3.97^{jk}	$22.6^{c–e}$
	F + B-NK	51.7^{g}	$5.32^{c–f}$	23.1^{cd}
	F + B-NP	44.3^{hi}	$4.83^{f–i}$	$20.2^{d–f}$
	B-PK	45.7^{hi}	$4.83^{f–i}$	10.3^{m}
	B-K	42.5^{i}	$4.89^{e–h}$	$19^{f–h}$
	B-P	45.7^{hi}	3.41^{k}	$14.9^{i–l}$
	F + B-NPK	57.2^{e}	3.59^{k}	25.5^{bc}
	Control	37.7^{j}	3.89^{jk}	5.9^{n}

I-80: 80% field capacity; I-50: 50% field capacity; B-NPK: living N-fixing bacteria + phosphate solubilizing bacteria + potassium solubilizing bacteria; B-N: living N-fixing bacteria; F-NPK, B-NP: nitrogen and phosphorus biofertilizers; B-NK: nitrogen and potassium biofertilizers; F + B-PK: the combination of NPK chemical fertilizer and phosphorus and potassium; F + B-NK: the combination of NPK chemical fertilizer and nitrogen and potassium biofertilizers; F + B-NP: the combination of NPK chemical fertilizer and nitrogen and phosphorus biofertilizers; B-PK: phosphorus and potassium biofertilizers; B-K: potassium solubilizing bacteria; B-P: phosphate solubilizing bacteria; F + B-NPK: the combination of NPK chemical fertilizer and living N-fixing bacteria + phosphate solubilizing bacteria + potassium solubilizing bacteria; and Control: without fertilizer. Means with the same letters in each column are not significantly different based on the LSD test at a 5% probability level.

Table 5. Interaction of year and nutritional treatments on plant height, number of sub-branches, the total number of pods, and 100-seeds weight in chickpea plants.

Year	Nutritional treatments	Plant height (cm)	Number of sub-branches	Total number of pods per plant	100-seeds weight (g)
2018	B-NPK	61.3^{a}	6.16$^{c–e}$	31.5^{a}	26.9$^{b–e}$
	B-N	53.3$^{c–h}$	4.59^{h}	18.2$^{j–l}$	24.1$^{g–j}$
	F-NPK	56.7^{bc}	6.26$^{b–d}$	25.9$^{c–e}$	25.4$^{e–h}$
	B-NP	55.8$^{b–e}$	6.51$^{a–c}$	27.5$^{b–d}$	26$^{d–f}$
	B-NK	54.2$^{b–g}$	5.40^{f}	16.7$^{k–m}$	26.4$^{c–f}$
	F + B-PK	53.7$^{c–h}$	5.33^{fg}	21.7$^{f–i}$	26.3$^{c–f}$
	F + B-NK	56.2$^{b–d}$	6.79^{ab}	24.5$^{d–f}$	25.3$^{e–h}$
	F + B-NP	54.2$^{b–g}$	6.99^{a}	21.2$^{g–j}$	27.8^{bc}
	B-PK	55.3$^{b–f}$	5.38^{fg}	13.8$^{m–o}$	25.6$^{e–h}$
	B-K	52.2$^{f–i}$	5.71$^{d–f}$	22.2$^{f–h}$	23.4$^{i–k}$
	B-P	55.7$^{b–e}$	3.46^{j}	19.3$^{h–k}$	23.5$^{i–k}$
	F + B-NPK	64.1^{a}	5.75$^{d–f}$	29.9^{ab}	29.8^{a}
	Control	49.8$^{i–k}$	5.65^{ef}	12.1^{o}	22.3^{k}
2019	B-NPK	54.7$^{b–g}$	4.50^{hi}	20.7$^{g–j}$	27.6$^{b–d}$
	B-N	50.3$^{h–j}$	4.66^{h}	13.4^{no}	24.9$^{f–i}$
	F-NPK	52.8$^{d–i}$	4.01^{ij}	18.6$^{i–l}$	28.3^{ab}
	B-NP	52.5$^{e–i}$	4.50^{hi}	15.7$^{l–n}$	23.6$^{i–k}$
	B-NK	51.5$^{g–i}$	4.50^{hi}	15.9$^{l–n}$	25.9$^{e–g}$
	F + B-PK	54.3$^{b–g}$	4.33^{hi}	19.6$^{h–k}$	25.5$^{e–h}$
	F + B-NK	57.3^{b}	4.33^{hi}	23.3$^{e–g}$	28.6^{ab}
	F + B-NP	53.2$^{d–i}$	3.66^{j}	26.6$^{f–h}$	24$^{h–k}$
	B-PK	52.2$^{f–i}$	4.83^{gh}	14.2$^{m–o}$	24.7$^{f–i}$
	B-K	47.2^{jk}	4.33^{hi}	12.8^{no}	24.1$^{h–i}$
	B-P	46.5^{k}	4.66^{h}	12.2^{o}	22.6^{jk}
	F + B-NPK	61.2^{a}	4.50^{hi}	28.5$^{a–c}$	28^{bc}
	Control	41.5^{l}	3.66^{j}	8.66^{p}	22.6^{jk}
ANOVA					
Year (Y)		**	*	*	**
Irrigation (I)		**	*	**	**
Y*I		Ns	Ns	ns	ns
Treatment (T)		**	**	**	**
Y*T		**	**	**	**
I*T		**	**	**	**
Y*I*T		**	**	**	**

B-NPK: living N-fixing bacteria + phosphate solubilizing bacteria + potassium solubilizing bacteria; B-N: living N-fixing bacteria; F-NPK, B-NP: nitrogen and phosphorus biofertilizers; B-NK: nitrogen and potassium biofertilizers; F + B-PK: the combination of NPK chemical fertilizer and phosphorus and potassium; F + B-NK: the combination of NPK chemical fertilizer and nitrogen and potassium biofertilizers; F + B-NP: the combination of NPK chemical fertilizer and nitrogen and phosphorus biofertilizers; B-PK: phosphorus and potassium biofertilizers; B-K: potassium solubilizing bacteria; B-P: phosphate solubilizing bacteria; F + B-NPK: the combination of NPK chemical fertilizer and living N-fixing bacteria + phosphate solubilizing bacteria + potassium solubilizing bacteria; and Control: without fertilizer. Means with the same letters in each column are not significantly different based on the LSD test at a 5% probability level. *, **, and ns: significant at $p \leq .05$, $p \leq .01$, and non-significant.

plant was observed in F + NPKB at I_{80}, which was 71% higher compared with the control at I_{50} and the control (Table 4). Moreover, it was observed that F + NPB led to a 50% increase in the number of sub-branches per plant compared with PB in 2018 (Table 5).

The number of pods per plant

The results demonstrated a significant effect of fertilizer treatments under irrigation regimes on the number of pods per plant in both years of the experiment. The application of F + NPKB obtained the maximum number of pods per plant at I_{80}, which was significantly higher (5.6-fold) than that in the control at I_{50} (Table 4). The highest number of pods per plant was observed in NPKB and F + NPKB, respectively, in 2018 and 2019 (Table 5).

100-Grain weight

The fertilizer treatments had a significant effect on the 100-grain weight. The highest 100-grain weight was observed in F + NPKB in 2018 with a 34% increase compared with the control. However, in 2019, the maximum 100-grain weight was observed in F + NKB, which was not significantly different from F (NPK chemical fertilizer) (Table 5).

Grain yield

The F + NPKB-treated chickpea plants showed the greatest grain yield at I_{80}, which was not significantly different from NPKB. At I_{50}, the application of PB reduced the adverse effects of water deficit on plants and increased grain yield (Table 6). However, in the absence of fertilizer application at I_{50}, the grain yield was severely affected, resulting in an 88% reduction.

Table 6. Interaction of irrigation regimes and nutritional treatments on grain yield, biomass, and HI in chickpea plants.

Irrigation treatments	Nutritional treatments	Grain yield (kg/ha)	Biomass (kg/ha)	HI (%)
I-80	B-NPK	1046^{ab}	2697^{bc}	40.2$^{a–c}$
	B-N	566$^{g–j}$	2478^{cd}	22$^{g–i}$
	F-NPK	484$^{j–l}$	1490^{k}	33$^{c–f}$
	B-NP	327^{m}	1933$^{f–i}$	15.8^{ij}
	B-NK	743^{ef}	2100$^{e–h}$	38.2^{bc}
	F + B-PK	532$^{h–j}$	2356de	22$^{g–i}$
	F + B-NK	893^{cd}	1988$^{f–i}$	46.2^{ab}
	F + B-NP	403$^{k–m}$	1994$^{f–i}$	19^{hi}
	B-PK	559$^{g–j}$	1592^{jk}	35.8$^{c–e}$
	B-K	464$^{j–l}$	2036$^{f–h}$	22$^{f–h}$
	B-P	653$^{f–h}$	2128$^{e–g}$	33.8^{c}
	F + B-NPK	1167^{a}	3177^{a}	36.1 ^{cd}
	Control	661^{gh}	1917$^{g–i}$	37.7 ^{cd}
I-50	B-NPK	843de	2863^{b}	29.2$^{e–g}$
	B-N	737^{ef}	2079$^{f–h}$	37^{cd}
	F-NPK	609$^{g–i}$	2182^{ef}	27.8$^{e–g}$
	B-NP	340^{m}	2089$^{f–h}$	14.7^{ij}
	B-NK	383^{lm}	2113$^{e–g}$	17.8$^{h–j}$
	F + B-PK	659^{fg}	1481^{k}	46.8^{a}
	F + B-NK	310^{m}	1753^{ij}	18^{hi}
	F + B-NP	542$^{g–j}$	1624^{jk}	34.7$^{c–e}$
	B-PK	288^{m}	1839$^{h–j}$	15.3^{ij}
	B-K	509$^{i–k}$	2077$^{f–h}$	25$^{d–g}$
	B-P	982^{bc}	2859^{b}	34.3$^{c–e}$
	F + B-NPK	373^{lm}	989^{l}	37.8^{c}
	Control	143^{n}	1389^{k}	9.83^{j}
ANOVA (*p* values)				
Year (Y)		ns	ns	ns
Irrigation (I)		ns	ns	ns
Y*I		ns	ns	ns
Treatment (T)		**	**	**
Y*T		ns	**	**
I*T		**	**	**
Y*I*T		**	ns	**

I-80: 80% field capacity; I-50: 50% field capacity; B-NPK: living N-fixing bacteria + phosphate solubilizing bacteria + potassium solubilizing bacteria; B-N: living N-fixing bacteria; F-NPK, B-NP: nitrogen and phosphorus biofertilizers; B-NK: nitrogen and potassium biofertilizers; F + B-PK: the combination of NPK chemical fertilizer and phosphorus and potassium; F + B-NK: the combination of NPK chemical fertilizer and nitrogen and potassium biofertilizers; F + B-NP: the combination of NPK chemical fertilizer and nitrogen and phosphorus biofertilizers; B-PK: phosphorus and potassium biofertilizers; B-K: potassium solubilizing bacteria; B-P: phosphate solubilizing bacteria; F + B-NPK: the combination of NPK chemical fertilizer and living N-fixing bacteria + phosphate solubilizing bacteria + potassium solubilizing bacteria; and Control: without fertilizer. Means with the same letters in each column are not significantly different based on the LSD test at a 5% probability level. *, **, and ns: significant at $p \leq .05$, $p \leq .01$, and non-significant.

Biomass

Plant biomass varied under irrigation regimes and fertilizer treatments in the 2 years of the experiment. Plant biomass was enhanced by increasing the availability of water and the application of F + NPKB (Table 6). Although at I_{50} the highest plant biomass was observed in NPKB, the highest plant biomass was obtained from F + NPKB at I_{80} (3177 kg/ha) (Table 6). The highest plant biomass was obtained in NPKB in 2018, resulting in a 51% increase compared with the lowest plant biomass obtained from the control in 2019 (Table 7).

Harvest index

The application of fertilizer treatments under irrigation regimes significantly affected the HI in both years of the experiment. The application of F + PKB resulted in the highest HI (46.8%) at I_{50} irrigation, which was not significantly different from F + NKB and NPKB at I_{80}, resulting in a 79% increase compared with the lowest HI in the control at I_{50} (Table 6). In 2018, the application of F + NPKB resulted in the highest HI, leading to a 68% increase compared with the lowest HI obtained from NPB-treated plants in 2019 (Table 7).

Shoot potassium content

The irrigation regimes and fertilizer treatments significantly affected shoot potassium content. Shoot potassium content was higher in 2019 than in 2018 at both levels of irrigation regimes. In 2018, the highest shoot potassium content was observed at I_{80}, which was 2.1 folds higher than I_{50} (Table 8). The highest shoot potassium content was obtained from PKB in 2019, while the lowest shoot potassium content was observed in the control in 2018 (Table 9).

Shoot phosphorus content

Fertilizer treatments and irrigation regimes significantly affected shoot phosphorus content. The highest shoot phosphorus content was observed at I_{80} in 2018 (Table 8). It was found that the maximum shoot phosphorus content was obtained from F + NPB at I_{80} with a 45% higher value

Table 7. Interaction of planting year and nutritional treatments on biomass and HI of chickpea plants.

Year	Nutritional treatments	Biomass (kg/ha)	HI (%)	Year	Nutritional treatments	Biomass (kg/ha)	HI (%)
2018	B-NPK	2944^{a}	$34.3^{a–d}$	2019	B-NPK	2617^{bc}	$35^{a–c}$
	B-N	2332^{de}	$31.6^{a–f}$		B-N	$2225^{d–f}$	$27.3^{c–h}$
	F-NPK	2158^{ef}	$29.5^{b–g}$		F-NPK	1514^{i}	$31.3^{a–f}$
	B-NP	2437^{cd}	18.3^{ij}		B-NP	1586^{i}	12.2^{j}
	B-NK	$2203^{d–f}$	$29.2^{c–g}$		B-NK	2010^{fg}	$26.8^{d–h}$
	F + B-PK	2149^{ef}	$31.3^{a–f}$		F + B-PK	1687^{hi}	37.5^{ab}
	F + B-NK	2051^{fg}	$31.8^{a–f}$		F + B-NK	1690^{hi}	$32.3^{a–f}$
	F + B-NP	2008^{fg}	$27.2^{c–h}$		F + B-NP	1609^{hi}	$26.5^{d–h}$
	B-PK	1864^{gh}	$31.7^{a–f}$		B-PK	1566^{i}	$19.5^{h–j}$
	B-K	2851^{ab}	$32.8^{a–e}$		B-K	$2363^{c–e}$	$26^{e–i}$
	B-P	2799^{ab}	$30.5^{a–f}$		B-P	$2188^{d–f}$	37.7^{a}
	F + B-NPK	1543^{i}	38.5^{a}		F + B-NPK	1523^{i}	$24.3^{f–i}$
	Control	1860^{gh}	$22.2^{g–i}$		Control	1446^{i}	$25.3^{e–i}$

B-NPK: living N-fixing bacteria + phosphate solubilizing bacteria + potassium solubilizing bacteria; B-N: living N-fixing bacteria; F-NPK, B-NP: nitrogen and phosphorus biofertilizers; B-NK: nitrogen and potassium biofertilizers; F + B-PK: the combination of NPK chemical fertilizer and phosphorus and potassium; F + B-NK: the combination of NPK chemical fertilizer and nitrogen and potassium biofertilizers; F + B-NP: the combination of NPK chemical fertilizer and nitrogen and phosphorus biofertilizers; B-PK: phosphorus and potassium biofertilizers; B-K: potassium solubilizing bacteria; B-P: phosphate solubilizing bacteria; F + B-NPK: the combination of NPK chemical fertilizer and living N-fixing bacteria + phosphate solubilizing bacteria + potassium solubilizing bacteria; and Control: without fertilizer. Means with the same letters in each column are not significantly different based on the LSD test at a 5% probability level.

Table 8. Interaction of year and irrigation regimes on shoot potassium, phosphorus, and nitrogen content in chickpea.

Year	Irrigation regimes	Potassium (mg/g DW)	Phosphorus (mg/g DW)	Nitrogen (mg/g DW)
2018	I-80	12.9^{b}	5.46^{a}	30.4^{a}
	I-50	8.05^{c}	4.01^{b}	25.9^{c}
2019	I-80	17.1^{a}	4.57^{b}	28.7^{ab}
	I-50	15.2^{ab}	4.26^{b}	26.9^{bc}
ANOVA				
Year (Y)		**	**	Ns
Irrigation (I)		**	**	**
Y*I		**	**	**
Treatment (T)		**	**	**
Y*T		**	**	**
I*T		ns	*	Ns
Y*I*T		**	*	**

I-80: 80% field capacity; I-50: 50% field capacity. Means with the same letters in each column are not significantly different based on the LSD test at a 5% probability level. *, **, and ns: significant at $p \leq .05$, $p \leq .01$, and non-significant.

compared with the control at I_{50} (Table 10). It was observed that the highest shoot phosphorus content belonged to the F + PKB in 2018. However, in 2019, the highest shoot phosphorus content was obtained from PKB (Table 9).

Shoot nitrogen content

The irrigation regimes and fertilizer treatments significantly impacted shoot nitrogen content. In 2018, the highest shoot nitrogen content was obtained from NPKB; however, the PKB-treated plants showed higher shoot nitrogen content in 2019. Furthermore, the experiment showed that the lowest nitrogen content was observed in 2018 when no fertilizer was applied, leading to a 36% decrease compared to NPKB in the same year (Table 9).

Discussion

Morphological traits, growth, yield, and yield components of chickpea plants under irrigation regimes and nutritional treatments

Integrated nutrient management is an advisable application of fertilizers from dissimilar sources to a field consecutively to preserve environmental sustainability. The present study was planned to study the effects of various biological fertilizers on chickpea growth and production alone and in combination with NPK fertilizers. Although the plant growth-promoting activity of biofertilizers has been well studied, there are only a few reports of synergistic effects of the combination of chemical and biofertilizers (Kang et al. 2017; Prabhukarthikeyan, Keerthana, and Raguchander 2018).

Biofertilizers have a potential role in mitigating the adverse effects of water deficit in plants (Azab 2016). Studies have shown that microorganisms are beneficial in increasing the abiotic stress resistance of plants (Olanrewaju, Glick, and Babalola 2017; Saadatfar et al. 2023). The microorganisms are involved in the biological activity of the rhizosphere and can effectively absorb nutrients, crop growth, and soil fertility improvement, affect the breakdown of organic matter, plant metabolism, plant tolerance to stress, and crop yield (Hamid et al. 2021; Saadatfar et al. 2023).

The present 2-year field trial showed that fertilization treatments with combinations of bio and chemical fertilizers significantly increased the growth attributes such as plant height, number of branches, and yield and yield components of chickpea plants under both irrigation regimes. The application of biofertilizers led to improvements in plant height, number of leaves, fresh and dry weights of shoot and root, and root length of different plant species compared with the untreated

Table 9. Interaction of planting year and nutritional treatments on shoot potassium, phosphorus, and nitrogen content, biomass, and HI of chickpea.

Year	Nutritional treatment	Potassium (mg/g DW)	Phosphorus (mg/g DW)	Nitrogen (mg/g DW)	Year	Nutritional treatments	Potassium (mg/g DW)	Phosphorus (mg/g DW)	Nitrogen (mg/g DW)
2018	B-NPK	13.2^{d-h}	5.33^{a-d}	31.5^{a}	2019	B-NPK	16.3^{b-d}	4.23^{h-j}	27.4^{d-f}
	B-N	7.6^{jk}	4.20^{ij}	26.4^{e-g}		B-N	14.6^{c-f}	4.11^{i-k}	27.7^{de}
	F-NPK	12.4^{e-i}	5.41^{ab}	30.9^{a}		F-NPK	15.5^{b-e}	4.70^{e-h}	28.6^{b-d}
	B-NP	9.38^{i-k}	4.86^{d-f}	30.5^{a}		B-NP	15.2^{c-e}	4.13^{i-k}	28.4^{cd}
	B-NK	10.9^{g-j}	4.36^{g-j}	28.3^{d}		B-NK	13.8^{d-h}	4.28^{g-j}	27.6^{de}
	F + B-PK	13.9^{d-g}	5.58^{a}	31.1^{a}		F + B-PK	15.6^{b-e}	4.18^{ij}	26.3^{e-g}
	F + B-NK	9.28^{i-k}	4.70^{e-h}	30^{a-c}		F + B-NK	16.7^{b-d}	4.93^{c-f}	28.7^{b-d}
	F + B-NP	10.2^{h-j}	5.06^{b-e}	30.1^{ab}		F + B-NP	18.1^{a-c}	5.20^{a-d}	30.9^{a}
	B-PK	11^{f-j}	4.71^{e-g}	25.8^{f-h}		B-PK	21.5^{a}	5.40^{a-c}	31.3^{a}
	B-K	10.9^{i-k}	4.01^{jk}	25^{gh}		B-K	16.4^{b-d}	4.56^{f-i}	28.4^{d}
	B-P	8.63^{jk}	4.56^{f-i}	24.5^{hi}		B-P	14.8^{c-e}	4.03^{jk}	26.1^{e-h}
	F + B-NPK	15^{c-e}	5.53^{ab}	31.2^{a}		F + B-NPK	12.5^{e-i}	3.66^{k}	22.9^{i}
	Control	5.85^{k}	3.15^{l}	20.2^{j}		Control	19^{ab}	3.95^{jk}	26.7^{ef}

B-NPK: living N-fixing bacteria + phosphate solubilizing bacteria + potassium solubilizing bacteria; B-N: living N-fixing bacteria; F-NPK, B-NP: nitrogen and phosphorus biofertilizers; B-NK: nitrogen and potassium biofertilizers; F + B-PK: the combination of NPK chemical fertilizer and phosphorus and potassium; F + B-NK: the combination of NPK chemical fertilizer and nitrogen and potassium biofertilizers; F + B-NP: the combination of NPK chemical fertilizer and nitrogen and phosphorus biofertilizers; B-PK: phosphorus and potassium biofertilizers; B-K: potassium solubilizing bacteria; B-P: phosphate solubilizing bacteria; F + B-NPK: the combination of NPK chemical fertilizer and living N-fixing bacteria + phosphate solubilizing bacteria + potassium solubilizing bacteria; and Control: without fertilizer. Means with the same letters in each column are not significantly different based on the LSD test at a 5% probability level.

Table 10. Interaction of irrigation regimes and nutritional treatments on shoot phosphorus content in chickpea.

Irrigation treatments	Nutritional treatments	Phosphorus (mg/g DW)	Irrigation treatments	Nutritional treatments	Phosphorus (mg/g DW)
I-80	B-NPK	5.05[b–d]	I-50	B-NPK	4.51[f–h]
	B-N	4.91[b–e]		B-N	3.40[lm]
	F-NPK	5.38[ab]		F-NPK	4.73[c–g]
	B-NP	4.85[c–f]		B-NP	4.15[h–k]
	B-NK	4.91[b–e]		B-NK	3.73[kl]
	F + B-PK	5.33[ab]		F + B-PK	4.43[f–i]
	F + B-NK	5.08[bc]		F + B-NK	4.55[e–h]
	F + B-NP	5.75[a]		F + B-NP	4.51[e–h]
	B-PK	5.68[a]		B-PK	4.43[f–i]
	B-K	4.85[c–f]		B-K	3.73[kl]
	B-P	4.58[d–h]		B-P	4.01[i–k]
	F + B-NPK	4.85[c–f]		F + B-NPK	4.35[g–j]
	Control	3.91[j–k]		Control	3.18[m]

I-80: 80% field capacity; I-50: 50% field capacity; B-NPK: living N-fixing bacteria + phosphate solubilizing bacteria + potassium solubilizing bacteria; B-N: living N-fixing bacteria; F-NPK, B-NP: nitrogen and phosphorus biofertilizers; B-NK: nitrogen and potassium biofertilizers; F + B-PK: the combination of NPK chemical fertilizer and phosphorus and potassium; F + B-NK: the combination of NPK chemical fertilizer and nitrogen and potassium biofertilizers; F + B-NP: the combination of NPK chemical fertilizer and nitrogen and phosphorus biofertilizers; B-PK: phosphorus and potassium biofertilizers; B-K: potassium solubilizing bacteria; B-P: phosphate solubilizing bacteria; F + B-NPK: the combination of NPK chemical fertilizer and living N-fixing bacteria + phosphate solubilizing bacteria + potassium solubilizing bacteria; and Control: without fertilizer. Means with the same letters in each column are not significantly different based on the LSD test at a 5% probability level.

plants (Batool et al. 2020; Ejaz et al. 2020; Gasemi et al. 2023). In the present study, biofertilizers also improved plant height compared with the untreated plants under water deficit. The superiority of the height of plants treated with the F + NPKB (NPK chemical fertilizer + N-fixing bacteria + P solubilizing bacteria + K solubilizing bacteria biofertilizers) was probably due to more availability of nutrients to plants under both irrigation regimes. It was also reported that inoculation of chickpea plants with some strains of *Rhizobium* sp. increased plant height by improving nutrient absorption and increasing plant photosynthesis (Singh, Singh, and Saravaiya 2018). Plant access to nutrients, especially nitrogen, is a determinant factor in increasing plant height by affecting cell division and enlargement (Campelo et al. 2019). In a study on cumin (*Cuminum cyminum* L.) ecotypes, bacterial siderophore also improved leaf physiochemical characteristics, nutrient uptake, and grain yield (Hafezi Ghehestani et al. 2021). They believed that the microorganisms can either increase the Fe availability for cellular use or regulate Fe homeostasis in the plant.

In the present study, the greatest number of sub-branches per plant was observed in F + NPKB in well-watered plants. The combined application of chemical fertilizers and nitrogen and phosphorus biofertilizers also enhanced the number of sub-branches when the water restrictions were not severe, which can be due to faster access to chemical fertilizers under moderate stress conditions (Fang et al. 2021). Besides, the favorable effects of phosphorus solubilizing bacteria on root growth help more water absorption and enhance the number of sub-branches under severe drought stress (Anli et al. 2020). Generally, the combination of biochemical fertilizers has affected the growth of various plant species (Widawati 2018; Sheteiwy et al. 2021). Previous research revealed that the maximum number of sub-branches of pinto bean (*Phaseolus vulgaris* L.) was obtained from full irrigation with biofertilizer, while severe stress without biofertilizer application decreased the number of sub-branches (Amini et al. 2020). It was reported that inoculation with *Azotobacter nigricans* significantly improved maize yield, and biochemical and physiological parameters compared to the control and NPK-treated plants (Sagar et al. 2022). However, the dual application of *Azotobacter nigricans* and NPK chemical fertilizer increased the grain yield more than the sole use of *Azotobacter nigricans* or NPK. The *Azotobacter nigricans* could reduce the use of chemical fertilizers; however, the increase in the plant growth parameters could be due to the greater availability of nitrogen in the integrated and organic treatments (Sagar et al. 2022).

The distribution and allocation of photosynthetic products to the flowers and seeds are critical for maintaining more pods per plant. Although the water deficit decreased the number of pods in chickpea plants, the combined application of biochemical fertilizers enhanced the number of pods per plant. Franco, Prajapati, and Maruthi Sankar (2022) found that the number of pods in pea (*Pisum sativum* L.) plants was higher in the irrigated than in water-stressed plants. They concluded that one of the reasons for reducing the number of pods in water deficit regimes is the reduction of the pollination period, resulting in a reduction in the number of pods. In another study, it was observed that the combination of three types of biofertilizers enhanced the number of pods in the sesame (*Sesamum indicum* L.) plants (Farokhian, Tohidi-Nejad, and Mohammadi-Nejad 2021). The combination of biochemical fertilizers enhanced the number of pods per plant in lentil (*Lens culinaris*) plants (Paul et al. 2020). These results indicate the vulnerability of the number of pods per plant to water deficit; however, the biological fertilizers, solely or in combination with the chemical fertilizers, could mitigate the adverse effects of water deficit.

The combination of biological and chemical fertilizers enhanced the 100-grain weight of chickpea plants. Chemical fertilizers could probably provide suitable nutritional conditions for the multiplication and activity of bacteria in biofertilizers because those bacteria need nutritional elements in a healthy environment for their growth and nitrogen fixation. Therefore, the appropriate biofertilizer treatments provided more suitable conditions for improving biological activities in the soil and increased the 100-grain weight through the improved absorption of nutrients by roots. Accordingly, it has also been found that the combined use of biological and chemical fertilizers increased the 100-grain weight (Abdalla, Abdelgani, and Osman 2013; Gomaa 2013; Kumar et al. 2022). The 100-grain weight had a positive correlation with the number of sub-branches and pods per plant in I_{80} (Table 11). A positive correlation was also observed between 100-grain weight and the number of pods per plant in I_{50} (Table 12). The number of sub-branches and the 100-grain weight in soybean were also positively correlated (El-Badawy and Mehasen 2012). Sub-branches directly affect the grain weight by influencing the pod formation and the number of grains.

The consumption of phosphorus-soluble biofertilizers under water deficit conditions promoted chickpea yield and alleviated stress intensity by stimulating root growth and nutrient adsorption. Singh, Sekhon, and Sharma (2011) also reported a significant increase in chickpea grain yield under the biofertilizer application and diminishing the effects of water limitation. In another study, the increase in soybean biomass was reported by the influence of phosphorus and nitrogen

Table 11. Pearson's correlation coefficient of the morphological traits, yield, yield components, and shoot nutrient element content of chickpea plants at I-80 (80% of the field capacity).

	Plant height	Number of sub-branches	Total number of pods per plant	100-grain weight	Potassium	Phosphorus	Nitrogen	Grain yield	Biomass	HI
	1	2	3	4	5	6	7	8	9	10
1	1									
2	0.36**	1								
3	0.64**	0.21 ns	1							
4	0.49**	0.26*	0.63**	1						
5	0.17 ns	0.26*	0.09 ns	0.06 ns	1					
6	0.34**	0.37**	0.21 ns	0.22 ns	0.75**	1				
7	0.24**	0.30**	0.16 ns	0.21 ns	0.66**	0.83**	1			
8	0.04ns	0.07ns	0.14ns	0.006ns	0.17ns	0.07ns	−0.09ns	1		
9	0.02ns	0.10ns	0.14ns	−0.06ns	0.19ns	0.14ns	−0.06ns	0.70**	1	
10	−0.02ns	0.02ns	−0.0001ns	0.08ns	0.04ns	−0.08ns	−0.11ns	0.52**	−0.17ns	1

*, **, and ns: significant difference at 5% and 1% probability levels and no significant difference, respectively.

Table 12. Pearson's correlation coefficient of the morphological traits, yield, yield components, and shoot nutrient element content of chickpea plants at I-50 (50% of the field capacity).

	Plant height	Number of sub-branches	Total number of pods per plant	100-grain weight	Potassium	Phosphorus	Nitrogen	Grain yield	Biomass	HI
	1	2	3	4	5	6	7	8	9	10
1	1									
2	0.16ns	1								
3	0.59**	0.43**	1							
4	0.34**	0.03ns	0.39**	1						
5	0.20ns	−0.05ns	0.24*	0.36**	1					
6	0.21ns	−0.12ns	0.29*	0.43**		1				
7	0.24*	0.03ns	0.28*	0.34**	0.56**	0.86**	1			
8	0.08ns	0.12ns	0.28*	−0.11ns	−0.11ns	−0.08ns	−0.08ns	1		
9	0.02ns	0.38**	0.13ns	−0.18ns	−0.22ns	−0.18ns	−0.13ns	0.77**	1	
10	0.20ns	−0.19ns	0.34**	0.14ns	0.09ns	0.15ns	0.11ns	0.60**	0.04ns	1

*, **, and ns: significant difference at 5% and 1% probability levels and no significant difference, respectively.

biofertilizers under water shortage conditions (Sheteiwy et al. 2021). Phosphorus availability increases the activity of hormones such as cytokinin, which plays a vital role in cell division and development in meristemic regions, and stimulates the growth of plant organs (Divjot et al. 2019). According to Shoghi-Kalkhoran et al. (2013), an amalgamation of bio and chemical fertilizers augmented grain yield, plant height, biological yield, HI, plant height, dry matter accumulation per plant, and Leaf Area Index (LAI) of sunflower over the chemical fertilizer. These beneficial effects can be attributed to the biosynthesis of biologically active substances, the stimulation of rhizospheric microorganisms, the production of phytopathogen inhibitors, and improved nutrient availability of N, P, carbon, and sulfur through Biological Nitrogen Fixation (BNF) and mineralization of organic residues in the soil (Patel et al. 2020). Moreover, the use of biostimulators under environmental stress conditions can shrink the effects of stress and boost soil water-holding capacity, root growth, and production (Shirkhani and Nasrolahzadeh 2016).

The grain yield was positively correlated with the number of pods per plant at I_{50} (Table 12). A positive correlation between the number of pods per plant and grain yield was also observed in lentil plants under heat stress (Choukri et al. 2020). The most effective yield component to increase grain yield was the number of pods under the condition of water deficit (Langat et al. 2019). Plant biomass was positively correlated with grain yield at both irrigation regimes (Tables 11 and 12). Plant biomass has a critical role in the grain yield of plants. To achieve greater grain yield, it is necessary to have proper vegetative growth (Sun et al. 2019); therefore, higher plant biomass production helps to increase grain yield.

The variations in the HI are highly dependent on the variation in grain yield and plant biomass. Water deficit adversely affected plant biomass, while its effect on grain yield was relatively less. Therefore, the HI showed a smaller reduction in these conditions. More precipitation and lower evapotranspiration in 2018 had a higher contribution in promoting the biomass and grain yield, and the HI. The biofertilizers contain bacteria that have a wide range of plant growth-stimulating properties that directly or indirectly enhance plant growth and the crop HI (Gouda et al. 2018). These results were consistent with previous studies on soybeans (Wangiyana and Farida 2019), mung beans (Singh, Singh, and Saravaiya 2018), and wheat (Din et al. 2021).

Biofertilizers inhibited the reduction of crop element content (K, P, and N) under water deficit conditions

The higher precipitation in 2018 led to an increase in the nutrient element content in chickpea shoots compared to 2019 (Table 1). It has been found that the reduction in rainfall and available water disturbs the transportation of elements in the plant. As a result, the plant suffers from a deficiency of various elements (Boring et al. 2018). Shoot potassium content was reduced under water deficit conditions. Under water stress conditions, root growth is inhibited and the potassium ions diffusion into the root is limited; therefore, the tolerance of the plant to the stress is reduced (Wang et al. 2013). In an experiment, the highest shoot potassium content of pea plants was obtained from the combined application of chemical fertilizers and potassium solubilizing bacteria (Mukhongo et al. 2017). Soil is the sole source of potassium and *Azotobacters* could promote the dissolution of the soil mineral potassium (Sagar et al. 2022). Previous studies showed that *Azotobacter* species can solubilize K and play a significant role in improving potassium absorption by plants (Singh, Biswas, and Marwaha 2010; Baba et al. 2021). Potassium solubilizing bacteria dissolve the insoluble potassium that stabilized in the form of minerals such as muscovite, orthoclase, biotite, feldspar, illite, and mica in the soil and make it available to the plant and improve the plant potassium absorption (Meena, Maurya, and Verma 2014).

Phosphorus adsorption was decreased under water deficit conditions especially when no fertilizer was applied. When phosphorus as a chemical fertilizer along with phosphorus biofertilizer was used, the solubility of phosphorus in the root zone was increased; as a result, phosphorus adsorption was enhanced by the plant. The use of nitrogen and phosphorus biofertilizers with chemical fertilizers enhanced the release of phosphorus from phosphorus fertilizers under water deficit conditions. Therefore, more phosphorus will be available to the plant (Moradzadeh et al. 2021). The nicotinamide adenine dinucleotide phosphate (NADPH) production, as a regenerating factor in the process of phosphorus adsorption, decreased under stressful conditions and caused the immobility of phosphorus in the soil and decreased the availability of phosphorus; therefore, root growth and activity were decreased in dry soil (Dey et al. 2021). The correlation results indicated that the shoot phosphorus content had a positive relationship with shoot potassium content in both irrigation regimes (I_{80} and I_{50}) (Tables 11 and 12). Given that potassium has a significant effect on the water relations of the plant, therefore, it can affect the adsorption of elements (Sarwar et al. 2019).

It was reported that the *Azotobacter nigricans* strain excretes extracellular phosphate solubilizing enzymes such as phytase (133UI in 48 hr of fermentation) and phosphatase (170UI in 48 hr of fermentation), which can solubilize the rock phosphate and make it available to plants (Sagar et al. 2022). Din et al. (2019) also observed a significant increase in the concentration of phytase, phosphatase, and soluble phosphorus after 48 hr of fermentation along with a decrease in soluble phosphorus concentration. This decrease may be due to the utilization of phosphorous by fungus mycelia. Although fungi produce these enzymes to solubilize phosphate and phytic acid for their own growth. Consequently, a considerable amount of phosphorus becomes available to plants as well.

Nitrogen is absorbed from the soil by water, so nitrogen absorption is disrupted under drought stress conditions. In various experiments, it has been found that the leaf nitrogen content of mung bean (*Vigna radiata* L.) (Ghassemi et al. 2018) and wheat (*Triticum aestivum*) (Cisse et al. 2019) grains were reduced with an increase in the water stress level. Shoot nitrogen content was increased when phosphorous biofertilizer was applied due to the significant role of phosphorus in providing energy as Adenosine triphosphate (ATP) because much energy is needed for nitrogen fixation (Marschner 2011). Therefore, phosphorus biofertilizers boosted nitrogen availability by reducing the effect of water deficit. It has been reported that in the chemical treatments, most of the nitrogen would be leached from the soil profile (Sagar et al. 2022). Although the nitrogen content of chickpea grain was not estimated in this study, several other studies showed that grain nitrogen content was enhanced by the plant growth promoting bacterias (PGPBs), which results in higher protein content of grains (dos Santos et al. 2020; Yadav et al. 2021).

Shoot nitrogen content had a positive correlation with plant height and the number of sub-branches at I_{80}. Furthermore, shoot nitrogen content was positively correlated with plant height, the number of pods per plant, and 100-grain weight at I_{50} (Tables 11 and 12). A balanced amount of nitrogen increased the number of pods in chickpea plants by reducing the water limitation effects (Branch 2009). Shoot nitrogen content had a positive relationship with shoot phosphorus and potassium contents under I_{80} and I_{50} irrigation regimes (Tables 11 and 12). It has been reported that there was a synergistic relationship between nitrogen and phosphorus in chickpeas (Ahmad, Khan, and Zaidi 2013; Ejaz et al. 2020). Increasing the ability to adsorb each element can increase the plant's ability to adsorb other elements (Xu et al. 2020). Phosphorus increases the length and volume of the root; therefore, more space of the soil would be in contact with the root, leading to an increase in the adsorption of nutrient elements, including nitrogen (Postma, Dathe, and Lynch 2014).

The presence of beneficial rhizosphere bacterial species and the structure of the bacterial community were significantly altered by the inoculation of *Bacillus amyloliquefaciens*, leading to improved uptake of essential elements such as N, P, and K (Qin et al. 2017). Under drought stress, the highest level of ATP content was observed in plants treated with mycorrhiza and *Bacillus amyloliquefaciens*. The H^+-ATPase is vital for plant response to stressful conditions (Ahmed et al. 2013). Positive relationships were observed between the activities of H^+-ATPase, Ca^{2+}-ATPase, and Mg^{2+}-ATPase, seed quality, and ATP. The enhanced ATP synthesis may contribute to providing a proton concentration gradient for the absorption of plant nutrients (Liang and Zhang 2018). The increased H^+-ATPase, Ca^{2+}-ATPase, and Mg^{2+}-ATPase activities, regardless of which biofertilizers were applied, elucidated that biofertilizers could help to maintain a higher electrochemical gradient across the plasma membrane to drive nutrient uptake under stressful condition (Ahmed et al. 2013).

Conclusion

Global agriculture will not only have to improve stress resistance and yield of crops for food and biomass production but also should reduce the dependence of producers on agrochemicals for a sustainable food system and environmental health. Despite its enormous potential, the application of combined biofertilizers and chemical fertilizers, as yet, has not been fully adopted by farmers. Although chickpea grain yield was decreased under water deficit, the use of biochemical fertilizers mitigated the adverse effects of water deficit on the yield. The F + NPKB treatment in I_{80} showed the highest plant height, number of primary branches, number of pods per plant, 100-grain weight, grain yield, and plant biomass. Hence, biochemical fertilization technology is more likely to be affordable for farmers in harsh areas and also those in developing countries for a sustainable crop-growing system.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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